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The analysis of spatial distribution of artificial reservoirs as anthropogenic fragmentation elements of rivers in the Dnipropetrovsk Region, Ukraine

Hennadii Hapich[1)] ✉, Vasyly Andrieiev[2)], Volodymyr Kovalenko[1)], Tatiana Makarova[1)]

[1)] Dnipro State Agrarian and Economic University, Faculty of Water Management Engineering and Ecology, Serhiia Yefremova St, 25, Dnipro, Dnipropetrovs'ka oblast, 49600, Ukraine

[2)] Institute for Nature Management Problems and Ecology, Dnipro, Ukraine

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Abstract: The purpose of the research is to summarise quantitative characteristics and to analyse the spatial distribution of artificial water bodies as anthropogenic fragmentation elements of medium and small rivers within the Dnipropetrovsk Region, Ukraine. The paper uses current data pertaining to existing reservoirs and mineralisation of water in rivers. Comparison included quantitative characteristics, water surface area, and the volume water in ponds and reservoirs. It has been established that although the total ratio was 97% for ponds to 3% for reservoirs, whereas their water surface area 48%, and the volume of water stored only 23% of the total resources. The paper shows the inexpediency and low efficiency of using ponds as water reservoirs feeding small rivers. Increasing the number of ponds in the river basin has a negative impact on the quality of water resources, in particular, by increasing water mineralisation – total dissolved solids (*TDS*). Depending on the river, the following indicator of river basin fragmentation has been determined: 6–20 reservoirs per 100 km^2 of the river catchment area, and on average 18–36 ponds and reservoirs are built for every 100 km of the river in relation to the length of the hydrographic network. It has shown the regularity of growing water mineralisation due to the fragmentation of rivers by a large number of artificial reservoirs. A strong correlation between regulation and fragmentation of river basins has been established (coefficient of determination R^2 ranges from 0.72 to 0.91). It proves the possibility to estimate the degree of change (increase) of water mineralisation based on the water flow coefficient K_w and the river fragmentation coefficient K^s_{fr} in the Dnipropetrovsk Region. The paper offers ways of further research for planning and implementation of a water management strategy concerning ecologically safe levels of water use in small and medium-sized river basins.

Keywords: artificial water reservoir, quality of water resources, pond, river, river fragmentation, water mineralisation

INTRODUCTION

Storage and effective use of water resources is one of the main factors of economic development. Currently, reservoirs and ponds are the main sources of water supply, irrigation, fish farming, recreation, etc. A significant number of artificial reservoirs have been built to create a proper supply of water in the 20th century in the world [Hogeboom *et al.* 2018] and in Ukraine [Khilchevskyi *et al.* 2020a]. According to the classification by the Water Code of Ukraine [Vodnyi kodeks … 1995], the pond is an artificial reservoir with a volume of water up to $1 \cdot 10^6$ m^3.

At present, the issue of studying the ecological status of rivers and the level of anthropogenic impact on aquatic ecosystems due to regulation of artificial reservoirs is extremely relevant worldwide [Bonada *et al.* 2020; Datry *et al.* 2014]. Scientists offer various approaches, among which studies based on biotic (natural) components and factors are the most common. For example, there is the assessment of the eco-systems ecological balance [Reimers 1990], and integrated assessment of geosystems ecological stability with the use of modern geo-information technologies [Dmitriev *et al.* 2012; 2016].

