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ORIGINAL ARTICLE

Hydropower impact on the dniester river streamflow

Roman Corobov[1] · **Ilya Trombitsky**[1] · **Alexandr Matygin**[2] · **Eduard Onishchenko**[2]

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Abstract

An assessment of the Dniester Hydropower Complex (DHPC) impacts on this river streamflow is presented. The study was based on a comparative analysis of Dniester water discharge in periods before (1951–1980) and after (1991–2015) this complex construction, using observation data at hydrological posts located at the entrance to the Dniester reservoir (Zalishchyky) and downstream of its dam (Mohyliv-Podilskyi and Bender). Compared statistics included annual and seasonal trends and averages of water discharge in two periods, and statistical significance of their differences. It was shown that a statistically significant increase of Dniester flow in 1951–1980 was later replaced by its small decrease, explained both by changes in basinwide climate and DHPC functioning manifested in transforming the river flow seasonal distribution. Accumulation of water in the Dniester reservoir has led to a decrease in the annual flow volumes by above 6% directly below its dam and about 9%—in the Lower Dniester. As a result, the role of the Upper Dniester' catchment, located in the Ukrainian Carpathians, sharply increased; now it provides 80% of the Dniester annual flow compared with 69% before DHPC construction. Another 11% of flow is formed by Dniester's tributaries in its sub-catchment from Zalishchyky to Mohyliv-Podilskyi and 9%—in its downstream part. Concerning the seasonal streamflow, a challenging reduction is evident in spring due to water accumulation for hydropower needs in DHPC reservoirs, which negatively affects the Low Dniester ecosystems. On the whole, in 1991–2015 the Dniester annual flow decreased from 10.22 to 9.15 km^3.

Keywords Hydropower · Dniester River · Climate change

Introduction

It is well known the anthropogenic activities in river basins trigger the modification of their hydrological regime, thus increasing the severity of issues associated with water security (Laušević et al. 2016; MacQuarrie and Wolf 2013; UNU 2013). Freshwater scarcity is more and more perceived as a global systemic risk, and its essence is considered as a global geographical and temporal mismatch between the needs for fresh water and its availability (WaterAid 2012). Although in different ways, but this mismatch leads to water scarcity in different regions and time periods. Therefore, meeting new water needs and protecting ecosystems through ensuring their sustainable levels are the most difficult, but also the most important challenges of this century (Mekonnen and Hoekstra 2016).

Hydropower is considered as one of the anthropogenic factors affecting the surface water resources. This influence has acquired new nuances on the background of a changing climate due to its undoubted impact on the rivers' adaptive capacity, introducing new aspects in the concept of relationships between renewable energy and water resources (IHA 2019). Transformation of a hydrological cycle due to climate change leads to a variety of impacts and risks caused by the interaction of climatic and non-climatic factors with corresponding consequences for water resources management. At the same time, hydropower projects are often promoted as a "clean and green" source of electricity, and based on this perspective many countries are stepping up their expansion. According to a survey of Ocko and Hamburg (2019), the hydropower is currently the leading renewable source of energy, contributing two-thirds of global electricity generation from all renewable sources combined. By 2040, an electricity generation from hydropower is expected to grow by 45–70%, depending on future policies, with 3700

✉ Roman Corobov
rcorobov@gmail.com

[1] International Association of River Keepers "Eco-Tiras", Teatrala str. 11a, 2012 Chişinău, Moldova

[2] Hydrometeorological Center for Black and Azov Seas, Frantsuzsky Blvd. 89, Odessa 65009, Ukraine

new hydroelectric facilities to be either planned or under construction. The last inventory of massive hydropower presence in European rivers (Schwarz 2019) reveals a total of 30,172 hydropower plants (HPPs), out of which 21,387 already exist, 8507 are planned to be built, and 278 are already under construction. Numerous HPPs also exist or are planned for construction in the Black Sea basin (Havrilyuk et al. 2019; Vejnovic 2017).

Although the HPPs' reservoirs provide a number of benefits thanks to water storage and supply or flood control and recreational opportunities, the relationship between hydropower and water security is not so unambiguous. Because any HPP requires a river to be dammed for creating a reservoir for water accumulation (DSU 2017), the numerous dams, weirs and sluices built on the European rivers cause a strong negative impact on their ecology. Now in Europe, according to Gough et al. (2018) estimations based on analyses and field validations, there is almost one barrier for each river kilometer, and such density is much higher than it was previously indicated in the national databases. The well-known detrimental effects of dams include the impoundment of free-flowing river habitats, blockage of fish migration and reduced water quality in reservoirs and river reaches downstream (Jager and Bevelhimer 2007; Jager and Smith 2008).

Nevertheless, the consequences for the environment from such water accumulation are less known, because a river is a much more complex natural system than just a source of fresh water. Changes in physical habitats and food bases profoundly influence biological communities from a river source to its mouth (McCabe 2011). With their banks, floodplains, pits and fords, rivers are among the richest ecological systems due to their biological diversity, and, as such, they are subjected to serious destruction by hydropower. A river is also an agent that brings most of the climate change impacts to society, its social, energy, agricultural, transport and other industries. Although water passes through the global hydrological cycle, it is nonetheless a locally variable natural resource, so that vulnerabilities associated with water hazards, such as floods and droughts, vary between regions, depending on local, often non-climatic anthropogenic drivers.

A study of these challenges is especially important when to consider a compounding detrimental impact of hydropower together with other influences (Smith et al. 2007). Coordination efforts between water, energy and environment sectors are especially challenging under the ongoing changes in climate (e.g., Casale et al. 2019). The complexity of coordination increases substantially in transboundary river basins, where the impacts spread from one country to another, while trade-offs and externalities may cause frictions between riparian countries. Management of interlinked resources emerged a "nexus approach" as a way to enhance water and energy security by increasing its efficiency, building synergies and improving governance while protecting ecosystems (UNECE 2015). However, despite some common features, every river basin has its important particular features, requiring their thorough study and consideration in the process of a river flow transboundary monitoring (Pegram et al. 2013). As an example of such a study, one can name the relevant to our work monograph of Negm et al. (2020).

