Central European Journal of Geography and Sustainable Development 2022, Volume 4, Issue 2, Pages: 24-49
ISSN 2668-4322, ISSN-L 2668-4322 https://doi.org/10.47246/CEJGSD.2022.4.2.2

Assessment of the impact of the Dniester Hydropower Complex on hydrological state of the Dniester River

Ana Jeleapov *,

Institute of Ecology and Geography, Chisinau, 1 Academiei Street, MD-2028, Republic of Moldova; anajeleapov@gmail.com

Received: 15 May 2022; Revised: 17 October 2022; Accepted: 21 October 2022; Published online: 27 October 2022

Abstract: Operation of the Dniester Hydropower Complex (DHC), build on the middle course of the Dniester River in the middle of the '80s of the last century and extended during last decades, on one hand, produces low-cost energy and contributes to local and regional economical development, but on the other hand, leads to modification of river flow and ecosystems in the downstream, creating a series of dilemmas that are difficult to manage and solve by bazinal countries, Ukraine and the Republic of Moldova. This research aims to assess the changes in flow, phases of the hydrological regime, water temperature and sediments' regime due to the DHC operation. Main utilized approach was comparative analysis of hydrological time series recorded at the stations situated upstream and downstream of the DHC, for two representative time periods: before and after construction of this hydropower complex. As a result, it was estimated that the mean annual flow downstream the DHC decreased by 9.2%. Seasonal flow changed mainly by significant decrease in February-April (February - 18%, March - 40%, April - 27%), and increase in the autumn months, by 10-14%. Minimum flows upstream of the DHC, increased by 52%, and downstream have doubled, reaching 107 m^3/s (compared to 51 m^3/s, before the DHC construction). Maximum annual flow, in the upstream part, in the second period, has slightly increased, while towards the downstream part, there is a reduction of this parameter by about 30%. One of the direct impacts of the DHC operation is hydropeaking effect. Intraday level amplitude downstream of the DHC amounts to 52 cm and the length of the sector that is influenced by this effect is over 100 km. Also, a long river sector is subject to water thermal modifications: when upstream the average annual water temperature has risen by 0.8°C, in the downstream it has diminished by 0.44°C. On a monthly scale, there is a decrease in the water temperature in the spring-summer period, and an increase in the autumn-winter period downstream of the DHC. Sediment transport process was also altered significantly. Due to the DHC operation, suspended sediments decreased by 92-98% downstream of it. The significant decrease in sediment volumes is specific to all months of the year. The reduction of sediment transport has increased the transparency of water, which, as a result, influences the development of the aquatic ecosystems.

Key words: Dniester Hydropower Complex, the Dniester River, flow regime, hydrological alteration, reservoirs

Citation: Jeleapov, A. (2022). Assessment of the impact of the Dniester Hydropower Complex on hydrological state of the Dniester River. *Central European Journal of Geography and Sustainable Development*, *4*(2), 24–49. https://doi.org/10.47246/CEJGSD.2022.4.2.2

1. INTRODUCTION

The power of rivers is used by humans for different needs for centuries. However, its intensive utilization began only 140 years ago by development of hydropower plants (HPP). From the'80s of the 19th century when the first HPPs were built, till now thousands of these structures were constructed and supply with energy millions of people and industries. Nowadays, worldwide there are over 65 ths. of large

* Corresponding author: anajeleapov@gmail.com; Tel.: +373-68-473-729

HPPs with installed capacity of 1,330 GW, and continues to grow with 1-1.5%/year [1]. Large development of HPPs is specific for East Asia and Pacific Region, Europe, South and Central Asia, etc. Main countries by hydropower production are China, Brazil, Canada, the United States, and Russia [1]. Rapid increase of HPPs construction was caused by certain advantages related to hydropower. Relative low-cost of HPPs and renewable and free source for energy – river flow – remains to be main reasons of continuing raise of hydropower use. Also, reservoirs formed as a result of the dams' construction across the rivers have a positive influence on the local or regional economic development, being a valuable source of water for irrigation, industry, recreation, fishery. So far, hydropower is a leading renewable source of energy, with a share of 58% (over 4,300 TWh) from total electricity generated by renewable sources in 2020 (7500 TWh) [2], and the increasing trend in hydropower production show global interest in further development of this sector.

However, as a consequence of a high increase of HPPs construction on rivers, the problem of their impact on river flow and downstream ecosystems has raised. In this context, large number of studies was developed in order to evaluate the HPPs effects [3-20]. Thus, a comprehensive study performed by a group of authors in 2015 [4] shows that, on a global basis, 48% of river volume is moderately to severely impacted by either flow regulation or river fragmentation, or both. Assuming completion of all dams planned and under construction, this number would nearly double to 93%, largely due to major dam construction in the Amazon Basin [4]. As a result of flow regulation and river fragmentation due to dam construction, many other consequences appeared. The most important of them are the following: loss of connectivity between the upstream and downstream parts of the river which stops the migration of fish and other aquatic organisms; reduction the sediments that, on the one hand, accumulate in the reservoir and lead to its siltation during the time, and, on the other hand, cause a more transparent water downstream of the dams, leading to abundant growth of aquatic plants and water quality secondary alteration; changes of surface and ground water connectivity; alteration of the river thermal regime, usually due to flow evacuation from lower water layers of the reservoirs with constant water temperature; appearance of hydropeaking effect downstream of dams due to turbine operation - effects that determine reduction of biodiversity and invasion of new species for which new hydrological conditions are favorable [19,20]. Also, due do alteration of natural resources (water and food from rivers), the quality of life of population situated downstream of dams decreases. The decline of fish number and species denote less food resources for people. Colder water discharged from HPPs leads to changes in agriculture practice, especially reduction of irrigation surfaces, as well as worsening of tourism sector. Hydropeaking and secondary water alteration cause difficulties in water abstraction for humans' supply.

Actual legislation in the field of water resources and protection, namely the EU Water Framework Directive (Directive 2000/60/EC) [21] and its implementation guidelines, stipulates that hydromorphological alteration, especially expressed by river lateral and longitudinal connectivity loses, cause substantial impacts on river flow and its biodiversity, thus, activities to decrease human impact must be applied in order to improve water bodies status/potential. Water managers have a challengeable responsibility, on the one hand, to find and implement the best practices in order to protect rivers with their ecosystems and, on the other hand, to provide the necessary water to supply the socio-economic needs. However, it should be clear that increasing global population, need in water and non-fuel energy resources, and different global and regional crises must not cause a greater impact on waters.

Operation of the Dniester Hydropower Complex (DHC), build on the middle course of the Dniester River in the middle of '80 of the last century and extended during last decades, also rises the controversy between various experts and even states (e.g., Ukraine and the Republic of Moldova), creating a series of dilemmas that are difficult to manage and solve. Several studies were performed so far in order to evaluate the effects of the DHC on downstream status of the river, most of which are mainly oriented to estimation of water quality and biodiversity state [22-26] and only a few researches were developed to demonstrate the changes of water flow characteristics [27,28,29]. In this context, the present study focuses only on the evaluation of hydrological alterations of the Dniester River, that, as a consequence, cause ecosystems and economic losses in its downstream part. Main objectives are: i) identification of changes in flow parameters: mean annual, seasonal and monthly flow, minimum and maximal flows; ii) estimation of hydrological regime phases modifications: spring and summer floods, low flow; iii) analysis of hydropeaking effect; iv) assessment of water temperature regime and v) evaluation of sediment transport processes alteration. All parameters were evaluated comparatively for two representative time periods: before (pre-) and after (post-) the DHC construction.

2. STUDY AREA

The Dniester River is located in the Eastern part of Europe and flows through Ukraine and the Republic of Moldova (Figure 1). The river length is 1362 km and the basin area is 72,100 km2. Over 70% of the basin is situated in Ukraine, 27% belong to Republic of Moldova, and 0.34% - to Poland. The basin is conventionally divided in three parts: the Upper Part represents the region from Dniester spring to confluence with Zolota Lypa River (nearby Zalischyky Village), the Middle Part is assigned to the region from Zolota Lypa River to Dubasari Town (in general situated in Podolia Plateau), and the Lower Part is characterized by plain relief. The Upper part lays in Carpathians and represents only 30% of the basin area, but due to the high amounts of precipitations, 70% of Dniester runoff is generated in this area. Precipitations over basin area decrease constantly from 1300-1000 mm in the Upper part to 450-500 in the Lower Part [30,31].

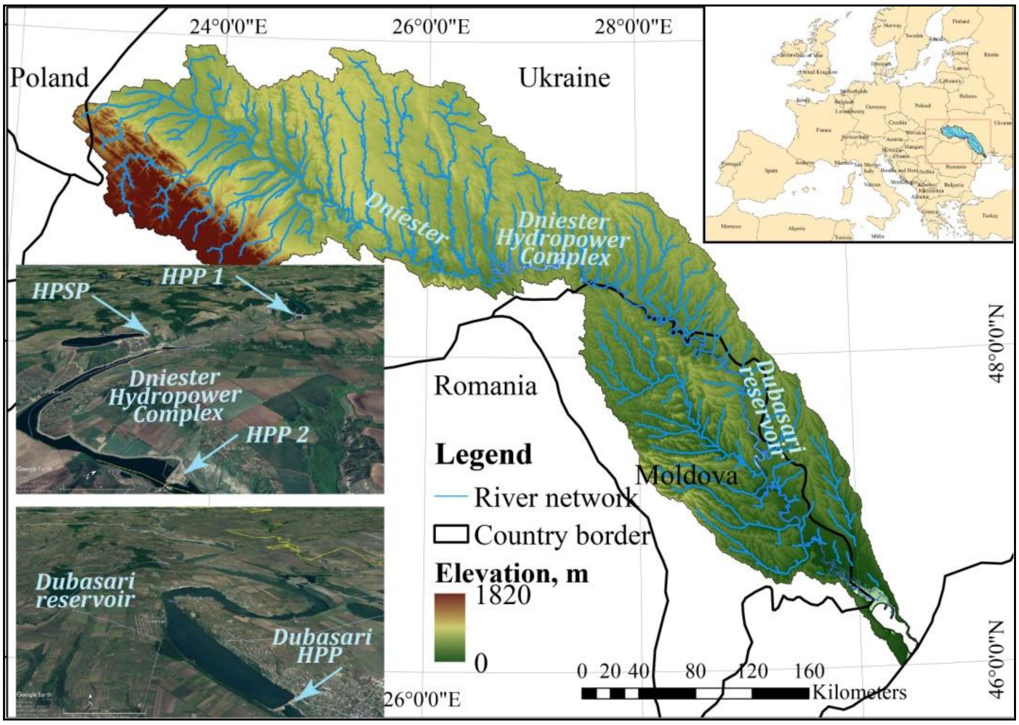


Figure 1. The Dniester River Basin.
Source: elevation extracted from [32], images extracted from [33].

The flow of the Dniester River is regulated by 3 reservoirs situated on the stream and one positioned lateral to the river. Three of these reservoirs form the Dniester Hydroelectric Complex: the Dnestrovsk reservoir with HPP-1, the buffer reservoir with HPP-2, the artificial reservoir with pumped storage hydroelectric power plant (HPSP). First reservoirs from this complex (the Dnestrovsk reservoir with HPP-1 and the buffer reservoir), were built during the years 1981-1983. The main functions of the Dnestrovsk reservoir are flood reduction, water supply, electricity production. Its length is 194 km, water volume at normal retention level (NNR) - 2.6 km^3, HPP-1 has a height of 54 m, and is equipped with 6 turbines, with capacity of 702 MW. Buffer reservoir was built to reduce hydropeaking effect caused due to operation of HPP-1 turbines. However, during the years 1999-2002, the dam was equipped with 3 turbines, with capacity of 40.8 MW, thus at present HPP-2 is also a producer of flow pulsation effect. After turbines installation and HPSP construction, the function of the buffer reservoir has been changed, currently it is used for electricity generation, water supply and attenuation hydropeaking effect from upper reservoirs. Its volume at NNR is 37 mil. m^3, with intentions from Ukrainian part to increase its value to 58 mil. m^3. Its length is 19.8 km, the average depth is 6 m. 9 km downstream of HPP-1, another reservoir with HPSP was built by damming. It is located on the upper right side of the river at approx. 150 m above the Dniester water level. The volume of water at NNR is 41.4 mil. m^3 [34,35,36]. HPSP is equipped with 3 turbines that were installed during the years 2013-2016, the capacity is of 972 MW in turbine mode and 1263 MW in pumping mode. Recently, the fourth turbine was installed (324 MW in turbine mode and 421 MW in pumping mode), and the construction of other 3 turbines (with a capacity of 972 MW in turbine mode and 1263 MW in pumping mode) is planned by Ukraine for next decade. As a result of the operation of all 7 turbines, the total capacity will be 2268 MW in turbine mode and 2947 MW in pumping mode [37]. At the end of the HPSP construction, it will be ranked 4th in the world [38]. The reservoirs' location and the original form of the Dniester River bed can be seen in Figure 2.

It should be noted that there is one more reservoir with dam with HPP constructed on the Dniester River, called Dubasari. It is situated in the Republic of Moldova. In comparison with DHC, it has a low impact on river regulation due to relatively small water volume, and high reservoir siltation. HPP was built in 1954, and is equipped with 4 turbines with a capacity of 48 MW [39].

3. METHODS

The main group of methods for assessment of changes in river hydrological regime due to HPP operation includes the direct ones that are based on the analysis of measurement data from the hydrologic monitoring network. Main designs that are usually applied are: (1) Paired-Before–After Control–Impact (BACIP), (2) Before–After (BA), (3) Control–Impact (CI), (4) Hydrological Classification (HC) and (5) Predicted Hydrological indices (HP) [7]. Also, one of modern approaches is determination of main Hydrological Alteration Indicators and Environment Flow Components [8-9], which is applied, in most of the cases, for estimation of impact of reservoirs operation on river flow [11,12,29 etc.]. This approached is performed using the special software IHA [40], where 33 IHA characteristics (monthly mean values, annual minima and maxima of 1, 3, 7, 30, 90 days and their date of occurrence, etc.), are calculated, as well as Environmental Flow Components (minimum monthly flow, extreme low flow, flow pulses, small and large floods) for pre- and post-impact periods. From all existing approaches, the best way to assess the anthropogenic impacts on river flow is the analysis of hydrological information for pre- and post-impact, pre/post-control periods. Thus, the comparative analysis of the hydrological data collected in natural conditions of the Dniester River flow generation, as well as during the impact of the DHC operation reflects the tendency of flow change determined by the human factor.

The hydrological regime of the Dniester River consists of flow characteristic phases: spring floods, pluvial floods, summer - autumn and winter low flows. Thus, these characteristic phases, as well as hydrologic indicators (e.g. multiannual flow, seasonal and average monthly flow, multiannual and monthly suspended sediments and water temperature) were assessed, time series being differentiated over 2 time periods, pre-DHC (before the DHC operation) and post-DHC (after the DHC operation). The focus of the study was also on evaluation of hydropeaking effect, which was performed using water level data from immediate proximity up to 140 km downstream of HPPs in order to understand the extension of this phenomenon.

3.2. Data

The basic approach of the study was to analyze and establish the hydrological characteristics at the Zalischyky station, situated upstream of the DHC, as well as those at the stations located downstream of the DHC: Mogilev-Podolsky, Naslavcea, Unguri, Soroca, Grushka, Sanatauca, Camenca, Dubasari, Bender. The time series was considered mainly from 1950 till 2020. In order to assess the impact of DHC on hydrological regime, from the whole time series, homogeneous data series were used for two times periods: the first one – the period of natural flow for the years 1950-1980 (before the DHC or pre DHC), and the second period – the regulated flow from the 1987 till 2020 (after the DHC construction or post DHC). The analysis was performed both in time profile, highlighting the trends of change over time, as well as in space profile, the focus being on the changes of characteristics from upstream to downstream of DHC.

The hydrological information used in the study was provided by the responsible data organizations in Moldova and Ukraine: the Hydrometeorological Service (SHS) [41,42] and State Water Agency, data were collected through UNDP in Moldova, Ministry of Environment of the Republic of Moldova, the Commission on Sustainable Use and Protection of the Dniester River Basin (the Dniester Commission). The table below summarizes the hydrological information used to assess the hydrological status of the Dniester River as a result of the impact of DHC.

