SOFIA UNIVERSITY
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ASSESSMENT OF RIVER RUNOFF AND WATER RESOURCES IN THE CATCHMENT AREAS WEST OF THE OGOSTA RIVER

ABSTRACT

of the PhD thesis for awarding the
educational and scientific degree „Doctor“ in a
professional field 4.4 Earth Sciences
(Hydrology and water resources)

Scientific supervisor: Prof. Nelly Hristova, PhD

Sofia, 2024

General information

The PhD thesis has undergone a preliminary discussion at a meeting of the Department of "Climatology, Hydrology, and Geomorphology" on 13.12.2023, at which a decision was made to refer a procedure to a public defense.

The doctoral dissertation consists of 212 pages, of which 133 pages are the main text and the remaining 79 pages are the appendices. The bibliographic review includes 142 sources, of which 86 are in Cyrillic and the remaining 56 are in Latin. The study is illustrated with 27 figures, 46 tables, and 14 appendices. The numbering of tables and figures in the abstract corresponds to that used in the PhD thesis.

The scientific jury has been approved by the Council of the Faculty of Geology and Geography. The commission includes:

Prof. Nina Nikolova, PhD
Assoc. Prof. Emilia Tcherkezova, PhD
Assoc. Prof. Kalina Radeva, PhD
Assoc. Prof. Krasya Kolcheva, PhD
Assoc. Prof. Kristina Gartsiyanova, PhD

The public defense will take place on 26.04.2024 from 12 h in a 242 hall at Sofia University “St. Kliment Ohridski”.

The materials are available in a 254 room.

CONTENT[1]

[1] The content is consistent with the structure of the abstract.

INTRODUCTION

Actuality of the problem. The study of the quantitative and qualitative change of streamflow and water resources under global warming and anthropogenic influences represents one of the most challenging tasks facing modern hydrology. A lot of authors worldwide found a decrease in the annual, monthly, and seasonal streamflow as a result of the rising air temperatures and anthropogenic impacts (Banasik *et al.*, 2012, Shengzhi *et al.*, 2015, Umar *et al.*, 2018, Arslan *et al.*, 2020, Zhong *et al.*, 2021, Xu *et al.*, 2022), an increase in the frequency of extreme hydrological events (Merz *et al.*, 2014, Thieken *et al.*, 2016, Weerasinghe *et al.*, 2018, Milanović-Pešić, 2020, Rivera *et al.*, 2021, Achite *et al.*, 2022), an increase in the volume of water use (Li *et al.*, 2015, Wada *et al.*, 2016), as well as a deterioration in surface water quality (Terrado *et al.*, 2010, Romero *et al.*, 2016, Thellmann *et al.*, 2017, Kirschke *et al.*, 2019, Kuczyńska *et al.*, 2021, Villanueva *et al.*, 2021). Those findings are confirmed in the Sixth report of the Intergovernmental Panel on Climate Change (IPCC) and occurred with varying intensity at the global and local scale, including on the territory of Bulgaria. The annual streamflow follows a negative tendency in recent decades (Lizama-Rivas & Koleva-Lizama, 2005, Artinyan *et al.*, 2021) and in dry years puts the population of the country in a situation of water stress (Hristova *et al.*, 2019). The declines in streamflow will most likely continue until the end of the 21st century, even according to the optimistic scenario RCP 2.6 ("River Basin Management Plan", 2022–2027). Those trends are combined with decreasing water use and improving water quality (Protich, 2013, Varbanov & Gartsiyanova, 2015, Varbanov *et al.*, 2015, Gartsiyanova, 2016, 2022, Radeva & Seymenov, 2021, Radeva, 2022, Seymenov, 2022, "Annual Report on the State and Protection of the Environment", 2022).

In this context, the current work analyzes the trends in the volume, regime, and physicochemical state of surface water in the northwestern part of the country, where small and medium rivers are located, which are most sensitive to climate changes and anthropogenic influences. The human pressures, although with a weakening force due to the negative demographic and economic processes in the last decades, still affect runoff and water quality.

The results of previous studies support the stated facts. The changes in runoff conditions (Nacheva, 2016), the sensitivity of streamflow to long-term climate variability (Seymenov, 2020), the flow abstraction and diversion (Zaharieva, 2005, Dimitrov, 2018, Temelkova, 2019, Seymenov, 2023), the increase of the amplitude between the minimum and maximum flow volume (Dakova, 1976, Hristova, 2014, Hristova *et al.*, 2017), as well as the change in the hydro-chemical properties (Vrbanov, 1992, Radeva & Seymenov, 2019, Seymenov, 2019, Radeva & Seymenov, 2020, Seymenov, 2021) prove the instability of the hydrological cycle in the region. Despite the growing number of papers, devoted to surface waters in the study area, no up-to-date data can be found in the scientific literature regarding annual, monthly, and seasonal runoff variations, extreme hydrological events, the degree of provision with water resources, and surface water quality in the face of climate change and anthropogenic impacts. The aspiration to expand and enrich the existing knowledge with new data for a current period argues the objective of the PhD thesis.

Object and subject of the study. The object of this study is the streamflow and water resources in the catchment areas of the rivers Topolovets, Voynishka, Vidbol, Archar, Skomlya, Lom, and Tsibritsa (grouped in the watershed of the rivers west of the Ogosta River, according to "River Basin Management Plan", 2022–2027). The subjects of this work are the annual, monthly, and seasonal flow variations, the extreme conditions of the runoff, the degree of provision with freshwater resources, and the quality of surface waters.

Aim and tasks of the study. The aim of the PhD thesis is an analysis and assessment of streamflow and water resources in the catchment areas west of the Ogosta River. This goal is achieved by the step-by-step implementation of the following tasks:

- Study of methods for quantitative and qualitative investigation of surface water resources in the face of climate change and anthropogenic impacts;
- Formation of times-series data about annual, monthly, and daily runoff values and physicochemical indices and assessment of their representativeness for the purposes of the study;
- Analysis of spatio-temporal and quantitative characteristics and tendencies in changes of annual runoff, monthly and seasonal streamflow, and extreme hydrological events;
- Evaluating the degree of provision of the population with water resources and assessing the surface water quality.

The realization of the goal and the implementation of the research tasks are expected to provide new information on the current state of the river runoff and water resources in the catchments west of the Ogosta River. The obtained results would serve as support for further theoretical analyses and management decisions.

Limitations of the study. The present study is limited by the lack of publicly available information on daily water quantities after 1983 and by aggregated water use data referring to the entire Danube River Basin Management Area rather than to individual catchments.

FIRST CHAPTER

THEORETICAL AND METHODOLOGICAL BASIS OF THE STUDY

The investigation of the quantitative and qualitative features of surface water is based on experimental, statistical, graphic, and cartographic methods (Hristova, 2010, Gartsiyanova, 2022).

SECOND CHAPTER
STUDY AREA, DATA AND METHODS

2.1 Study area. The investigated region includes the catchments of the rivers Topolovets, Voynishka, Vidbol, Archar, Skomlya, Lom, and Tsibritsa – right tributaries of the Danube River in Northwestern Bulgaria (Fig. 1). The studied region covers an area of 3790 km^2 (Hristova, 2012).

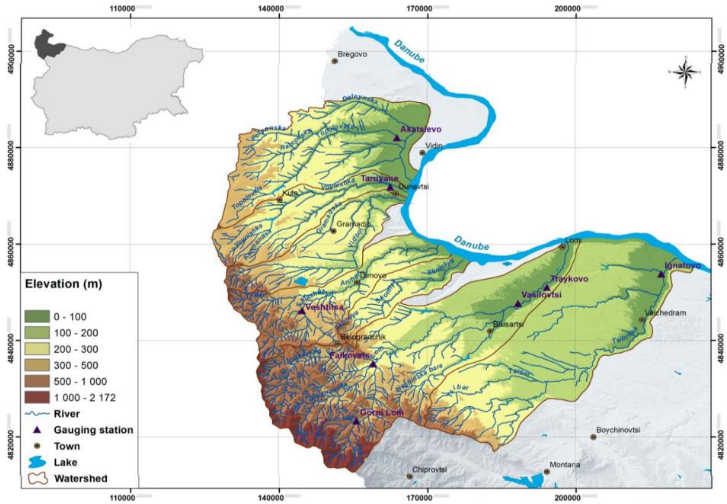

Figure 1. Map of the relief, drainage systems, and gauging stations in the catchments west of the Ogosta River (Hristova *et al.*, 2017)

2.2 Data. The basis of this study is data from the National Institute of Meteorology and Hydrology (NIMH) regarding annual, monthly, and daily discharge at eight hydrometric stations (HMS), as well as information from the control monitoring of the Environmental Executive Agency (EEA) concerning ten physicochemical variables measured at eight water sampling points.