The aim of this paper is to provide a detailed and statistically comprehensive analyze of hydropower impact on the streamflow of the transboundary Dniester River, using historical hydrological information of Moldova and Ukraine—its two riparian countries.

Study area

The Dniester River (hereafter, *Dniester*) belongs to the Black Sea basin and is the largest river of Western Ukraine and Moldova. The river is used in common by both countries, while the share of Poland is very small (only its small left tributary). In the West, the Dniester basin borders with the Prut basin, in the Northwest—with the Vistula basin, in the North—with the Dnieper basin, in the East—with the Southern Bug basin, in the Southeast and Southwest—with several small river basins also flowing into the Black Sea (Fig. 1a).

The total length of the Dniester is about 1350 km, from its source in the Ukrainian Carpathians at an altitude of 911 m to its inflow into the Dniester Liman, separated from the Black Sea by a sandy spit. The length of the Dniester Basin is about 700 km; the basin's average width is about 100 km, the maximum—140 km in its mountain part and the narrowest one—60 km. The basin area is more than 72.3 thousand km^2, from which the Ukrainian part is 52.7 thousand km^2 (72.1%), the Moldavian part—19.4 thousand km^2 (26.8%) and the Polish part—226 km^2 (0.4%) (GEF et al. 2019). Lack of big tributaries and many small ones (more than 14,000 tributaries having less than 10 km in length) is a specific feature of the Dniester's river network. About two-thirds of its annual flow is formed in the mountain Carpathians. The average long-term historical annual volume of the Dniester flow is about 10 km^3, although annually there are up to five floods with a rise of water level by 3–4 m, and sometimes even more.

The Dniester and its tributaries are the main source of water in the region, providing water for agriculture, industry, and many settlements, including the major cities of Moldova and Ukraine. At present, water scarcity does not represent a serious issue in the basin as a whole, but maintaining this situation for a long time depends on future changes in the river's water regime and economic development in both countries. The great bulk of environmental problems here

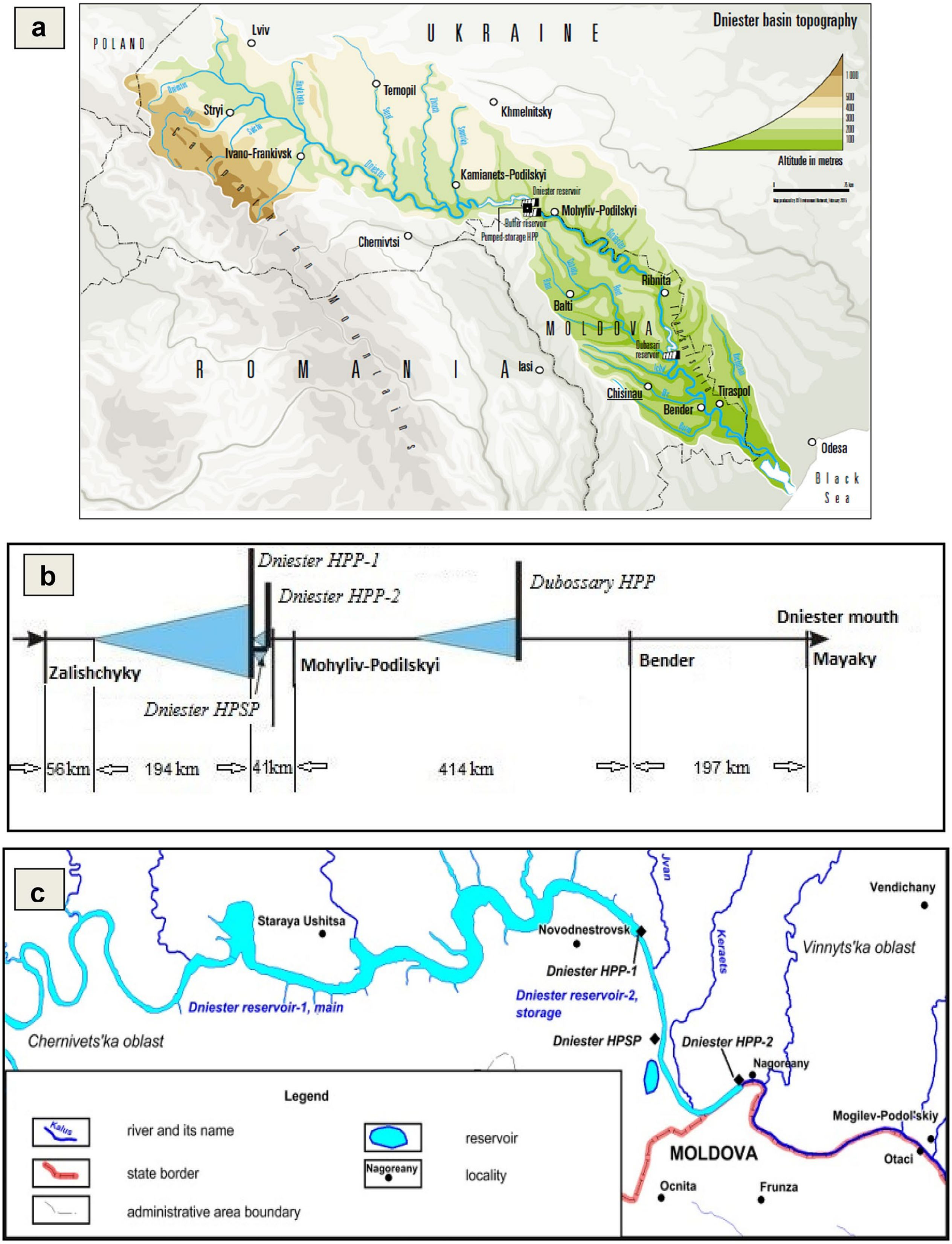

Fig. 1 Dniester River basin and hydropower plants (HPP) in its riverbed. **a** Physical-geographical map of the Dniester basin (ENVSEC et al. 2015). **b** Linear layout of hydropower plants and reservoirs in the Dniester basin (Adapted from UNDP et al. 2019). **c** The Dniester hydropower complex (Khilchevsky and Grebnya 2014)

has a transboundary nature and can be successfully solved only with the use of transboundary cooperation mechanisms.