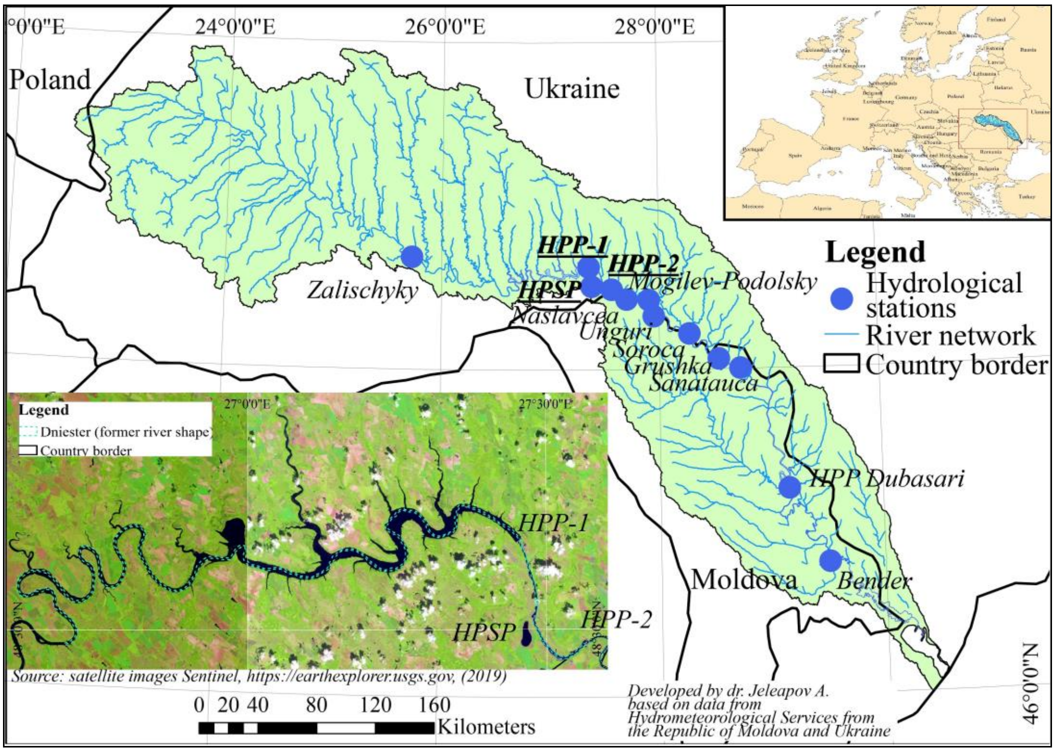


Figure 2. Location of the hydrologic stations on the Dniester River considered in the study.

Table 1. List of hydrological stations and data used for the study [based on 41,42].

Hydrologic station	Basin surface till station (km²)	Distance till river mouth (km)	Data used for the study	Time period
Data from SHS Ukraine				
Zalischyky	24,600	936	Daily/monthly flow (discharges), monthly water temperature, monthly suspended sediments	1950-2016
Reservoir with HPP-1	40,500	677.7	Daily/monthly flow (discharges), levels	1982-2020
Mogilev - Podolsky	43,000	630	Daily/monthly flow (discharges), monthly water temperature, monthly suspended sediments	1950-2016
Data from SHS Moldova				
Naslavcea	-	653	Water levels (from 15 to 15 minutes)	2013-2020 (some missing data)
Unguri	-	627.4	Water levels (from 15 to 15 minutes)	2013-2020 (some missing data)
Soroca	47,000	550	Water levels (from 60 to 60 minutes)	2017-2020 (some missing data)
Grushka	48,700	509	Daily/monthly flow (discharges), monthly water temperature, monthly suspended sediments	1968-2020
Sanatauca	49,000	473	Water levels (from 60 to 60 minutes)	2017-2020 (some missing data)
Camenca	49,000	473	Daily/monthly flow Water temperature	1952-1966 1951-1977, 1993-2015
HPP Dubasari	53,600	351	Daily/monthly flow (discharges), monthly water temperature, monthly suspended sediments	1956-2020
Bender	66,100	214	Daily/monthly flow (discharges), monthly water temperature, monthly suspended sediments	1950-2020

4. RESULTS AND DISCUSSIONS

4.1. Hydrological regime

4.1.1. The dynamic of multiannual flow and volume

First hydrological indicators that were evaluated and compared are average flow and volume. Thus, for two considered time periods, upstream of the DHC, at Zalischyky, approximately equal values are observed: 7022 mil.m^3 and 6964 mil.m^3. Downstream of the DHC at Mogilev-Podolsky, both river flows and volumes decrease: the volumes have decreased from 8753 mil. m^3 to 7952 mil. m^3 or by 800 mil. m^3 which is 9.2%. The decrease of water resources continues towards the river mouth: at Bender the average flows before the DHC construction were 320 m^3/s and after its construction the value decreases to 272 m^3/s, and volumes diminished from 10089 to 8579 mil. m^3 or with 1.5 km^3 of water, i.e. 15% (Figures 3 and 4).

As usual, the volumes of water in the basin increase with its area. Thus, in natural regime, the increase in volumes from Zalischyky was by 25% to Mogilev-Podolsky, by 34% to Grushka and by 44% to Bender. During the second period, the flow increase changed, being only by 14% to Mogilev-Podolsky (10% less than in the previous period), and only by 23% to Bender which is by 2 times lower than in the period pre DHC (Figure 5). Thus, if, in the previous period at Zalischyky about 70% of water resources were formed and towards Mogilev-Podolsk the value increased to 87%, at present, in the upper part of the basin towards Zalischyky, 81% of water flow is already formed and towards Mogilev-Podolsky, it increases to about 90%. This means that in the limits of the Republic of Moldova only about 10% of the water resources of the Dniester River are generated.

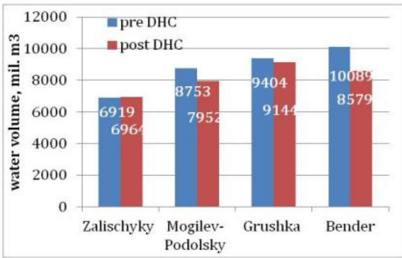


Figure 3. Average annual flow.

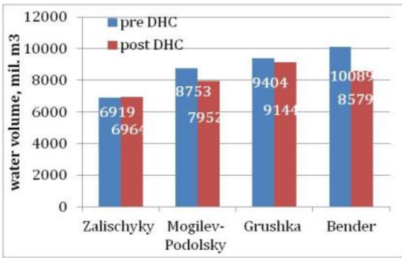


Figure 4. Average annual volume.

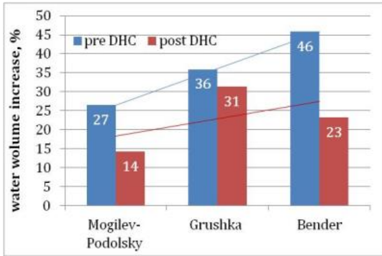


Figure 5. Share of volume increase with basin area in comparison with Zalischyky.

The increase of water losses for the sector from DHC to the river mouth can be explained by several factors, including water use for various economic needs, decrease in water resources brought by tributaries and slope runoff, declining ground water supply, the increase of evaporation rate caused by rising temperatures in recent decades due to climate change, etc. Future climate change scenarios show that for the upper part of the Dniester River basin, on the territory of Ukraine, where the main water volumes are formed, due to climate change the water resources would decreases by 5-10%, while in the downstream part, in the Republic of Moldova, the decrease would be more substantial, of about 20-25% [43]. This fact makes middle and lower part of the river more vulnerable to assurance with water resources, and more dependent to releases from DHC.

4.1.2. The dynamic of seasonal and monthly flow and volume

An important analyzed indicator is the seasonal flow. In natural regime, the seasonal flow is distributed as follows: 34% (17% each season) is generated in the autumn and winter. The most important resources are formed in the spring - 37% and in the summer - 30%, namely: at Zalischyky, 325 m^3/s (2573 mil. m^3) and 261m^3/s (2074 mil. m^3), and at Mogilev-Podolsky, 413 m^3/s (3274 mil. m^3) and 312 m^3/s (2474 mil. m^3) respectively. During the DHC operation, a redistribution of the share of water volumes is observed. Upstream, the volumes decreased by 3% in summer and increased by 2% in autumn and winter. Downstream of the DHC, the flow decreased during the spring period by 6%, while it increased in the summer by 2% and in autumn by 4%.

In temporal and spatial profile, after the DHC construction, the hydrological characteristics have slightly increased during the cold period of the year. The flows at Zalischyky and Mogilev-Podolsky stations are 167 m^3/s (1311 mil. m^3) and 211 m^3/s (1657 mil. m^3) for the autumn period, and 161 m^3/s (1248 mil. m^3) and 181 m^3/s (1406 mil. m^3) for the winter period. After commissioning the DHC, low decreases in flow and volume were noticed at both hydrological stations in summer. For the spring period, upstream of the DHC, flows and volumes have been reduced insignificantly from 325 m^3/s to 316 m^3/s. However, downstream, decreases of streamflow by about 100 m^3/s (from 413 m^3/s to 312 m^3/s), and of the volume by about 0.8 km^3 of water, compared to the values recorded before the DHC construction were found (the decreases being equal to 24%). For the spring season, at Zalischyky, the flow is 316 m^3/s (2507 mil. m^3), and for Mogilev-Podolsky is 312 m^3/s (2474 mil. m^3). Thus, on one hand, it can be assumed that the water resources from tributaries flowing into the DHC in the Zalischyky - Mogilev-Podolsky sector, for this season are accumulated in the DHC and do not participate in the increase of water volume of the Dniester River. On the other hand, it can be supposed that there is a change in the spring phenomena under the DHC impact, which leads to a reduction in water resources during this period (Figures 6, 7 and 8).

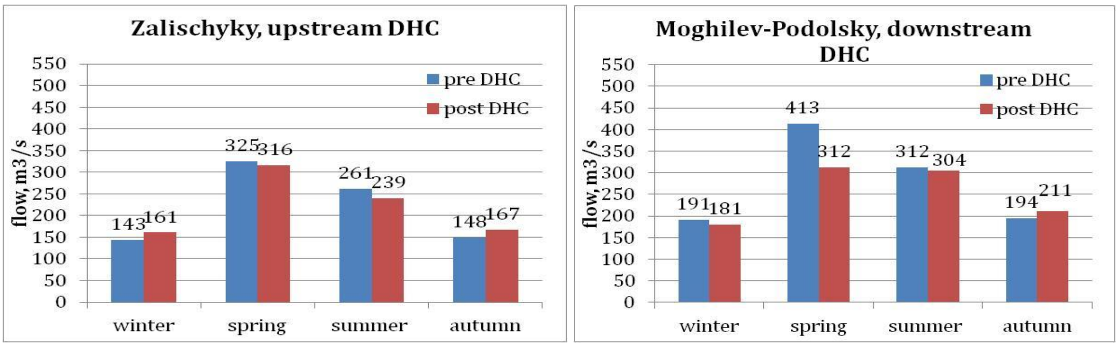


Figure 6. Seasonal water flow.

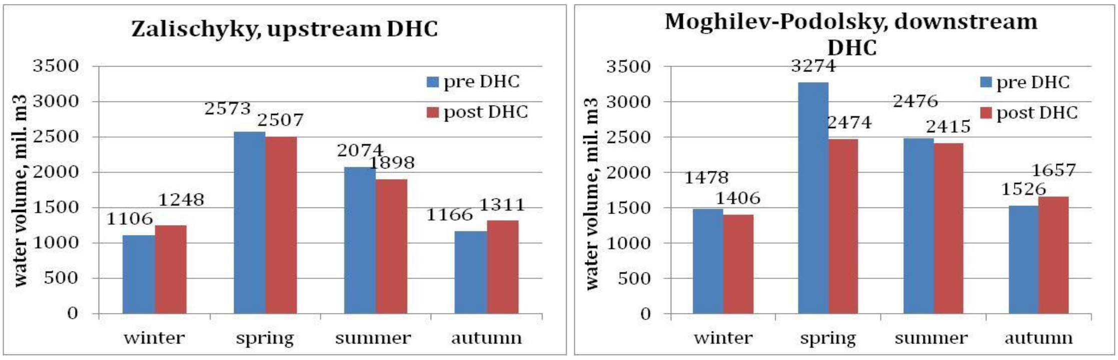


Figure 7. Seasonal water volumes.

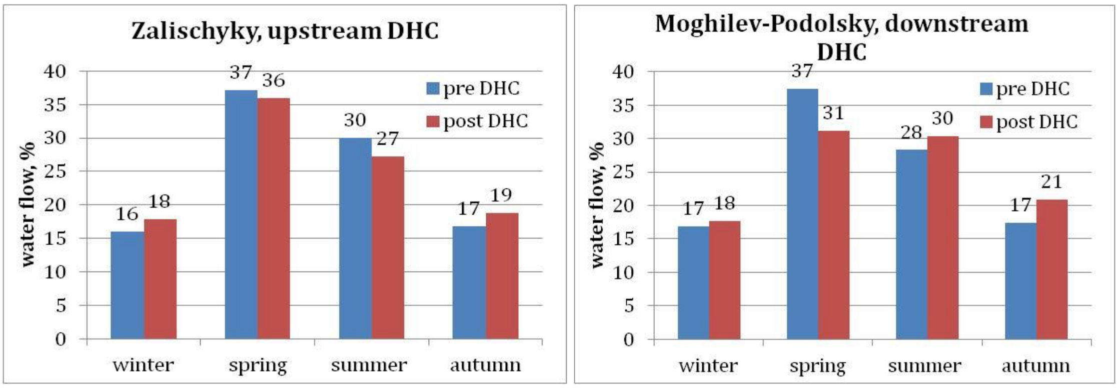


Figure 8. Seasonal distribution of the water flow.

4.1.3. The dynamic of monthly flow and volume

For a more detailed assessment of the DHC impact on the hydrological regime, the monthly flows were also analyzed using the same principle presented above. In natural flow regime, monthly flows hydrograph at Zalischyky station shows that the highest flows are in April (428 m^3/s), followed by the other two spring months (approx. 280 m^3/s), June (315 m^3/s) and July (272 m^3/s). In autumn and winter months the flow varies between 110 and 170 m^3/s. After the DHC construction, upstream of the DHC, the flows increased by approx. 40% in January, 13-14% in October, November, and decreased by 11-15% in April, July, August.

At the Mogilev - Podolsky station, in natural regime, the highest flows are also observed in the spring and summer months, but the values are higher than those from Zalischyky: 523 m^3/sin April, 387 m^3/s in March, and 320-350 m^3/s in May-July. In autumn and winter months the flows are close to 200 m^3/s. In flow regulated regime, downstream the DHC, in autumn months the situation is similar with the upstream station, in the summer months the changes are minor, but in February-April significant decreases in flows were noticed: 40% in March, 27% in April, and 18% in February. The same tendencies were observed at the stations located towards the mouth (Figures 9 and 10). Thus, a general decreasing trend of average monthly flow of the Dniester River for spring (significant) and summer is attested, on the whole sector downstream of the DHC. The slight flow increase is generally observed for the seasons characterized by lower flow (autumn and winter).

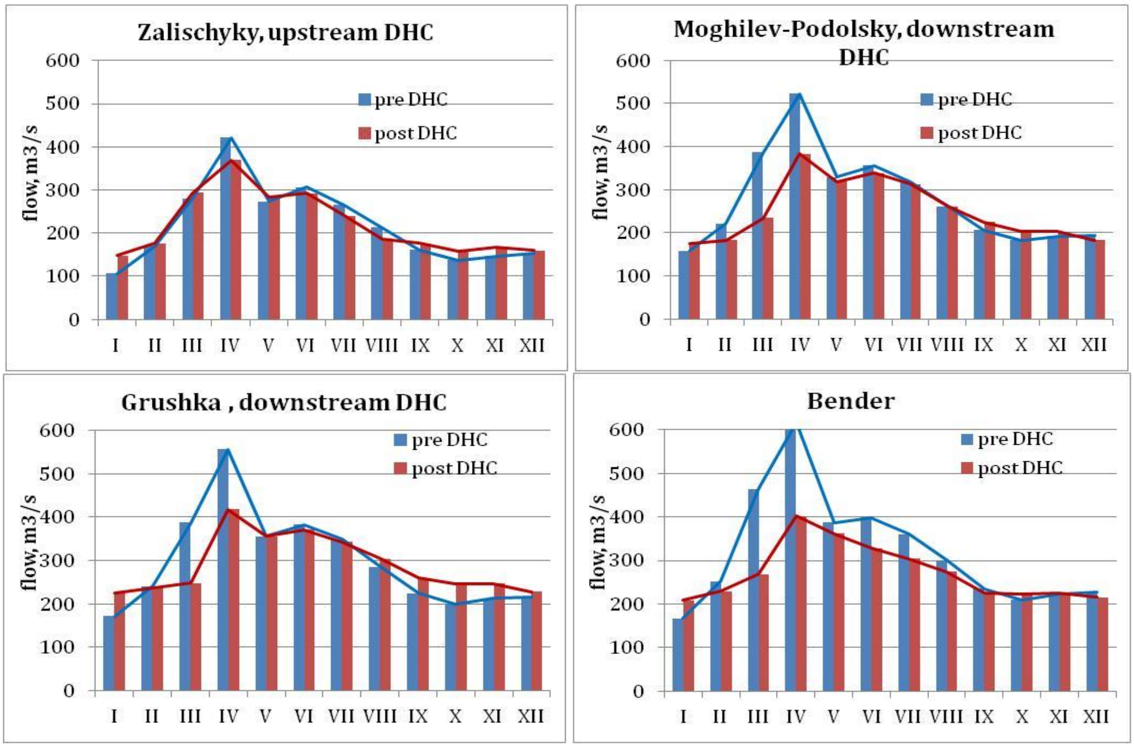


Figure 9. Distribution of monthly flow.