In Ukraine, the majority of current research is based on the study of hydrological characteristics of rivers [UHMI 2013] and water management due to climate change [KOZHUSHKO *et al.* 2018; VISHNEVSKY *et al.* 2011]. Hydrochemical indexes and quality of water resources are studied, they indicate a change in the general level of mineralisation (dry residue of minerals in water, defined as total dissolved solids – *TDS*) of rivers in Dnipropetrovsk region in the range from 1.5 to 3 $g{\cdot}dm^{-3}$ in the period from 2000 to 2020 [KHILCHEVSKYI *et al.* 2020b; OSADCHYI 2017]. Normative standards of the World Health Organization, the European Union, and Ukraine [Council Directive 98/83/EC; DSanPiN 2.2.4.-171.10] for maximum acceptable concentrations ($C_{\text{max acc}}$) determine the level of water salinity from 0.6 to 1.5 $g{\cdot}dm^{-3}$ for drinking, recreation, fish farming, etc. Thus, current indicators of water hydrochemical composition in artificial reservoirs on the rivers in the Dnipropetrovsk Region enable to use water resources provided their quality improves.

Meanwhile, the influence of ponds and reservoirs on the geo-ecological transformation of river basins is not sufficiently taken into account in Ukraine. This situation is especially acute for small and medium rivers. Over a long period of operation, which lasts more than 40–50 years, ponds and reservoirs transform completely the natural state of river ecosystems. It causes changes in the species composition of flora and fauna; artificial reservoirs reduce the self-cleaning capacity of the river and worsen the quality of water resources, form hydrogeological regime and geochemical composition of groundwater, and change the microclimate of surrounding areas; artificial water bodies transform the river course into a chain of separate reservoirs that do not have a hydraulic connection, etc. In fact, all small rivers of the steppe zone in Ukraine in general and in Dnipropetrovsk Region in particular are transformed into cascades of artificial water bodies [ANDRIEIEV *et al.* 2020; YATSYK *et al.* 1991]. In addition, the majority of ponds were built using local resources (by communities living in vicinity of rivers) without proper engineering and hydrological designs. Full accounting and determination of the actual number of ponds begun only at the beginning of the 21st century by state bodies responsible for water resources management [SHEVELEV *et al.* 2005] and this work continues to this day.

Water from ponds is practically not used for water supply or irrigation, so in fact the water exchange in such artificial reservoirs is low. Due to this, long-term desiltation deteriorates water resources in ponds and small reservoirs. In summer, ponds become evaporators. According to Academician Romashchenko [Hromadske radio 2020], with current climate change, evaporation from water surface in the region reaches 900–1000 mm per year during the last decade.

Intense evaporation from water surface worsens the hydrochemical composition of water and increases its mineralisation. This tendency prevents the use of water resources from ponds and small reservoirs for irrigation and other water management needs [RUDAKOV *et al.* 2020; RUDAKOV, HAPICH 2019].

Thus, the purpose of our study and an important issue for effective water management, restoration and preservation of river ecosystems is to determine the actual number of reservoirs and ponds, as well as to establish peculiarities of their spatial location in river basins as elements of anthropogenic fragmentation within the Dnipropetrovsk Region, Ukraine.

MATERIALS AND METHODS

Spatial analysis of artificial reservoirs is performed taking into account peculiarities of the hydrographic network and its distribution in the region, and the recording system is developed based on the administrative subordination of reservoirs to the Regional Office of Water Resources in the Dnipropetrovsk Region and its structural units. Statistical data from departmental institutions [DOVR 2020] and reference sources regarding water found in the region [HREBIN *et al.* 2014] were used in the research.

The main statistic indicators are as follows: number of ponds and reservoirs, regulatory water surface area, and volume of water stored at the headwater level. The distribution of artificial reservoirs in the hydrographic network of river basins is made in accordance with the EU Water Framework Directive [Directive 2000/60/EC] which corresponds to the basin principle of water resources management and the Water Code of Ukraine [Vodnyi kodeks… 1995].

The analysis of mineralisation indicators (*TDS*) applicable to water resources in river basins was performed on the basis of reference informative data [KHILCHEVSKYI *et al.* 2007; OSADCHYI 2017] and statistical reporting [DOVR 2020].

