# SUB MER GED

ANNEX C

## SUBMERGED:
## Study of the Destruction of the Kakhovka Dam and Its Impacts on Ecosystems, Agrarians, Other Civilians, and International Justice

# Expert analysis of the impact caused on water resources and environmental elements as a result of the Kakhovka HPP Dam break

TRUTH HOUNDS

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The modern approach in the process of studying water and environmental problems always considers both the surface (groundwater) and surface (surface water) water environment as an interconnected system. Thus, a disruption of one component of the system usually inevitably entails deterioration in the other. Generally, this applies only to hydrologically connected hydroecosystems, which is exactly the case with the hydrological and hydrogeological conditions that have developed around the Kakhovka hydronode and the tributary part of the Lower Dnipro. It should be noted that before the catastrophic event of the explosion at the Kakhovka HPP Dam, the Kakhovka Reservoir was an ecosystem of an artificial lake-like reservoir of the Dnipro River basin (within the Lower Dnipro sub-basin), the flora and fauna of which, as well as the hydrological and hydrogeological components, were transformed over the course of about 70 years under the influence of anthropogenesis. The main changes under the influence of anthropogenic burden, which were reflected in the hydrosphere, are: the complete replacement of natural conditions with disturbed ones; regulation of the discharge of the lower reaches of the Dnipro; regional changes in the conditions of the development of groundwater, including the transformation of discharge areas into feeding areas; artificial replenishment of groundwater reserves (mainly in the areas of irrigation and laying of irrigation systems, as well as in the areas of lateral infiltration from the reservoir and the canal part of the Dnipro); changing rate of water exchange (acceleration of water exchange due to increased infiltration); and changes in the chemical zoning of the geological environment.

Considering these changes, which had stabilized for almost a century and functioned in a single hydrological-hydrogeological ecosystem disturbed by anthropogenic influence, one should expect a sensitive reaction of the underground hydrosphere to the events that occurred as a result of the explosion of the

Dam, the subsequent shallowing of the reservoir and disturbed balance of the artificial system.

In our opinion, the scale of the catastrophic events and hydro-ecological consequences of the explosion of the Kakhovka HPP dam with the subsequent shallowing of the reservoir has not been fully assessed, because until now there have been no estimates, not even approximate ones, of the losses suffered by **water resources** in the area influenced by the reservoir in the territories of Dnipropetrovska, Zaporizka, and Khersonska Oblasts, neither in the total volume nor based on qualitative criteria. Notably, subsurface and surface water is a source of drinking water supply, a formative component of the water balance of any territory, a necessary resource for the industry, and, most importantly, a formative criterion for the health and well-being of the population.

# Conditions for the Formation of Water Resources in the Territories Adjacent to the Kakhovka Reservoir and Within the Catchment Area of the Lower Dnipro

## Groundwater resources and water supply

The catchment area of the Lower Dnipro sub-basin, within which the Kakhovka Reservoir is located, has limited resources of groundwater and surface runoff due to unfavorable conditions caused by the geological structure and climatic factors. The southern part of the sub-basin is in an insufficiently hydrated area, which limits the supply of groundwater and causes a shortage of local surface runoff. The recent climate change, which comes with an increase in the duration of dry seasons and an increase in average annual temperatures, contributes to the harsher water-scarce climate conditions. Since the 1980s, the average annual air temperature in the environs of the Kakhovka Reservoir has already risen by more than $2^0$ C. The most significant increase in air temperature over the past 30 years (compared to 1961-1990) was observed in January-March – by $1.4$-$1.9^0$ C, and June-August – by $1.2$-$1.7^0$ C. A significant increase in temperatures in the winter and early spring period has a negative effect water content of local water bodies and increases evaporation from them in the summer period. Meanwhile, the annual amount of precipitation in the region remains mostly unchanged, with significant fluctuations over the years, and the potential evaporation has increased by a total of 73 millimeters per year, including 40 millimeters in the summer period. Currently, the potential annual evaporation in the region exceeds 950 millimeters, while the average annual rainfall is about 500 millimeters[1]. Thus, the deficit of the water balance in this territory is more than 50%.

The catchment area of the lower Dnipro sub-basin
(source: RBMP for the Dnipro river Maps_UA_01032021.pdf (davr.gov.ua))

The availability of local water resources in the Khersonska, Zaporizka, and Dnipropetrovska Oblasts in thousand m³/year per person according to 2020 data was 0.22, 0.32, and 0.24, respectively. For comparison, the same indicator for Zakarpatska Oblast is 6.29 (the highest in Ukraine), and for Kyivska Oblast – 0.46 thousand m³/year per person.[2] This indicates **low and very low supply** of surface runoff in the southern regions.

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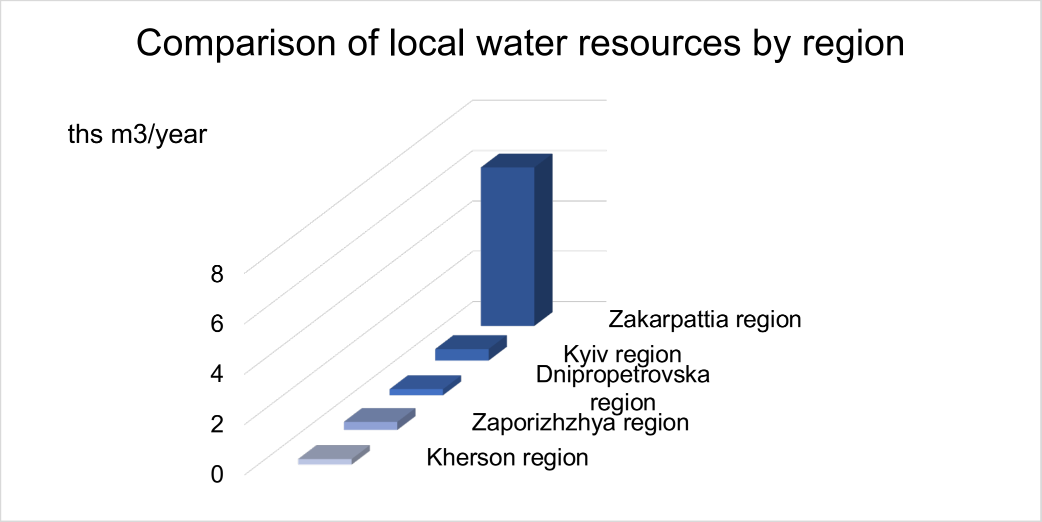
[1] Analytical Note // Institute of Water Problems and Land Reclamation of the National Academy of Sciences of Ukraine, Kyiv, 2023.

[2] AN ANALYSIS OF THE IMPACT OF CLIMATE CHANGES ON WATER RESOURCES OF UKRAINE (full report based on project outputs). / Snizhko S., Shevchenko O., Didovets Y. // Ecodiia Center for Environmental Initiatives, 2021, 68 pages.