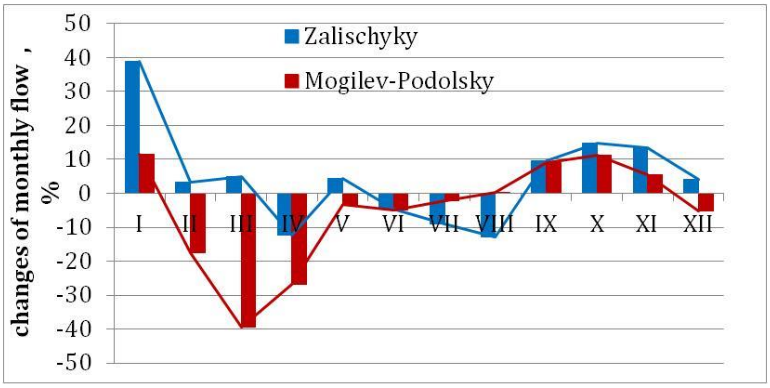


Figure 10. Changes of monthly flow between two time periods.

4.1.4. Low water season and low flow

The hydrological regime of the rivers situated in temperate zone, including those from Ukraine and Moldova, is characterized by several phases: spring floods - caused by melting snow (sometimes rain and melting snow), pluvial floods - formed as a result of summer heavy rains, low water season - caused by precipitation reduction, especially in summer–autumn as well as in winter time.

Low water is a component part of the hydrological regime of the rivers. It is a seasonal phenomenon. Main factors influencing the formation of minimal flow are the climatic and hydrogeological ones. On one hand, precipitation absence causes reduction of rivers rainwater supply, on the other hand, the groundwater supply is the main water source for rivers during this season. Within the Dniester River basin, the low water is manifested in the summer - autumn and winter periods. During the warm season, the minimum flows are lower compared to those in the cold season, due to high evaporation processes. The winter low water coincides with the winter phenomena. The periods with minimum flows are observed annually and, in some years, they can be extended even for 4-5 months (Figure 11).

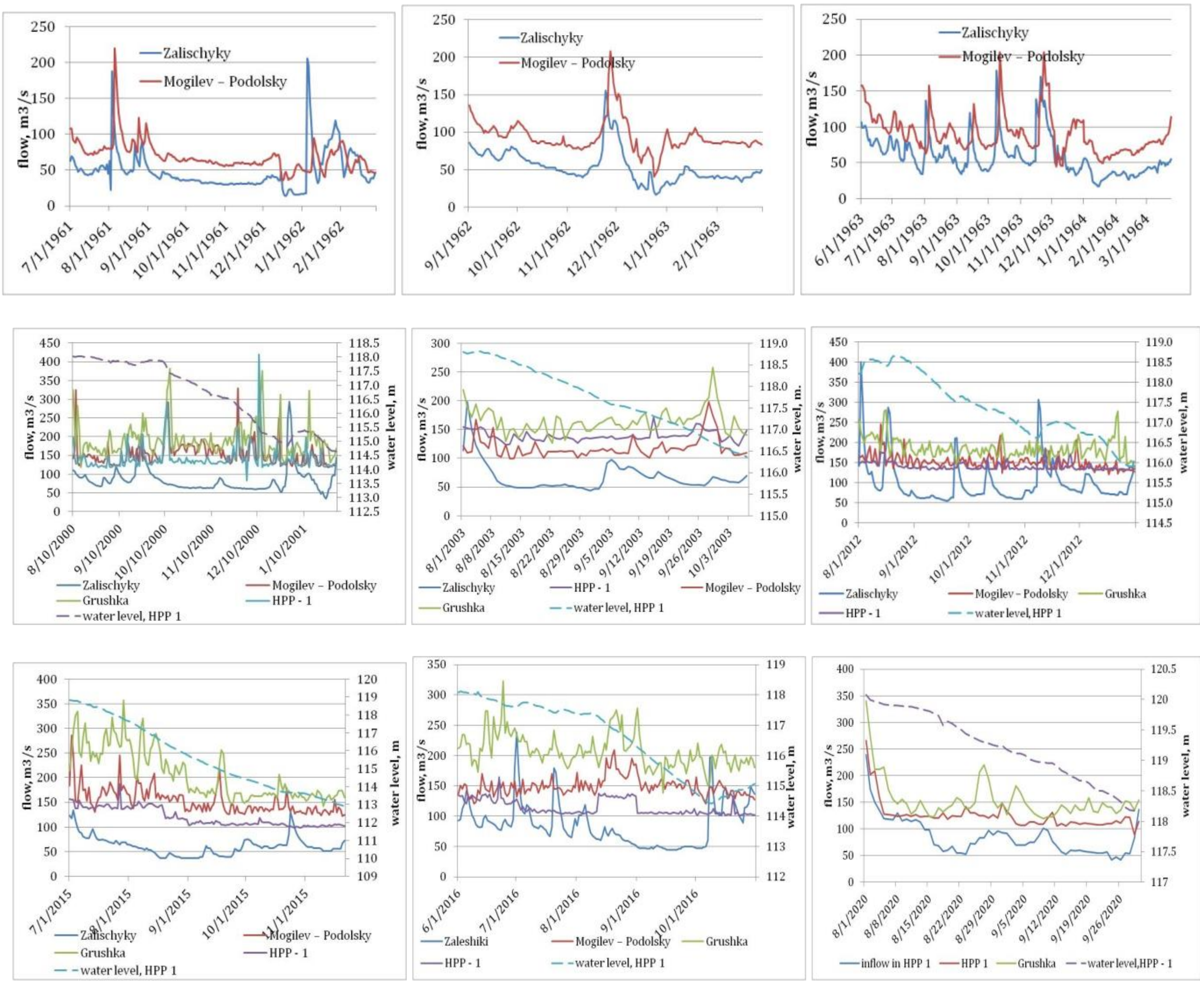


Figure 11. Low water phase.

In order to evaluate certain events of low water, data with values below 100 m³/s were extracted from the time series of Zalischyky (as reference station), HPP-1, Mogilev – Podolsky, Grushka hydrological stations. 100 m³/s is the minimum flow that must be discharged from DHC according to Operation Rules [34-36]. Examples of low water periods are shown in the figure above. In the pre-DHC period, low waters are highlighted in the years 1961, 1962, 1963 and 1967 with long periods of flows below 100 m³/s. In the years 1961-1963, the flows below 100 m³/s continue from July 1961 until February 1962, then from September 1962 until February 1963, after that from June to March 1964. Another long period with flows below 100 m³/s is August 1967- January 1968. After the DHC construction, low flows seasons are observed especially in the early 2000s (2000, 2003) and in the last 10 years: 2011, 2012, 2015, 2016, 2020, 2022. The period of occurrence of minimum flows continues to either July – January.

Finally, the low water is a natural phase of the hydrological regime of the Dniester River. This is largely formed between July and February. Its duration is significant, in some years it can last 1-1.5 months, but there are many years in which the duration is extended to 8 months - a significant period that has an impact on both biodiversity and economical activities. During the low water season before the DHC construction, the flows in the Zalischyky - Mogilev-Podolsky sector were even around 50 m³/s for a long time. Under the DHC impact, during this phase the minimum flows are characterized by an increase, and are not reduced below the value of 100 m³/s in the downstream (with some exceptions). The DHC maintains the water flow within the reference value even if in upper part of the basin the natural flow is reduced to 50 m³/s for a long period. In this sense, in order to maintain the minimum reference flow, the volume from the HPP-1 reservoir is reduced in order to compensate the flow for the downstream. The water level at HPP-1 decreases on average by 3.2 m. in comparison to the initial one. Thus, the DHC has a positive effect on maintaining the minimum flow and reduction of the risk of extreme hydrological droughts in the downstream sector.

4.1.5. Minimum (low) flow

For assessment of changes in minimum flow, a couple of indicators were analyzed: minimum flow, annual minimum flow for 7, 30, 90 days. As a result of the analysis, at the station upstream the DHC, the minimum average flows for the pre-DHC and post-DHC periods are equal to 34 m^3/s and 52 m^3/s respectively, the increase being of 52% (Figure 12). At the downstream stations, the minimum flows also have been doubled in the second period. At Mogilev-Podolsky the minimum average flow was evaluated to 107 m^3/s post DHC, compared to 51 m^3/s, pre-DHC, and at Grushka - 115 m^3/s, compared to 63 m^3/s for the pre-DHC period.

The general trend of minimum annual flows for the whole period is increasing at the Zalischyky station (Figure 13). Extreme minimum flows are recorded in 1953 - 14.4 m^3/s, 1956 - 13.3 m^3/s, 1957 - 17 m^3/s, 1959 - 7.18 m^3/s, 1961 - 14.2 m^3/s, 1993 - 15 m^3/s. The highest values of the minimum flows were recorded in 1971, 1975, 1980 - 70 m^3/s in each year, 1997, 1998 - 80-84 m^3/s, 2008 - 76.3 m^3/s. At Mogilev- Podolsky, the extreme minimum flows were observed in 1953 - 18.9 m^3/s, 1960 - 21.2 m^3/s, 1973 - 25.7 m^3/s. After the DHC construction the lowest flows were approx. 95-99 m^3/s, registered in the years 2003-2006. The highest values of the minimum flows of approx. 120-133 m^3/s were recorded in 1993, 1997-1999, 2008, 2009.

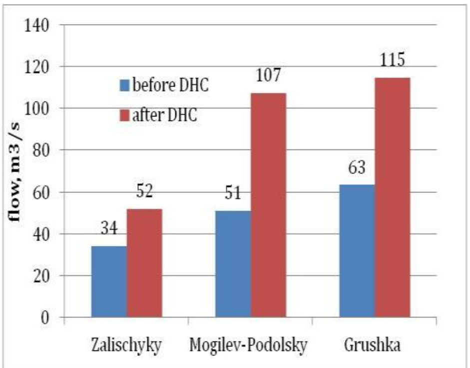


Figure 12. Minimum average.

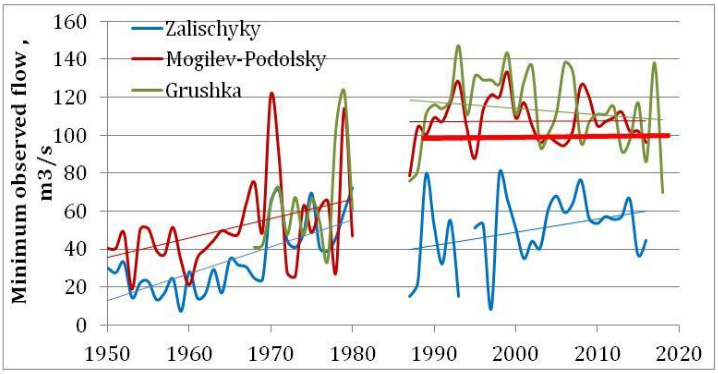


Figure 13. Minimum observed flow.

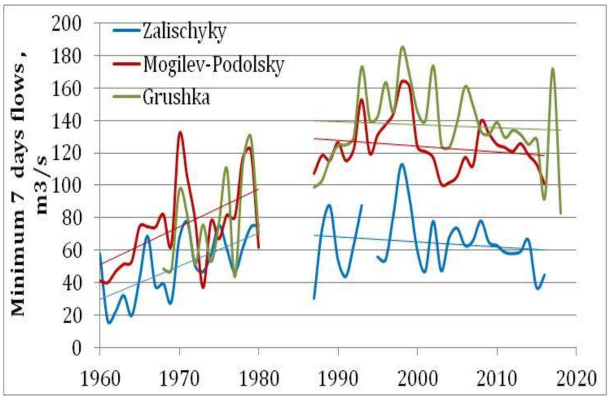


Figure 14. Minimum 7 days flows.

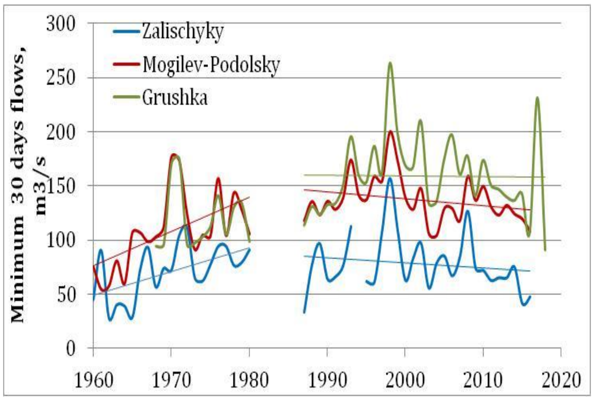


Figure 15. Minimum 30 days flows.

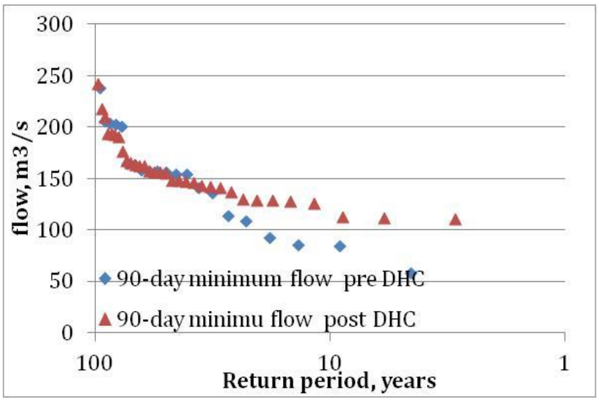


Figure 16. Frequency of 90 days flows at Mogilev-Podolsky.

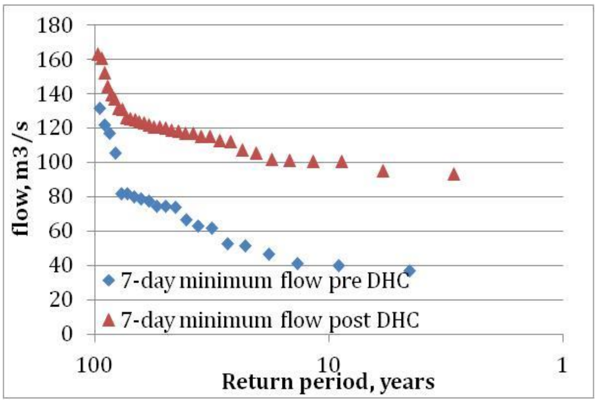


Figure 17. Frequency of 7 days flows at Mogilev-Podolsky.

Trends of minimum flows for 7 and 30-days are shown in the Figures 14 and15. Broadly speaking, they coincide with the conclusions regarding the minimum flows. In Figures 16 and 17, it can be seen that the magnitude of the curves for 90 and 7-days minimum flow probabilities knows major shifts. Such phenomena are observed in the downstream parts of the DHC, generally due to discharges of minimum flow which is established by Operation Rules of DHC being equal to 100 m³/s.

As a conclusion, the assessments show that, for all the periods, the minimum flow has increased significantly. This means, in practice, that, for example, hydrological droughts with low probabilities that occurred in the past, in the DHC downstream, at present would be much rarer events. In general, the periods with minimum flow were changed downstream of the DHC and more water is now present in the river during the low water period. However, for the last decades it was observed that the low flow frequency has increased, fact that has a disastrous impact on aquatic ecosystems as well as on economy. In this regard, reevaluation of minimum flow discharged from DHC in order to improve the state of ecosystems and population is considered important.

4.1.6. Low flow and the DHC Operation Rules

A special analysis was performed in order to assess the compliance with the Operation Rules [34-36] in term of assurance of the minimum flow discharged from the DHC (100 m³/s). Initially, the number of days with water flows lower than 100 m³/s was calculated for all stations and periods. Thus, at Zalischyky, before the DHC construction, the duration of flows below 100 m³/s is, on average, 118 days per year, which is about 32% of the year, the trend being downward. During the decade 1950-1960 the duration of the mentioned flow was, on average, 160 days/year or 44%. Over the next 15 years, by the '80, the share of days decreased to an average of 77 days/year or 21%. At present, after the DHC construction, flows below the value of 100 m³/s appear, on average, in 91 days/year or 25%, the trend being ascendant. Between 2011-2016 the number of days increased on average to 146 days/years or 40%. At the Mogilev-Podolsky and Grushka, in the pre-DHC period, the flows with values below 100 m³/s occurred on average 62 days/year and 19 days/years, which constitute 17% and 5%, respectively. In the post-DHC period, the number of days is reduced to 6 days and 13 days/year, respectively, the share being 2-4% (Figures 18, 19 and 21).