To enable priority assessment of the ecological status and level of anthropogenic impact on rivers, it is proposed to introduce a river fragmentation coefficient (K_{fr}) [ANDREEV *et al.* 2021]. It is suggested to calculate the coefficient by the ratio of the total number of artificial water bodies to the length of the river or the river catchment area (within the administrative unit – region):

$$K_{\text{fr}}^{L} = \frac{N}{L} \text{ or } K_{\text{fr}}^{S} = \frac{N}{S} \tag{1}$$

where: N = total number of artificial reservoirs on the river (unit), L = length of the river (km), S = area of the river basin (km^2).

The correlation between the fragmentation coefficients and the generally accepted regulation indicator has been established. To determine the degree of water flows regulation in the main river basins in the Dnipropetrovsk Region, relevant hydrological values were determined: catchment area (based on QGIS geographic information system and reference data [KAGANER (ed.) 1971]), water flow module [LITOVCHENKO 2007] and the volume of regulation [DOVR 2020] which is expressed by factor K_w according to the formula:

$$K_w = \frac{V_r}{V_a} \tag{2}$$

where: V_r = volume of regulated water flow at the river catchment (m^3), V_a = annual water flow rates (m^3).

RESULTS AND DISCUSSION

The main waterway of the region is the Dnipro River with a cascade of large reservoirs, together with the system of large main canals. They provide water resources to all sectors of the economy by more than 90% [DAVR 2020a]. Thus, peculiarity of the hydrographic network is the relative division of all river basins into tributaries of left bank and right bank of the Dnipro River (Fig. 1). The main left tributaries which flow within the

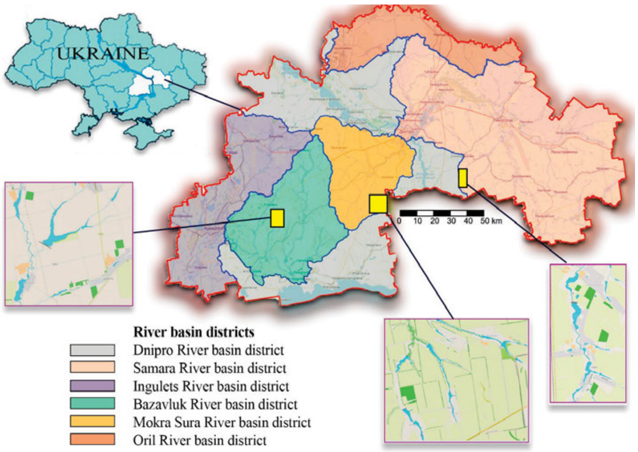

Fig. 1. Basins of the largest rivers in the Dnipropetrovsk Region and examples of regulation of small rivers by cascades of ponds and reservoirs; source: own study

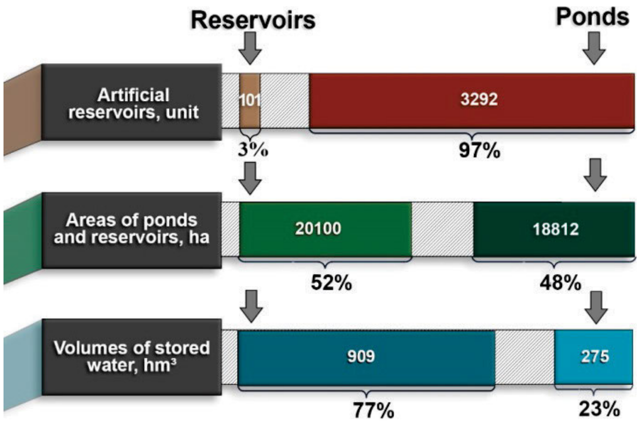

Fig. 2. The ratio of ponds and reservoirs main parameters in the Dnipropetrovsk Region; source: own study

region are the following: Oril, Samara and its main tributary Vovcha. The largest right tributaries of the Dnipro River are: Mokra Sura, Bazavluk, Ingulets and one of its largest tributaries Saksagan.