According to UNDP et al. (2019), to date in the Dniester basin a total number of various design dams has already reached 50 units (45 in Ukraine and 6 in Moldova), but the three largest, which provide operation of three HPP (Dniester HPP-1 and HPP-2, and Dubossary HPP), are located directly in the river's main channel (Fig. 1b). Therefore, the part of its basin downstream of the so-called Dniester Hydropower Complex (DHPC) was selected as a case study for assessing hydropower impacts on the river's streamflow.

This complex, located on the northern border of Moldova with Ukraine, includes HPP-1 with the Dniester Reservoir and HPP-2 20 km downstream. The influence of Dubossary HPP is not considered separately in this work due to its insignificant power capacity and reservoir's volumes (about 48 thousand kW; 0.485 km^3) and, consequently, a weak impact on the Dniester streamflow. Moreover, there is a lack of a sufficiently long series of observations on the streamflow before this power plant was built (in 1950–1955).

As for the "history" of DHPC (Fig. 1c), the construction of HPP-1 began in 1973, and the last sixth unit was launched under industrial load in December 1983; its design capacity is 702 MW (6 × 117 MW). Construction of HPP-2 (27 MW) was started in 1982; the first generator was put into operation in August 1999 and the last third one—in December 2002. According to the European classification (Schwarz 2019), these HPPs, based on their installed capacity, can be attributed to classes 5 and 3, respectively. The construction of the pumped storage power plant, originally planned and started in 1983, was temporarily abandoned because of lack of funds and political instability of the 1990s and then re-launched much later.

The Dniester Reservoir (Fig. 1c) was put into operation in 1981 to carry out seasonal regulation of the Dniester water discharge. Large length and depth, a relatively small width and significant tortuosity are its specific features. By its morphometric characteristics (Table 1), this reservoir belongs to large riverbed water bodies. In accordance with an initial project, its main purpose was, additionally to streamflow regulation, providing the flood control, water supply, irrigation and navigation needs, the electricity generation as well. To ensure these functions, it was assumed that in normal conditions the reservoir's flood capacity should be free and ready to receive an additional runoff. *The buffer reservoir (Dniester reservoir-2* or *Storage reservoir)* belongs to small, shallow channel reservoirs. It was commissioned in 1987 by building an overflow dam 20 km downstream of Dniester HPP-1. Initially, it was used as a technical mechanism for smoothing a water flow coming from Dniester reservoir into the river's lower part to avoid daily high water-level amplitudes, thereby providing a daily and weekly streamflow regulation. However, in the late 1990s—early 2000s, the dam of this reservoir was reconstructed to provide operation of the new HPP-2, with installation of three hydroelectric generators.

Following the launch of HPP-2, on the right bank of the buffer reservoir, the Hydro Pumped Storage Pond (HPSP) was created (Fig. 1b). This so-called upper pond can be classified as a fillable reservoir with medium depths. During nighttime, when power demands are low, water is pumped up from the buffer reservoir, now considered as the DHPC's lower pond, while during morning and evening peak demands the water is discharged back, passing through hydropower units. After installation of three hydroelectric generators and a corresponding change of HPP-2′s operating mode, at present, it already targeted to solve exclusively energy tasks. *As a result, management of the Dniester hydropower complex, originally conceived to address primarily environmental issues, is currently dominated by energy interests.* Moreover, due to the DHPC construction, a significant part of the river's middle course was transformed

Table 1 Morphometric characteristics of Dniester reservoirs (adapted from GEF et al. 2019)

Characteristic	Dniester reservoir	Buffer reservoir	HPSP* upper reservoir
Normal retaining level (NRL) (m)	121.0	77.1	229.5
Forced retaining level (m)	125.0	82.0	–
Dead storage level (m)	102.5	67.7	215.5
Area of the water table at NRL (km^2)	136.0	7.3	2.61
Reservoir volume at NRL (mln. m^3)	2657	58.1	41.43
Useful volume (mln. m^3)	1907	31.8	32.7
Length (km)	194.0	19.8	2.90
Average width (m)	701.0	369.0	900.0
Maximum depth (m)	54.0	17.1	29.75
Average depth (m)	19.5	6.7	15.90

**HPSP* - Hydro Pumped Storage Pond

into water reservoirs that causes a series of unavoidable and not completely foreseen environmental and other problems directly affecting the water security in the Dniester Basin as a whole (GEF et al. 2019; UNDP et al. 2019).

Initial material and methods

Transboundary nature of the Dniester River has determined a corresponding approach to selection of the initial material. In particular, information on its streamflow was based on hydrological data of both riparian countries. Such an approach was also driven by the specifics of this study, carried out in the international project' framework (see: Acknowledgements). Based on these circumstances the long-term observations of Dniester water discharge at the Ukrainian hydrological posts Zalishchyky and Mohyliv-Podilskyi (sometimes, Mohyliv) and Bender (Moldova) have been used. This choice was caused, on the one hand, by a need to correctly identify the impact of DHPC and its reservoirs on the downstream river flow, and, on the other hand, by the availability of necessary information. From the first point of view, Zalishchyky post is the best choice. Located at a distance of 56 km upstream the Dniester reservoir (Fig. 1b), it records a long-term (since 1895) runoff generated in the upper part of the Dniester basin that is not disturbed by the DHPC operation. This factor allows also correct assessing a possible contribution of global warming to changes in this river flow. The hydrological post in Mohyliv-Podilskyi is important as the closest post downstream the DHPC (about 40 km from the Dniester reservoir's dam); it also has a fairly long (since 1950) series of reliable measurements of water discharge. The post in Bender records the Dniester streamflow in its lower part or practically a total runoff from the basin due to absence of any significant tributaries downstream.