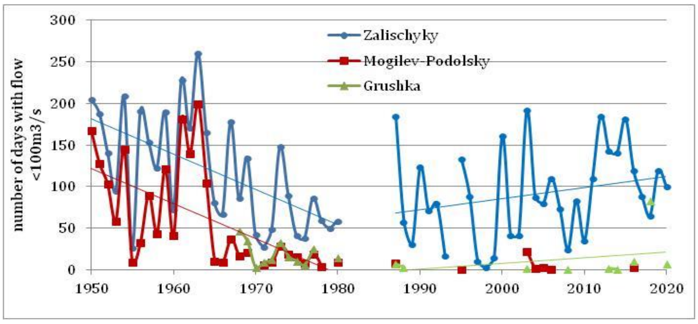


Figure 18. Duration of flow less than 100 m³/s.

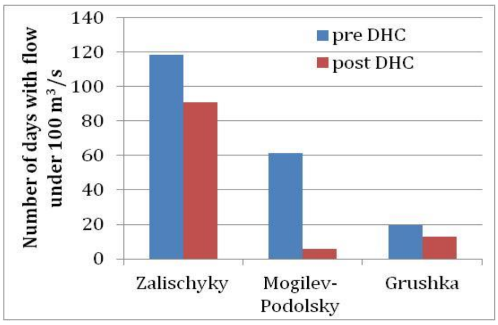


Figure 19. Number of days with flow less than100 m³/s.

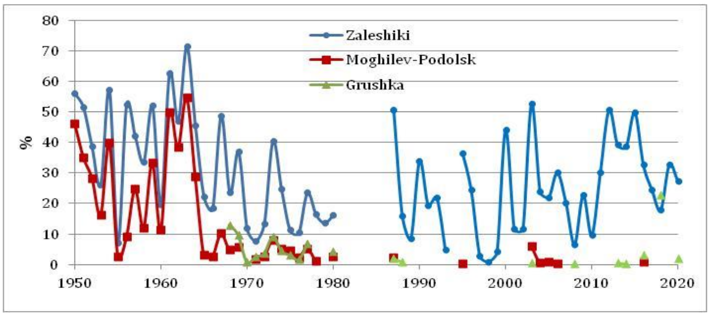


Figure 20. Share of annual days with flow less than 100 m³/s.

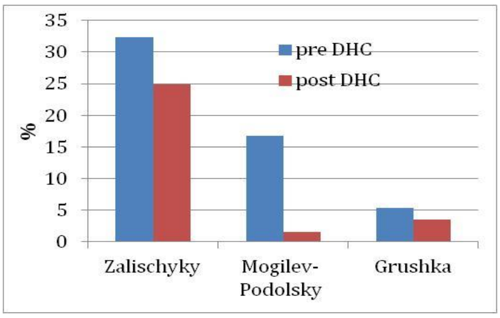


Figure 21. Average share of days with flow less than 100 m³/s.

At Zalischyky, the average values of flows below 100 m³/s are 72.4 m³/s before the DHC and 80 m³/s post DHC. At the downstream stations the values are, on average, 78 m³/s at Mogilev-Podolsky and 76 m³/s at Grushka in the pre-DHC period, practically 20-30 m³/s less than the reference value. After the commissioning of the hydropower complex, the values increased to 95 m³/s. The flows below 100 m³/s downstream of the DHC occurred occasionally, and do not decrease much compared to the reference (Figures 22 and 23).

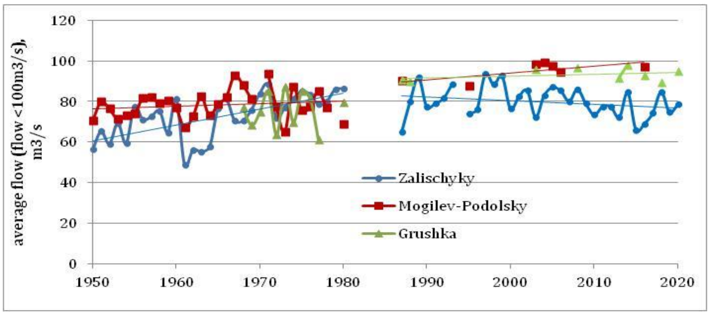


Figure 22. Average flow less than 100 m^3/s.

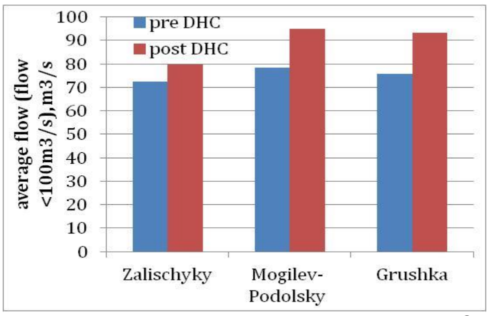


Figure 23. Average flow less than 100 m^3/s

4.1.7. Spring floods

Spring floods are the phase of the hydrological regime formed as a result of snow melting or rain associated with snow melting, characterized by rising river levels and flow, quite long duration and large volumes. Sometimes, as a result of this phenomenon, the floodplains are flooded. The period of this phase occurrence is spring, in some years the beginning being registered in February, and the end in early June. The main natural factors that determine spring floods generation are: water reserves stored in snow, especially in the upper part of the basin, melting intensity and duration, water retention processes (infiltration, forest cover, etc.), climatic conditions (e.g. temperatures, precipitation and their character, etc.), etc. Water propagation process through the riverbed is determined by winter phenomena (ice formation/melting, etc.), reservoirs and dams' operation etc.

In order to assess the changes of the spring floods characteristics due to the DHC impact, the hydrological data from the Zalischyky, Grushka and Bender stations were analyzed for the pre-DHC and post-DHC periods. The statistics on spring floods were recalculated on the basis of daily data, synchronously for all stations, and certain calculation errors were excluded.

In natural flow regime, before the DHC construction, spring floods occurred on average on March 1, the earliest this phase began in the first decade of February (1957-1961, 1967, 1974), and the latest - in the last decade of March or even April (1952, 1956, 1964, 1980). The maximum flow is formed in 2-3 weeks from the beginning of the phase: at Zalischyky its date of occurrence is March 16, and at Bender March 22, with the 5 days propagation. The end of the phase is estimated for April 23 at Zalischyky and after 6 days, on April 29, at Bender. The latest the phase ended in the first days of June (1951, 1952, 1964), and the earliest, in the second decade of March (1955, 1956, 1966, 1977) (Figure 24). The duration of spring floods is 54 days at Zalischyky and 60 days at Bender. The duration of the phase has a decreasing trend: in the first period it is 51 days at Zalischyky and 69 days at Bender and in the second one, 50 days at both stations.

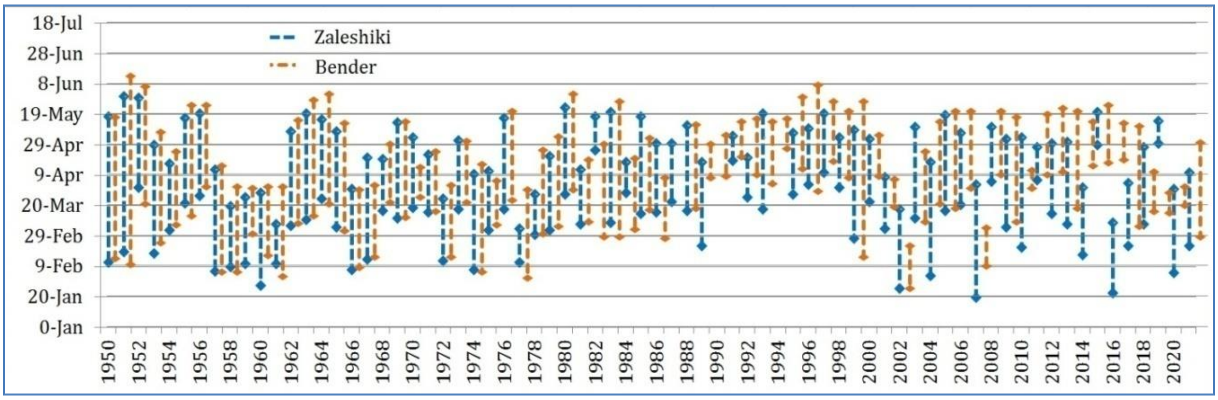


Figure 24. Spring flood occurrence at Zalischyky and Bender stations.

In the post-DHC period, spring floods dynamics change in the Zalischyky-Bender sector. In the first 10 years there is a significant delay but also a short duration of spring floods at all hydrological stations: it is approx. 40 days at Zalischyky and 44 days at Bender. Over the last 20 years, spring floods occurrence is characterized by a large variation. In some years, at Zalischyky, there is also a significantly delay, the beginning being in the last decade of March and end in the first decade of May, duration being on average 1.5 months. However, during this period, the number of years with early occurrence (the last decade of January - the first decade of February) increased (2002, 2004, 2007, 2016 and 2021). The duration of these phases in the mentioned years is on average 2 months. At Bender, the phase occurrence in the last

20 years, in general, maintains its trends from the '90s, and only in 2002, 2007, 2021 the spring floods started at the end of winter and last on average 1.5 months. In the last decade, the period of phase occurrence at Bender differs substantially from that at Zalischyky. At Bender, the phase begins in the second half of April and ends in the second decade of May. Duration of spring floods is characterized by a slight decreasing trend at all hydrological stations (Figures 25-28).

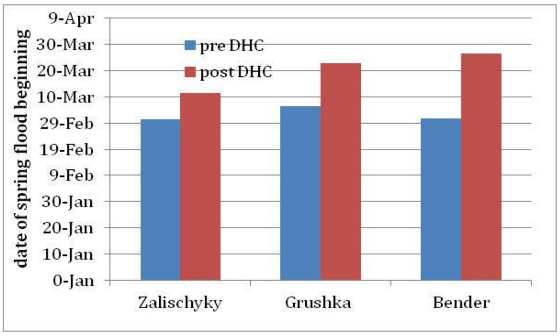


Figure 25. Average date of spring flood beginning.

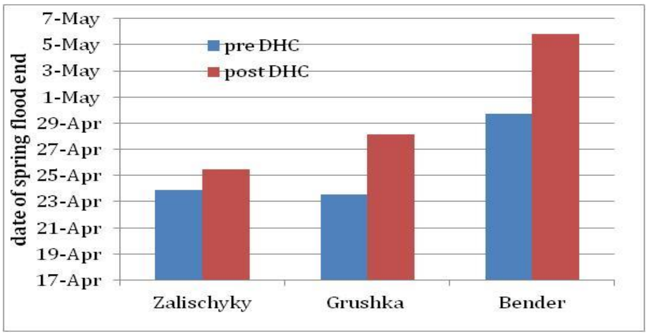


Figure 26. Average date of spring flood end.

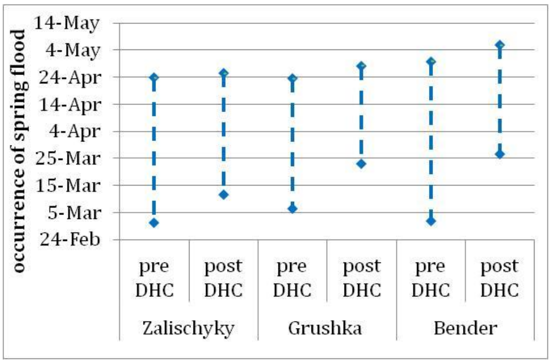


Figure 27. Average occurrence of spring flood.

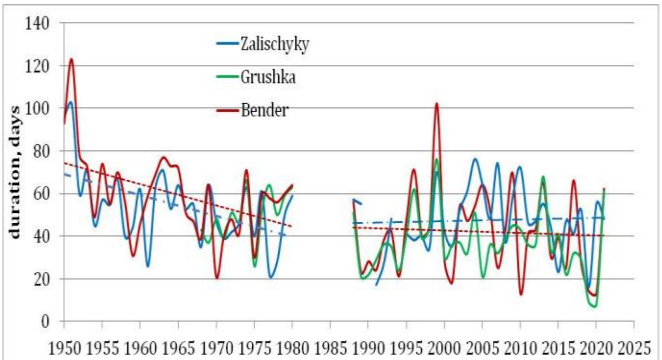


Figure 28. Spring flood duration.

Finally, for the two periods, at Zalischyky and Bender, the beginning of the phase is March 1, pre DHC, March 11 and March 26 - post DHC, respectively, the delay is 10 days in natural regime and 25 days in regulated regime. At Grushka this delay is 17 days (Figure 25). Occurrence of maximum flow, pre DHC, at Zalischyky is March 16, Grushka and Bender March 22, and post DHC, at the same posts it is March 27, April 5, April 11 or a change of 11, 13 and 21 days compared to previous period. The end of spring flood period is in the limits of April 23-29 before the DHC and April 25-May 5 after the DHC construction at the 3 analyzed stations (Figure 26), the changes being minor, 2-6 days. The duration of the natural phase is 54 days at Zalischyky and 60 at Bender and decreases in the post DHC period, to 46 days at Zalischyky, 36 days at Grushka and 42 days in Bender (Figure 29), being a decrease of the period by 8 days (14%) upstream of the DHC, and 13 days (26%) at Grushka and 18 days (30%) at Bender.

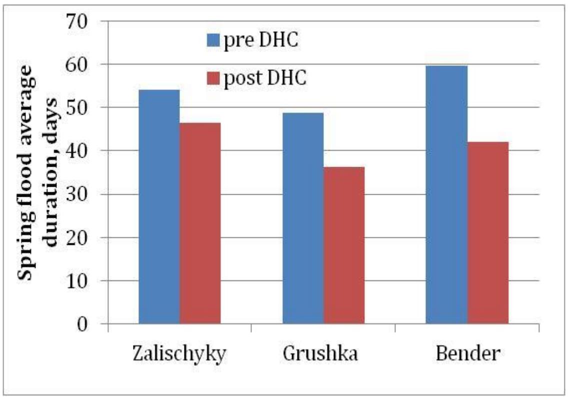


Figure 29. Spring flood average duration.

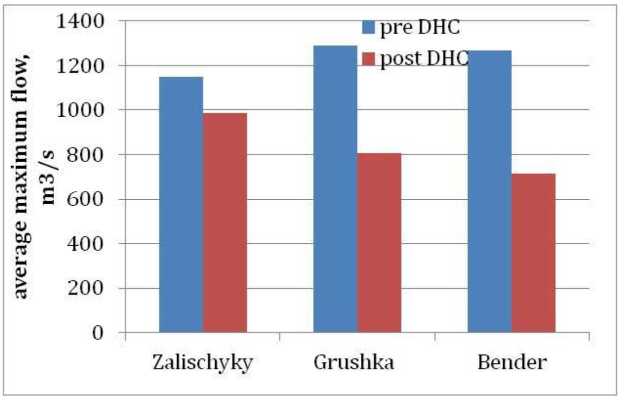


Figure 30. Maximum flow of spring flood.

The maximum flow of spring floods tends to decrease at the Zalischyky station and increase at the Bender station during the pre-DHC period. After the DHC construction, the flow decrease is observed at all hydrological stations (Figure 30). During the pre-DHC period at the Zalischyky, Grushka and Bender hydrological stations, the average maximum flows are equal to 1150 m^3/s, 1289 m^3/s, 1265 m^3/s, spatial increase being 115-140 m^3/s. During the post-DHC period, the maximum average flow is characterized by spatial decrease. Thus, at Zalischyky it is 988 m^3/s or 14% lower than in the previous period, at Grushka the value is 805 m^3/s or by 38% lower than before DHC, and at Bender the flow is 716 m^3/s or 43% less. Spatially, the value of the maximum flow no longer increases as in pre-DHC period but decreases by 180-270 m^3/s (Figures 30 and 31).

The spring flood average volume for the two periods is generally decreasing. At Zalischyky, its value is 1805 mil. m^3 before the DHC construction and 1616 mil. m^3 after DHC, the decrease being by 10%. At Grushka station, the average volume is within the limit of 2282 mil. m^3 before the DHC and 1480 mil. m^3 after the DHC, the decrease being by 35% or 800 mil. m^3. At Bender, the values are 2802 mil. m^3 before the DHC and 1707 mil. m^3 in the period after the construction of the DHC, the decrease being by 39% or 1.1 km^3. In terms of space, pre-DHC, the increase of spring floods volume was practically by 0.5 km^3 on Zalischyky - Grushka sector and 1 km^3 on Zalischyky - Bender sector, while after DHC it practically does not change on the same sectors, being similar to that of Zalischyky (Figures 32 and 33).