Water resources availability in the southern regions with local water resources per capita

Prospects and opportunities for the use of groundwater in any specific territory are assessed based on their estimated resources, which, unlike the operational reserves, are determined based on certain assumed locations of water intake structures, and also take into account the specific features of geological and hydrogeological conditions, such as the rate and nature of water exchange (renewal rate), the quality of the groundwater (for example, its mineralization), as well as the availability of resources for further extraction.

In other words, the potential or forecast groundwater resources describe a certain intake volume (at the maximum possible costs) that can be obtained from the entire area of productive aquifers, and which depends on a set of conditions, the most important of which are: availability of layers with high infiltration properties; favorable (natural or anthropogenic) conditions for feeding and replenishing underground water reserves; groundwater quality (as mentioned above), matching the established conditions; the possibility of protecting groundwater from pollution.

According to the data provided in the RBMP (River Basin Management Plan) of the Lower Dnipro sub-basin (an official document[3]), within the catchment area, taking into account the specifics of the geological and hydrogeological structure and the groundwater formation conditions, the largest volume of forecast groundwater resources (FGWR) is contained the Dnipro-Donetsk and Black Sea artesian basins, which are located in the Kherson Oblast and the south of the Zaporizka Oblast. The hydrogeological area of the Ukrainian Shield and the Donetsk Fold Region have a smaller amount of groundwater resources; they are located in the Dnipropetrovska Oblast, and partially in the Mykolaivska Oblast. Accordingly, the FGWR are distributed as follows:

| | |
|---|---|
| Khersonska Oblast | 2312.6 thousand $m^3$/day |
| Dnipropetrovska Oblast | 1092.6 thousand $m^3$/day |
| Zaporizka Oblast | 641.1 thousand $m^3$/day |
| Mykolaivska Oblast | 120.4 thousand $m^3$/day |

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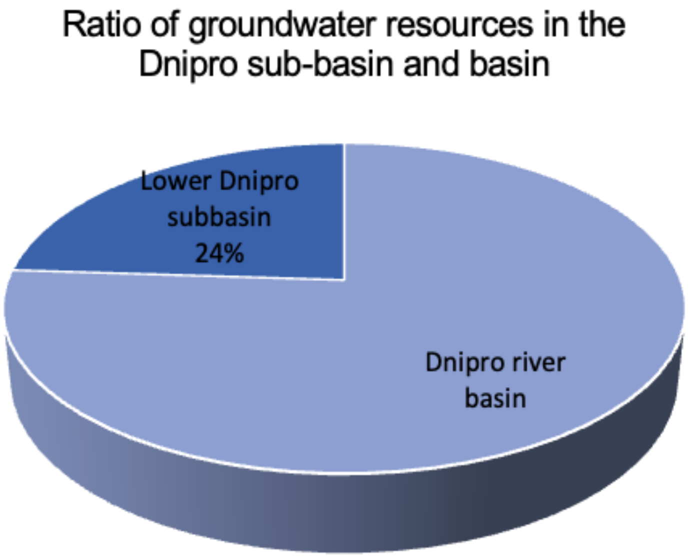
[3] Draft Management Plan for the Lower Dnipro Sub-Basin. Part 1 (2025-2030). https://davr.gov.ua/plan-upravlinnya-richkovim-basejnom-dnipra1.



For comparison, the resources of the Kyiv region are estimated at about 4,000 thousand $m^3$/day

According to the data of the regional assessments, the forecast groundwater resources (FGWR) of the Dnipro river basin is about **35,600 thousand $m^3$/day**. This is an important strategic deposit of clean, pollution-free drinking water. Within the sub-basins, no special effort was taken to assess the FGWR, but according to analytical assumption, the volume of FGWR of the Lower Dnipro sub-basin is about **8,800 thousand $m^3$/day**, which makes only **24%** of all underground water resources of the entire river basin

This is not much, even very little compared to the volume of underground water resources of the Volyn-Podillia artesian basin and the Dnipro-Donetsk artesian basin, that is, the central, northern, and northwestern parts of Ukraine.

Moreover, the distribution of groundwater resources in the territories of the Zaporizka, Dnipropetrovska, and Khersonska Oblasts, i.e., within the catchment area of the Kakhovka Reservoir and the Lower Dnipro, is extremely heterogeneous.

Based on this distribution of the available volumes of groundwater resources by administrative and territorial units of the specified oblasts we can identify the following areas with **insufficient groundwater resources and areas with close to no groundwater resources of sufficient quality**:

- Settlements of the Dnipropetrovska Oblast located in the area of fracture waters of the Ukrainian crystalline shield and the Black Sea artesian basin: Apostolivskyi, Kryvorizkyi, Nikopolskyi, Sofiivskyi, Tomakivskyi Rayons, etc., which have extremely insufficient volumes of groundwater resources—under 1 thousand $m^3$/day, while the groundwater resources **of Kyiv City** are ~ **900 thousand $m^3$/day**.**[4]** It should also be noted that about 91% of water resources in the Dnipropetrovska Oblast at large belong to underground waters with mineralization >1 g/$dm^3$ (from 1 to 1.5 g/$dm^3$), while the maximum permissible concentration for the total mineralization of drinking fresh water according to government regulations on the quality of drinking water is <1 g/dm.[35]

- Vilnianskyi, Zaporizkyi, and Novomykolaivskyi Rayons of Zaporizka Oblast with forecast resources of <8 thousand $m^3$/day. The rest of the territory of Zaporizka Oblast, which is within the catchment area of the Kakhovka Reservoir has groundwater resources in the amount of 50,000-200,000 $m^3$/day, which is also below the average indicators for the territory of Ukraine.

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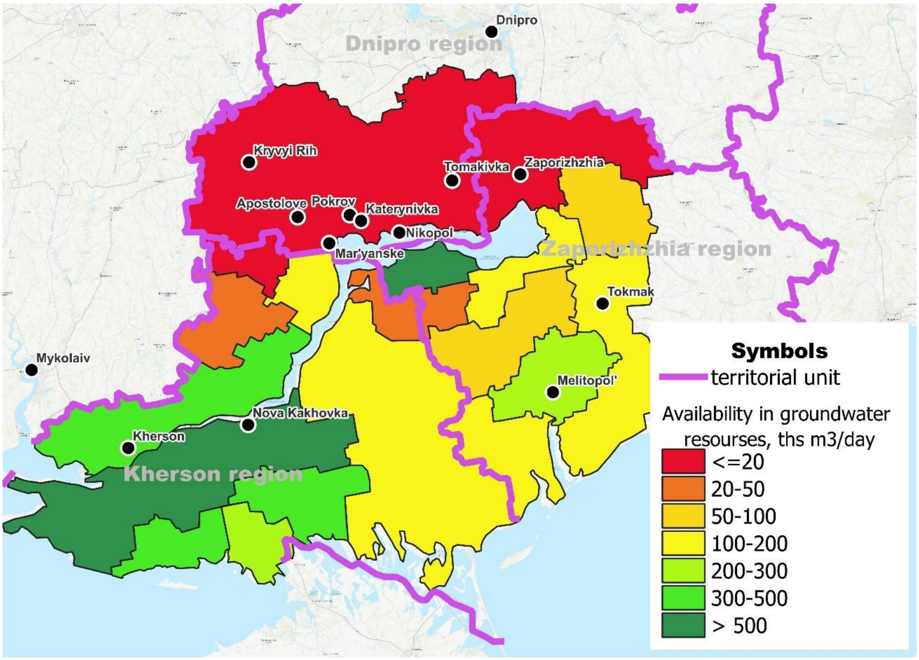
[4] The values of FGWR are provided based on the results of the last reassessment of est groundwater resources on the territory of Ukraine, 2016, SSPE "Geoinform of Ukraine", Kyiv.

