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WIRTSCHAFT, MANAGEMENT UND MARKETING, TOURISMUS, MEDIZIN, BIOLOGIE UND ÖKOLOGIE, LANDWIRTSCHAFT

HERITAGE OF EUROPEAN SCIENCE

ECONOMICS, MANAGEMENT AND MARKETING, TOURISM, MEDICINE, BIOLOGY AND ECOLOGY, AGRICULTURE

Monographic series «European Science»
Book 27. Part 4.

In internationalen wissenschaftlich-geometrischen Datenbanken enthalten
Included in International scientometric databases

MONOGRAPHIE

MONOGRAPH

ScientificWorld-NetAkhatAV
Karlsruhe 2024

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Erbe der europäischen Wissenschaft: Wirtschaft, Management und Marketing, Tourismus, Medizin, Biologie und Ökologie, Landwirtschaft. Monografische Reihe «Europäische Wissenschaft». Buch 27. Teil 4. 2024.

Heritage of European science: Economics, Management and Marketing, Tourism, Medicine, Biology and Ecology, Agriculture. Monographic series «European Science». Book 27. Part 4. 2024.

ISBN 978-3-98924-039-1

Published by:

ScientificWorld-NetAkhatAV

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 ISBN 978-3-98924-039-1

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 ISBN 978-3-98924-039-1

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DOI: 10.30890/2709-2313.2024-27-00-028

Introduction.

The detonation of the Kakhovka hydroelectric power station (HEPS) on June 6, 2023, which was the main factor regulating the hydrological regime in the lower reaches of the Dnieper and the Dnieper-Buh mouth region in general, had an extremely negative impact on all aspects of the water ecosystems functioning of the region [24, 26, 31, 32]. Violation of the regulated fresh water inflow, which caused this man-made disaster, had a negative impact on the condition of all elements of the hydrographic network located below of Nova Kakhovka city with a total area of about 1,440 km^2 [6, 17, 30]. If we also take into account the water ecosystem of the now completely drained Kakhovka reservoir, the total area of the damage zone from the explosion of the Kakhovka dam for freshwater ecosystems can be estimated at 3,600 km^2 [14].

Violation of the hydrological regime of the lower reaches of the Dnieper has already caused significant negative environmental consequences for the research region. The absence of the usual daily fluctuations of the water level, which were previously formed under the action of water discharge through the Kakhovka HEPS dam, is, of course, a negative factor for the existence of the region's floral and faunal complexes, which directly threatens the disappearance of their unique biological diversity in the coming years [15, 18, 19, 22, 29, 33].

The destruction of the Kakhovka HEPS dam completely changed the hydrological regime in the lower reaches of the Dnieper, the elements of which can be divided into three blocks of the most ecologically significant factors [23, 27]:

1) water balance and external water exchange;

2) dynamics of water masses;

3) hydrophysical properties of water masses and bottom sediments.

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With this in mind, the goal of our work is to study the impact of the Kakhovka HEPS dam destruction on changes in the main ecologically significant elements of the hydrological regime in the lower reaches of the Dnieper.

9.1. Water balance and external water exchange

The most important abiotic factor in the formation of the ecological state of the lower reaches of the Dnieper is the external water exchange, which is formed under the influence of water level fluctuations in the channel network and the mode of water inflow through the Kakhovka HEPS dam [7, 9, 25].

The main factor determining the external water exchange in the floodplain lakes lower reaches of the Dnieper is the water level fluctuations in the channel network, which until June 2023 were formed by the discharge of water through the Kakhovka HEPS dam [9, 26]. At the present time, this factor is completely missing. Fluctuations in the water level in the lower reaches of the Dnieper are currently formed only under the influence of bending and shearing phenomena and natural water level fluctuations in the Dnieper-Buh estuary. It should be noted that these fluctuations of the water level are almost not manifested in the before-delta section of the lower reaches river and mostly spread only to the delta part (Table 1).

Table 1 – Average daily amplitudes of water level fluctuations in the lower reaches of the Dnieper channel network (*A*, m) before and after the dam of Kakhovka HEPS was destroyed

Point of observation	Nova Kakhovka	Lvove	Kherson	Kizomys
Distance from Kakhovka HEPS dam, km	0	18	65	90
A, before the dam was destroyed, m	1.04	0.60	0.18	0.20
A, after the dam was destroyed, m	0.04	0.04	0.08	0.14

With such values of water level fluctuations, water exchange between the Dnieper channel network and the floodplain practically does not occur, which endangers the existence of numerous floodplain lakes (with an area of more than 75 km^2) and unique natural ecosystems that have formed within the floodplain over many decades. Without sufficient daily fluctuations of the water level in the channel network, fresh Dnieper water transits along the main channel and does not reach the floodplain and the small channels and numerous lakes located there.