2.3 Methods. The current research is based both on general (analysis, synthesis, comparison, etc.) and specific (statistical, hydrological, graphic, etc.) scientific methods, which are described in detail in the dissertation.

THIRD CHAPTER

FACTORS AFFECTING STREAMFLOW AND WATER QUALITY IN THE CATCHMENTS WEST OF THE OGOSTA RIVER

The third chapter describes the nature-geographical factors (climate, relief, geology, soil, vegetation, etc.) and anthropogenic conditions (agriculture and industry), influencing river runoff and water quality (Fig. 4, Fig. 9, etc).

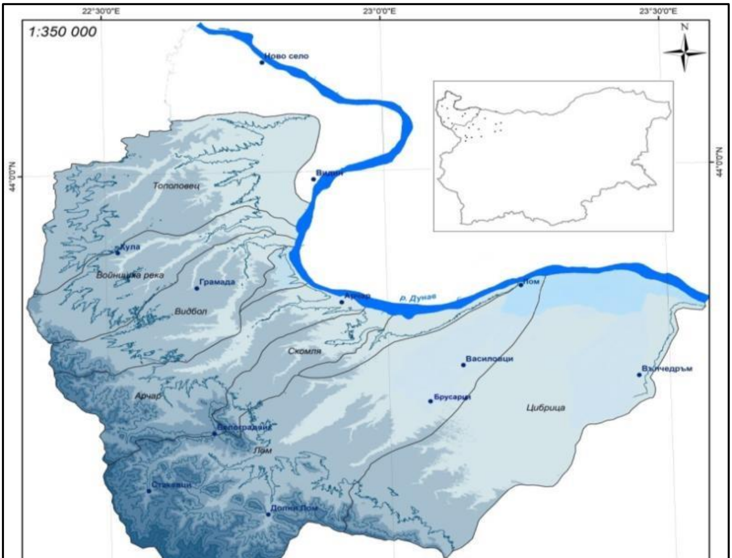

Figure 4. Map of the mean annual amount of precipitation for the period of 1961–2020

(according to published data in Climate reference book to 1985 and information from NIMH for 1986–2020)

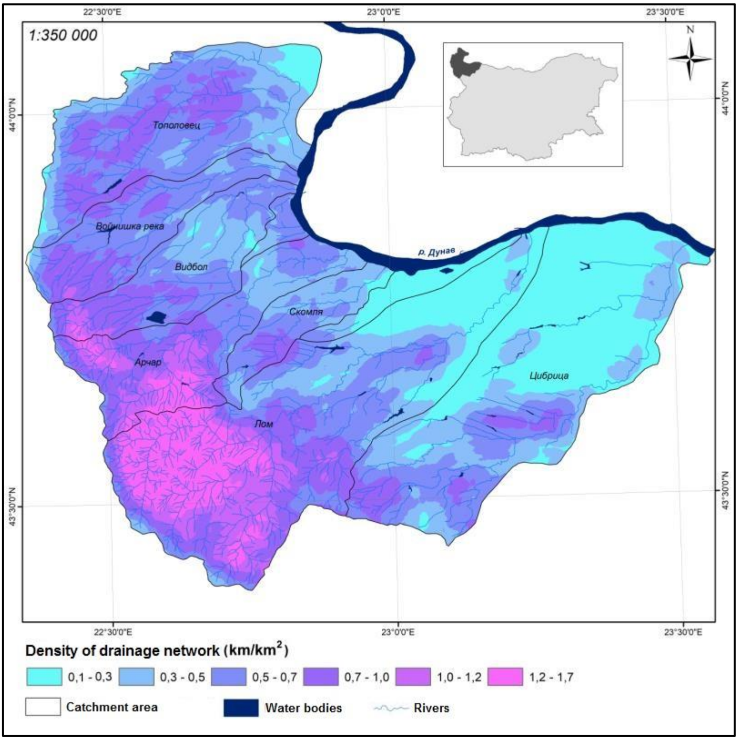

Figure 9. Map of the density of drainage network in the catchments west of the Ogosta River

(according to Topographic map of Bulgaria, 1989)

Conclusions

The hydrological processes in the studied area:

- occur in relatively homogeneous nature-geographical and anthropogenic conditions;

- presuppose an occurrence of altitudinal zonation;

- suggest changes in the volume, regime, and physicochemical status of surface water resources.

FOURTH CHAPTER

STREAMFLOW AND WATER RESOURCES IN THE CATCHMENTS WEST OF THE OGOSTA RIVER

4.1 Quantitative investigations of streamflow and water resources

4.1.1 *Statistical features of annual streamflow. Mean annual streamflow.* The check for homogeneity of time-series data reveals that most of them have statistically significant non-uniformity, which is confirmed by the double-mass curves. The homogeneity is impaired around the middle of the 1980s (between 1983 and 1987 for the individual river basins). To the extent that there is no evidence of an increase in the anthropogenic pressure on the examined river systems after the second half of the 1980s, the reason for the impaired structure of the time-series data should be sought in climate change and methods of collecting and processing hydrometric information. Since 1982, a tendency toward a hydrological drought has begun in watersheds from the northwestern, southern, and southwestern sections of Bulgaria (Gerasimov & Bozhilova, 2003, Gerasimov *et al.*, 2004, Dimitrov, 2018, Hristova *et al.*, 2020, Kirilova, 2022). Added to this circumstance are the changes in the methods and approaches for performing hydrometric observations and measurements in the country after the 1980s (Angelov, 2021).

The obtained results are grounds for dividing the multi-year period into two sub-periods (with conditionally unimpaired and impaired flow), which contain homogeneous data and have approximately the same length. Based on the sub-periods, the descriptive statistical characteristics of the annual runoff were calculated and presented (Table 19). Exceptions are the drainage basins of the Stakevska River at the village of Falkovets and the Lom (Barza) River at the village of Gorni Lom, for which the homogeneity of the time series is established. A normal type of distribution is registered for the same river basins, and a log-normal theoretical model of distribution is accepted for the rest of the catchment areas.

The mean annual flow for the sub-period with unimpaired runoff conditions varies between 0.65 m^3/s (the Salashka River at the village of Veshtitsa) and 6.72 m^3/s (the Lom River at the village of Vassilovtsi) with a relatively small standard error of the arithmetic mean value and a moderate variability of water quantities – the coefficient of variation (C_v) ranges from 0.22 (the Lom (Barza) River at the village of Gorni Lom) to 0.47 (the Topolovets River near the village of Akatsievo) (Table 19), which testifies to the constancy of the runoff-forming conditions, especially in the mountainous part of the catchment areas.

The mean annual flow decreases after the mid-1980s in all drainage basins with impaired runoff conditions and varies from 0.42 m^3/s (the Salashka River at Veshtitsa) to 5.32 m^3/s (the Lom River near Vasilovtsi) (Fig. 13, Table 19). The annual streamflow increases its variability compared to a first sub-period – C_v ranges between 0.44 (the Tsibritsa River at the village of Ignatovo) and 0.81 (the Voynishka River at the village of Tarnyane) (Table 19), which is indicative of a change in the runoff-forming complex.