[5] State sanitary norms and rules "Hygienic requirements for drinking water intended for human consumption" (DSanPiN 2.2.4-171-10), approved by order of the Ministry of Health of Ukraine dated May 12, 2010 No. 400. State standard of Ukraine "Drinking water. Requirements and methods of quality control" (DSTU 7525:2014), approved by order of the Ministry of Economic Development of Ukraine dated October 23, 2014 No. 1257.



The availability of groundwater resources in the administrative-territorial units of Dnipropetrovska, Zaporizka, and Khersonska Oblasts in the catchment area of the Kakhovka Reservoir

Khersonska Oblast has sufficient underground water resources, unlike Dnipropetrovska and Zaporizka Oblasts. The main part of underground water resources (75% of the oblast's FGWR) is concentrated in its southwestern part, in the lower reaches of the river.  Dnipro. The northern and northeastern rayons of the oblast (Velykolepetyskyi, Velykooleksandrivskyi, Verkhniorohachytskyi, Visokopilskyi, Ivanivskyi, Nizhnyosyrogozskyi) have scarcer forecast resources; their total forecast resources are 500 thousand $m^3$/day, including water with mineralization up to 1.5 g/$dm^3$—290.11 thousand $m^3$/day. But until today, the water supply of the **Khersonska Oblast** was mainly sourced from surface water (surface water of the Lower Dnipro and the Kakhovka Reservoir), since the use of groundwater is limited by its insufficiently good condition, which is the result of long-term technogenic burden. However, groundwater was the main source for **private households'** domestic and drinking water supply and was by water sourcing facilities since the early 20th century.

The water supply in **Zaporizka Oblast** relies on the use of both surface and groundwater sources. However, up to 96% of the total water comes from surface water, and only 4% from groundwater. Therefore, the water supply in the region mostly relies on surface water. The water resources of the Dnipro River and the Kakhovka Reservoir (before the explosion) were the main sources of water supply for industrial enterprises in the region, in particular the metallurgical and energy industries.

The situation in the areas of the **Dnipropetrovska Oblast** adjacent to the Kakhovka Reservoir is the most critical. Ironically, some of the rayons relying on groundwater were the ones that had the least groundwater of drinking quality: the Apostolivskyi, Kryvorizkyi, Nikopolskyi, Sofiivskyi, and Tomakivskyi Rayons. That is, they used groundwater to supply settlements remote from surface water mains, as well as for the needs of individual consumers.

**Thus, the water supply for drinking, utilities, and economic needs of settlements within the catchment area to which the Kakhovka Reservoir (before it exploded) was mainly sourced from the reservoir itself through a system of water intakes.**

Having assessed the average capacities of water intakes located along the coast of the Kakhovka Reservoir, we can calculate the total losses of the water supply system of the region. These are **irreversible** losses since the shallowing of the reservoir does not allow and will not allow in the future (in any scenario alternative to the restoration of the Kakhovka Reservoir) to maintain even the minimum required water levels in the water intakes, which were between 12.7 and 14.5 meters.[6] Therefore, the amount of consumption at water

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[6] Rules for the use of reservoirs of the Dnipro cascade/ Yatsyk A.V. et al. – Kyiv, 2003.

intakes, which were located in the cities of Nikopol, Marganets, Pokrov, etc., from where water was sourced for the purposes of industrial, household, and other kinds of water supply, including water supply to the Zaporizhzhia NPP and TPP, was about **1,200-1,300 million $m^3$/year in the most recent years before the full-scale invasion**. According to the 2021 statistics, there were 5,988 water pumping stations with an average total actual capacity of **4,640 million $m^3$/year** operating in the water supply systems of Ukraine.[7] The volume of water raised and fed into the water supply system of the Dnipropetrovska Oblast—the largest water consumer in Ukraine—in 2021 was only about **332 million $m^3$/year.** That is, as a result of the destruction of the Kakhovka HPP Dam, Ukraine lost a quarter of the water supply system supplies.

## The Kakhovka land reclamation complex as an engineering and technical solution created to overcome the shortage of water resources in the south of Ukraine

The Kakhovka reservoir was built in the lower reaches of the Dnipro River near Kakhovka in 1956 not only for the purpose of creating a hydroelectric power plant but also to overcome the water shortage in the territories of the southern oblasts and the Crimea. For the most part, the problem of water supply in the south of Ukraine at the beginning of the 1960s was solved with the construction of a land reclamation complex and a set of canals and systems starting from the Kakhovka Reservoir.

The Kakhovka Reservoir was a source of fresh water, which was supplied to the remote southern regions by large-capacity main canals and irrigation systems – Znamyanska, Kakhovska, Chaplynska systems, etc.

The water from the Kakhovka Reservoir was also supplied to the North Crimean Canal (NCC) and the Kakhovka Main Canal

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[7] National report on the quality of drinking water and the condition of drinking water supply in Ukraine in 2021.

(KMC), the Dnipro-Kryvyi Rih Canal, and collective agricultural water pipelines in the Khersonska and Zaporizka Oblasts, to fill the Karachunivske, Pivdenne, and Zhovtneve Reservoirs, which were used for drinking water supply of the cities of Kryvyi Rih and Mykolaiv, as well as for water supply systems of companies, cities, and towns of the Kryvyi Rih industrial complex.