The rate of change of water masses to new ones in floodplain lakes at the present time has decreased by an order of magnitude compared to the period before the destruction of the Kakhovka HEPS dam (Table 2).

Table 2 – Periods of external water exchange of the lower reach of the Dnieper largest lakes in the summer before and after the dam of Kakhovka HEPS was destroyed

The name of the lakes		Distance from Kakhovka HEPS dam, km	Period of external water exchange, days	
			before the dam was destroyed*	after the dam was destroyed
Before-delta section	Sabetskiy Liman	11	2.5	20.4
	Kaznachyivskiy Liman	17	3.5	27.0
	Frolovo Lake	19	3.6	27.4
	Glukhiy Liman	35	7.0	47.8
	Oleksiyvskiy Liman	54	7.8	51.6
	Golubov Liman	55	5.3	31.1
Delta of the Dnieper	Kardashynskiy Liman	65	8.3	43.2
	Krugle Lake	67	7.9	41.4
	Zakytne Lake	69	8.9	51.8
	Steblyivskiy Liman	71	9.4	49.8
	Nazarovo-Pohorile Lake	73	21.8	53.9
	Bile Lake	75	9.4	21.5
	Krasniukove Lake	87	8.4	11.6
	Zolote Lake	89	8.1	11.0
	Didove Lake	90	8.6	11.6

Note: * - the data are relevant for the beginning of the 21st century

An increase in the period of water change in floodplain lower reaches of the Dnieper lakes is a negative factor that will affect their ecological condition. Given the ecologically favorable values of the external water exchange period of 5-9 days [7, 20, 21], this indicator currently ranges from 20-50 days or more. When the period of water exchange is increased to 15 days or more, unfavorable ecological conditions are created in lakes – stagnant zones with a lack of oxygen and a high concentration of organic substances are formed. In fact, the most flowing lakes of the region, located in the before-delta section, lost this status after the destruction of the dam and passed to the category of weakly flowing with signs of dystrophy. The periods of external water exchange in them increased by 520-820% from those they were before the destruction of the dam. Water bodies located in the immediate vicinity of the former Kakhovka HEPS dam were particularly affected, such as Sabetskiy Liman, Kaznachyivskiy Liman, Frolovo Lake and other lakes. The intensity of water exchange processes in them decreased by 7-8 times (see Table 2).

According to our studies [1, 3, 8, 10, 13, 21, 34], in lakes with a period of change of water masses to new ones of more than 15 days, the conditions for the degradation of phytocenoses, accumulation of plant residues (swamping), weak development of phytoplankton, zooplankton, zoobenthos, ichthyofauna, worsening indicators of the hydrochemical regime of water. Because of this, a sharp deterioration in the ecological condition of most floodplain lakes and small channels of lower reaches of the Dnieper should be expected in the coming years.

The least weakening of water exchange processes is noted in lakes located in the Dnieper delta closer to its sea edge (Krasniukove, Zolote, Didove Lakes, etc). This happens due to the spread in this part of the lower reaches of the Dnieper of noticeable natural fluctuations of the water level, which are formed under the action of water surges and surges, weak tidal fluctuations and natural water level fluctuations in the Dnieper-Buh estuary.

Due to these level fluctuations, which remained unchanged after the Kakhovka HEPS dam destruction, the water ecosystems of the lowest part of the Dnieper delta did not experience a significant weakening of water exchange processes. The periods of water exchange here after the Kakhovka HEPS dam destruction on individual lakes increased by only 35-39%.

 ISBN 978-3-98924-039-1

9.2. Dynamics of water masses

A sharp disruption of water exchange processes between the channel and floodplain parts of the lower reaches of the Dnieper had a negative impact on the dynamics of water masses in the lakes of the region.

Currently, most of the water bodies below the Dnieper are under the control of the Russian army, which makes it impossible to carry out field studies of this territory. Because of this, we used the method of mathematical modeling of water flows according to the full flow method adapted to small depths [11], which was successfully tested on these water bodies [12, 16], to study the changes in the flow regime in the lower reaches of the Dnieper floodplain lakes. The results of the calculations are given in the table. 3.