The task to be solved also has determined the choice of applied methods, which included three principal components:

> The study of *time trends* in historical data. Usually, a trend analysis of observation series provides useful information to understand any changes caused by one or another factor. Equally, the trend analysis of river streamflow characteristics is important for water resources management (e.g., Dinpashoh et al. 2019; Drissia et al. 2019). In our study, trend analysis was used to estimate tendencies in the Dniester water discharge (Q) before and after its reservoirs filling.
>
> *A descriptive analysis* was used to describe and compare the basic features of the Dniester streamflow in the compared periods. Descriptive statistics included the annual and seasonal Q averages and standard deviations (SD).
>
> *The assessment of statistical significance* of observed differences between estimated statistics for the selected time periods. The test on significance was considered as reliable evidence of the presence or absence of changes in the Dniester streamflow caused by hydropower operation.

All statistical analyzes were performed, using appropriate tools provided by the *Microsoft Excel* and Statgraphics (2014) software.

Results and discussion

Trends in water discharge

In a number of the most recent and relevant publications on trends in water discharge, the streamflow characteristics are considered in various combinations with climatological variables. Thus, Nikzad Tehrani et al. (2019) evaluated trends of hydro-climatic variables (precipitation and streamflow) in northern Iran; Potopová et al. (2019) applied hydro-climatic indicators for study droughts in the Prut River basin. Overall, a basinwide approach is used more and more frequently in the trend analyses (e.g., Aili et al. 2019; Corobov et al. 2019; Luiz Silva et al. 2019).

To assess changes in the long-term dynamics of the Dniester water discharge, two periods (1951–1980 and 1991–2015) were selected as the time intervals. The first period characterizes Q in the Dniester before the filling of DHPC reservoirs, the second one reflects the water discharge state after DHPC became fully operational. Some shortening of the second observation period (25 years) is explained by the availability of information at selected hydrological posts at the time of this study.

Linear trends of the Dniester annual water discharge at each post in these two periods are shown in Fig. 2; the most important statistics of its annual and seasonal values are presented in Table 2. Here, a slope shows the value of change in corresponding Q per year, while its sign points at the direction of change. p value less than 0.05 means the statistical significance of a linear regression model at 95.0% or higher confidence level; R^2-statistic (Coefficient of determination) indicates the share of variability of an estimated parameter explained by the model (Statgraphics 2014). The second term in the linear regression equations, which are shown as examples in Fig. 2 ('*intersection'* in the Statgraphics's terminology), is not shown in Table 2 because it depends only on the selected parameter for the x-axis.

As can be seen from the above-mentioned figure and table, in the first 30 years at all posts and during all seasons the positive trends of Q had approximately the same shape. The observed differences in the slope absolute values are explained by a natural direct increase of water flow

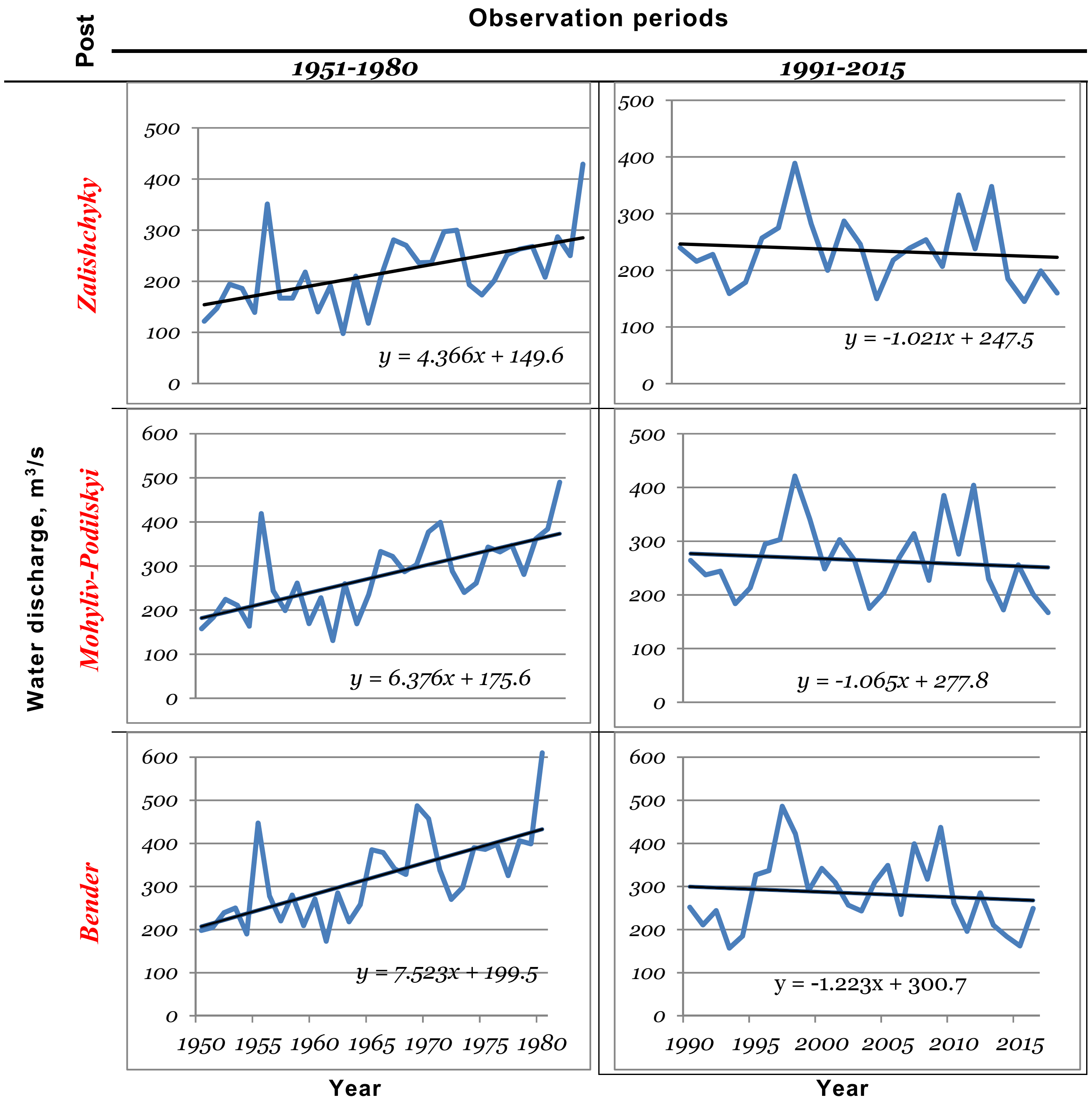

Fig. 2 Linear trends of the Dniester annual water discharge before (1951–1980) and after (1991–2015) the Dniester reservoir filling at different hydrological posts