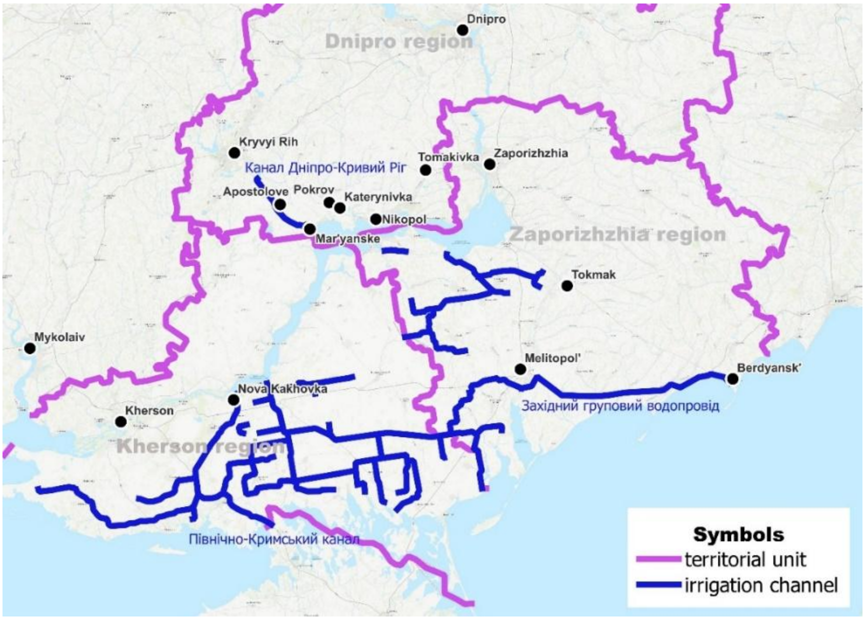
Supplying water from the Dnipro River to the population of the most dehydrated southern part of the Zaporizka Oblast – namely, to the settlements of Yakymivskyi, Melitopolskyi, Pryazovskyi, Prymorskyi, and Berdyanskyi Rayons, as well as the towns of Kyrylivka, Pryazovske, and the cities of Melitopol, Berdyansk, and Prymorsk with a population of 493,000 inhabitants, was implemented through a unique water supply complex – the **Western Group Water Pipeline.**

Another important water supply complex that used water from the Kakhovka Reservoir is the **Ivanivskyi Group Water Pipeline (IGWP)** in the Khersonska Oblast.

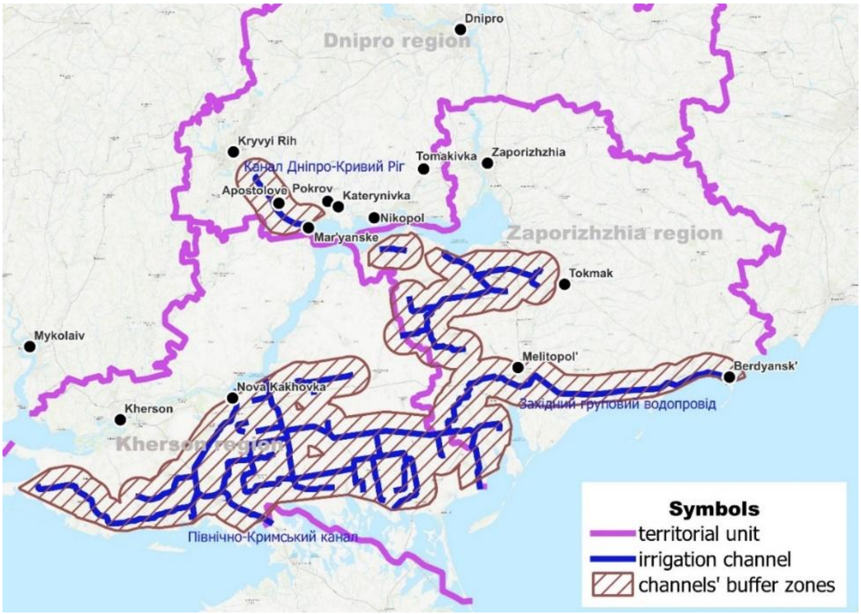
**The Dnipro-Kryvyi Rih canal** was built to supply water to the industrial areas of Kryvyi Rih, in particular, water was supplied to the Southern Reservoir, where it was purified, after which drinking water was supplied to the city of Kryvyi Rih. Today, the main problem is that in the event of the termination of the functioning of this canal, the Karachunivske Reservoir, which used to feed the Pivdenne Reservoir, becomes the main source of water supply for the city. The Dnipro-Ingulets canal was used to fill the Karachuniv Reservoir; it has also been damaged and stopped supplying water from the Kremenchuk Reservoir.

The main irrigation canals of the land reclamation system are linear objects. Therefore, taking into account the branching of the canals, the radius of their influence on the irrigated lands (coverage density), as well as the estimated areas of filtration losses from the canals and the size of additional groundwater supply areas, buffer areas were created around vector elements of the canals with an average radius of 10 kilometers. The coverage area, or the resulting area that has undergone drainage and will suffer from water shortages in the future due to the cessation of functioning of irrigation systems, according to a preliminary estimate, is **1.8 million hectares**. For comparison, the area of the Khersonska Oblast is **2.8 million hectares.** According to the results of the inventory of the State Water Agency of Ukraine, in 2013 the area of irrigated land sourcing water from the Kakhovka Reservoir was **1.1 million hectares with a design capacity of 1.9 million hectares**. That is, the estimated areas of potential damage correspond to the maximum area of land that could be involved in agriculture under the conditions of full capacity of the irrigation system with water from the Kakhovka Reservoir.

**The forecast losses of the Ukrainian economy from the suspension of the use of irrigation water from the Kakhovka Reservoir are estimated at UAH 47.0 billion. According to the Ministry of Agrarian Policy, in pre-war 2021, 4 million tons of grain and oilseeds worth $1.5 billion were grown in these territories.**



The Kakhovka irrigation system (main canals)



Buffer zones established around the main canal

## The impact of Subsequent Degradation Processes that Occurred as a Result of the Shallowing of the Kakhovka Reservoir on the Condition of the Land Reclamation Complex

The drainage of the bed of the Kakhovka Reservoir, which occurred as a result of the breach of the dam of the Kakhovka hydronode, entailed the formation of unstable drained soils of sandy-clay composition. As a result of the event, the territories occupied by the Kakhovka Reservoir, as well as the riparian territories and water areas of the Lower Dnipro downstream, were drained by a total of 80%.

Rapid drainage creates a number of negative consequences and is a factor in the development of chemical and wind erosion of soils, as well as the development of the following processes:

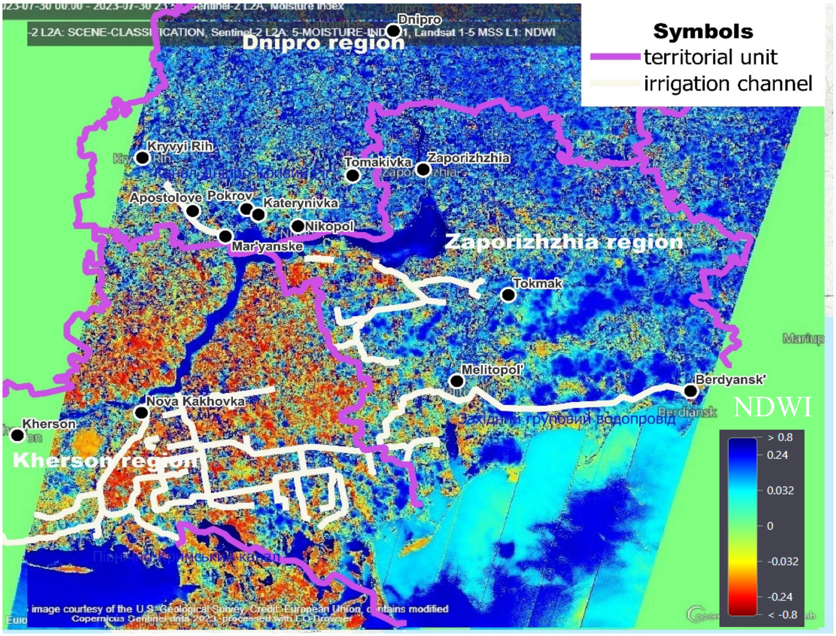
1. Rapid spread of aggressive invasive plant species, especially shrubs and trees;
2. Soil degradation; and
3. Desertification with the opening of the sandy bottom with further changes in the microclimate.