Table. 3 – Average water flow velocities in floodplain lakes of the lower reaches of the Dnieper, cm/s

The name of the lakes		Field observation data (2018-2021)	Calculated data	
			before the dam was destroyed*	after the dam was destroyed
Front delta section	Sabetskiy Liman	20.0	19.2	2.3
	Kaznachyivskiy Liman	15.0	15.2	2.5
	Frolovo Lake	15.0	15.1	2.4
	Glukhiy Liman	4.0	3.8	0.9
	Oleksiyvskiy Liman	3.0	2.8	0.2
	Golubov Liman	5.0	5.2	1.3
Delta of the Dnieper	Kardashynskiy Liman	5.0	4.7	1.2
	Krugle Lake	4.0	4.3	1.1
	Zakytne Lake	1.0	1.1	0.3
	Steblyivskiy Liman	5.0	4.8	1.4
	Nazarovo-Pohorile Lake	1.0	1.0	0.2
	Bile Lake	4.0	3.8	0.7
	Krasniukove Lake	5.0	4.8	3.2
	Zolote Lake	8.0	7.6	4.9
	Didove Lake	8.0	7.9	5.2

Data from field observations are closely related to data obtained using mathematical modeling. The correlation coefficient between them is 0.99, the value of

 ISBN 978-3-98924-039-1

the largest and average absolute error between the data is 0.8 cm/s and 0.11±0.69 cm/s, respectively. The close relationship between field observation data and calculated data shows that the chosen method of mathematical modeling well reflects the distribution of water flow velocities in the lakes of the region and may be acceptable for their assessment.

Table 3 shows that the most flowing series of lakes before the Kakhovka HEPS dam was destroyed were waters located in the immediate vicinity of it (Sabetskiy Liman, Kaznachyivskiy Liman, Frolovo Lake). Their average water flow rate was higher than 15 cm/s. For most other water bodies, which can be attributed to water bodies with moderate flow, velocities in the range of 4-10 cm/s were characteristic. In weakly flowing lakes of the region, where stagnation phenomena, processes of degradation of aquatic ecosystems and impoverishment of species composition are most evident, the average current velocities were lower than 4 cm/s.

In connection with a sharp change in the hydrological regime as a result of the destruction of the Kakhovka HEPS dam, the dynamics of water masses in the lower reaches of the Dnieper lakes decreased sharply. According to calculations, the average current speed in almost all studied lakes currently does not exceed 3 cm/s, and on average varies between 1-2 cm/s. At the present time, a decrease in water flow rates of 8-14 times from those before the destruction of the Kakhovka HEPS is recorded. There is almost no water current in the most stagnant lakes, the average speed of the current in such lakes as Glukhiy Liman, Oleksiyvskiy Liman, Zakytne Lake, Nazarovo-Pohorile Lake does not exceed 1 cm/s (see Table 3).

The water flow regime changed the least in the lakes of the sea edge of the Dnieper delta, on which the impact of the Kakhovka HEPS operation was minimal. In these lakes, the water regime has not undergone significant changes due to the predominant influence on them of the Dnieper-Buh estuary water regime, which is natural and to a greater extent formed under the influence of climatic factors. In fact, it is possible to say about the lakes of the sea edge of the delta that they were the only ones that survived the Kakhovka HEPS destruction dam and suffered minimal violations of the hydrological regime elements.

9.3. Hydrophysical properties of water masses and bottom sediments

A significant decrease in the dynamics of water masses in the lower reaches of the Dnieper floodplain lakes and weakening of the water exchange with the channel network is an extremely negative ecological phenomenon not only for the research region but also for the entire Dnieper-Buh mouth region.

The weakening of the intensity of water masses change to new ones and the slowing down of currents in natural water bodies inevitably leads to the activation of the overgrowth processes, siltation and swamping of their bed. Stagnant zones formed when water masses slow down form places of sedimentation of substances suspended in water and their active accumulation in bottom sediments. An increase in the organic mass of bottom soils becomes a supplier of even more substances that contribute to the enhanced development of higher aquatic plants and algae. The excess of organic and biogenic substances in the lake leads to the fact that consumers do not have time to consume them, which causes gradual organic pollution and general degradation of the aquatic ecosystem.

According to our research in the lower reaches of the Dnieper floodplain lakes, the above-mentioned signs of deterioration of the ecological condition begin to appear in lakes with a rate of water change to new water more than 15 days. The speed of the current in such lakes does not exceed 5 cm/s, at the bottom there is a layer of fine-fraction organically saturated silt with a thickness of more than 0.5 m, the average depth is less than one meter, the color of the water is from yellow to brown, the percentage of projective coverage by higher aquatic plants is more than 70% of the entire area of the water surface [7, 20, 21].

The hydrophysical properties of water masses after the explosion of the Kakhovka HEPS underwent the greatest changes according to the following parameters:

- number of substances suspended in water;
- transparency and color of water;
- accumulation of bottom sediments.