downstream: from the smallest values in Zalishchyky (~4.37 m^3/s per year) to the largest one in Bender (~7.52 m^3/s per year). Moreover, this increase was statistically significant with a high level of confidence for annual and seasonal Q in almost all cases, except for the winter-spring period ($p > 0.05$) in Zalishchyky (Table 2).

A completely different picture was observed in 1991–2015. The previous statistically significant increase in the average annual water discharge was replaced by its ubiquitous annual decrease, although small (~1–1.2 m^3/s per year) and statistically insignificant for all seasons and year (except autumn, where p value < 0.05). The low significance level means that results for 1991–2015 should be carefully interpreted only as certain signs of changes in Q trends direction. Such conclusion is confirmed by a sharply decreased R^2 that in most seasons has become less than 1%. In other words, with starting the DHPC operation, the linear

Table 2 Slope, Coefficient of determination (R^2) and statistical significance (*p* value) of linear trends of Dniester water discharge before and after the Dniester reservoir filling at different hydrological posts

Season	1951–1980			1991–2015		
	Slope (m^3/s)	R^2 (%)	*p* value	Slope (m^3/s)	R^2 (%)	*p* value
Zalishchyky						
Winter	1.034	2.53	0.401	– 0.598	0.72	0.687
Spring	2.570	3.94	0.293	– 0.917	0.47	0.745
Summer	8.698	20.2	0.012	– 0.503	0.06	0.905
Autumn	4.305	23.2	0.007	– 5.468	24.2	0.013
Year	4.366	26.5	0.004	– 1.021	4.49	0.309
Mohyliv-Podilskyi						
Winter	3.764	19.2	0.016	– 1.151	3.31	0.384
Spring	5.353	11.3	0.049	1.076	0.49	0.741
Summer	10.097	22.7	0.008	0.866	0.14	0.858
Autumn	5.630	27.6	0.003	– 5.027	26.8	0.008
Year	6.376	40.6	0.000	– 1.065	1.24	0.596
Bender						
Winter	3.648	21.25	0.009	0.304	0.14	0.816
Spring	6.964	14.86	0.032	– 0.401	0.45	0.916
Summer	12.62	28.36	0.002	– 0.513	0.05	0.910
Autumn	6.816	33.50	0.001	– 4.284	17.46	0.030
Year	7.523	45.50	0.000	– 1.223	1.293	0.572

Slope—the value of a water discharge change per year

regressions that describe trends explain a negligible part of observed changes in the Dniester water discharge.

Nevertheless, this fact doesn't exclude a further transition of the observed tendencies to a statistically significant process. Undoubtedly, such change in trends direction of the Dniester streamflow is associated with an air temperature increase and precipitation decrease in the Dniester catchment caused by global warming, the intensification of which has been distinctly manifested since the 1990s (Corobov et al. 2019). However, negative trends in *Q* can be fully explained by global warming only in Zalishchyky, where the impact of the Dniester reservoir is excluded, and, as such, they could serve as indicators of climate change impacts on the Dniester streamflow that is formed in its catchment upstream the reservoir.

At the same time, indirectly they also evaluate these impacts on all Dniester flow, since this sub-basin provides for about two-thirds of its flow. However, main reasons for the trends change downstream DHPC should be sought in its creation and operation. As confirmation of this conclusion, unlike the water discharge in Zalishchyky, which in 1991–2015 decreased in all seasons, its slight increase, expressed through positive trends, was observed in Mohyliv-Podilskyi in spring and summer, and in Bender – in winter.

Hydropower impact on water discharge

Following the chosen methodology, the assessment of changes in the Dniester streamflow due to DHPC operation was based on a comparison of main water discharge statistics at hydrological stations located upstream (Zalishchyky) and downstream (Mohyliv-Podilskyi and Bender) of the complex (Fig. 1b), in periods before and after its construction. As in the trends analysis, the construction period (1981–1990) was excluded. The conclusions of comparison were based on evaluating the statistical significance of differences between the averages and standard deviations of Q in the two periods (Table 3).

An analysis of Table 3 demonstrates the following:

In all seasons a gradual increase in annual Q is visible as a hydrological post moves from the Dniester's source down to its mouth: from 222.7 m^3/s in Zalishchyky to 320.1 m^3/s in Bender in 1951–1980 and, respectively, from 230.6 m^3/s to 283.6 m^3/s in the last three decades;

The last decades' approximately 13% increase of winter streamflow in Zalishchyky indicates an earlier onset of snowmelt caused by climate warming in the upper Dniester; similarly, 27% increase in autumn streamflow here results from an autumn precipitation increase (Didovets et al. 2019; Spinoni et al. 2015). However, against the background of an increase in winter-spring streamflow, which was not disturbed by DHPC in Zalishchyky, Q decreased at other posts, especially in Mohyliv-Podilskyi. This fact undoubtedly indicates a winter water accumulation in the Dniester reservoir.