Table 19. Descriptive statistics of annual streamflow in the catchments west of the Ogosta River

River – HMS	**Unimpaired runoff**			**Impaired runoff**		
	Period	**$Q_{av.}$ (m^3/s)**	**C_v**	**Period**	**$Q_{av.}$ (m^3/s)**	**C_v**
Topolovets – Akatsievo	1952–1985	1.17	0.47	1986–2011	0.79	0.69
Voynishka – Tarnyane	1946–1985	0.94	0.45	1986–2020	0.63	0.81
Salashka – Veshtitsa	1947–1986	0.65	0.38	1987–2020	0.42	0.54
Stakevska – Falkovets	1960–2020	3.23	0.30	–	–	–
Lom (Barza) – G. Lom	1954–2020	0.68	0.22	–	–	–
Lom – Gorni Lom	1946–1983	1.98	0.33	1984–2020	1.24	0.48
Lom – Vasilovtsi	1959–1987	6.72	0.29	1988–2020	5.32	0.50
Tsibritsa – Ignatovo	1951–1984	2.09	0.38	1985–2007	1.43	0.44

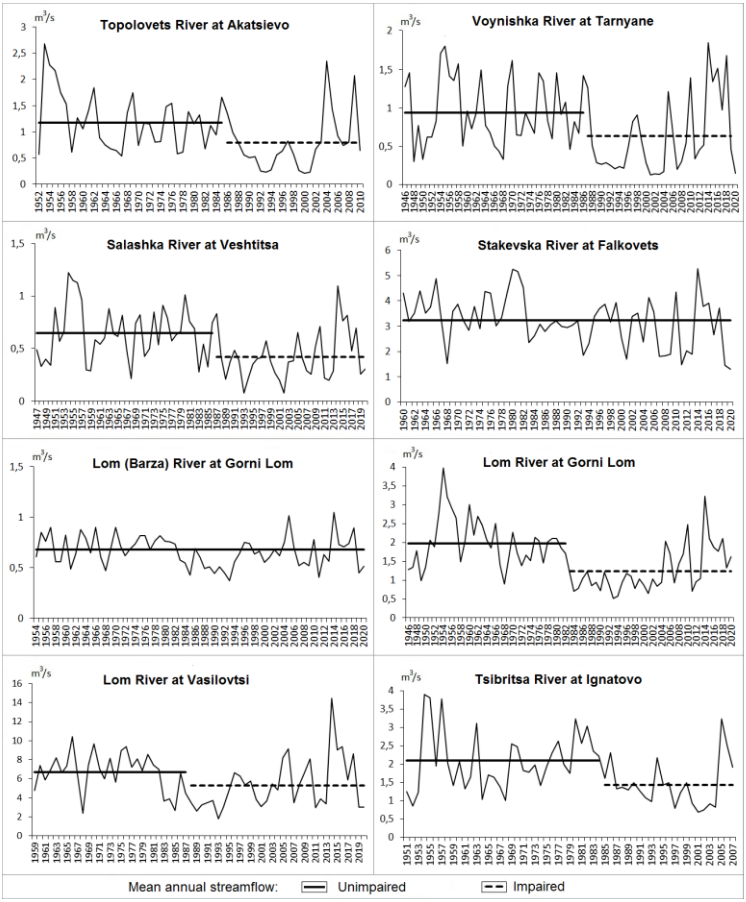

Figure 13. Mean annual streamflow in the catchments west of the Ogosta River

4.1.2 *Annual streamflow variability*. The chronological fluctuations of the river runoff coincide with those established for the entire territory of Bulgaria (Penchev *et al.*, 1971, Mandadzhiev, 1989, Hristova *et al.*, 2018). The moving average values and the integral difference curves show a synchronous alternation of positive and negative cycles: in almost all river basins, a period of increased water levels was recorded in the mid-1950s of the 20th century (with the largest discharge values from 1953 until 1957), a series of normal water years in the 1960s and 1970s (except for the dry year 1968), a negative cycle between 1982 and 2004, and unclear runoff dynamics after 2005 (Fig. 14).

As per the runoff fluctuations outlined in this work, there is a short period with streamflow volumes above the reference norms and a longer cycle with discharge values under the mean numbers.

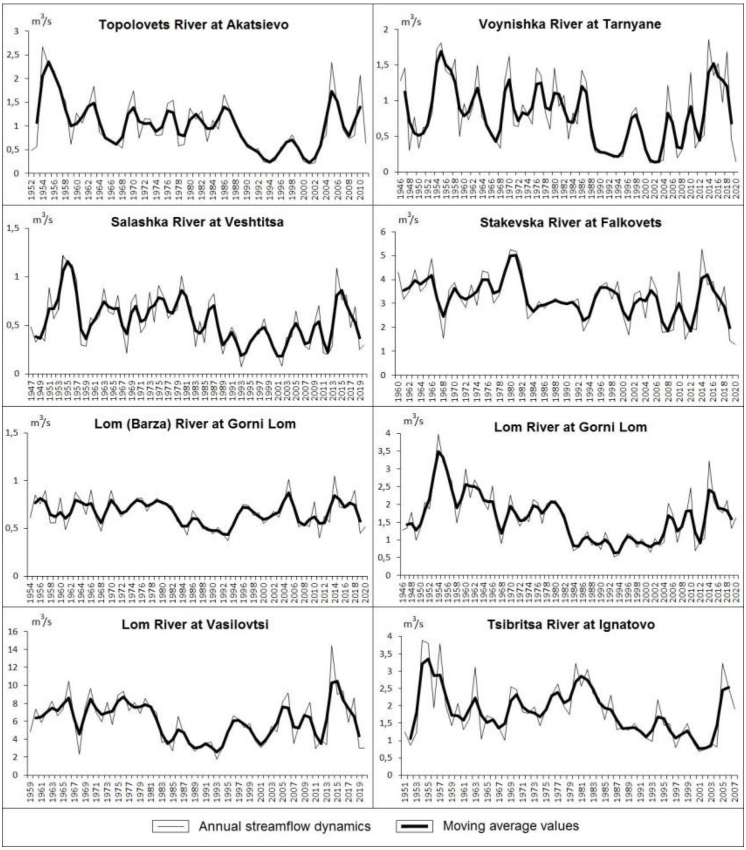

Figure 14. Dynamics and moving average values of annual streamflow in the catchments west of the Ogosta River

The linear trend shows a negative tendency in annual runoff volumes at all river basins during the reporting period (Fig. 16).

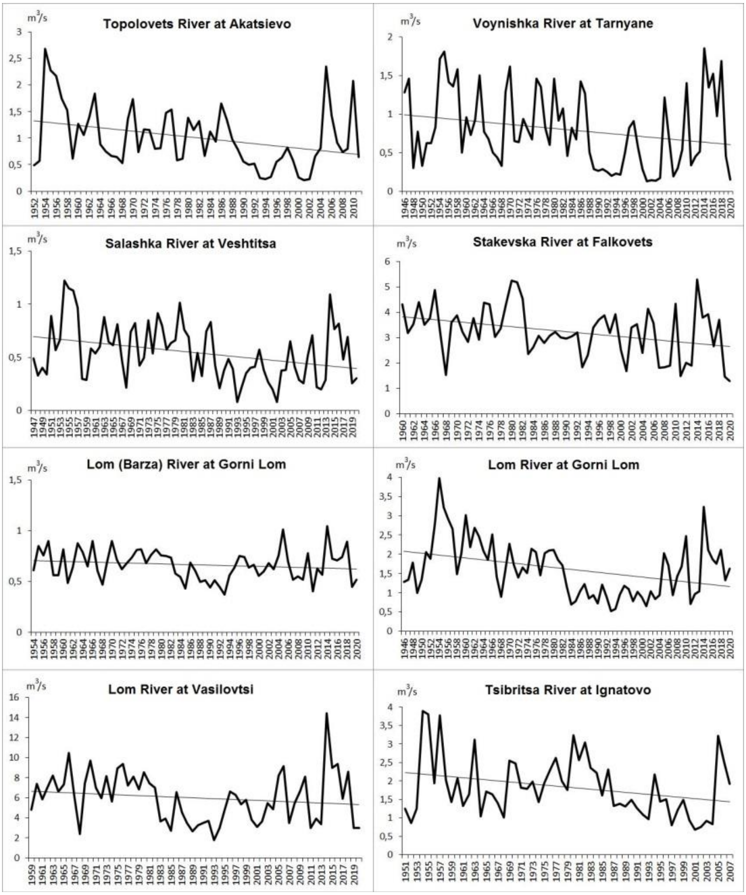

Figure 16. Linear trend of annual streamflow in the catchments west of the Ogosta River

The Mann-Kendall test indicates that the slope of the regression line is statistically significant for almost all of the gauging sites, excluding the Lom (Barza) River at Gorni Lom and the Lom River at Vasilovtsi (Table 20).