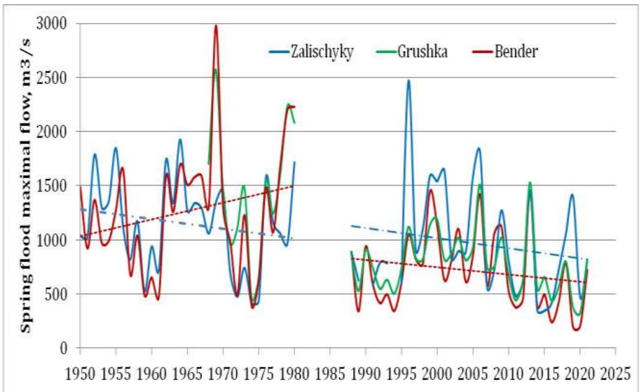


Figure 31. Spring flood maximal flow.

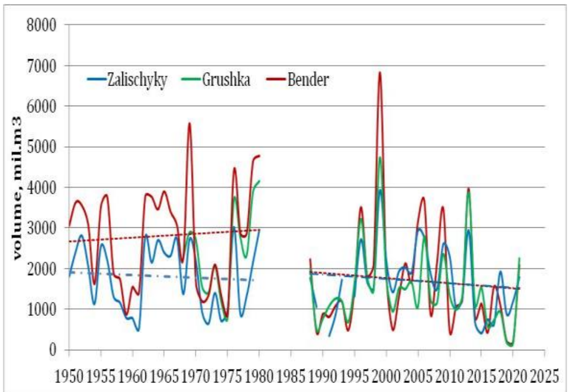


Figure 32. Spring flood volume.

Spring floods form important water resources of the Dniester River. Their share from the total annual water volume was on average 27-29% in the pre-DHC period, in the post-DHC period this value decreases significantly: upstream, at Zalischyky, the share is already 23%, downstream, at Grushka it is 16%, and at Bender -19%. The general trend is of significant decrease in the pre-DHC period and a slight decrease after DHC at all hydrological stations (Figure 34).

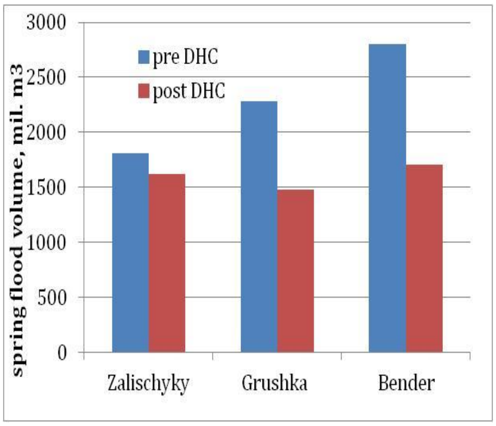


Figure 33. Average spring flood volume.

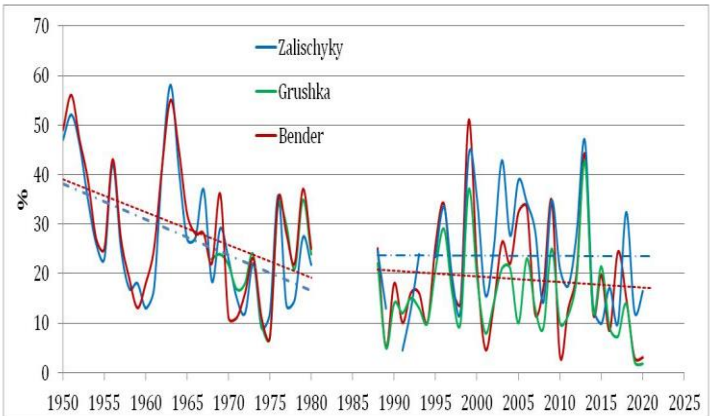


Figure 34. Share of spring floods from annual water volume.

The dynamics of spring floods in natural regime depends on the processes of water propagation in the riverbed and floodplain system and after DHC construction – it is regulated by hydrotechnical structures. The change in spring flood occurrence is significantly influenced by the planning processes of the so-called spring ecological flood. Its purpose is to provide sufficient water volumes for the Dniester riverbed to ensure reproduction of fish and stability of the Dniester ecosystems. Since the 1990s, experts from Moldova and Ukraine have been making efforts to plan and carry out this type of ecological flood. Thus, according to analyzed information four situation of spring ecological flood releases were identified:

- spring ecological flood coincides with natural spring flood;
- spring ecological flood is realized after generation of spring flood;
- spring ecological flood coincides with the beginning or end of spring flood - it is a component of it;
- spring ecological flood is released in the absence of spring flood occurrence.

Several elements are important to consider in order to discharge an efficient ecological flood: water temperature, water volume, duration, shape of hydrograph etc. All these should be studied in more details in order to plan and release from DHC an efficient spring ecological flood. Also, parameters for spring ecological flood efficiency should be developed and applied for ecosystems and fish benefit.

4.1.8. Pluvial floods

Pluvial floods are a phase of hydrological regime characterized by rapid increase of river flow and level and volume as a result of heavy rains. These are formed in the warm period of the year, on average, in the summer months: June and July. Main factor that determines generation of pluvial flood on the Dniester River are heavy rains formed in the upper part of the basin. In natural conditions (before reservoirs and dykes' construction), spatial reduction of the maximal flow of pluvial floods was determined by basin surface and floodplain width increase. As an example, the flood hydrograph of 1948 (Figure 35) shows the flood wave attenuation in natural regime, in particular, the change in hydrograph shape, as well as the decrease in maximum flow values due to water accumulation in the floodplain in the downstream part of the Dniester River.

In regulated regime, the flood wave dynamics has changed. In particular, it should be mentioned that a certain threshold for flood maximal flow is considered. Thus, according to the DHC Operation Rules, its value is 2600 m^3/s in case of flood inflow of 1-10% probability. During the DHC operation, this value was exceeded only once, in case of 2008 flood event when maximal flow discharged from the DHC was 3500 m^3/s. Thus, reservoirs operation during floods plays a significant role in flood protection of the downstream part from potential damages. However, in certain conditions, operation mistakes can create dangerous situation for population and industries from the floodplain.

Last flood event was the one from 2020, when the maximal flow at Zalischyky was 3740 m^3/s which was reduced to 2020 m^3/s at Grushka, and at Bender it was of approx. 1800 m^3/s (Figure. 36). The total volume was 2 km^3 at all stations. In general, the flood hydrograph, under the DHC impact, was changed from triangle to trapezoid thus causing a delay in the occurrence of the maximum flow by increasing the rising limb and slightly decreasing the recession limb of the flood wave.

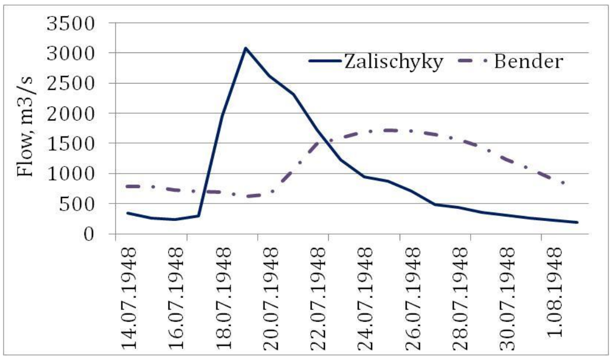


Figure 35. Flood hydrographs of 1948.

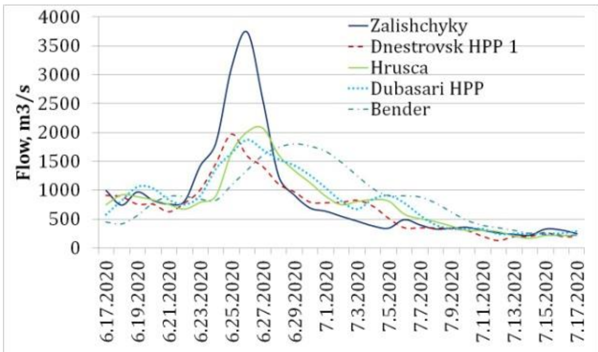


Figure 36. Flood hydrographs of 2020.

For the assessment of the DHC impact on pluvial flood phase, statistical analysis of different characteristics was performed for the mentioned periods. For the pre-DHC period, maximum daily flows are characterized by upward trends at all hydrological stations, and for the post-DHC, the trends are characterized by stability at Zalischyky and a slight decrease at downstream stations (Figure 37).

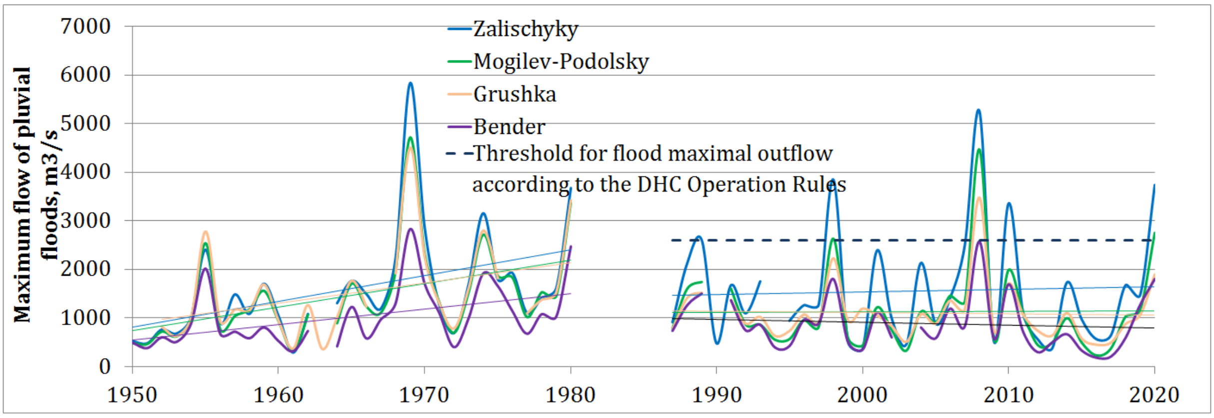


Figure 37. Maximum flow of pluvial floods.

The average values of maximum daily flows at Zalischyky station have slightly decreased in the post-DHC period, from 1609 m³/s to 1558 m³/s or by 3.2%. At DHC downstream stations, maximum flow has decreased by 25-30%. At Mogilev-Podolsky station, it decreases from 1500 m³/s to 1130 m³/s, by 370 m³/s or 25%. At Grushka, maximum instantaneous and daily flow decrease is approx. 30%: first characteristic diminishes from 1598 m³/s to 1095 m³/s or by 31.5% and the second one from 1477 m³/s to 1041 m³/s or by 29.5%. At Bender station, before the DHC construction, maximum flow, on average, is a little over 1000 m³/s and after the DHC, itis a little below 900 m³/s, the decrease being approx. by 14% (Figure 38).

Spatially, from the upper to lower part of the river, in natural regime, the maximum flow is reduced from 1609 m³/s to 1477 m³/s or by 8% on the Zalischyky - Grushka sector, however, in regulated regime, this decrease is 33%, from 1558 m³/s to 1041 m³/s. At the Bender station, during Dubasari HPP operation, the maximum flow decreased by 36% compared to Zalischyky, and after DHC construction the share is already 43%, thus, maximum flow regulation by the entire cascade of reservoirs being significant. However, the occurrence of maximum flows that exceeds 2600 m³/s increased in the last decades. Thus, for pre-DHC period, the flow over mentioned value at Zalischyky was recorded in 1969, 1970, 1980. After the DHC construction so far flows of over 2600 m³/s at the same station were manifested more often: in 1989, 1998, 2008, 2010, 2020 (Figure 37). Respectively, increasing the frequency of major floods also requires special attention for catastrophic floods management.

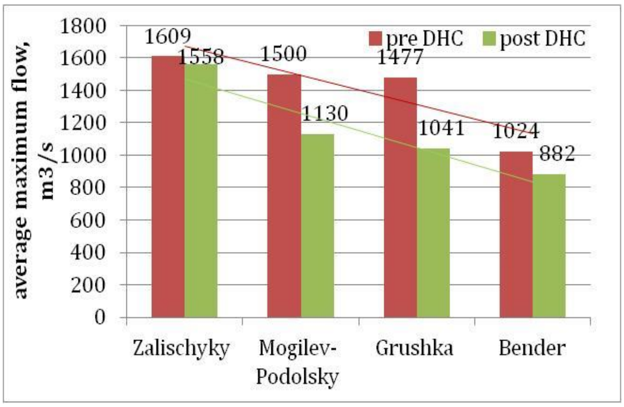


Figure 38. Average maximum flow of pluvial floods.

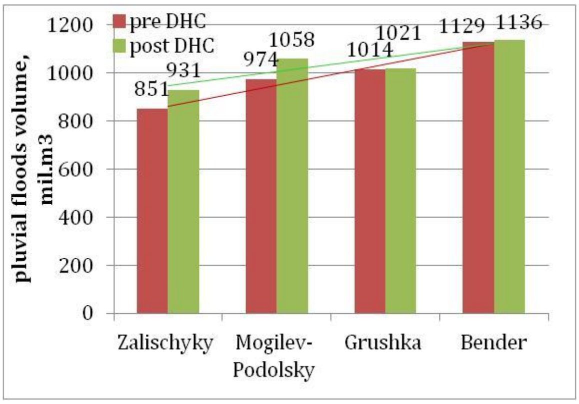


Figure 39. Pluvial floods volume.

Average flood volumes, for two considered periods, are: in the DHC upstream - 851 mil. m³ and 931 mil. m³ and in the downstream - 974 mil. m³ and 1058 mil. m³, the increase for the second period being about 9%. At Bender station, the pluvial flood volume increased to 1.1 km³ (Figure 39). The increase of this indicator together with basin surface, on the Zalischyky - Bender sector, is, on average, of 20%. For the period pre-DHC the share is 25%, and post-DHC - 18%, thus, a larger part of the flood volume being formed in the upper part of the river basin in the current period compared to the previous one.

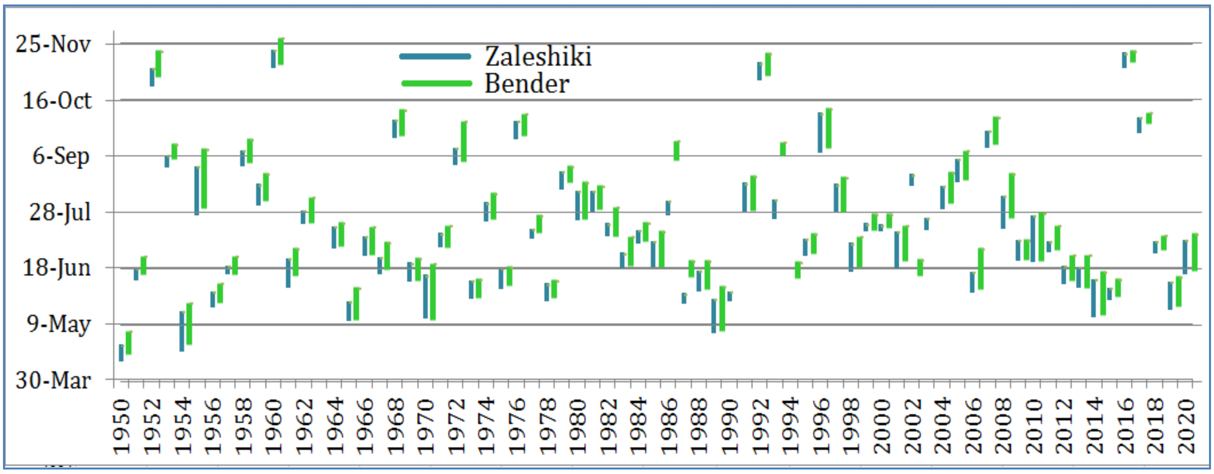


Figure 40. Pluvial floods occurrence.

In general, pluvial floods occurrence is considered to be the summer season, June and July, but there are years when the maximum flow is observed in both spring and autumn months. Figure 40 shows the pluvial floods appearance and duration. Thus, in comparison with spring floods, this phenomenon is quite short, and the occurrence differs from year to year and may include the period from April to November.