The maximal and statistically significant ($p < 0.05$) decrease of Q downstream of DHPC (above 20%) took

Table 3 Statistical comparison of Dniester water discharge (m^3/s) before and after the DHPC construction

Post	Season	Average					Standard deviation		
		1951–1980	1991–2015	Difference		*p* value	1951–1980	1991–2015	*p* value
				Abs	%				
Zalishchyky	Winter	142.5	160.6	18.10	12.70	0.227	57.2	51.9	*0.630*
	Spring	330.0	332.3	2.30	0.70	*0.938*	113.9	98.7	*0.477*
	Summer	268.2	252.4	– 15.80	– 5.89	*0.718*	170.1	147.8	*0.486*
	Autumn	150.0	177.3	27.30	18.20	*0.213*	52.4	46.2	*0.830*
	Year	222.7	230.6	7.90	3.55	*0.670*	70.9	64.6	*0.648*
Mohyliv	Winter	190.3	186.6	– 3.70	– 1.94	*0.834*	75.6	46.5	***0.018***
	Spring	420.2	330.8	– 89.40	– 21.28	***0.013***	140.1	113.6	*0.298*
	Summer	319.8	317.9	– 1.90	– 0.59	*0.968*	186.5	168.7	*0.621*
	Autumn	196.5	220.7	24.20	12.32	*0.298*	94.3	71.5	*0.169*
	Year	281.7	264.0	– 17.70	– 6.28	*0.412*	85.8	70.1	*0.315*
Bender	Winter	215.0	233.5	18.50	8.60	*0.307*	72.0	63.7	*0.533*
	Spring	489.3	360.4	– 128.90	– 26.34	***0.003***	164.3	149.3	*0.626*
	Summer	353.8	305.6	– 48.20	– 13.62	*0.361*	215.6	177.7	*0.320*
	Autumn	222.2	235.1	12.90	5.81	*0.612*	107.1	81.4	*0.159*
	Year	320.1	283.6	– 36.50	– 11.40	*0.147*	101.3	85.4	*0.381*

Bold values indicates an observed difference statistically significant at $p < 0.05$

> place in spring. Undoubtedly, this is also one of the manifestations of this complex's *negative impacts*. Namely, in spring the Lower Dniester's ecosystems, for example, ichthyofauna and its spawning grounds, especially require water supply sufficient for their wellbeing. A slight increase in an autumn–winter water discharge in Bender is due to a flow into the Dniester's mainstream of surface runoff from its sub-catchment below Mohyliv-Podilskyi. Also, in this period, along with an additional inflow from tributaries and some decrease in water requirements from users, Q increases thanks to more abundant autumn precipitation and earlier snowmelt in winter.

Thus, the fact that in 1991–2015 in Zalishchyky, despite the above-shown trends towards a decrease in annual Q, its some increase (by about 4%) compared to the previous period has preserved, while in Mohyliv-Podilskyi and Bender it has decreased (respectively, by 6.3% and 11.4%), should undoubtedly be attributed to the influence of the Dniester hydropower complex.

To compare whether or not the differences between Q in two periods are statistically reliable, the *Two-Sample Comparison* procedure was used. Usually, this procedure is run to test whether or not there are significant differences between averages and standard deviations of populations from which the samples were taken, using the *t*-test to compare averages and *F*-test to compare standard deviations of these samples (Stargraphics 2014).

In our case (Table 3), in Zalishchyky the seasonal and annual differences both of averages and SD in compared periods are not statistically significant (all *p* values are much greater than 0.05). This fact confirms the above shown statistical insignificance of *Q* decreasing trend in the upper Dniester streamflow due to observed changes in the regional climate (Corobov et al. 2019). Some shift of the first period of averaging in the present work in comparison with the cited article (1951–1980 instead of 1961–1990) can be neglected due to a relative climate stationarity in the years preceding an intensive global warming. Equally, this conclusion applies to the absence of statistically significant differences in variability (SD) of the Dniester interannual and interseasonal streamflow upstream the DHPC.

In addition to the statistically significant difference in *Q* averages downstream of DHPC in spring, which have been noted above, there is also, with a high confidence level (*p* value < 0.02), a corresponding difference in variability of its winter values in Mohyliv-Podilskyi. This significant variability is caused by an operational regulation of water discharge from the Dniester reservoirs in hydropower interests. Although in other comparisons the differences in *Q* variability below the dam are statistically insignificant, the level of this "insignificance" is much lower than in Zalishchyky; it is enough to compare *p* values at three posts.

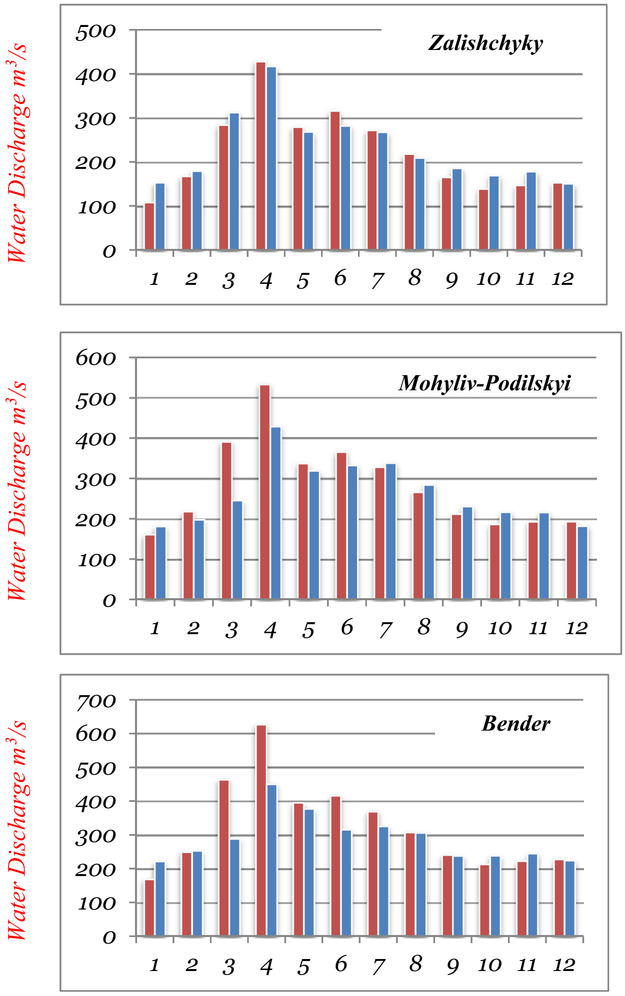

Fig. 3 Dniester monthly water discharge before and after of the DHPC complex creation at different hydrological posts. 🟥 1951–1980, 🟦 1991–2015