Table 20. Trend analysis of annual flow according to Mann-Kendall

River – HMS	Kendall's tau	Sen's slope
Topolovets – Akatsievo	**-0.239**	**-0.012**
Voynishka – Tarnyane	**-0.205**	**-0.007**
Salashka – Veshtitsa	**-0.231**	**-0.004**
Stakevska – Falkovets	**-0.213**	**-0.018**
Lom (Barza) – G. Lom	-0.138	-0.001
Lom – Gorni Lom	**-0.257**	**-0.013**
Lom – Vasilovtsi	-0.156	-0.021
Tsibritsa – Ignatovo	**-0.207**	**-0.014**

Bold – statistical significant trend (p-value ≤ 0.05)

4.1.3 *Degree of probability of annual streamflow. Water resources.* Data from the Flow duration curves (FDC) confirm the significant variability of annual streamflow. The runoff values in a dry year with a probability of 75% (recurrence once every four years) vary between 0.32 m^3/s (the Salashka River at Veshtitsa) and 3.63 m^3/s (the Lom River at Vasilovtsi). The river runoff in a normal water year with a probability of 50% ranges from 0.50 m^3/s to 5.89 m^3/s – values close to the reference norm. The streamflow in a wet year with a probability of 25% varies between 0.75 m^3/s and 8.08 m^3/s, respectively.

The distribution of annual streamflow by a degree of probability is shown in Fig. 17. Those results to some extent coincides with the series of wet and dry years, established for the entire territory of the country from 1931 until 2003 (Lazarov *et al.*, 2004).

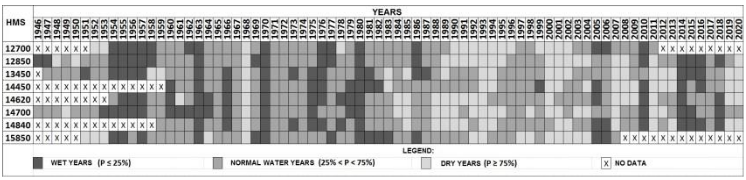

Figure 17. Annual streamflow with a various degree a probability in the catchments west of the Ogosta River

The results obtained are a basis for an analysis of surface water resources. The volume of water resources varies widely over the years (Table 22).

Table 22. Volume of water resources in years with a various degree of probability

River – HMS	**Dry years ($P≥75\%$)**		**Normal water years ($25\%<P<75\%$)**		**Wet years ($P≤25\%$)**	
	***W* min. $^*10^6m^3$**	***W* max. $^*10^6m^3$**	***W* min. $^*10^6m^3$**	***W* max. $^*10^6m^3$**	***W* min. $^*10^6m^3$**	***W* max. $^*10^6m^3$**
Topolovets – Akatsievo	6.49	18.35	19.24	42.89	43.52	84.51
Voynishka – Tarnyane	4.01	10.72	13.87	39.73	40.36	58.66
Salashka – Veshtitsa	2.46	10.21	10.41	23.34	23.65	38.47
Stakevska – Falkovets	40.64	78.99	82.30	119.52	122.04	166.39
Lom (Barza) – G. Lom	11.67	17.47	17.66	23.81	23.96	33.05
Lom – Gorni Lom	16.34	31.22	32.27	64.94	65.59	125.51
Lom – Vasilovtsi	56.07	114.55	115.23	234.78	254.93	455.28
Tsibritsa – Ignatovo	21.54	39.42	39.81	72.84	72.95	122.67

Of interest is the degree of provision of the population with water resources during dry years, when the freshwater amounts are limited. The *Falkenmark Index* (*FI*) informs about water volumes per capita/per year (Table 23).

Table 23. Maximum and minimum values of *FI* in a dry year (m^3/per capita/per year)

River basins	***FI* min.**	***FI* max.**
Topolovets		
• incl. the population of Vidin	85	235
• excl. the population of Vidin	384	1063
Voynishka	1211	5554
Lom		
• incl. the population of Lom	967	2758
• excl. the population of Lom	2020	6371
Tsibritsa	746	1218

The *FI* values in a dry year vary in a wide numerical range between 85 m^3/per capita/per year (for the Topolovets River basin including the population of Vidin in 1994) and 6371 m^3/per capita/per year (for the Lom River basin excluding the population of Lom in 2013) which shows "absolute water scarcity" and "lack of water stress" (Table 23). The results indicate that water stress and water scarcity are mainly reported in the drainage basin of the Topolovets River (including and excluding the inhabitants of Vidin) and Tsibritsa, while the lack of water stress is present in the river basins of the Voynishka and Lom. The reason for the greater freshwater provision of the inhabitants in the Voynishka River basin can be found in the smaller number of the population in catchment area. The sufficient freshwater availability in the Lom River basin is explained by the water abundance and the lower population density in the mountainous section of the catchment area. In contrast, the inhabitants in the drainage basin of the Topolovets River experience a permanent water shortage, while with data on water stress, the catchment area of the Tsibritsa River stands out.

4.1.4 *High and low streamflow.* The high flow occurs every year during the spring hydrological season lasting from one up to five months, with an average beginning between the third week of February and the first decade of April and ending between the last week of April and the second half of June (Table 24). A linear relationship was established between the average altitude of the river basins and the average date of the beginning of high flow with a coefficient of determination of 0.90.

High flow most often occurs between one and two months (March/April–April/May) – 42.1% (the Lom River at Vasilovtsi village) and 51.1% (the Tsibritsa River at Ignatovo) of the events. Exceptions are the Lom (Barza) River at Gorni Lom and the Lom River at Gorni Lom, where the high flow most often lasts between two and three months (March/April–May/June) – between 38.5% and 44.4% of the events, and more rarely lasting up to two months.

The average runoff during the high flow period ranges from 1.80 m^3/s (the Salashka River near Veshtitsa) to 18.34 m^3/s (the Lom River near Vasilovtsi) and concentrates between 52.3% and 58.9% of the annual streamflow volumes (Table 24).

Table 24. Characteristics of spring high flow in the catchments west of the Ogosta River

River – HMS	Temporal characteristics			Qualitative characteristics		
	Dates		Mean duration (days)	$Q_{av.}$ m^3/s	$W_{av.}$ 10^6m^3	% of $W_{an.}$
	Start	End				
Topolovets – Akatsievo	21.02.	02.05.	71	2.81	17.23	52.3
Voynishka – Tarnyane	19.02.	27.04.	68	2.26	13.28	55.3
Salashka – Veshtitsa	05.03.	13.05.	70	1.80	10.89	57.6
Stakevska – Falkovets	14.03.	17.05.	66	10.07	57.42	55.5
Lom (Barza) – G. Lom	03.04.	18.06.	76	1.86	12.15	58.3
Lom – Gorni Lom	01.04.	13.06.	73	3.93	24.78	53.4
Lom – Vasilovtsi	12.03.	22.05.	71	18.34	112.51	58.9
Tsibritsa – Ignatovo	25.02.	30.04.	65	5.50	30.88	53.3

In the studied river basins, two prolonged low flow phases are registered. They are typical for the summer-autumn and winter hydrological seasons.

In some years, the summer-autumn low flow passes without interruption into winter low flow, which causes a state with runoff under the norm lasting more than six months, but more often those phases are interrupted by a short-term increase of water levels lasting about a month.

The summer-autumn low flow period occurs annually with a duration of one to six months, beginning on average between the first and fourth weeks of July and ending between the second and third decade of October (Table 25). Low discharge values outside the summer-autumn hydrological season, but associated with the main low flow period, are found most often in the months of June and November, although not in every hydrological year.

Table 25. Characteristics of summer-autumn low flow in the catchments west of the Ogosta River

River – HMS	Temporal characteristics			Qualitative characteristics		
	Dates		Mean duration (days)	$Q_{av.}$ m^3/s	$W_{av.}$ $10^6 m^3$	% of $W_{an.}$
	Start	End				
Topolovets – Akatsievo	12.07.	19.10.	100	0.41	3.54	10.8
Voynishka – Tarnyane	15.07.	18.10.	96	0.31	2.57	10.2
Salashka – Veshtitsa	20.07.	25.10.	98	0.23	1.94	10.5
Stakevska – Falkovets	18.07.	28.10.	103	1.37	12.19	11.7
Lom (Barza) – G. Lom	26.07.	23.10.	90	0.28	2.17	10.5
Lom – Gorni Lom	25.07.	23.10.	91	0.73	5.74	12.1
Lom – Vasilovtsi	15.07.	01.11.	110	2.43	23.09	12.1
Tsibritsa – Ignatovo	07.07.	28.10.	114	0.98	9.65	16.6

The summer-autumn low flow is longer – most often it lasts from two to three months (July/August–September/October) in the mountain drainage basins and from three to four months (June/July–September/October) in the lower reaches of the rivers. Rarely, low flow lasts from five to six months (May/June–November/December). Hydrogeological conditions have the greatest effect on the temporal and quantitative parameters of the summer-autumn low flow. The average runoff during the low flow phase varies between 0.23 m^3/s (the Salashka River at Veshtitsa) and 2.43 m^3/s (the Lom River at Vasilovtsi), concentrating approximately from 10.2% to 16.6% of the annual streamflow volumes (Table 25).