The high risk of wind erosion, deflation, and desertification is confirmed by the data of satellite photographs, which were obtained for the studied territory taking into account the differential humidity index.

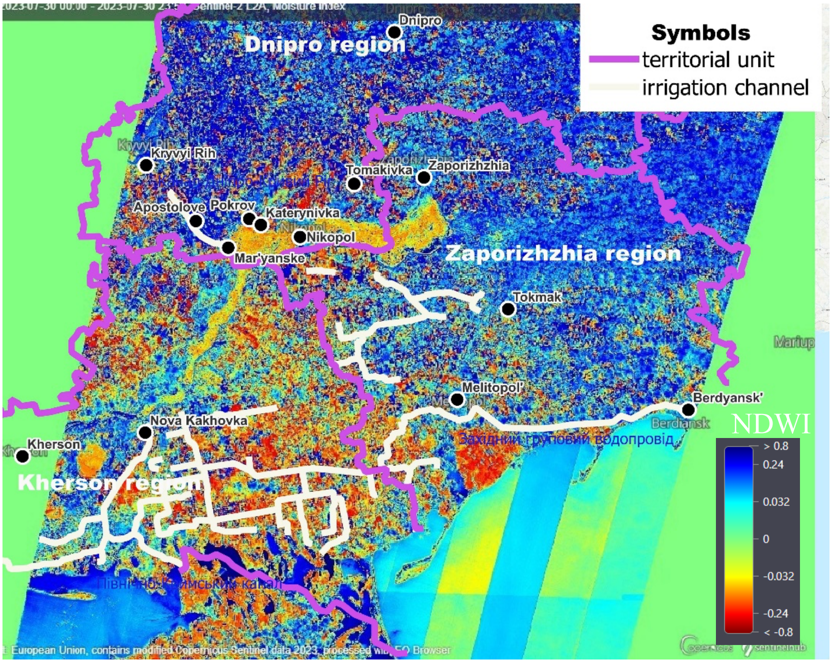
The normalized differential moisture index (NDMI) is used to determine the moisture content of vegetation and to monitor droughts. Negative values of the indicator (closer to -1) correspond to open soil areas. Values close to zero indicate an aquatic environment. High positive values correspond to a high level of vegetation cover.

Picture *a* shows the distribution of the normalized differential index in the territories in the area influenced by the hydro-engineering system as of July 2020 (before the Dam was blown up). Picture *b* shows the change in the moisture index distribution in the same area in July after the Dam was blown up. The system of irrigation canals that belongs to the hydraulic system of the Kakhovka Reservoir is superimposed on the pictures.

The images confirm the fact of planar development of drought and degradation of the surface soil and plant layer as a result of drainage caused by dehydration of the Kakhovka reservoir and the system of irrigation canals, which is manifested in the prevalence of negative values of the index. The increase in the area of drained areas according to satellite data obtained in the summer period after the HPP explosion, in comparison with the historical values of annual variability according to the analysis of satellite data with the application of overlay analysis, is about 45%.



*a* - Analysis of the subsurface soil moisture content within the areas adjacent to the Kakhovka Reservoir, for the period July 2020 (source: open geospatial data resource www.sentinel-hub.com)



*b* - Analysis of changes subsurface soil moisture content within the areas adjacent to the Kakhovka Reservoir as a result of the Kakhovka Dam destruction, for the period July 2023 (source: open geospatial data resource www.sentinel-hub.com)

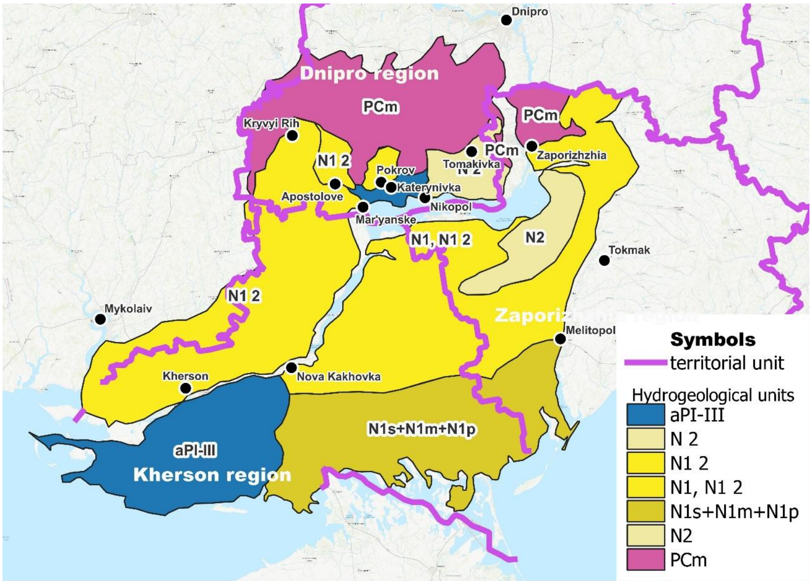
*Thus, the territories of the Dnipropetrovska, Zaporizka, and Khersonska Oblasts, which are located within the catchment area of the Kakhovka Reservoir and the Lower Dnipro, are situated in a climatic zone with an insufficient annual level of moisture and are characterized by unfavorable water balance conditions, which is reflected in the insufficient volumes of water resources both in surface and underground drainage. The deficit of the climatic water balance, in view of the unfavorable climate changes, poses a risk of reducing the flow by half, to an indicator of 2 l/s per km*$^2$*or less, as well as the desertification of territories even if the pre-disaster conditions (surface and underground water flow formed due to the construction of the Kakhovka Dam and regulation of the Lower Dnipro flow) are* *preserved. The underground component of the water resources of the territory – underground water resources – are distributed extremely unevenly (due to the peculiarities of the geological and hydrogeological conditions of the territory) and cannot provide the population with a sufficient amount of drinking water, especially water that would be used for industrial and agricultural water supply. All the water intakes of the Zakhindyi and Ivanivskyi group waterworks are tied to the water levels of the Kakhovka irrigation system, which is no longer achievable due to the catastrophic shallowing of the reservoir, while the water supply systems of the region can function only if the design levels of water in the reservoir are maintained. The above emphasizes the important role of the Kakhovka Reservoir (as well as the role of other reservoirs in the Dnipro cascade) in regulating river flow and accumulating water resources for their use in low-water and dry periods in regions of Ukraine with a natural shortage of water resources.*