Changes in the Dniester streamflow annual regime

Damming of the Dniester riverbed and HPPs operation not only affect the streamflow volume but also transform its annual regime. Examination of the monthly distribution of an undisturbed water discharge in Zalishchyky (Fig. 3) reveals that its annual course in both observation periods has not essentially changed. Q has its main maximum in March–April, a subsequent decrease follows in May and a slight increase in June-July, while the first minimum is maintained in October and the second one in January. However, in this paper, we will not dwell on details of the streamflow redistribution among months at this post, which is possibly caused by changes in temperature and humidity conditions in an upper part of the Dniester catchment (Didovets et al. 2019; Spinoni et al. 2015).

More important is a situation observed downstream. If in 1950–1980 the monthly distribution of Q at Mohyliv-Podilskyi and Bender posts was, in relative terms, almost identical to that of Zalishchyky, then since the DHPC construction it has changed. In particular, there is seen an accumulation of spring streamflow in the Dniester reservoir in March–April, expressed as a decrease of differences between Q in the two compared periods. An analogous difference is not observed in Zalishchyky, which indicates the accumulation of water in the Dniester reservoir. Such conclusion confirms an observation of Gulyaeva (2013, p. 94): "Typically, the Dniester reservoir is discharged in winter and filled in spring".

Based on the needs of end-users, the observed changes in volumes of the Dniester runoff downstream of the DHPC's dams are of particular interest.

Hydropower impacts on the Dniester water volumes

If water discharge (Q) characterizes the quantity of water passing a particular river or stream location per unit time, expressed usually as units of volume per unit time (in our work, m^3/s), then a river runoff (W) is the volume of water passing this location in a certain period of time (McCabe 2011). Therefore, W is a more obvious indicator for any impact comparison, both in temporal and spatial dimensions. Some basic indicators of the Dniester's W at hydrological posts under consideration, expressed in this work in km^3, averaged for each compared periods, are given in Table 4. A set of statistics, placed in this table, should be considered only as a kind of summary "sheet" of the comparison results, which enables the potential readers to analyze them for their specific tasks. Below, only a few of the most important points will be highlighted.

1. In all seasons, a W gradual increase is clearly visible as we move downstream from the Dniester source to its mouth: from about 7.0 km^3 per year in Zalishchyky to 10.2 km^3 in Bender in 1951–1980 and, respectively, from 7.3 to 9.2 km^3 in subsequent years;
2. In 1991–2015, with a slight increase against 1951–1980 of annual W (by 0.25 km^3) in Zalishchyky, it decreased by ~ 0.6 km^3 in Mohyliv-Podilskyi and ~ 1.1 km^3 in Bender, thereby confirming the DHPC impact on the Dniester downstream flow;
3. In the same years, a certain decrease in the maximum W, along with an increase in its minimum, is observed in all seasons that also can be explained by a regulatory function of Dniester reservoirs. As a result, if the range of an interannual fluctuation of flow volumes decreased by 2.4 km^3 (from 10.5 to 8.1 km^3) in Zalishchyky (upstream of DHCP), then it decreased by 3.4 km^3 downstream: from

Table 4 Main indicators of the seasonal and annual volumes of the Dniester runoff (km^3) upstream and downstream of the Dniester hydrological complex before and after its construction

Season	Post	Statistics											
		Av	SD	CV	Max	Min	*R*	Av	SD	CV,	Max	Min	*R*
		1951–1980						1991—2015					
Winter	Zalishchyky	1.10	0.44	39.5	2.08	0.34	1.72	1.25	0.40	31.9	2.01	0.65	1.36
	Mohyliv	1.48	0.58	39.1	3.28	0.55	2.73	1.45	0.36	24.5	2.01	1.00	1.01
	Bender	1.67	0.56	33.7	2.89	0.73	2.17	1.81	0.47	26.2	2.69	1.06	1.64
Spring	Zalishchyky	2.62	0.90	34.5	4.64	1.00	3.64	2.63	0.78	29.5	4.42	1.61	2.81
	Mohyliv	3.33	1.11	33.3	5.70	1.33	4.37	2.62	0.90	34.3	4.88	1.43	3.45
	Bender	3.92	1.30	33.2	6.49	1.42	5.08	2.95	1.18	39.9	6.33	1.46	4.86
Summer	Zalishchyky	2.13	1.35	63.4	6.05	0.55	5.50	2.00	1.17	58.6	4.78	0.76	4.02
	Mohyliv	2.54	1.48	58.4	6.44	0.80	5.64	2.53	1.34	53.1	6.19	0.96	5.23
	Bender	2.87	1.70	59.3	7.61	0.97	6.64	2.51	1.44	57.6	6.54	1.21	5.33
Autumn	Zalishchyky	1.18	0.62	52.4	2.71	0.28	2.43	1.39	0.64	46.1	2.54	0.61	1.93
	Mohyliv	1.54	0.74	48.0	3.15	0.50	2.65	1.73	0.56	32.4	2.84	0.91	1.93
	Bender	1.77	0.85	47.9	3.82	0.65	3.16	1.89	0.65	34.4	3.48	1.07	2.41
Year	Zalishchyky	*7.03*	*2.25*	*32.0*	*13.57*	*3.06*	*10.51*	7.28	2.05	28.1	12.27	4.13	8.14
	Mohyliv	8.89	2.71	30.5	15.50	4.12	11.38	8.33	2.22	26.6	13.29	5.28	8.01
	Bender	*10.22*	*3.18*	*31.1*	*19.29*	*5.45*	13.84	9.15	2.68	29.3	15.36	4.95	10.41