The winter low flow occurs annually and lasts between one and four months, starting from the last decade of November or the second week of December and ending throughout February (Table 26). There are episodic cases in which winter low flow is registered in the first month of the spring hydrological season – March, but only in the mountain river basins due to the longer period with subzero air temperatures.

Table 26. Characteristics of winter low flow in the catchments west of the Ogosta River

River – HMS	Temporal characteristics			Qualitative characteristics		
	Dates		Mean duration (days)	$Q_{av.}$ m^3/s	$W_{av.}$ $10^6 m^3$	% of $W_{an.}$
	Start	End				
Topolovets – Akatsievo	21.11.	03.02.	75	0.58	3.82	11.7
Voynishka – Tarnyane	24.11.	01.02.	70	0.46	2.90	11.5
Salashka – Veshtitsa	27.11.	09.02.	75	0.31	2.03	11.0
Stakevska – Falkovets	01.12.	12.02.	74	2.05	13.11	12.6
Lom (Barza) – G. Lom	11.12.	04.03.	84	0.36	2.57	12.4
Lom – Gorni Lom	13.12.	03.03.	81	1.06	7.41	15.6
Lom – Vasilovtsi	29.11.	11.02.	75	3.96	25.66	13.4
Tsibritsa – Ignatovo	28.11.	07.02.	72	1.44	8.95	15.5

The winter low flow phase most often continues from two to three months (November/December–January/February). The mean runoff during the low flow period ranges from 0.31 m^3/s (the Salashka River at Veshtitsa) to 3.96 m^3/s (the Lom River at Vasilovtsi) and concentrates between 11.0% and 15.6% of the annual streamflow volumes (Table 26).

4.1.5 *Monthly and seasonal streamflow*

Monthly streamflow. The intra-annual distribution of river flow belongs to the first sub-type of the temperate-continental type runoff regime (Hristova, 2004) with increasing streamflow from autumn to spring months and decreasing in the opposite direction.

The streamflow is concentrated mainly during the months of March, April, and May, or for the time of snowmelt and maximum precipitation. No concentration of water quantities in the months of November and December, when the secondary precipitation maximum is registered in some of the river basins. The spatio-temporal features of the intra-annual distribution of runoff include the shift of the discharge maximum from the month of March to the month of May from the flat to the mountainous part of the drainage areas, as well as the concentration of the lowest flow during the months of August and September (Fig. 19).

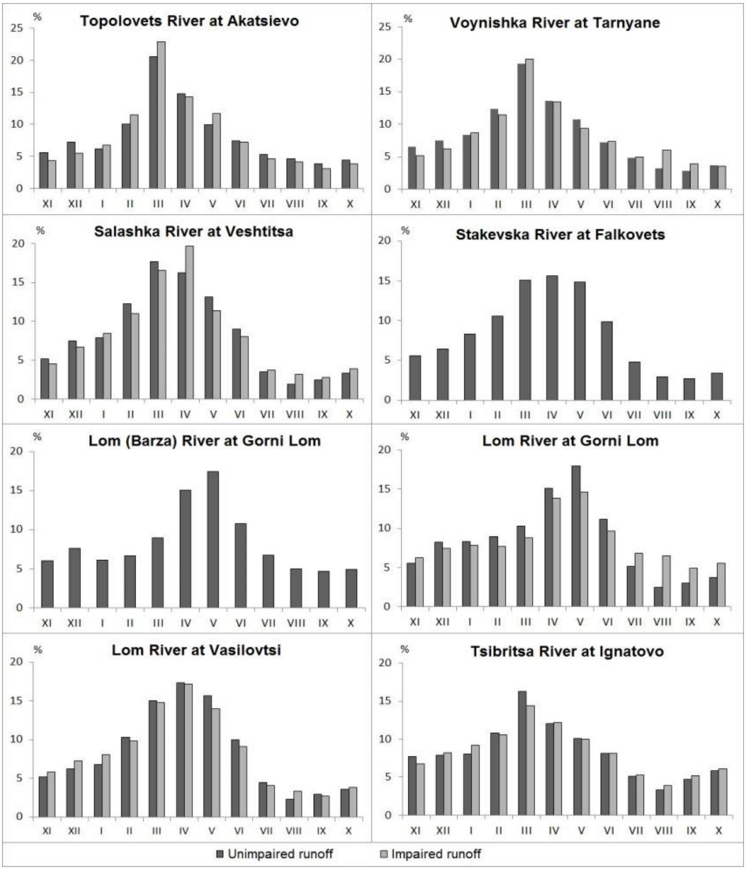

Figure 19. Monthly distribution of streamflow (% of annual streamflow volume)

Comparing the average runoff values, we found a decrease in flow volumes after the 1980s, especially during the months of December, January, February, March, April, and May, as well as an increase in discharge amounts during the month of August. The trend analysis evaluates as statistically significant in most part of the catchment areas the drop of water volumes in the months of December, February, and May with a slope of the regression line between -0.005 and -0.084 (Table 28).

The uneven intensity of the monthly runoff dynamics after the 1980s causes changes in the temporal structure of the runoff maxima and minima. Although the generally negative trend in flow volumes of the Salashka River near Veshtitsa during the months of March and April, the more intensive drop in the runoff during the month of March causes a shift of flow maximum to the month of April. The increase in runoff values during the summer-autumn months is accompanied by changes in the structure of flow minima, which are redistributed from the month of August to the month September (at the Salashka River near Veshtitsa, the Lom River near Gorni Lom, and the Lom River near Vasilovtsi) and from the month of September to the month of October (for the Voynishka River at Tarnyane) (Fig. 19). The redistribution of the largest and smallest monthly water quantities indirectly shows a change in the climatic conditions within the investigated drainage basins.

Comparing the frequency of the runoff maxima we establish a more stable temporal manifestation of the largest water volumes in the months of March, April, and May for the second sub-period. The obtained result testifies to more intense snowmelt and to a weaker dispersion of precipitation outside the spring months after the mid-1980s of the 20th century. Runoff minima are established most often during the months of August and September with similar stability after the second half of the 1980s compared to the first sub-period.

Seasonal streamflow. The seasonal streamflow distribution in both sub-periods is characterized by the highest runoff amounts in the spring hydrological season, but with a smaller relative share of the annual water volumes after the mid-1980s: between 46.5% (the Tsibritsa River at Ignatovo) and 58.1% (the Lom River at Vasilovtsi) for the first sub-period and from 44.8% (the Tsibritsa River at Ignatovo) to 55.7% (the Salashka River at Veshtitsa) for the second sub-period. An exception is Topolovets River at the stream gauge near Akatsievo, in whose catchment the relative share of the spring runoff increased from 52.7% to 56.2% (Fig. 21).

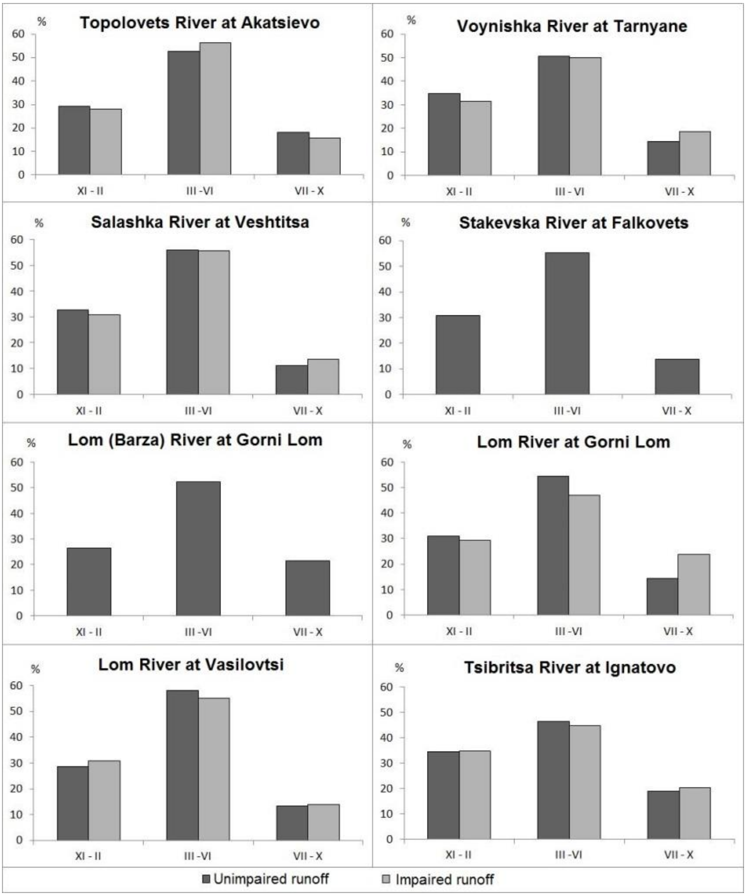

Figure 21. Seasonal distribution of streamflow (% of annual streamflow volume)