## The Effect of the Shallowing of the Kakhovka Reservoir on the Condition of Underground Water Resources

As mentioned, the Kakhovka Reservoir is united into a single hydrosystem, not only with the  Dnipro River, but also with the first aquifers from the surface and pressure aquifers within the sub-basin, which have a hydraulic connection with the overlying aquifer complexes. For the territories of the Khersonska Oblast, the southern part of the Dnipropetrovska Oblast, and Zaporizka Oblast, the forecast groundwater resources are reflected to a greater extent in the dynamic component of the water balance (dynamic groundwater resources), which can be described by the total supply of groundwater due to infiltration of atmospheric precipitation, filtration from rivers (the Dnipro river and its tributaries, the Kakhovka Reservoir), as well as an additional supply of water due to economic activity (for example, the irrigated lands). Therefore, as a result of the complete disappearance of the support of the Kakhovka Reservoir, which was formed at the level of 15.0-16.0 meters, further drops in the levels and pressures of groundwater located in the riparian areas, as well as in other parts of the catchment area of the Kakhovka Reservoir either have occurred or are expected to occur and which entails a decrease in the volume of underground water resources.

In order to assess the scale of irreversible losses in groundwater resources that have occurred and will have a prolonged effect in the future, it is necessary to consider the features of the hydrogeological structure of the territory and consider the main factors of the long-term impact of the support created by the Kakhovka Reservoir on the underground water regime.

The main sources of drinking water supply in the territory are aquifers in Neogene sediments, to a lesser extent Paleogene (in the north of the region), and Quaternary (south-western part) deposits.



Hydrogeological zoning of the area of interest (the Kakhovka catchment area)

In general, the hydrogeological section of the catchment areas of the Kakhovka Reservoir consists of the following aquifers and complexes:

- The aquifer in the alluvial deposits of the Lower-Upper Neopleistocene of the floodplain terraces of the Dnipro River associated with sands and loamy sands (aPI-III);
- Aquifer in undissected deposits of the upper and lower Pliocene, associated with sands and clayey sands (N1 2);
- The aquifer in the deposits of the Middle-Upper Sarmatian sub-regional stage, the Meotic and Pontic regional stages of the Upper Miocene is associated with limestones with low-thickness interlayers of marls and sands (N1s2+3+N1m +N1p);
- The aquifer in the deposits of the Middle-Upper Sarmatian sub-regional stage and the Motic regional stage of the Upper Miocene is associated with limestones with low-thickness interlayers of marls and sands (N1s2+3=n1m);
- The aquifer in the deposits of the Middle-Upper Sarmatian sub-regional stage of the Upper Miocene is associated with shell limestones, marls, and sands (N1s2+3);
- The aquifer in Middle Miocene sediments, associated with sands, limestones, and marls (N1); and
- Aquifers of the fractured zone of Precambrian crystalline rocks (PCm).

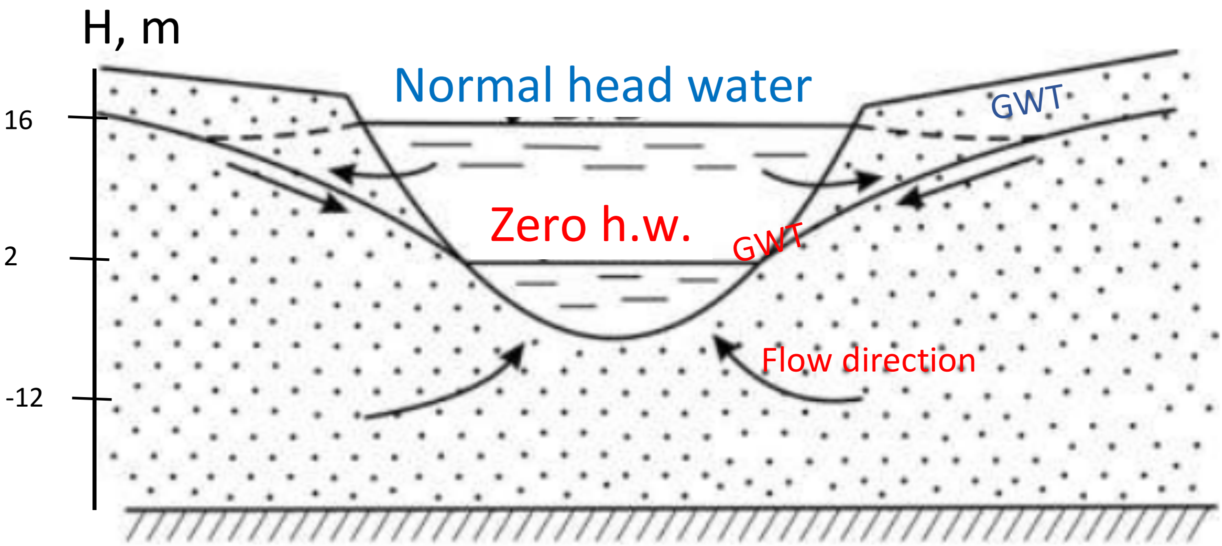
Thus, the territory features an aquifer complex contained in a thick layer of Neogene sediments, the section of which starts with a thick layer of Lower and Middle Sarmatian clays. They lie at depths of up to 100 meters in the north and up to 200 meters in the south. The thickness of clay increases from north to south from 5-10 to 65-120 meters. They are spread over the entire area and are a regional impermeable layer, on the top of which lies a limestone-marl stratum with layers of sand and clay of the Pontic-Meotis-Sarmatian age (N1s2+3+N1m +N1p).

This stratum is mainly represented by water-permeable rocks that form a series of hydraulically interconnected aquifers, which are united into a single aquifer complex known as **the main Neogene or Upper Miocene**. The thickness of water-bearing rocks of the Upper Miocene increases from north to south, from 5-10 to 50-60 meters on the right bank of the Dnipro and from 5-10 to 200 meters on the left bank.

In the south, a thick layer (up to 50 meters) of water-saturated sand-clay Pliocene formations with high filtration coefficients is located at the top of the Upper Miocene aquifer complex, which is overlain by Pliocene-Quaternary clays of uneven thickness. The aquifer lies on Pliocene clays in eolian-deluvial Quaternary loess loams.

All existing channel and shore water intakes of water supply systems, as well as the height of the main structures of the canals are dependent on the water levels in the Kakhovka Reservoir. According to the Order of the Ministry of Environmental Protection and Natural Resources of Ukraine No. 210 dated May 27, 2022 “On approval of the Rules for the operation of reservoirs of the Dnipro Cascade,” the normal support level of the Kakhovka reservoir is 16 meters, and the dead volume level is 12.7 meters. If the water levels are 15.6-16.0 meters, all water users are provided with water in full.

Throughout the existence of the Kakhovka Reservoir, the absolute water level in it was about 16 m. Achieving such a level became possible after the construction of the Kakhovka Dam and the regulation of the Lower Dnipro discharge. Before the construction of the Dam, the absolute marks of the bottom of the reservoir were 0-2 meters above sea level.