Av average value, *SD* standard deviation, *CV,%* coefficient of variation (SD/Av × 100), *Max and Min* maximal and minimal flow values, *R* the range of flow fluctuations

Table 5 Dniester River absolute (km^3) and relative (%) streamflow volume upstream and downstream the Dniester hydroelectric complex as compared to its value at the Bender hydrological post, considered as 100%

Period	Post	Winter		Spring		Summer		Autumn		Year	
		km^3	%	km^3	%	km^3	%	km^3	%	km^3	%
1951–1980	*Zalishchyky*	1.10	65.9	2.62	66.8	2.13	74.2	1.18	66.7	7.03	68.9
	Mohyliv	1.48	88.6	3.33	85.0	2.54	88.5	1.54	87.0	8.89	87.2
	Bender	1.67	100	3.92	100	2.87	100	1.77	100	10.22	100
1991–2015	*Zalishchyky*	1.25	69.1	2.63	89.2	2.00	79.7	1.39	73.5	7.28	79.6
	Mohyliv	1.45	80.1	2.62	88.8	2.53	100.1	1.73	91.5	8.33	91.0
	Bender	1.81	100	2.95	100	2.51	100	1.89	100	9.15	100

11.4 to 8.0 km^3 and from 13.8 to 10.4 km^3 in Mohyliv-Podilskyi and Bender, respectively.

The results, obtained for recent decades in Zalishchyky, are generally consistent with estimates of Gulyaeva (2013) on the incoming part of the Dniester reservoir water balance: on average 6–8 km^3 per year, with fluctuations from 12 to 4–5 km^3. These general conclusions are illustrated by an additional analysis of Table 5, where the DHPC impact is estimated through contribution of individual parts of the Dniester catchment to the total flow volume at the Bender hydrological post, conditionally taken as 100%.

In particular, the results for 1951–1980 have confirmed well-established estimates that approximately 2/3 of the Dniester annual streamflow is formed in the upper part of its basin (68.9% at the Zalishchyky post); in Mohyliv-Podilskyi this share increased to 87.2%. However, after the DHPC construction, a share of runoff in Zalishchyky increased by 10.7%, but in Mohyliv-Podilskyi—only by 3.8%. In other words, now the upper part of the Dniester basin generates already about 4/5 (79.6%) of its annual runoff! Another 11% is formed due to the Dniester lateral tributaries in its subcatchment from Zalishchyky to Mohyliv-Podilskyi and only 9%—in the rest of the catchment.

Such redistribution of the Dniester flow is caused by the seasonal regulation of water storage in the Dniester reservoir. For example, an increase in 1991–2015 of a winter flow in Zalishchyky by 0.15 km^3 (in comparison with 1951–1980) has led to its almost equivalent (by 0.14 km^3) increase in Bender. However, in spring, albeit with an insignificant but increased W in Zalishchyky, there was its sharp decrease downstream of the DHPC's dams: by 0.73 km^3 in Mohyliv-Podilskyi and by 0.97 km^3 in Bender. In summer, with 0.13 km^3 flow decrease in the upper Dniester, its volume in Bender diminished by 0.36 km^3. It has led to worsening of the water supply in this part of the basin during the warm season when natural and social systems especially need water. The worst situation is created in summer when *W* in Mohyliv-Podilskyi even excesses that in Bender, located downstream. This, seemingly paradoxical, situation indicates that during this period the volumes of water withdrawal for various socio-economic and other needs in the Dniester's section from Mohyliv-Podilskyi to Bender exceeds the volumes of additional flow entering into its mainstream here.

And at last, it also can be noted that the Dniester total annual flow continues its decline, decreasing in 2016–2019 to 8.72 km^3 in Bender. If to look at the last 10 years (2010–2019), then during this period the average annual flow was already 7.64 km^3 against 10.22 km^3 in 1951–1980 and 9.15 km^3 in 1991–2015.

Conclusion

Based on the analysis of historical data and using the sound statistical approaches, the comprehensive research on responses of the Dniester River streamflow to intensive hydropower development in its floodplain has resulted in fairly original results, which add new knowledge to this pressing problem. The main principal conclusions from the research can be formulated as follows:

- The statistical comparison of the Dniester streamflow in 1951–1980 and 1991–2015, which, respectively, represent periods before and after the Dniester hydropower complex construction, has clearly demonstrated its influence on this river's total annual water discharge and its seasonal and monthly distribution. The accumulation of water in the DHPC's reservoirs has led to a decrease in the Dniester annual streamflow volumes by above 6% at the downstream hydrological post closest to the dam and by about 9% in the Lower Dniester.
- As a result of the DHPC construction, the role of the Upper Dniester catchment, located in the Ukrainian Carpathians, in maintaining the river water discharge has sharply increased. Today, it provides for 4/5 of the annual flow downstream the complex compared with 2/3 before its construction. Given the Dniester flow upstream of the reservoir, which is not disturbed by this factor and which remains practically with no response to various natural impacts, including climate change, there is no doubts that observed transformations in the downstream flow have resulted from DHPC functioning.
- The statistically confirmed impact of hydropower on the Dniester streamflow once again accentuates a need in clear planning of such facilities and strict observance of their management rules. These rules should be guided by permanent changes in the annual water volumes and their seasonal distribution. Nevertheless, it can also be expected that with an optimal combination of the installed hydropower capacity and the available volume of surface runoff, as well as under competent management, a successful combination of energy, economic and environmental requirements in the Dniester basin is possible to be met.

Finally, the authors would like to highlight the present work had a rather specific goal: to make a statistically competent analysis of changes caused by the large hydropower plant built in the riverbed. The results, presented here, should be considered only as a kind of supplement to the studies that have already been carried out or are being conducted (e.g., GEF et al. 2019; UNDP et al. 2019) based on information about both natural factors (for example, evaporation from the HPP's reservoir surface, water drainage in it, etc.) and water withdrawal for various economic and social needs.

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