The flow dynamics during the winter hydrological season are analogous to that described for the spring months. The winter runoff is second in terms of volume and relative share, but with decreasing values of those indicators. It concentrates from 26.4% (the Lom (Barza) River at Gorni Lom) to 34.8% (the Voynishka River at Tarnyane) of the annual streamflow volumes during the first investigated sub-period, and from 26.1% (the Topolovets River at Akatsievo) to 34.4% (the Tsibritsa River at Ignatovo) in the second one. An exception is the Lom River at Vasilovtsi with rising relative share of the winter runoff – from 28.6% to 30.9% of the annual streamflow, respectively (Fig. 21). The reduced relative share of spring and winter flow probably reflects the smaller depth of snow cover after the 1980s. The summer-autumn flow is third in terms of volume and relative share for both sub-periods but with increasing values of those indicators. It forms between 11.2% (the Salashka River at Veshtitsa) and 21.4% (the Lom (Barza) River at Gorni Lom) of the annual flow volume in the first sub-period, and from 13.6% (the Salashka River at Veshtitsa) to 23.8% (the Lom River at Gorni Lom) during the second one. An exception is only the Topolovets River at Akatsievo, where the relative share of the summer-autumn runoff decreases from 18.2% to 17.7% (Fig. 21).

The comparison of the average values of the seasonal flow shows a decrease in runoff during the winter and spring hydrological seasons after the 1980s, which is most likely due to the more intensive snow melting.

The Mann-Kendall Test established that the negative trend is statistically significant with a slope of the regression line from -0.004 to -0.076. An exception is the summer-autumn flow, which does not follow a statistically significant tendency (Table 32).

The variability of climatic conditions over the years is expressed by the seasonal index α showing a ratio between winter and spring streamflow. The mean annual value of the index in the sub-period with unimpaired flow regime varies between 0.51 (the Lom (Barza) River at Gorni Lom) and 0.88 (the Tsibritsa River at Ignatovo), while for the sub-period with impaired runoff conditions its value ranges from 0.60 (the Topolovets River at Akatsievo and the Lom River at Vasilovtsi) to 0.89 (the Tsibritsa River at Ignatovo). The obtained results indicate a predominant temperate-continental climatic impact on the hydrological processes with a more intense decrease of the spring runoff compared to the winter streamflow in recent decades.

Table 32. Trend analysis of seasonal flow according to Mann-Kendall

River – HMS	Indicators	Hydrological seasons		
		Winter	Spring	Summer-autumn
Topolovets – Akatsievo	Kendall's tau	**-0.239**	-0.167	**-0.209**
	Sen's slope	**-0.009**	-0.015	**-0.006**
Voynishka – Tarnyane	Kendall's tau	**-0.289**	**-0.172**	0.023
	Sen's slope	**-0.008**	**-0.008**	0.001
Salashka – Veshtitsa	Kendall's tau	**-0.211**	**-0.178**	-0.041
	Sen's slope	**-0.004**	**-0.007**	-0.001
Stakevska – Falkovets	Kendall's tau	-0.125	**-0.290**	0.042
	Sen's slope	-0.014	**-0.058**	0.003
Lom (Barza) – Gorni Lom	Kendall's tau	-0.005	-0.128	0.032
	Sen's slope	-0.001	-0.003	0.001
Lom – Gorni Lom	Kendall's tau	**-0.240**	**-0.341**	0.047
	Sen's slope	**-0.012**	**-0.028**	0.001
Lom – Vasilovtsi	Kendall's tau	-0.067	**-0.179**	-0.082
	Sen's slope	-0.013	**-0.076**	-0.008
Tsibritsa – Ignatovo	Kendall's tau	**-0.242**	**-0.189**	-0.071
	Sen's slope	**-0.015**	**-0.022**	-0.003

Bold – statistically significant trend (p-value ≤ 0.05)

4.1.6 *Extreme streamflow*

Extremely high flow is detected between one and five times in almost all hydrological years except 1967/1968, 2000/2001, and 2001/002, when due to prolonged drought such events are not reported in most river basins. The highest number of those events is concentrated in hydrological years 1953/1954, 1954/1955, and 2004/2005, when torrential and intense rainfall caused sharp peaks in the hydrographs. The total number of events with extremely high flow varies from 124 (the Stakevska River at Falkovets) up to 174 (the Lom River at Gorni Lom) and does not increase/decrease moving from upper to lower reaches of the rivers.

Extremely high runoff is typical for the spring hydrological season, especially in the months of March, April, and June. Such events are also measured in the months of February (in the lower part of the rivers) and June (in the mountainous sections) due to the hypsometric differences suggesting non-simultaneous snowmelt.

The average duration of extremely high flow events ranges from three to five days. The torrential rainfalls, which are the main factor for a rapid rise in water levels, have a short duration, which explains the large share of extremely high flow events with a duration of up to a week. The relatively close average duration of the extremely high flow events does not allow the detection of spatial differences between upper and lower parts of the rivers and proves similarity in the hydrological response to climatic conditions.

The geographic analysis does not establish an increase/decrease in the duration of extremely high flow events with changes in altitude, which confirms their dependence on torrential and intense precipitation. The threshold runoff volumes of the extremely high flow vary from 1.52 m^3/s (the Salashka River at Veshtitsa) to 14.33 m^3/s (the Lom River at Vasilovtsi) with a large amplitude between the highest and lowest values. Water volumes are less variable only in the mountain catchment areas, occupied by forest vegetation and fed by snow-rain sources.

Extremely low flow is registered in all hydrological years of the studied period, except for 1955/1956, 1962/1963, and 2004/2005, when such events are not reported in about half of the river basins. Extremely low runoff is established most commonly from two up to five times in the year, except for 1967/1968, 2000/2001, and 2001/2002 with six to eight events. The number of the events with extremely low flow varies from 85 (the Stakevska River near Falkovets) to 126 (the Tsibritsa River near Ignatovo) and rises from upper to lower reaches of the rivers due to the decrease in precipitation and the increase in evaporation and infiltration.

The extremely low flow events are typical for the summer-autumn months, but they are also recorded in the winter months – mainly in February (in the mountainous drainage basins), as well as in June. A flow deficit is not detected in all catchments only in the month of April. The mean duration of the extremely low flow ranges from one to two weeks, but the maximum one reaches from 13 up to 24 weeks. The longest drought periods continue over 100 days in almost all drainage basins. The threshold values of the extremely low streamflow range from 0.04 m^3/s (the Salashka River at Veshtitsa) to 0.49 m^3/s (the Lom River at Vasilovtsi) and vary in relatively narrow limits due to the predominant hydrogeological feeding during the summer-autumn hydrological season.

4.2 Water quality assessment

4.2.1 *Component analysis***.** The calculations demonstrate differences in the measured content of the physicochemical parameters. The component analysis gives information about the main pollutants (Table 43).

The values of the *pH indicator* reveal that the water courses in the catchments west of the Ogosta River are characterized by a neutral to slightly alkaline reaction. The values of *electrical conductivity (EC)* vary significantly increasing from upper to lower parts of the rivers. The stream courses are saturated with *dissolved oxygen* (DO_2) and do not suffer from a deficit that would endanger the vital function of aquatic ecosystems. The results obtained indicate that river waters are not loaded with *ammonium nitrogen* ($N\text{-}NH_4$) and the measured concentrations remain in the range of "excellent" and "good status". The monitoring data reveals the water courses are seriously polluted with *nitrate nitrogen* ($N\text{-}NO_3$). For all water sampling points, values exceeding by three to four times the reference norms for "good status" are established, as a result of which the physicochemical condition is categorized as "moderate". The surface waters are not contaminated with *nitrite nitrogen* ($N\text{-}NO_2$) – the recorded values of this parameter remain within the numerical range for "good" and "excellent condition" (Table 43).