The conceptual model for understanding the connection between normal headwater and discharge into the groundwater system (blue colors – previous normal conditions of the Kakhovka reservoir: surface waters discharge into the groundwater system; red color—the situation after the normal head of the Kakhovka reservoir dropping down—groundwater discharge into the reservoir and groundwater)

After the flow of the Dnipro was regulated by the Dam of the Kakhovka Reservoir, the Dnipro River and the Kakhovka Reservoirs, which were the discharge area (drains) turned into the supply area of the first aquifers from the surface (downstream to the city of Beryslav), and in some places – the areas of additional feeding due to overflow (south-eastern part of the reservoir).

That is, on the one hand, it contributed to the additional replenishment of underground water resources with fresh river waters in the riparian strip up to 30-50 kilometers wide, on the other hand, to the activation of dissolution, leaching, and ion exchange processes.

In fact, the intensive lateral bank filtration of waters from the Kakhovka Reservoir contributed to the formation of a lens of unconfined groundwater on clayey rocks of the Upper Miocene-Pliocene with a depth of 5-8 meters of the underground water mirror. According to scientists, the development of such a lens as an additional source of fresh groundwater of the hydrocarbonate calcium type and a source of additional vertical filtration into Neogene aquifers took place over 10 to 15 years.

| Component of the water balance | Middle-Upper Miocene aquifer complex (N1) | | Pont-Meotis-Sarmatian aquifer (N1s2+3+N1m+N1p) | |
|---|---|---|---|---|
| Infiltration | - | - | **521.5** | - |
| Water sourcing | - | 26.62 | - | **740** |
| Interconnection with the ground waters of the Crimean Plain | 2.04 | - | 10.2 | 10.0 |
| **Interconnection with the Kakhovka Reservoir** | 2.62 | - | 59.6 | 1.8 |
| Interconnection with the Dnipro | - | 0.95 | 22.5 | 122.3 |
| Interconnection with the sea | 0.24 | 0.09 | 11.2 | 14.1 |
| Interconnection with the aquifer complex of Middle-Upper Pliocene sediments (N2) | - | - | **687** | 54.01 |
| Interconnection with the aquifer complex of the Pont-Meotis-Sarmatian and Middle Miocene sediments (N1s2+3+N1m +N1p) | 26.36 | 5.56 | 5.56 | 26.36 |
| Consumption at the boundary of the catchment area (discharge into the Molochna River) | 0.76 | - | 0.16 | 1.11 |
| Volumetric component | - | - | 25.4 | 367.24 |
| **Total** | **32.22** | **33.22** | **1343.12** | **1336.92** |

A significant change in the groundwater level occurred on the left bank of the lower Dnipro. The rise in the level of groundwater was thus caused by the development of support from the Kakhovka Reservoir and irrigation. On the left bank, the replenishment of underground water resources in the Middle-Upper Miocene was so intense that water withdrawal from underground sources was completely compensated by support from the Kakhovka Reservoir and infiltration feeding on irrigation massifs.

The analysis of the components of the groundwater balance of the aquifer complexes of the Neogene of the left bank of the Kakhovka Reservoir, compiled during the period of operation of the Kakhovka hydroelectric shows that infiltration feeding and flow from the overlying Middle-Upper Pliocene complexes (N 2) into the productive aquifer in the Pont-Meotis-Sarmatian sediments (N1s2+3 +N1m +N1p) was 1.6 times higher than the water withdrawal from the latter.

**Groundwater balance of operational aquifer complexes of Neogene sediments on the left bank of the Kakhovka Reservoir and the Lower Dnipro, thousand $m^3$/day, according to V.M. Shestopalov[8]**

***Blue—positive elements of the balance; red—negative elements of the balance***

After the Dam breach, the Kakhovka Reservoir shallowed to the critical zero mark of absolute heights, as a result of which, the former water area of the Kakhovka Reservoir and the Lower Dnipro (due to the drop in flow and level) turned into a groundwater discharge zone. According to the results of a field survey in September 2023, which was carried out by scientists of the Institute of Environmental Geochemistry of the National Academy of Sciences of Ukraine, the private wells of the residents of the coastal strip of the Kakhovka Reservoir in the settlements of Katerynivka, Nikopol, Maryanske, etc. (the right bank part of the Dnipropetrovska Oblast) had shallowed, which indicates a critical drop in the level of non-pressure water and a decrease in the volume of underground water in non-pressure aquifers.

In the absence of support, which was created by the Kakhovka Reservoir as well as the irrigation system, it is possible to use simple means to calculate the volumes by which groundwater

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[8] Water exchange in hydrogeological structures of Ukraine: Water exchange in disturbed conditions / Shestopalov V.M., Ognianik N.S., Drobnokhod M.I. et al. Kyiv, Naukova Dumka, 1991. —528 pages.

resources will decrease in the main operational aquifer complex (N1s2+3+N1m+N1p) in the absence of infiltration supply and overflow from the overlying Middle-Upper Pliocene sediments.

According to the formula, the flow rate of a unit flow element of underground flow, which also represents the volume of dynamic reserves of groundwater per unit cross-section of the flow, is calculated as follows:

$Q=khI$,

Where k is the filtration coefficient, m/day; h – pressure or height of the underground water level, m; I – hydraulic slope, dimensionless.

Thus, using basic geological data of hydrogeological parameters of aquifer complexes, it is possible to estimate flow rates of a unit section in aquifers of alluvial deposits and sandy deposits of the Upper Pliocene, which are hydraulically connected to the main Neogene aquifer:

$Q=2*5*0.05=0.5$ $m^2$/day

The distribution area of the aquifer can be clearly marked on the right bank of the Kakhovka Reservoir. It is about 30 $km^2$ (F) and stands out in the form of coastal strips.

Thus, the total volume of groundwater resources in Quaternary sediments and Upper Pliocene sediments, which were lost due to the disappearance of support from the Kakhovka Reservoir, and the associated drop in the level is:

$Q=khI*F$

$Q=khI*F=0.5*30{,}000{,}000=41{,}700$ $m^3$/day or 41.7 thousand $m^3$/day

For comparison, it is worth noting that according to the most recent estimate of 2016[9], the volumes of estimated resources within the catchment area of the Kakhovka Reservoir are:

| | |
|---|---|
| Forecast resources of underground water in Pliocene-Pleistocene complexes | 47.0 thousand $m^3$/day |
| Forecast groundwater resources in Upper Miocene (Middle-Upper Sarmatian, Meotic, and Pontic) deposits of the Neogene | 3991.68 thousand $m^3$/day |
| Forecast groundwater resources in Mid-Miocene sediments | 1114.89 thousand $m^3$/day |

Thus, the loss of the groundwater resource of the upper unconfined aquifer complex in the Quaternary and Pliocene sediments is 88% of all the groundwater resources estimated in the Pliocene-Pleistocene complexes. This is **a catastrophic loss from the standpoint of the water balance and future water supply of the territory.**

The results of studies assessing the water exchange in the hydrogeological structures of Ukraine enabled the identification of the empirical value of the water exchange rate in the near-surface layer of the hydrogeological section. According to researchers, it is 0.2-0.3 m/year. Also, field researchers documented the condition of water intake wells and boreholes of private households in the Dnipropetrovska and Khersonska

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[9] Summary of the assessments of the estimated resources and operational reserves of underground water using the automated database of estimated resources of underground water of Ukraine / SGE "Geoinform of Ukraine"; author: Yurkova N.A. Kyiv, 2001.