The manifestation of pluvial floods is synchronous for upstream and downstream stations, which shows that DHC does not cause a significant temporal and spatial shift of the analyzed phase. On average, for the two periods, pluvial floods occurrence is at Zalischyky July 9 - July 24, July 9 - July 25, at Mogilev – Podolsky, July 10 - July 27, July 9 - July 26, and at Bender, July 12 - July 31, July 12 - August 1 (Figure 41).

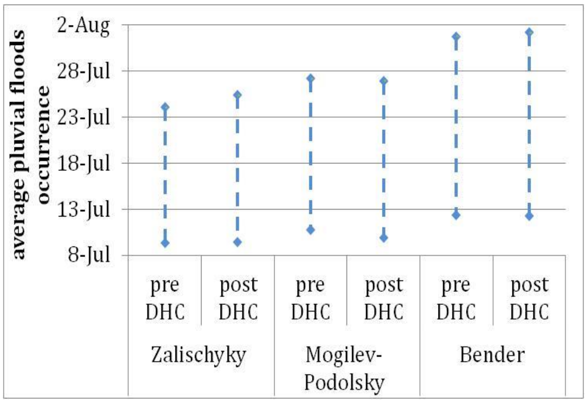


Figure 41. Average pluvial floods occurrence.

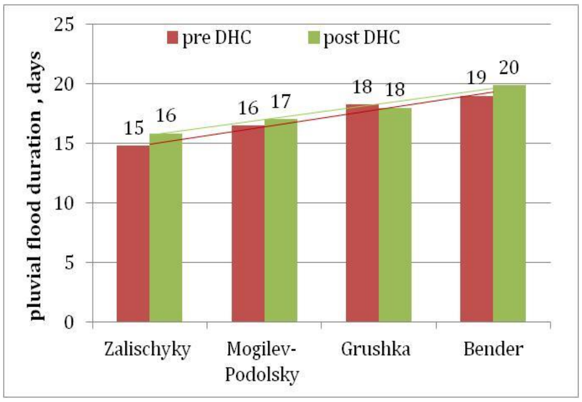


Figure 42. Pluvial flood duration.

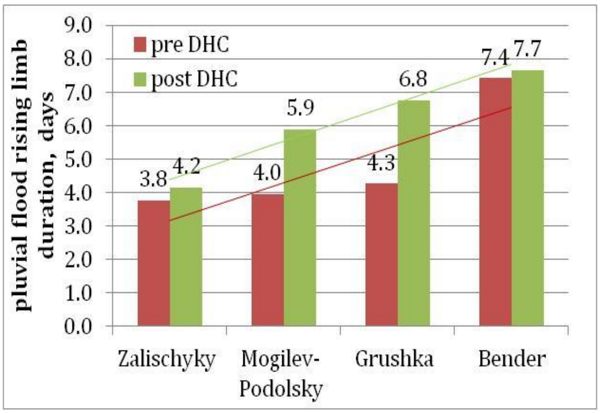


Figure 43. Pluvial flood rising limb duration.

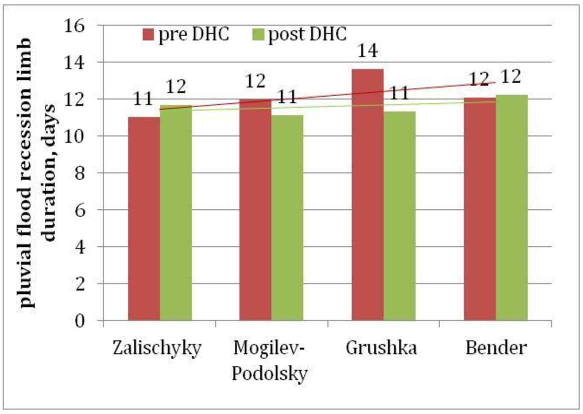


Figure 44. Pluvial flood recession limb duration.

Total duration of pluvial floods is 15-16 days at Zalischyky and Mogilev-Podolsky and 19-20 days at Bender, large differences between pre-DHC and post-DHC periods were not identified (Figure 42). However, division of flood hydrographs into two parts: rising and recession limbs, shows that changes are observed mainly for the first one. Thus, rising limb average duration, at Zalischyky, is 4 days for both periods. In the downstream, at Mogilev-Podolsky and Grushka, the number of days increased from 4 days pre-DHC to 6-7 days post- DHC (Figure 43). Flood wave recession limb is maintained within 11-12 days in the upper part of the DHC, while downstream of the DHC, it has a slight decreasing tendency, at Grushka the decrease being from 14, in natural regime to 11 days, in regulated regime (Figure 44).

Thus, the DHC impact on pluvial floods is manifested by changes of maximum flow, it decreased by about 30% in the downstream part, modification of flood wave hydrograph from triangle to trapezoid, thus causing a delay in the maximum flow by increasing the rising limb and decreasing the recession limb of the flood wave. Pluvial flood total duration does not change, and no major shift of the flood wave in space profile is observed. However, the increase in the frequency of natural floods must lead to a serious preparation of the DHC for the management of these phenomena and protection of areas in the lower part against major floods.

4.2. Hydropeaking effect

One of the direct effects of the DHC operation is the hydropeaking effect that is felt in the downstream part. It is determined by operation of HPP-2 turbines and is characterized by major intraday variations in level and flow. For analyzing this effect, we used the intraday data recorded at the automatic level stations situated downstream of HPP-2: Naslavcea (5 km downstream), Unguri (30 km downstream), Soroca (100 km downstream) and Sanatauca (180 km downstream). Time series for the first two stations consist of levels data for every 15 minutes for 2013-2020, and those from Soroca and Sanatauca consist of water levels measured hourly for the period 2017-2020. Data series contain many gaps.

For evaluation of hydropeaking effect, following characteristics were analyzed: level variation, daily level amplitudes, increasing and decreasing rate. It should be noted that actual Operation Rules do not contains information regarding any threshold for evaluation of hydropeaking effect. However, in the draft of Operation Rules, 2017 [36], it is mentioned that the water level variation in the downstream part (June – November) must not exceed 20-25 cm. In spring and summer, water level fluctuations downstream of the HHP-2 must not exceed 5cm/h or 20cm/day. Also, according to [44], one of the criteria for identification of heavily modified water bodies is water level fluctuations downstream HPP dam of over 50 cm during the day for most of the year. Thus, as threshold values, for water level fluctuation, 20 cm/day and 50 cm/day were considered, and for increasing and decreasing rate - 5cm/h or 0,08 cm/min. It should be noted that increasing and decreasing rates are changes in water level over a certain threshold in a certain period of time and are important to be estimated for evaluation of the risk of death of aquatic organisms due to turbine shutdown and discontinuity and water discharge from the HPP-2. The increasing and decreasing rates describe the rates at which water levels rise or fall during an event and are considered to have a significant effect on aquatic organisms [15-17].

4.2.1. The amplitude of the intraday water level

The first analyzed parameter to evaluate the hydropeaking effect is the water level amplitude: the daily difference between the maximum level and the minimum level (intraday level difference). As a result of performed analysis, it was found out that at Naslavcea station, the water level amplitude far exceeds the reference values. The exceedance of the 50 cm is on average 37%, being higher in 2013, 2014 - 46-58%, and lower in 2016-25%. The exceedance of the 20 cm was significant, on average - 70%, in the years 2013, 2014 being highlighted by higher values (93-99%), and in 2016, 2018 and 2019 by lower values (55-62%). At Unguri, there is an insignificant decrease in the share of values that exceed the reference. The level amplitude of over 50 cm is 33%, over 20 cm (70%). The lowest share of value that exceed 50 cm was estimated for 2016 and 2017 (14-25%), and the highest for 2013, 2014, 2020 (37-47%). Significant exceedance of the water level amplitude over 20 cm was observed in 2013, 2014 (90-96%), and less obvious in 2016 (44%). At Soroca and Sanatauca stations, the parameters of the hydropeaking effect are significantly reduced. Exceedance of the reference value of 50 cm are few (8% and 3%), and of the value of 20 cm, 33% and 14% respectively.

Based on the intraday data, the average daily water level amplitude was calculated for the entire monitoring period for all station (Figure 45). The largest fluctuations are recorded between April-July, November-January at Naslavcea and Unguri stations. At Soroca and Sanatauca such periods are in the first part of the year, and the months of June, July, the hydropeaking effect being diminished towards the sectors concerned (Figure 45).

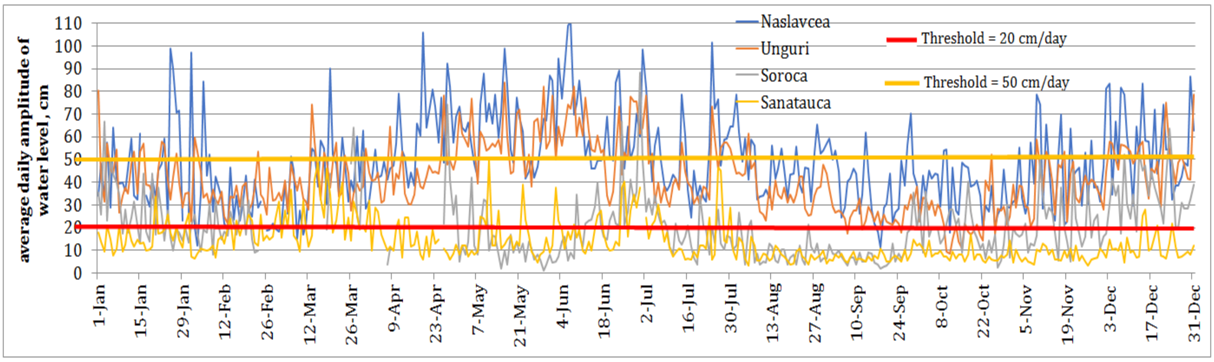
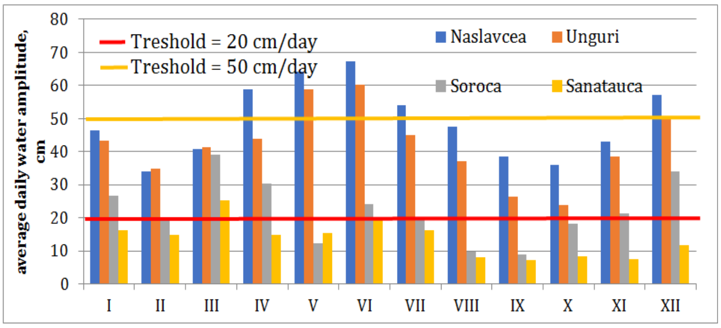


Figure 45. The average daily amplitude of the water level at all hydrological stations for the entire monitoring period.

At the monthly level, the highest values were found in April, May, June, July and December, when the averages at the stations near the HPP-2 were equal or exceeded 50 cm. The lowest values of the level's amplitude (30-35 cm), were observed in February, September and October. There are no months in which averages smaller than 20 cm were recorded at the mentioned stations. At Soroca and Sanatauca, monthly average values are below the value of 20 cm in February, May, July, August, September, October. In the other months, the averages exceed to a certain extent the reference value but not much (Figure 46).

At annual level, the largest water level variations are estimated for the first years of monitoring, 2013 and 2014, the values decreasing from 2015, and increasing towards 2020. At stations near the HPP-2, the average annual values are approx. 30 cm in 2016, approx. 40 cm in 2015, 2017, 2019, and over 50 cm in 2013, 2014, 2020 (Figure 47). At Soroca and Sanatauca stations, the amplitude values are close to 20 cm and 13 cm.



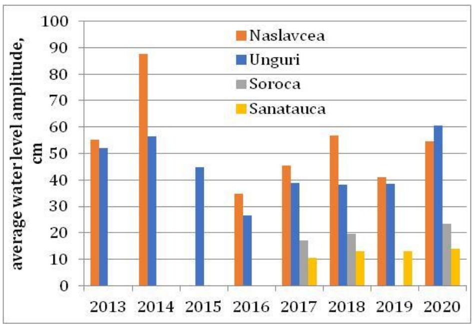


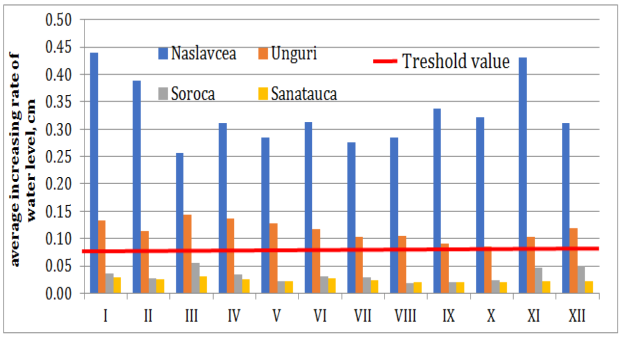
Figure 46. Average daily water amplitude at monthly level. **Figure 47.** Average water level amplitude.

On average, the intraday amplitude of the level rises to 52 cm near the DHC (at Naslavcea), decreases to 42 cm to 30 km downstream (Unguri station), is doubly reduced to 100 km at Soroca, and decreases to 14 cm at Sanatauca. Thus, the sector that is significantly influenced by hydropeaking effect is over 100 km (HPP-2 - Soroca).

The hourly analysis of water levels shows that, in general, these increase in the afternoon and in the evening, when the demand for electricity is high. During these periods, water level values increase significantly in comparison to those between 0:00 and 6:00.

4.2.1. Increasing and decreasing rate

Increasing and decreasing rates were calculated for the 4 mentioned above hydrological stations, the averages being calculated for days, months and years. Based on performed analysis of the monthly averages of both types of rates, it can be concluded that the values at Naslavcea far exceed the threshold value, being over 0.25 cm/min and -0.15cm/min in all months of the year. At Unguri, the situation is changing, the rates being close to the reference value in autumn, and exceeding it in other months even twice. At Soroca and Sanatauca stations, the rates do not exceed 0.05 cm/min and -0.04 cm/min (Figures 48 and 49).



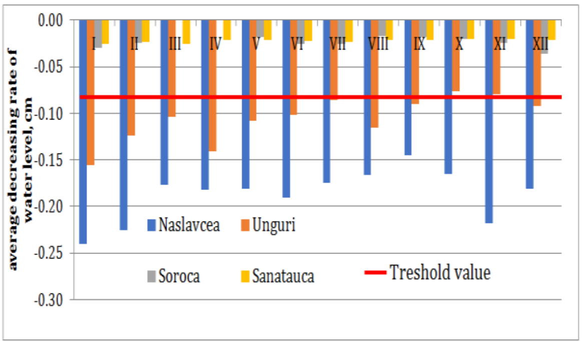


Figure 48. Average increasing rate of water level caused by hydropeaking effect at monthly level.

Figure 49. Average decreasing rate of water level caused by hydropeaking effect at monthly level.

At annual level, the averages of increasing and decreasing rates at Naslavcea are 0.25-0.45 cm/min and -0.14 – -0.25 cm/min, at Unguri the values are between 0.09-0.18 cm/min and -0.08 – -0.18 cm/min. At Soroca and Sanatauca stations, the rates are below 0.04 cm/min and -0.03 cm/min (Figures 50 and 51, Table 2).

Table 2. Dynamics of hydropeaking effect indicators.

Indicators	Hydrologic station			
	Naslavcea	Unguri	Soroca	Sanatauca
Water level amplitude (cm)	52	42	20	14
Increasing rate (cm/min)	0.35	0.14	0.04	0.03
Decreasing rate (cm/min)	- 0.19	- 0.12	- 0.03	- 0.03

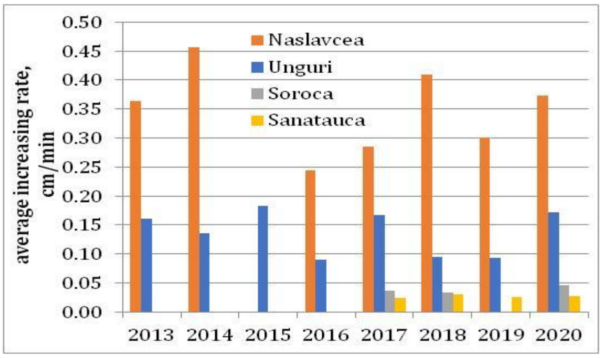


Figure 50. Average increasing rate.

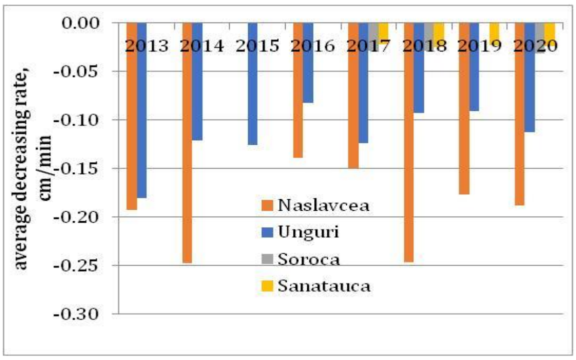


Figure 51. Average decreasing rate.