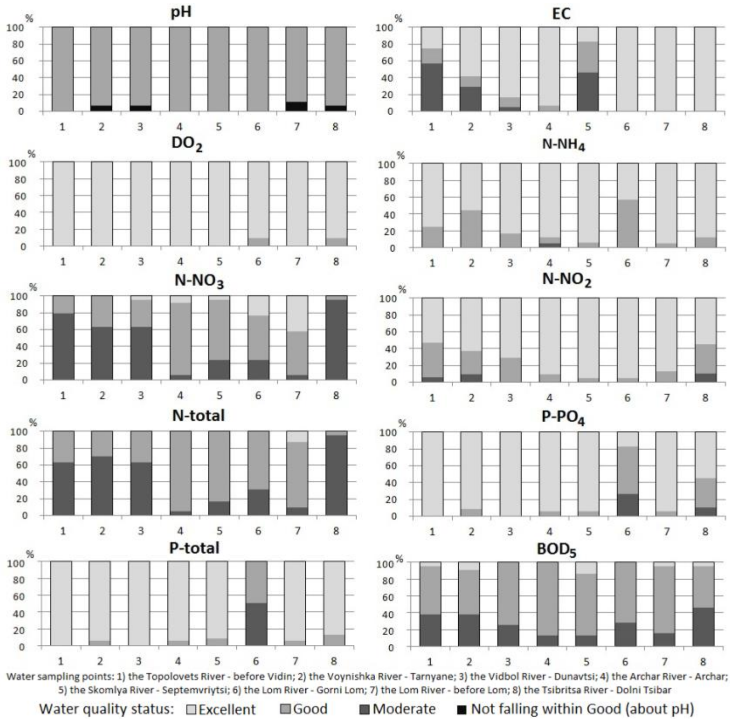

Figure 25. Frequency (% of all samples) of physicochemical parameters in a given status according to the reference standards in Regulation № H-4/14.09.2012

The results show that the river waters are loaded with *total nitrogen (N-tot)* and do not meet the norm of "good status", therefore the physicochemical conditions are categorized as "moderate". The most polluted are the Topolovets River before Vidin, the Voynishka River at Tarnyane, and the Tsibritsa River at Dolni Tsibar with concentrations exceeding the regulatory standards by three times. *Orthophosphate ($P\text{-}PO_4$)* values do not exceed the reference norm and are more often in the "excellent" to "good condition" range. The water courses are not polluted with *total phosphorus (P-tot)* whose content remains under the highest permissible limit of "good status". An exception is the Lom River at Gorni Lom, where the physicochemical properties are "moderate". The results establish an excessive *biochemical oxygen demand* (BOD_5) at all water measuring points, and thus the state of the river courses is assessed as "moderate" according to this indicator (Fig. 25, Table 43).

The obtained results confirm past works, but also show some differences. Varbanov & Gartsiyanova (2015) inform that for the period of 1990–2014 constant exceedances for the rivers west of the Ogosta River up to 20 times above the norm are established in the values of nitrates, ammonium nitrogen, and orthophosphates. The current study draws a different situation – the content of nitrate nitrogen exceeds three to four times the norms, and the values of ammonium nitrogen and orthophosphates are to two times higher than the requirements, which proves an improvement in water quality. Radeva & Seymenov (2019, 2020) analyzed hydroecological status of the Lom River for 2012–2016. Those authors reported concentrations of nitrate nitrogen, nitrite nitrogen, and total nitrogen exceeding the presented in the current paper, which confirm that during the period of 2015–2020 there is an improvement in water quality.

4.2.2 *Composite analysis.* The mean values of CCME WQI reveal "good" and "very good" water quality during the reporting period, i.e. the water courses are "slightly polluted" and "almost unpolluted" regarding the ten analyzed physicochemical parameters (Table 44).

Table 44. Mean annual values of CCME WQI for 2015–2020

River – Water sampling point	**CCME WQI values**	**Interpretation**
Topolovets – before Vidin	71.58	good quality
Voynishka – Tarnyane	74.14	good quality
Vidbol – Dunavtsi	80.11	very good quality
Archar – Archar	94.04	very good quality
Skomlya – Septemvriytsi	83.42	very good quality
Lom – Gorni Lom	76.45	good quality
Lom – before Lom	90.99	very good quality
Tsibritsa – Dolni Tsibar	70.75	good quality

Such a summary assessment does not allow a chronological analysis of changes in water quality. For this purpose, the annual CCME WQI values are calculated and presented (Fig. 26).

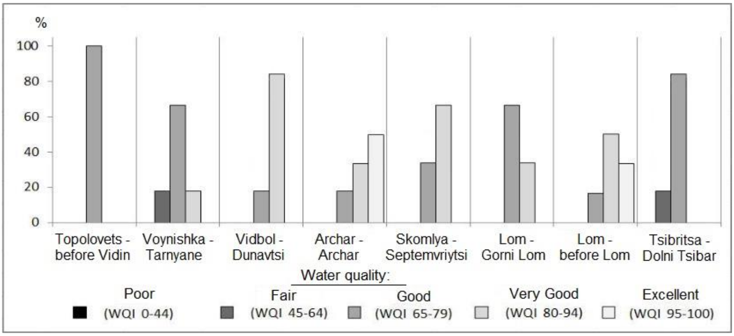

Figure 26. Frequency (% of all years) of annual values of CCME WQI in a certain status

Conclusions

The rising air temperatures and the changes in precipitation regime after the 1980s:

- impair the homogeneity of time series of annual, monthly, and seasonal streamflow;
- cause a decrease in annual runoff and increase its variability;
- lead to redistribution of the monthly and seasonal flow and increase the frequency of the extreme hydrological events;
- do not affect water quality.

The anthropogenic impact has declined in recent decades and almost does not affect the runoff volume and water quality.

CONCLUSION

The hydrological processes in the catchments west of the Ogosta River are a reflection of regional climate changes and are less responsive to anthropogenic activities, which weakened their influence after the 1980s. The annual river runoff has decreased statistically significantly in recent decades, while the fluctuations around the norm increase due to the inclusion in the time-series data of extreme values with very rare repeatability. The multi-year runoff dynamics do not prove the presence of pronounced cyclicality and are described by synchronously alternating series of wet and dry years according to the long-term flow variations for the entire territory of the country.

The volume of freshwater resources varies in a wide numerical range over the years, which presupposes a significant contrast in the degree of provision of the population. Regardless of the decreasing volume of water use, the runoff conditions in a dry year and the poor state of the public water supply system face the inhabitants with water stress, water scarcity, and an absolute water shortage. The asbestos-cement pipes built a couple of decades ago have been amortized, as a result of which over 60% of the freshwater volumes supplied to households and industry are lost in them. Modernization of the water supply network is need-ed to minimize the loss of freshwater resources.

The hydrological regime has spring high flow (February/March–May/June), summer-autumn (June/July–October/November) and winter (November/December–January/February) low flow with altitude-conditioned differences in the beginning and duration of the runoff phases. The intra-annual runoff dynamics after the 1980s are characterized by an increase in the amplitude between the minima and maxima values of the monthly and seasonal runoff, by a statistically significant decrease in winter and spring streamflow and an unclear trend in summer-autumn runoff, with a redistribution of the monthly runoff maxima and minima, and an increase in the frequency of the extreme hydrological events – indirect evidence for climate changes in the investigated region.

Water quality is improving due to the weakening anthropogenic pressure, but elevated concentrations are still registered for some of the physicochemical parameters (such as nitrate nitrogen, total nitrogen, and biochemical oxygen demand). Although the prescriptions in Directive 91/271/EEC for the treatment of urban wastewater in agglomerations with a population equivalent of more than 2000 people, the tendentious delay in the process of construction of wastewater treatment plants continues. In addition, the operating treatment facilities in the settlements with a population equivalent of more than 10000 people are technically outdated and ineffective. Maintaining a "good chemical state" of water courses requires the liquidation of illegal landfills, expansion of the sewage system in the settlements, and construction of modern wastewater treatment infrastructure. The acceptance of agricultural practices with limited use of fertilizers and pesticides is an additional measure to reduce surface water pollution in the studied area.

RESEARCH CONTRIBUTIONS

Scientific contributions

Statistically significant negative trends in the annual runoff, as well as changes in the intra-annual distribution of streamflow have been detected. A positive tendency in water quality has been proven.