According to data collected [Department … 2020], during last five years, the volume of fresh water uptake from surface sources of the Dnipropetrovsk Region has been in the range of 850–1050·10^6 m^3 a year. In 2019, 696.2·10^6 m^3 of water was used for production needs, 129.2·10^6 m^3 for drinking and sanitary needs, 30.3·10^6 m^3 for irrigation.

According to the Regional Office of Water Resources [DOVR 2020], the total number of artificial water bodies in the Dnipropetrovsk Region is 101 reservoirs and 3292 ponds. The total area of reservoirs is 20,100 ha, and ponds 18,812 ha. The volume of water stored reach 909·10^6 m^3 and 274.8·10^6 m^3, in reservoirs and in ponds respectively. Thus, the percentage distribution indicates a low efficiency of ponds as reservoirs for the storage and use of water resources (Fig. 2).

It is determined that the percentage of ponds is 97%, water surface area is 48%, and the volume of water stored only 23% in the general structure of artificial reservoirs. The significance of this ratio justifies irrationality of their operation and inexpediency of their construction due to the current climate change.

Thus, the actual volumes of fresh water taken from surface water-supply sources are less than the volumes of water stored in ponds and reservoirs. It should be noted that the majority of used water is taken from reservoirs of the Dnipro River cascade and large main canals.

Peculiarities of artificial reservoirs distribution and summary results of determining the river fragmentation coefficient as an anthropogenic factor in the main river basins of the Dnipropetrovsk Region are presented in Table 1.

It is established that the majority of artificial reservoirs are located in basins of the Samara, Ingulets, and Bazavluk rivers (Fig. 3). The estimated level of anthropogenic fragmentation of river basins shows a significant load on aquatic ecosystems of all rivers. Depending on the river, the defined fragmentation of river basins is as follows: 6–20 reservoirs per 100 km^2 of the river

Table 1. Distribution of artificial reservoirs and fragmentation coefficients of the main river basins in the Dnipropetrovsk Region

River	Area of river basin (km^2)	Length of hydrographic network (km)	Amount of artificial reservoirs – ponds and reservoirs (unit)	Coefficient of river fragmentation	
				by area[1] K^S_{fr}	by length[2] K^L_{fr}
Oril	3652	1152	204	5.6	17.7
Samara	8861	6100	1410	15.9	23.1
– including Vovcha	3830	2402	431		
Mokra Sura	2706	1727	331	12.2	19.2
Bazavluk	4200	2245	529	12.6	23.6
Ingulets	3836	2201	781	20.4	35.5
– including Saksagan	2025	1180	225		
Other rivers	–	–	138	–	–

[1] Amount of artificial reservoirs per 100 km^2 of river basin area.
[2] Amount of artificial reservoirs per 100 km of river length.
Source: own study.

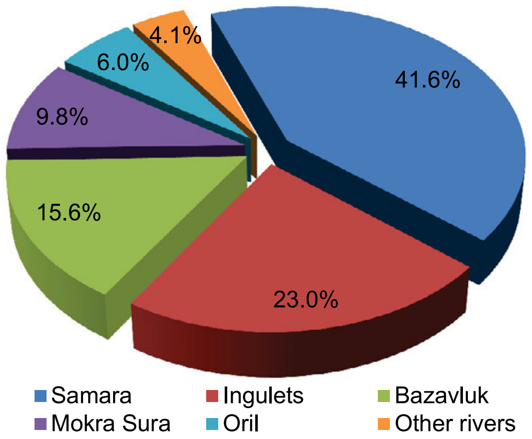

Fig. 3. Percentage distribution of artificial reservoirs in river basins; source: own study