On average, increasing and decreasing rates is 0.35 cm/min and –0.19 cm/min near the DHC, the values being reduced 2 times downstream (30 km) and 5 times towards Soroca and Sanatauca.

4.3. Water temperature

The major impact of reservoir with HPP-1 on the thermal regime of the Dniester River is caused by the fact that water is discharged from the lower layers of the reservoir. The water temperature from the surface layer changes under the impact of climatic factor, but with the depth, the so-called thermal jump occurs which is characterized by a sudden drop in temperature followed by the thermocline layer characterized by constant low temperature throughout the year. Thus, flow discharged from the bottom of reservoir brings low temperatures downstream during warm period and warm waters during cold one.

For the analysis of the water temperature changes, data recorded before and after the DHC construction at the Zalischyky, Mogilev-Podolsky, Grushka, Camenca, Dubasari and Bender stations were used. Annual average values show that pre-DHC, the general trend of water temperature is constant, while in the post-DHC period the linear trend is ascending at all stations (Figure 52).

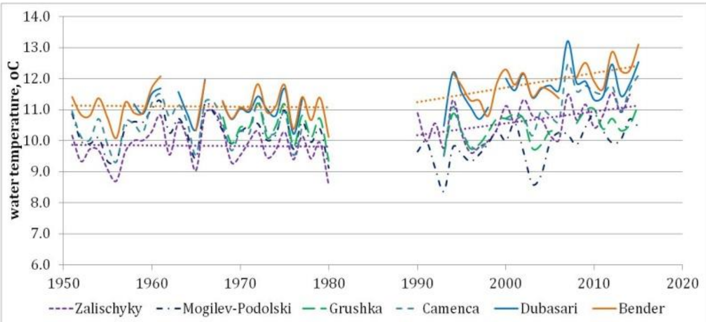


Figure 52. Dniester River water temperature dynamics.

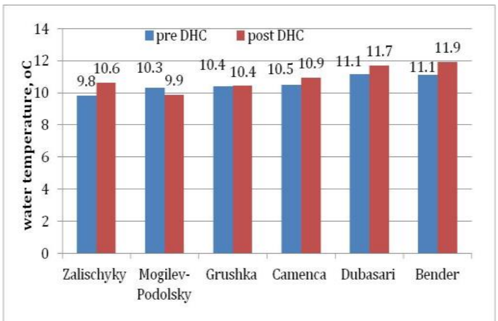


Figure 53. Average water temperature of the Dniester River pre- and post-DHC.

However, if during those 2 periods, upstream of the DHC (at Zalischyky), the average water temperature is 9.84°C and 10.64°C, the increase being 0.8°C, at Mogilev-Podolsky it is observed a decrease in average temperature by 0.43°C, from 10.29°C to 9.86°C. At Grushka, the average temperature for both periods is 10.4°C. Spatially, the temperature rise starts from Camenca, where before the DHC construction was 10.5°C, and after the DHC commissioning was 10.93°C. At Dubasari HPP these temperatures were 11.14°C and 11.7°C, the increase being 0.56°C, and at Bender 11.1°C and 11.92°C, the increase being 0.82°C, similar to that at Zalischyky. Respectively, on the DHC downstream sector, despite increasing temperature trends, the data analysis shows that the average temperature decreases downstream of the DHC, remains unchanged near Grushka sector, and begins to rise from Camenca to river mouth, the increase at Bender being similar to that at Zalischyky. In this sense, if we consider that the water temperature throughout the sector should increase by 0.8°C, then at Mogilev-Podolsky, the current temperature should be 11.1°C, at the moment it is 9.86°C, i.e.by 1.24°C lower (Figure 53).

In spatial profile, pre DHC, the water temperature rises proportionally from 9.84 °C at Zalischyky to 11.1°C at Bender (by 1.26°C). After the DHC construction, the water temperature decreased from 10.64 ° C at Zalischyky to 9.86°C at Mogilev-Podolsky or by 0.8°C, the increase being highlighted from Camenca proportionally to river mouth. After the DHC commissioning, the difference of temperature from Zalischyky and Bender is 1.3°C.

In the monthly profile, at Zalischyky, maximum temperatures are observed in the summer months (19-20°C), and minimum - in winter (0.5-1.17°C). In post-DHC period, the increase of water temperature is from 0.4 °C, in the winter months to 1.3-1.4 °C in the spring-summer period (Figure 54).

At Mogilev-Podolsky, in winter time, in pre-DHC period, the temperatures were 0.1-0.86°C and after the DHC construction, these are already 2.14-5.83°C or by 2-5°C higher than in the previous one (Figure 54). In spring, the temperatures are between 2-16.15°C in pre DHC and post DHC these are already 3-10°C. In March the water temperature increases by 1 °C, and in April and May it decreases by 3.6 and 6°C. During summer time the temperature changes are the highest: if, pre DHC, the temperatures were on average 20-21°C, post DHC these are already by 3.9-7.2°C lower (13.1 °C in June, 15.6 °C in July and17.5 °C in August). During autumn, there is an increase in water temperature by 0.9-5.56 °C, in September the modifications are minor, in October the increase is from 10.3 to 14.4 °C, and in November from 4.68 to 10.25 °C. It is observed that post-DHC, the maximum temperatures shift from July-August to August-September, with values rising only to 17.5 °C, or by 3.6 °C lower than pre-DHC.

At Grushka and Camenca, the average monthly water temperature has the same trends as at Mogilev-Podolsky, but the changes are smaller. The differences in the sense of decreasing temperatures are observed between April and August: before the DHC construction, the temperatures are in the limits of 10-21°C and post DHC these decreased by up to 3.5°C (especially between April-June). In other months, the water temperatures increase by up to 3.4 °C; in the autumn months: in September, the temperatures are in the limits of 17-18°C in both periods, in November 4-5 °C before DHC and 8°C post DHC, and, in winter, temperatures rise from 0-0.5°C to 2.7°C. At Dubasari and Bender stations the water temperature is generally increasing by 0.5-0.7°C, in March the increase being 1.8°C (Figure 54).

Finally, it is observed that the sector most affected by the change in water temperature caused by the DHC operation extends to Camenca; it is observed a decrease in water temperature in warm period and an increase in the cold period, as well as shifting of the maximum temperature by 1 month.

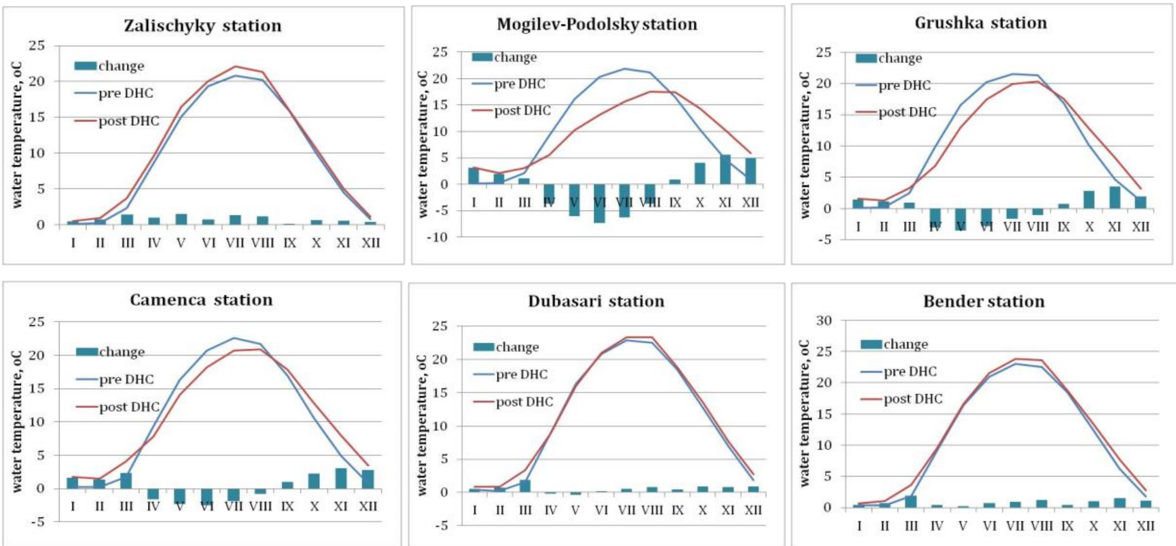


Figure 54. Monthly water temperature dynamics.

4.4. Suspended sediments

One of the main characteristics of river water dynamics is erosion, transport and accumulation of sediments. As usual, main erosion processes are specific for upper part of the basin, while sediment accumulation – for lower part. From all types of sediments (dissolved, suspended, and bed sediments), present assessment is limited to the analysis of suspended sediments transport in the Dniester River (other types are not monitored). The assessment was performed, as usual, for 2 representative periods. For Dubasari and Bender, the reference year for which the two periods were divided is 1954, when the exploitation of the Dubasari HPP has begun.

The average values of suspended sediments are shown in figures 55 and 56. The highest values at all hydrological stations are observed in the pre-DHC period. The average of this feature is approx. 100 kg/s at Zalischyky, 160 kg/s at Mogilev-Podolsky and 230 kg/s at Grushka. Thus, in the Zalischyky-Grushka sector, suspended sediments double. During the time, '70s and' 80s are highlighted when values of this characteristic were much higher compared to other years, due to floods occurrence, as well as the '60s when droughts were monitored, with suspended sediments characterized by minimum values. In the post-DHC period, suspended sediments are estimated at 59 kg/s at Zalischyky, being lower compared to the previous period by 40%, the change being caused by natural factors. At the stations downstream of the DHC, the values are significantly lower compared to previous period, thus, at Mogilev-Podolsky the average value of suspended sediments is 2.8 kg/s and at Grushka 19.6 kg/s, the decrease being 92-98% (Figure 55).

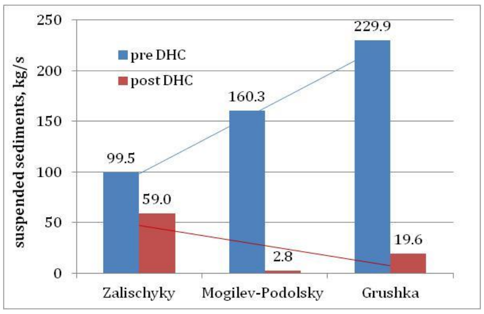


Figure 55. Suspended sediments.

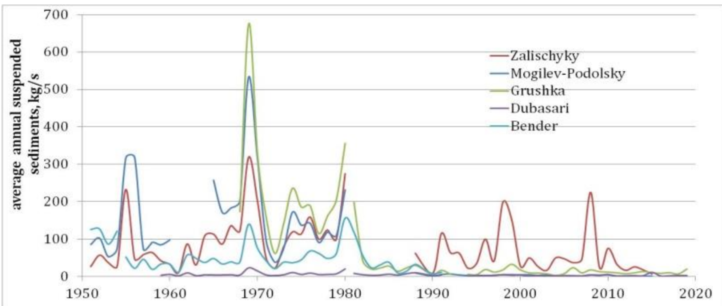


Figure 56. Average annual suspended sediments.

On monthly level, in river natural regime (at Zalischyky), most of the sediments volume is formed during spring and pluvial floods occurrence (Figure 57). Thus, the biggest amounts of sediments are observed in March-April and June-July, respectively, when large volumes of water are generated and propagated through the floodplain. Post-DHC, at Zalischyky, suspended sediment decreased by approx. 40-50% in the spring-summer months, the largest decrease being specific to February. Small increases of this element are observed for autumn months. This is caused by natural conditions of flow generation, without any reservoirs influence.

Spatially, during the pre-DHC period, there is a continuous increase of suspended sediments in the Zalischyky - Grushka sector, being by 2 - 2.8 times higher for April, June, July, November, and by 3-4 times higher for September and October, in the other months the increases being smaller (Figure 57).

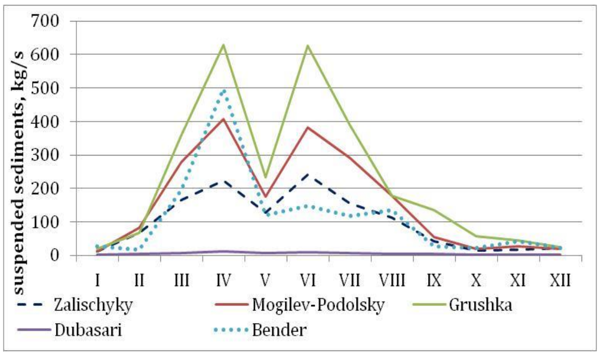


Figure 57. Monthly suspended sediments before the construction of HPP-1.

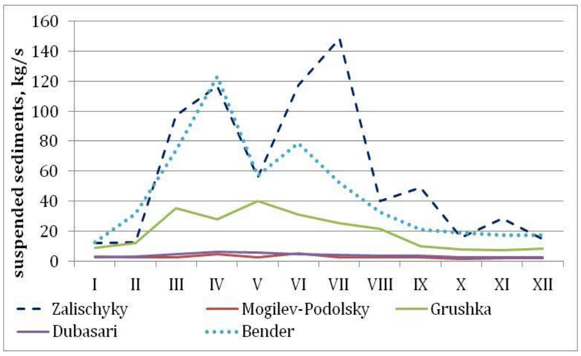


Figure 58. Monthly suspended sediments after the construction of HPP-1 and Dubasari HPP.

Post-DHC, there is a decrease of suspended sediments, due to their retention in reservoir with HPP-1. Significant decrease in sediment volumes is specific for all months of the year, so the average monthly values greater than 5 kg/s are not recorded at Mogilev-Podolsky. At Grushka, suspended sediments increase slightly, values being in limits of 7-10 kg/s in cold period and of 20-40 kg/s in warm period (Figure 58). However, these values are tens of times lower than those before the DHC construction. An increase in the suspended sediments load downstream of Mogilev-Podolsky can be observed, but the values are insignificant compared to sediments retained by reservoirs. Therefore, there is a high impact of the DHC on suspended sediments formed in the Dniester River. Also, high amounts of sediments are accumulated in the Dubasari reservoir, as seen from figure 58. Although a cumulative impact of the dams is observed, it can be noted that at the Bender station there is a certain reappearance of suspended sediments. It should be noted that analyzed data at Bender are those before 1954 (before Dubasari HPP), the length of time series being only for 1951-1954 and those for the post Dubasari reservoir construction until 1991, so the length of time series can influence the evaluation results.

5. CONCLUSIONS

Operation of the Dniester Hydropower Complex, constructed in the middle course of the Dniester River, on the territory of Ukraine, causes modification of river flow characteristics in its downstream part, region which mainly is positioned in the limits of the Republic of Moldova. This study provides detailed investigations and arguments in order to prove the statement. As a result of performed analysis of the hydrological time series for two representative periods (before and after construction of the DHC) for the upstream and downstream stations, several conclusions were drawn and shown below.

The main impact caused by the DHC and its reservoirs construction is considered the **interruption of the longitudinal connectivity of the river**, which in turn limits the river upstream-downstream connection and modifies hydrological characteristics and other vital river components. Some of river flow elements are subject to major changes, while the others are less modified. In this regard, the main hydrological characteristics that are of great importance are **water flow and volumes**. **Annually**, for the two analyzed periods (before and after the DHC construction), these are approximately equal in the upstream part of the DHC, while in the downstream of the DHC, they decrease from 278 m^3/s to 252 m^3/s, and from 8.7 km^3 to 7.9 km^3 or by 0.8 km^3, which represents 9.2%. This tendency continues towards the Dniester River mouth where water volumes decrease by 1.5 km^3, i.e. by 15%. In terms of monthly flow, downstream the DHC, in conditions of controlled flow regime, it was noted **significant decrease** in February-April (February - 18%, March - 40%, April - 27%), and **increase** during the autumn months, by 10-14%. Thus, a decrease of flow is estimated for seasons with higher flows and an increase for the seasons characterized by lower flow (autumn and winter).

One of the main and very sensitive hydrological parameters for economy and society is **minimum flow**. Its analysis for the two time periods shows that in the second period in the upstream part of the DHC, the minimum flow increased by 52%, and in downstream has doubled reaching 107 m^3/s (compared to 51 m^3/s, before the DHC). Thus, the hydrotechnical complex has a positive impact on minimum flow and provide more water during droughts to the downstream part. With regard to the DHC Operation Rules and release of the minimum flow of 100 m^3/s as a threshold, it should be mentioned that the rule is respected: the share of days with lower flow values are 2%, minimum daily flows below mentioned value being occasionally observed. However, it was not proven that the rule is maintained with regard to instantaneous intraday flow.