Practical contributions

The volume of and the degree of provision with freshwater resources have been documented. Advices and recommendations have been given to reduce the loss of water resources and improve their quality.

Methodological contributions

An original methodological algorithm for an assessment of streamflow and water resources has been compiled. Based on it, numerous hydrological indicators were calculated and analyzed, and a quantitative and qualitative assessment of water resources was prepared.

RELATED ARTICLES

Seymenov, K. 2023. Annual flow dynamics in the catchments west of the Ogosta River. – *Annual Book of Sofia University, Faculty of Geology and Geography*, Book 2 – Geography, ISSN: 2535-0579, vol. 115 (in press).

Seymenov, K. 2021. Water quality assessment of the Danube's tributaries west of the Ogosta River. – Book of Proceedings of the Third conference *"Climate, atmosphere, and water resources in the face of climate change"*, 14–15 October 2021, Sofia, Bulgaria, ISSN: 2683-0558, vol. 3, 51–60.

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Table 28. Trend analysis of monthly flow according to Mann-Kendall Test

River – HMS	Indicators	Months											
		XI	**XII**	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**
Topolovets – Akatsievo	Kendall's tau	**-0.307**	**-0.331**	-0.146	-0.087	-0.083	-0.162	-0.152	**-0.202**	-0.175	**-0.241**	**-0.207**	-0.156
	Sen's slope	**-0.009**	**-0.009**	-0.004	-0.005	-0.008	-0.016	-0.010	**-0.008**	-0.005	**-0.007**	**-0.005**	-0.004
Voynishka – Tarnyane	Kendall's tau	**-0.286**	**-0.258**	**-0.231**	**-0.227**	**-0.157**	-0.127	-0.105	-0.146	-0.058	0.072	0.026	-0.054
	Sen's slope	**-0.006**	**-0.007**	**-0.006**	**-0.011**	**-0.009**	-0.005	-0.004	-0.004	-0.001	0.001	0.000	-0.001
Salashka – Veshtitsa	Kendall's tau	-0.093	-0.115	**-0.158**	**-0.172**	-0.075	-0.090	**-0.168**	-0.142	-0.050	0.042	0.010	0.085
	Sen's slope	-0.001	-0.002	**-0.005**	**-0.006**	-0.005	-0.004	**-0.005**	-0.003	-0.001	0.000	0.000	0.001
Stakevska – Falkovets	Kendall's tau	0.076	-0.173	-0.025	-0.142	-0.121	**-0.181**	**-0.270**	-0.074	0.058	**0.225**	-0.062	0.105
	Sen's slope	0.009	-0.019	-0.003	-0.032	-0.023	**-0.050**	**-0.084**	-0.011	0.004	**0.016**	-0.002	0.004
Lom (Barza) – Gorni Lom	Kendall's tau	0.009	-0.098	-0.039	-0.016	0.064	-0.069	**-0.166**	-0.157	-0.019	0.028	0.020	0.147
	Sen's slope	0.001	-0.001	-0.001	0.000	0.002	-0.002	**-0.008**	-0.004	0.000	0.004	0.001	0.002
Lom – Gorni Lom	Kendall's tau	-0.117	**-0.272**	-0.122	**-0.238**	**-0.221**	**-0.344**	**-0.266**	**-0.228**	-0.033	**0.200**	0.106	0.123
	Sen's slope	-0.006	**-0.018**	-0.006	**-0.013**	**-0.015**	**-0.034**	**-0.029**	**-0.018**	-0.001	**0.005**	0.002	0.003
Lom – Vasilovtsi	Kendall's tau	-0.059	-0.068	-0.059	-0.057	-0.067	-0.130	-0.119	-0.062	-0.096	0.014	-0.152	-0.045
	Sen's slope	-0.010	-0.014	-0.017	-0.020	-0.041	-0.074	-0.051	-0.020	-0.011	0.002	-0.015	-0.004
Tsibritsa – Ignatovo	Kendall's tau	**-0.248**	**-0.234**	-0.075	**-0.198**	-0.139	-0.120	-0.138	-0.084	-0.001	-0.075	-0.103	-0.177
	Sen's slope	**-0.016**	**-0.018**	-0.003	**-0.016**	-0.018	-0.016	-0.011	-0.006	0.000	-0.004	-0.005	-0.007

Bold – statistically significant trend (p-value ≤ 0.05)

Table 43. Values of physicochemical parameters in the river water during the period of 2015–2020

River – Water sampling point	Values	Parameters									
		pH	EC, µS/cm	DO_2, mg/l	N-NH_4, mg/l	N-NO_3, mg/l	N-NO_2, mg/l	N-tot, mg/l	P-PO_4, mg/l	P-tot, mg/l	BOD_5, mg/l
Topolovets – before the town of Vidin	minimum	7.4	392	7.2	0.013	1.699	0.008	1.835	0.009	0.028	1.7
	average	7.9	743	8.8	0.069	2.798	0.030	3.081	0.033	0.062	3.8
	maximum	8.2	935	13.0	0.241	6.360	0.081	7.010	0.067	0.104	5.9
Voynishka – at the village of Tarnyane	minimum	7.6	334	7.3	0.020	1.240	0.010	1.640	0.010	0.027	1.1
	average	8.1	672	9.2	0.101	2.546	0.029	3.215	0.030	0.069	3.4
	maximum	8.6	973	12.9	0.206	6.040	0.084	7.420	0.085	0.150	5.2
Vidbol – at the town of Dunavtsi	minimum	6.3	247	7.6	0.012	0.420	0.007	1.540	0.008	0.017	2.0
	average	7.7	588	9.1	0.063	2.238	0.024	2.848	0.025	0.054	3.5
	maximum	8.2	893	13.8	0.165	4.570	0.050	5.200	0.057	0.096	5.4
Archar – at the village of Archar	minimum	7.4	245	7.3	0.010	0.200	0.005	0.834	0.008	0.015	2.4
	average	7.9	543	9.6	0.064	1.225	0.014	1.652	0.028	0.059	3.3
	maximum	8.3	727	13.2	0.389	2.170	0.030	2.800	0.074	0.162	5.3
Skomlya – at the village of Septemvriytsi	minimum	7.6	236	7.2	0.008	0.546	0.005	0.922	0.006	0.019	1.7
	average	8.0	725	9.7	0.053	1.704	0.010	1.975	0.026	0.065	3.1
	maximum	8.3	853	14.4	0.276	3.000	0.033	3.110	0.087	0.226	6.3
Lom – at the village of Gorni Lom	minimum	7.2	79	7.5	0.006	0.120	0.003	0.347	0.007	0.012	1.1
	average	7.8	135	9.9	0.043	0.410	0.005	0.742	0.016	0.031	2.3
	maximum	8.2	202	13.7	0.092	1.150	0.011	1.800	0.040	0.057	3.3
Lom – before the town of Lom	minimum	6.9	163	7.8	0.010	0.141	0.003	0.580	0.005	0.010	1.8
	average	8.0	358	9.4	0.035	0.944	0.015	1.348	0.025	0.044	3.1
	maximum	8.8	539	12.9	0.148	2.580	0.042	2.940	0.126	0.153	5.7
Tsibritsa – at the village of Dolni Tsibar	minimum	7.4	126	6.2	0.013	1.890	0.007	2.150	0.018	0.035	1.4
	average	8.1	334	9.0	0.078	5.075	0.034	5.421	0.071	0.103	4.2
	maximum	8.8	517	12.5	0.220	8.110	0.069	8.300	0.213	0.267	7.8

DECLARATION OF ORIGINALITY

I declare that the current PhD thesis on the topic "Assessment of river runoff and water resources in the catchment areas west of the Ogosta River" for the acquisition of an educational and scientific degree "doctor" is an original author's work, and the sources of scientific and empirical information used are correct documented and cited according to the standards in force in the Republic of Bulgaria.

I guarantee that:

1. Acknowledgment of foreign authorship of the used texts, tables, diagrams, graphics, images, etc. is indicated according to the academic style of citation established in the scientific field.

2. The bibliographic list at the end of the dissertation includes all cited and used printed and electronic sources.

With this declaration, I certify that I am familiar with the rules in the Code of Ethics of the academic community of Sofia University "St. Kliment Ohridski" respecting authorship, correct citation, and the inadmissibility of plagiarism.

November 9, 2023
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