By the middle of 2023, the average content of suspended substances in the

Dnieper riverbed near Kherson was 15-20 g/m^3, during the spring irrigation period it could reach values of 35-40 g/m^3. The average annual content of suspended solids in the Dnieper delta arms is slightly higher than in the bed of the delta section. The average amount of substances suspended in water is 24.2 g/m^3 in the Rvach branch, 19.6 g/m^3 in the Bakai branch, and 21.8 g/m^3 in the Konka branch. The suspensions had a mainly mineral composition, losses during roasting amounted to 20-30%. Such low values were noted here due to significant sedimentation of mineral particles of suspended substances along the cascade of reservoirs. Only a small part of the overhang carried by the current reached the lower reaches of the Dnieper.

Currently, we can expect an increase in the number of suspended substances in the channel network of the Dnieper. Due to the dehydration of the Kakhovka reservoir, the length of coastal rocks that can be eroded and transported by the water flow has increased significantly. In addition, the dewatered bed of the reservoir is a fairly good supplier of organic and biogenic substances, which also enter with the flow of water to the lower reaches of the Dnieper water system.

The content of suspended substances in the lower reaches of the Dnieper floodplain lakes has a larger fluctuation range. According to our monitoring observations in 2009-2023, the indicator varied between 2-363 g/m^3. Most of the suspension in the lakes of the region consists of organic substances. Losses during burning were 70-80%, in some seasons (mid-summer, early autumn) they could reach 95% [4, 5].

An important aspect is that the number of substances suspended in lakes water is closely related to the intensity of external water exchange and the water masses transparency. In lakes with an outdoor period of less than 2 days, suspended substances are 15–18 g/m^3, transparency is to the bottom, water colors are from yellowish-green to greenish-yellow (according to the standard color scale). With a water exchange period of 2–15 days, waters contain 15–60 g/m^3 of suspended substances, the average transparency of water decreases to 0.7–1.5 m, the color becomes greenish-yellow – brownish-yellow. In lakes with a period of external water exchange of more than 15 days, as a rule, there are more than 30-50 g/m^3 of suspended substances, water

 ISBN 978-3-98924-039-1

transparency decreases to 0.2-0.8 m, the color changes to yellowish-brown, brown.

These dependencies, taking into account the critical weakening of water exchange processes in the lower reaches of the Dnieper floodplain lakes after the Kakhovka HEPS dam destruction, make it possible to predict the dynamics of changes in certain hydrophysical parameters of water bodies in the research region in the near future, in particular, the transparency, color of water, and the content of suspended substances in waters.

In the coming years, a characteristic decrease in the transparency of water masses and an increase in the content of suspended substances in water can be predicted for floodplain lakes. Due to the fact that in conditions of weakened water exchange there is an active production of organic and biogenic substances, it is possible to expect an increase in their content in water to the level of organic pollution. Accordingly, such a change in the conditions of existence will lead to the impoverishment of the species diversity of plants and animals that inhabit large lakes, will cause a significant overgrowth of the lakes bed with higher aquatic vegetation and the gradual transformation of floodplain lakes into moistened wetlands.

Another, but more long-term, problem is the shallowing and siltation of the lower reaches of the Dnieper floodplains. If the channel network of the lower reaches of the Dnieper after the destruction of the Kakhovka HEPS dam became even more flowing and watered due to the reduction of water consumption for evaporation from the surface of the Kakhovka reservoir and the people's economic consumption of water resources in the region, then the opposite processes will occur in floodplain lakes.

Due to the reduction in the fresh water inflow to lakes and the active production of organic and biogenic substances, especially in the warm period of the year, the lake beds will quickly be filled with products of vital activity and dead parts of aquatic plants and animals. Intensive accumulation of organic mass at the lakes bottom can lead to almost complete silting, shallowing and significant overgrowth of even large lakes already in the next decade.

Lakes Skadovsk-Pohorile, Nazarovo-Pohorile, and Zakytne are an example of lakes in which external water exchange with the Dnieper bed significantly weakened at the end of the last century. They had a fairly large area for lakes of this region – 0.20, 0.13 and 0.16 km^2, respectively, and average depths within 1.2 m with a maximum value of 1.5-2.0 m. The ecological condition of these lakes was assessed as good [2, 28, 29]. After the disruption of the hydraulic connection with the Dnieper channel network (1990s years) as a result of significant overgrowth of the canals through which they maintained this connection, their external water exchange significantly deteriorated. According to the field survey of these lakes in 2008-2010, almost their entire bed was overgrown with higher aquatic plants, the depth everywhere did not exceed 0.5 m, and below was a significant layer of viscous silt with a thickness of 1.0-1.5 m, which consisted of organic substances and undecomposed particles mainly of plant origin.