In terms of maximum flow, which also represents a hazard for the population of the Dniester River basin, it is also subject to change in the downstream part due to DHC. In general, **maximum annual flows**, upstream the DHC, in the second period, has slightly increased compared to the first period, while in the downstream part, there is a reduction of this parameter by about 30% because of the DHC impact. This fact shows a reduction of flood risk, but in condition of climate change and increasing frequency and magnitude of natural hazards, flood regulation under DHC operation must be performed with high attention.

From the two flood phases of **spring flood** and **fluvial flood**, the first one is changed more under the impact of DHC operation. One of the aspects subject to change is the spring flood occurrence. In the downstream, DHC caused a delay of spring flood starting date by over 2 weeks in comparison with natural regime, while no major changes are observed in case of end date. Thus, spring flood duration is affected in terms of its decreasing in regulated regime by about 30% (in the upstream part the decrease is only 14%). Another important remark is the change of maximum flow. While in natural regime, this flow tended to increase in space by about 115-140 m^3/s, (pre DHC maximum average flow at the Zalischyky, Grushka, Bender was 1150 m^3/s, 1289 m^3/s, 1265 m^3/s), in post DHC time it decreases by 180-270 m^3/s (post DHC maximum average flow for three mentioned stations is already 988 m^3/s, 805 m^3/s and 716 m^3/s). The spring flood average volume for the two periods is generally decreasing. In the upstream part of the basin, it decreases by 10% to second studied time period, while in the downstream at Grushka station the decrease is 35% or 800 mil. m^3, and at Bender is 39% or 1.1 km^3. It should be mentioned that, in the downstream of DHC, an important role in spring flood dynamics plays so-called spring ecological flood, organized by water experts and released by DHC operators every year after its construction in order to provide sufficient water volumes for the Dniester riverbed to ensure reproduction of fish and stability of the Dniester ecosystems. Even if the spring ecological flood has noble purposes, its effectiveness is not yet clear, so in-depth studies are needed to optimize the process of evacuation and propagation of spring ecological flood through the Dniester River bed.

In conditions of **pluvial floods**, DHC operation mainly leads to modification of maximum flow by decreasing it by about 30% in the downstream part. Pluvial flood hydrograph is changed from triangle to trapezoid, thus causing a delay in the maximum flow by increasing the rising limb and decreasing the recession limb of the flood wave. No major shifts are observed in pluvial flood total duration as well as in flood wave propagation in longitudinal profile. However, the increase in the frequency of natural floods must lead to a serious preparation of the DHC for the management of these phenomena and protection of areas in the lower part against major floods.

One of the direct impacts of DHC operation is **hydropeaking effect**. Intraday level amplitude downstream of the DHC amounts to 52 cm (5 km downstream, Naslavcea post), the pulsating effect being reduced by increasing distance form DHC. Thus, near Soroca, water level fluctuation reaches the values of 20 cm and near Sanatauca of 14 cm, the sector influenced by this effect being over 100 km. Thus, considered the described impact, the operation of HPP-2 turbines must be changed in a way as to significantly reduce hydropeaking effect to the downstream part;

Due to DHC operation along river sector is subject to **water thermal modifications.** While in the upstream part of the hydrotechnical complex, average annual water temperature has increased by 0.8°C, from 9.8°C to 10.6 °C in the second period, it has diminished by 0.43°C (from 10.29°C to 9.86 °C), in the downstream, in the close proximity of the DHC. In the lower sectors, water temperature is unchanged and only closer to river mouth, it increases with the same 0.8°C, like in the upstream, from 11.1°C to 11.92°C (Bender station). In these conditions, close to the DHC, at present, water temperature should be 11.1°C, but is 9.86°C, i.e. by 1.24°C lower. At monthly time scale, there is a decrease in the water temperature in the spring-summer time, and an increase in the autumn-winter time downstream of the DHC. Also, in the post-DHC time period, close to these hydrotechnical constructions, it is noted a maximum temperature shift from July-August to August-September, with values rising only to 17.5°C, or by 3.6°C lower than pre-DHC. In this regard, reconstruction of HPP-1 is absolutely needed in order to reduce the impact of water thermal fluctuations on the development of ecosystems and the local economy.

Other obvious impact of the DHC is the significant alteration of **sediment transport process.** Thus, suspended sediment loads decreased by 92-98% after DHC constructions. The significant decrease in sediment volumes is specific to all months of the year. The reduction of sediment transport led to the increase of the water transparency, favoring the development of the aquatic ecosystems.

In order to improve the hydrological state of the Dniester River, provide water supply to people and economy, optimize hydrological hazards regulation and mitigate the impact of the DHC on the downstream part of the river, it is of great importance to ensure integrated cooperative Moldovan-Ukrainian management of the basin, as well as a clear and transparent management and operation of the DHC.

ACKNOWLEDGMENT

The study on assessment of the impact of the Dniester Hydropower Complex on hydrological state of the Dniester River was performed within the project "The Dniester Hydro Power Complex Social and Environmental Impact Study" project that was implemented between September 2018 and December 2021 by the United Nations Development Programme in Moldova (UNDP Moldova), at the request of the Ministry of Environment of the Republic of Moldova, with the financial support of the Embassy of Sweden in the Republic of Moldova. Special acknowledgments refer to data providers: the State Hydrometeorological Service and State Water Agency from Moldova and Ukraine, Ministry of Environment of the Republic of Moldova, the Dniester Commission.

REFERENCES

1. International Hydropower Association. *Hydropower Status Report. Sector trends and insights. 2021* (2022), 27. P Retrieved from https://assets-global.website-files.com/5f749e4b9399c80b5e421384/60c2207c71746c499c0cd297_2021%20Hydropower%20Status%20Report%20-%20International%20Hydropower%20Association%20Reduced%20file%20size.pdf
2. Ritchie, H., Roser M., & Rosado P. (2020), *Energy.* Retrieved from https://ourworldindata.org/energy https://ourworldindata.org/renewable-energy#how-much-of-our-primary-energy-comes-from-renewables
3. Schwarz, U. (2019). *Hydropower pressure on European Rivers. The story in numbers*. Retrieved from https://wwfeu.awsassets.panda.org/downloads/hydropower_pressure_on_european_rivers_the_story_in_numbers_web.pdf
4. Grill, G., Lehner, B., Lumsdon, A. E., MacDonald, G. K., Zarfl, C., & Reidy Liermann, C. (2015). An index-based framework for assessing patterns and trends in river fragmentation and flow regulation by global dams at multiple scales. *Environmental Research Letters,* 10, 015001,
5. Hunt, J. D., Falchetta, G., Zakeri, B., Nascimento, A., Smith Schneider, P., Weber, N. A. B., Mesquita, A. L. A., Barbosa, P. S. F., de Castro, N. J. (2020). Hydropower impact on the river flow of a humid regional climate. *Climatic Change* 163, pp. 379–393, Retrieved from https://doi.org/10.1007/s10584-020-02828-w
6. Wang, Y., Zhang, N., Wang, D., Wu, J., & Zhang, X. (2018), Investigating the impacts of cascade hydropower development on the natural flow regime in the Yangtze River, China. *Science of the*

Total Environment, 624, pp. 1187–1194, Retrieved from https://doi.org/10.1016/j.scitotenv.2017.12.212

7. Peñas, F.J., Barquín, J., & Álvarez, C. (2016). Assessing hydrologic alteration: Evaluation of different alternatives according to data availability. *Ecological Indicators*, 60, 470–482. Retrieved from https://doi.org/10.1016/j.ecolind.2015.07.021
8. Richter, B., Baumgartner, J., Powell, J., & Braun, D. (1996). A method for assessing hydrologic alteration within ecosystems. *Conservation Biol*ogy, *10*(4), pp. 1163–1174.
9. Richter, B., Baumgartner, J., Robert, W., & Braun, D. (1997) How much water does a river need? *Freshwater Biology, 37*(1), pp. 231–249.
10. Richter, B. D., & Thomas, G. A. (2007). Restoring environmental flows by modifying dam operations. *Ecology and Society*, *12*(1). Retrieved from http://www.ecologyandsociety.org/vol12/iss1/art12/
11. Jiang, L., Ban, X., Wang, X., & Cai, X. (2014). Assessment of Hydrologic Alterations caused by the Three Gorges dam in the middle and lower reaches of Yangtze river, China. *Water,* 6(5), pp. 1419–1434.
12. Pfeiffer, M., & Ionita, M. (2017). Assessment of Hydrologic Alterations in Elbe and Rhine Rivers, Germany, *Water,* 9(9), 684. Retrieved from https://www.mdpi.com/2073-4441/9/9/684/htm
13. Jumani, S., Deitch, M. J., Kaplan, D., Anderson, E. P., Krishnaswamy, J., Lecours, V., & Whiles, M. R. (2020). River fragmentation and flow alteration metrics: a review of methods and directions for future research*. Environmental Research Letters, 15*(12), 123009. Retrieved from https://doi.org/10.1088/1748-9326/abcb37
14. Masaki, Y., Hanasaki, N., Biemans, H., Müller Schmied, H., Tang, Q., Wada, Y., Gosling, S. N., Takahashi, K., & Hijioka, Y. (2017). Intercomparison of global river discharge simulations focusing on dam operation-multiple models analysis in two case-study river basins, Missouri–Mississippi and Green–Colorado, *Environmental Research Letters, 12*(5), 055002. Retrieved from https://doi.org/10.1088/1748-9326/aa57a8
15. Auer, S., Zeiringer, B., Führer, S., Tonolla, D., & Schmutz, S. (2017). Effects of river bank heterogeneity and time of day on drift and stranding of juvenile European grayling (Thymallus thymallus L.) caused by hydropeaking. *Science of the Total Environment, 575*, pp. 1515–1521. Retrieved from https://doi.org/10.1016/j.scitotenv.2016.10.029
16. Halleraker, J.H., Salveit, S.J., Harby, A, Arnekleiv, J.V., Fjeldstad, H.-P., & Kohler, B. (2003). Factors influencing stranding of wild juvenile brown trout (Salmo trutta) during rapid and frequent flow decreases in an artificial stream. *River Research and Application*, *19*(5-6), pp. 589–603. Retrieved from https://doi.org/10.1002/rra.752
17. Greimel, F., Schülting, L., Graf, W., Bondar-Kunze, E., Auer, S., Zeiringer, B., & Hauer, C. (2018). Hydropeaking Impacts and Mitigation. In Schmutz, S., Sendzimir, J. (eds) *Riverine Ecosystem Management.* Aquatic Ecology Series, 8, pp. 91–110. Springer, Cham. Retrieved from https://doi.org/10.1007/978-3-319-73250-3_5
18. Šilinis, L., Punys, P., Radzevičius, A., Kasiulis, E., Dumbrauskas, A., & Jurevičius, L. (2020). An Assessment of Hydropeaking Metrics of a Large-Sized Hydropower Plant Operating in a Lowland River, Lithuania. *Water, 12*(5), 1404. Retrieved from http:/dx.doi.org/10.3390/w12051404
19. Bacal, P., Burduja, D., Cazanteva, O., Cojocari, A, Corobov, R., Donica, A., Filipenco, S., Jeleapov, A., Lozan, A., Melian, R., Miron, V., Purcic, V., Railean, V., Sirodoev, G., Talpa, N., Trombitsky, I., Zaharia, F., Zlate-Podani, & I., Chilaru, N. (2021). *Dniester Hydro Power complex social and environmental impact study. Non-technical summary*, Ministry of Environment, United Nations Development Program in Moldova, Chisinau. Retrieved from https://www.undp.org/moldova/publications/dniester-hydropower-complex-social-and-environmental-impact-study-non-technical-summary
20. UNDP - OSCE - UNECE (2019). *Analysis of the effects of Dniester reservoirs on the state of the Dniester river*. Vienna – Geneva – Kyiv – Chisinau. Retrieved from https://zoinet.org/wp-content/uploads/2019/12/Dniester-hydropower-effects-EN.pdf
21. Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy. *Official Journal of the European Communities* L327, 22.12.2000.
22. Zubcov, E. (2007). Influence of hydroconstruction on the ecological state of the Dniester River. *Akademos*, *2-3* (7), pp. 23-29 (in Russian)
23. Zubcov, E., Bagrin, N., Andreeva, N., Zubcov, N., & Borodin, N. (2019). Impact of hydropower construction on the Dniester flow of suspended solids. In *Hydropower impact on river ecosystem functioning. Proceedings of the International Conference,* Moldova, pp. 135–139. (in Russian)
24. Lebedenco, L., Nabokyn, M., Andreev, N., & Kovalyshyna, S. (2021). The state of zooplankton communities in the lower Dniester area under the conditions of river regulation and actual climatic

changes. In *Proceedings of the 10th International Conference of Zoologists "Sustainable use and protection of animal world in the context of climate change"*, pp. 57–66.
25. Zubcov, E., Zubcov, N., Ene, A., Bagrin, N., & Biletchi, L.. (2010). The dynamics of trace elements in Dniester river ecosystems. *Journal of Science and Arts, 2*(13), pp. 281–286.
26. Kovalyshyna, S., Chuzhekova, T., Grandova, M., Onishchenko, E., Zubcov, E., Ukrainskyy, V., Goncharov, O., et al. (2021). Ecological Conditions of the Lower Dniester and Some Indicators for Assessment of the Hydropower Impact. *Applied Sciences, 11*(21), 9900. Retrieved from http://dx.doi.org/10.3390/app11219900
27. Corobov, R., Trombitsky, I., Matygin, A., & Onishchenko, E. (2021). Hydropower impact on the Dniester river streamflow. *Environmental Earth Sciences,* 80: 153. Retrieved from https://doi.org/10.1007/s12665-021-09431-x
28. Jeleapov, A.. (2019) Effect of reservoirs operation on the Dniester river flow regime. In *The 14th Edition of Present Environment and Sustainable Development International Symposium. Book of abstracts*, pp. 22–23.
29. Jeleapov, A. (2020). *Study of pluvial floods in the context of anthropogenic impact on the environment*. Chisinau: Impressum. (in Romanian)
30. Cazac, V., Mihailescu, C., Bejenaru, G., & Gilca G. (2007). *Water Resources of the Republic of Moldova. Surface waters.* Chișinău: Stiinta. (in Romanian)
31. Jeleapov, A., Melniciuc, O., & Bejan, I. (2014). Assessment of flood risk areas in the Dniester River basin (in the limits of the Republic of Moldova*)*. In Gh. Duca (Ed.), *Management of water quality in Moldova* (pp. 157–173). Cham, Switzerland: Springer International Publishing. Retrieved from https://www.springerprofessional.de/assessment-of-flood-risk-areas-in-the-dniester-river-basin-in-th/2043896
32. USGS, *SRTM, Sentinel* (2020) Retrieved from https://earthexplorer.usgs.gov
33. Google Earth (2019). Retrieved from https://earth.google.com/web/@23.74017362,12.61497184,-2609.32370094a,10919547.26230502d,35y,0h,0t,0r
34. *Operation rules of the Dniester hydropower complex* (1987). GIDROPROEKT. (in Russian)
35. *Operation rules of the Dniester reservoirs* (first redaction) (2011). UNIIVEP. (in Russian)
36. *Regulations to operate water reservoirs of the HPP and PSPP Dniester cascade with buffer storage reservoir normal headwater level 77.10 m*. Draft (2017). UKRGIDROENERGO.
37. *On approval of the Program of hydropower development for the period till 2026.* (2016). Order of the Cabinet of Ministers of Ukraine dated 13 July 2016 No. 552-p. Retrieved from http://d2ouvy59p0dg6k.cloudfront.net/downloads/program_of_hydropower_development_in_ua_till_2026.pdf
38. *List of pumped-storage hydroelectric power stations*. (2022). Retrieved from https://en.wikipedia.org/wiki/List_of_pumped-storage_hydroelectric_power_stations
39. *Operation rules of the Dubasari reservoir*, Chisinau, Republic of Moldova (1983). (in Russian)
40. The Nature Conservancy. (2009). *Indicators of Hydrologic Alteration Version 7.1 User's Manual*. Retrieved from https://www.conservationgateway.org/Documents/IHAV7.pdf
41. Actual observation network stream gauge. (2022). Retrieved from http://nistru.meteo.gov.ua/en/autoposts_operational_data/
42. Hydrological database of the State Hydrometeorological Service of Moldova and Ukraine (2020).
43. Organization for Security and Co-operation in Europe. (2015). *Strategic Framework for Adaptation to Climate Change in the Dniester River Basin*. Retrieved from https://dniester-commission.com/wp-content/uploads/2019/09/Dniester_English_web-1-1.pdf
44. Organization for Security and Co-operation in Europe. (2019). *Transboundary diagnostic analysis of the Dniester river basin*. Retrieved from https://dniester-commission.com/en/news/the-transboundary-diagnostic-analysis-for-the-dniester-river-basin-issued/