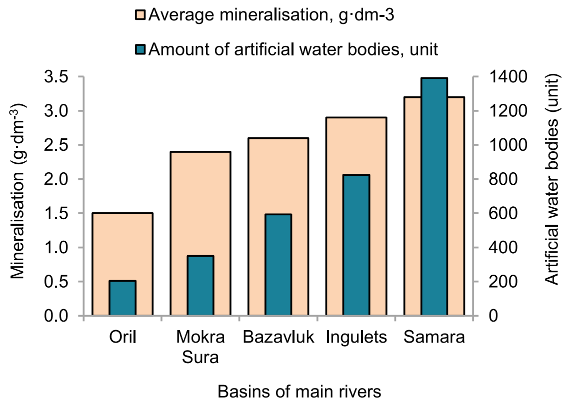

Fig. 4. Indicators of artificial reservoirs amount and water quality in rivers; source: own study

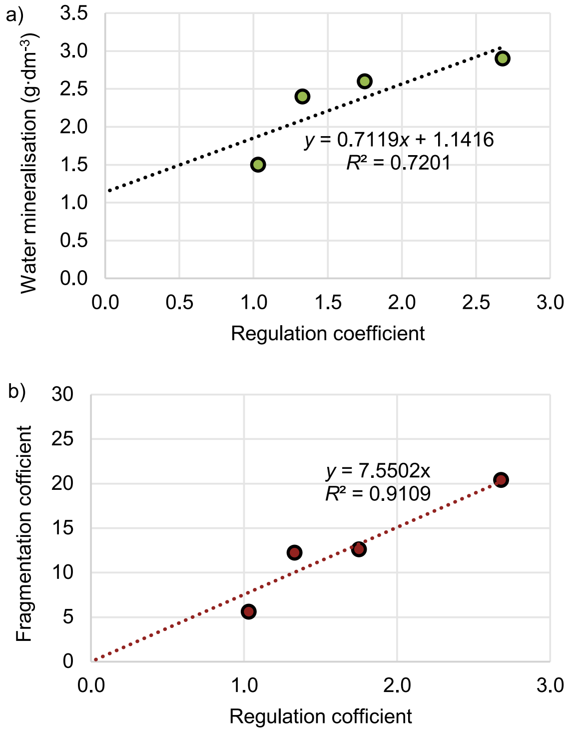

Fig. 5. Correlation of water flow regulation coefficient K_V with water mineralisation in: a) rivers, b) river fragmentation coefficient by area $K^S{}_{fr}$; source: own study

catchment area, and in relation to the length of the hydrographic network for every 100 km of the river on average 18–36 ponds and reservoirs are built. River basins of Ingulets, Samara, and Bazavluk are the most fragmented.

Based on reference data (Khilchevskyi *et al.* [2007], Osadchyi [2017], DOVR [2020]), the comparison of water mineralisation trends in rivers and the quantity of artificial water bodies (Fig. 4) shows a strong direct correlation.

According to Equation (2), the coefficients of regulation of the main river basins in the Dnipropetrovsk Region are established (Tab. 2).

A significant (strong) correlation between water mineralisation in rivers and the fragmentation coefficient by area $K^S{}_{fr}$ with the value of quantitative regulation of water flow has been established (Fig. 5).

The strong correlation between these factors (coefficient of determination R^2 ranges from 0.72 to 0.91) proves the possibility to assess the change (increase) of water mineralisation level by the coefficient of flow regulation K_V and the coefficient of river fragmentation by area $K^S{}_{fr}$.

The analysis of data obtained shows a general tendency toward deterioration of water quality and change of its hydrochemical composition depending on the level of anthropogenic impact and the number of artificial reservoirs.

Table 2. Indicators of water flows regulation in the main river basins in the Dnipropetrovsk Region

Index	River basin within the Dnipropetrovsk Region			
	Ingulets	Oril	Mokra Sura	Bazavluk
Catchment area (km^2)	3836	3652	2706	4200
Water flow modulus (dm^3·s^{-1}·km^{-2})	0.62	0.85	0.51	0.6
Annual flow rate V_a, 1·10^6 m^3	75.0	97.9	43.7	79.5
Regulation volume V_r, 1·10^6 m^3	200.8	101.2	58.2	138.8
Water flow regulation coefficient K_w	2.68	1.03	1.33	1.75
Regulated flow, in % of the annual flow of the river	5	38	26	15

Source: own study.