Similar changes in living conditions should be expected in all floodplain lakes in the research region, in which there was a significant weakening of water exchange processes and the period of external water exchange reached values of 15-20 days or more. This series of water bodies includes all the lower reaches of the Dnieper lakes, except for a small part of the lakes located within the sea edge of the delta. Particular concern is caused by the state of water bodies that until recent events were considered the most flowing in Ukraine: Sabetskiy Liman, Kaznachyivskiy Liman, Frolovo Lake. Also, prone to complete disappearance due to drying out and complete overgrowth of the bed are lakes whose external water exchange was 15 days or more even before the destruction of the Kakhovka HEPS dam. These include Skadovsk-Pohorile, Nazarovo-Pohorile, Zakytne, Oleksiyvskiy Liman and other weakly flowing water bodies.

Summary and conclusions.

The destruction of the Kakhovka HEPS dam in June 2023 radically changed the hydrological regime of the lower reaches of the Dnieper. The changes affected all the key factors of the region's water ecosystems functioning.

The main factor shaping the flow of Dnieper waters to the floodplain was the daily fluctuations of the water level, which were formed when water was released through the Kakhovka HEPS dam. The greater the amplitude of the level fluctuations, the greater the volume of water entering the floodplain lakes and arrays. At present, this hydrological factor is completely absent.

Calculations showed that the periods of external water exchange, due to the lack of necessary fluctuations in the water level, deteriorated in them by 520-820% of what it was before the dam destruction. Water bodies located in the immediate vicinity of the former Kakhovka HEPS dam were particularly affected, such as Sabetskiy Liman, Kaznachyivskiy Liman, Frolovo Lake and other lakes. The intensity of their water exchange processes has decreased by 7-8 times, which will practically destroy their unique ecosystem and good ecological condition.

A sharp disruption of water exchange processes between the channel and floodplain parts of the lower reaches of the Dnieper had a negative impact on the dynamics of water masses in the lakes of the region. At the present time, the average current speed in almost all studied lakes does not exceed 3 cm/s, and on average varies between 1-2 cm/s. We record a widespread decrease in water flow rates in the region's floodplain lakes by 8-14 times from those before the dam of Kakhovka HEPS was destroyed. There is almost no water flow in the most stagnant lakes, its average value in Glukhiy Liman, Oleksiyvskiy Liman, Zakytne Lake, Nazarovo-Pohorile Lake does not exceed 1 cm/s.

Due to the reduction in the fresh water inflow to the lakes and the active production of organic and biogenic substances, especially in the warm period of the year, in the near future we can expect the active filling of the lakes bed with products of vital activity and dead parts of aquatic plants and animals. Intensive accumulation of organic mass at the bottom of lakes can lead to almost complete siltation, shallowing and significant overgrowth of even large water bodies in the region already in the next decade. Other, small and shallow water bodies, are generally on the verge of complete disappearance.

In fact, due to the reduction of water consumption on the Lower Dnieper for evaporation from the surface of the now-defunct Kakhovka reservoir and domestic water consumption, the water consumption in the channel network downstream of the river has increased somewhat. Thus, the channel network of the lower reaches of the Dnieper is the only element that has not undergone significant negative environmental changes. Instead, the lack of sufficient water level fluctuations and normal water exchange of the floodplain with the channel network will actually turn the unique water ecosystems of numerous lakes, small channels and islands into wetlands with an impoverished species composition.

The development of negative ecological processes in the lower reaches of the Dnieper can only be counteracted by the construction of a new, more powerful, modern hydroelectric power station within Novaya Kakhovka. During the construction of a new hydropower station, attention should be paid to the use of the latest hydropower technologies and hydrotechnical equipment, which at the current stage of development are the most environmentally friendly and cost-effective.

Restoring the regulated fresh water flow and increasing the amplitude of daily water level fluctuations in the lower reaches of the Dnieper water system is an extremely urgent issue for preserving the unique biological diversity not only of the lower course of the river, but also of the entire Dnieper-Buh mouth region.

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The scientific achievements of the authors of the monograph were also reviewed and recommended for publication at the international scientific symposium
«Erbe der europäischen Wissenschaft / Heritage of European science '2024»
(February 28, 2024)

Monograph published in the author's edition

The monograph is included in
International scientometric databases

500 copies
February, 2024

Published:
ScientificWorld -NetAkhatAV
Lußstr 13,
Karlsruhe, Germany

e-mail: editor@promonograph.org
https://desymp.promonograph.org

ISBN 978-3-989240-39-1
9 783989 240391