It should be noted that in basins of Samara and Ingulets, a significant number of tailing ponds and desilts of mine and industrial water have been built. These waters are periodically discharged into the main river courses in winter and during spring flooding. To support environmental standards of water quality, sanitary washing is performed after the discharges on the Ingulets River [DAVR 2020b].

At the same time, all small rivers are regulated and they lost their function of alimentation of medium and large watercourses. They respond much faster to anthropogenic interference in their ecosystems, and ponds and reservoirs are factors contributing to water resources low quality and the environmental risk in the case of further water use.

The results of empirical studies on the current state of small rivers in the Dnipropetrovsk region confirm the high level of anthropogenic degradation and further development of negative processes in the transformation of river ecosystems into separate fragmented reservoirs. Transparency of data on quality indicators and environmental assessment of water resources is provided by an interactive online map of the State Water Agency of Ukraine [DAVR 2021]. Thus, with a total of about 5,430 rivers and streams within the Dnipropetrovsk Region, according to the interactive map, only ~50 observation posts are active. The low level of monitoring studies and practical lack of observation posts for hydrochemical parameters of small rivers and located on them artificial reservoirs are significant disadvantages. To solve this problem, it is necessary to continue field research with a simultaneous construction of a spatial model for environmentally safe water use in small river basins.

CONCLUSIONS

1. In the second half of the twentieth century, unreasonable and irrational creation of reservoirs and ponds on small rivers, which are tributaries of medium and large water courses, has led to a significant fragmentation of river basins by artificial reservoirs. Currently, the large number of ponds and the lack of natural in flow of rivers are key factors in the deterioration of water quality.
2. The analysis of the spatial distribution of 3393 artificial water bodies shows their predominant concentration within river basins of Samara (41.6%), Ingulets (23.0%), and Bazavluk (15.6%). The growing trend in the river regulation quantitative indicators is directly related to the deterioration of water quality and high level of mineralisation of water resources (Samara – 3.2 $g \cdot dm^{-3}$, Ingulets – 2.9 $g \cdot dm^{-3}$, Bazavluk – 2.6 $g \cdot dm^{-3}$) in river basins as a whole, which prevents further use of water resources for water supply, irrigation, fish farming, recreation, etc.
3. The level of anthropogenic impact, defined as an indicator of river basin fragmentation, shows that on average there are 6–20 reservoirs per 100 km^2 of a river catchment area, and in relation to the length of the hydrographic network for every 100 km we have from 18 to 36 ponds and reservoirs built.
4. The increased number of artificial reservoirs in the river basin has a negative impact on water quality. In particular, its mineralisation increases, which prevents further use of water resources for water supply and irrigation.
5. A strong correlation between river basins regulation factors and the level of water mineralisation in reservoirs has been established; the correlation coefficient is 0.85, and the coefficient of determination $R^2 = 0.72$. The correlation between the fragmentation of the river basin and the level of water mineralisation is 0.95, and the coefficient of determination $R^2 = 0.91$. In Dnipropetrovsk region, it proves the possibility to assess the change (increase) of water mineralisation level and the negative impact on river basin ecosystems by the flow regulation coefficient K_V and the coefficient of river fragmentation by area $K^S{}_{\mathrm{fr}}$.
6. Due to the lack of data and a proper system to monitor water quality hydrochemical indicators in small rivers and streams, the situation needs further study and research. It is reasonable to introduce a "pilot project" to provide regime observation and to assess the degradation of a small river basin under regulation, which is not subject to anthropogenic load from industrial facilities but only fragmented by ponds.
7. In addition, it is necessary to develop a regional programme to study environmental and economic practicability of further operation of ponds and small reservoirs and their gradual elimination in order to restore the natural flow of rivers.

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