Oblasts, which mainly use underground water of the first aquifer from the surface in the Quaternary and Upper Pliocene deposits. They documented a significant drop in groundwater levels (5-8 meters) and complete drainage of wells. This indicates a possible drop of the level by a total amount that corresponds to the height of the support from the Kakhovka Reservoir, which can be estimated by its former depth of 5-8.4 meters. Currently, without the Kakhovka Reservoir, this underground water resource is completely lost. In the hypothetical case of its restoration and filling of the Kakhovka Reservoir, it will take the following time to restore the groundwater resources to the previous level in time (the worst-case scenario – the lowest rates of water exchange, the average drop in the level is 6.7 meters):

6.7 meters / 0.2 m/year = 33.5 years

Though the assessment was completed based on fundamentally significant indicators, it still requires validation through further field studies to assess the changes in the underground water regime and its monitoring in larger areas for the accumulation of data to create a detailed numerical model of geofiltration and a more detailed assessment of the damage suffered by the groundwater resources.

## Land Salinization as a Result of the Drainage of Irrigated Lands Due to the Loss of Water from the Kakhovka Reservoir and the Loss of Groundwater Resources

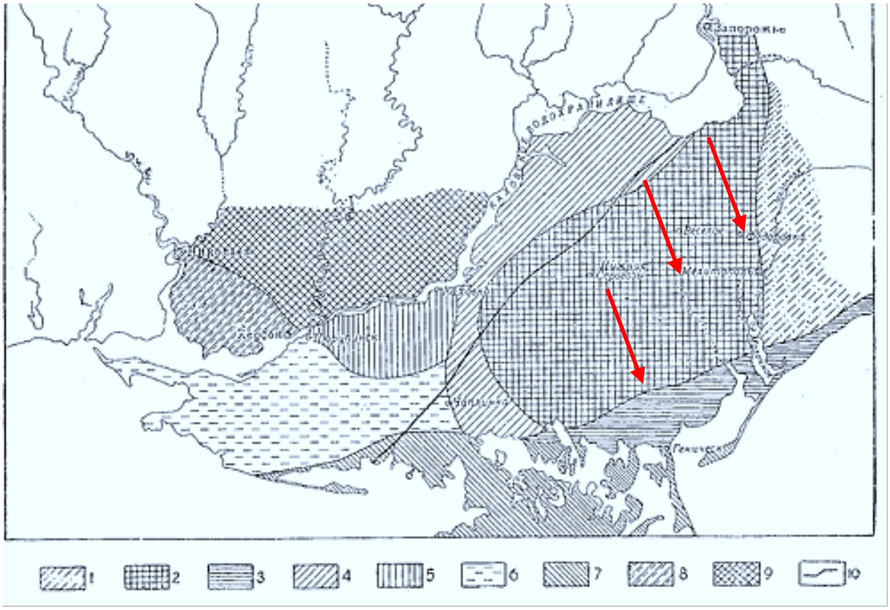
Based on the preliminary analysis of the hydrogeological conditions of the territories located within the catchment area of the Lower Dnipro River, it can be concluded that the main collector of underground water resources of the latter is the Neogene limestone of the intensive water exchange area.

During the historical course of geological processes, the structure of the Black Sea basin was formed in arid climatic conditions associated with the active transfer of salts by impulverization (from the surface, that is, by the transfer of salts from the surface of the seas through the atmosphere). The surface layers of the Black Sea geological section, including the Neogene complex, have a naturally high salt content.

Thus, the salts dissolved in groundwater mainly come from water-resistant sediments rich in salts of marine origin (traces of recent marine transgressions) preserved in rocks due to poor washing of the axial zones of the Black Sea Basin, especially in the southern coastal part.

According to the studies by E. Burkser, the excess elements in the Quaternary sediments of the region, compared to their Clarke numbers for soils, are calcium (3.88%, clarke – 1.37%), sulfur (0.26%, clarke – 0.09%), chlorine (0.021%, clarke – 0.01%). The region features significant sulfate-chloride salinization of the entire layer of Quaternary sediments, underlying Pliocene red-brown clays, and groundwater. The salts mainly originate from the seas and the Syvash Bay. The sea salts ($NaCl$, $Na_2SO_4$, $CaCO_3$, $MgCO_3$) are carried by the wind and fall on the land surface with precipitation and dust. In Askania-Nova, 8.2 kg of salts per 1 hectare per year are added to the soil with dust and 285.6 kg per 1 ha per year with precipitation.

The degree of salinity of soils, the aeration area, and the unprotected aquifers closest the surface increases in the direction to the south of the Kakhovka Reservoir. The area of sulfate-chloride-hydrocarbonate magnesium-sodium waters with mineralization of 1-3 g/dm$^3$ (area 9 in the figure below) is a potential accumulation area of of excess salt deposits in the soil.



Hydrogeochemical scheme of the main Neogene aquifer[10]:

1 – chloride-hydrocarbonate and hydrocarbonate-chloride sodium and sodium-calcium waters (mineralization 1-3 g/dm3); 2 – chloride-sulfate and sulfate-chloride magnesium-sodium and calcium-magnesium-sodium waters (1-3 g/dm3); 3 – sodium chloride (1-14.6 g/dm3); 4 – sulphate-hydrogen carbonate and hydrogen carbonate-sulphate magnesium-calcium-sodium and calcium-magnesium-sodium (0.5-1.5 g/dm3); 5 – calcium chloride-hydrogen carbonate and magnesium-calcium (0.1-0.4); 6 – calcium-magnesium and sodium-magnesium (0.1-0.6 g/dm3); 7 – calcium chloride-hydrogen carbonate and calcium-sodium-magnesium (0.1-1 g/dm3); 8 – hydrocarbonate-chloride

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[10] Babinets A.E. Underground waters of the south-west of the Russian platform (distribution and formation conditions) / Babinets A.E. - Kyiv: The Publishing House of the Academy of Sciences of the Ukrainian SSR, 1961. – 380 pages.

magnesium-sodium and magnesium-calcium (1-3 g/dm3); 9 – sulfate-chloride-hydrocarbonate magnesium-sodium (1-3 g/dm3); 10 – hydrogeochemical profile line

The most mineralized waters, the chemical composition of which is dominated by chlorine ions, are found in the coastal regions of the Azov and Syvash Regions. The source of chlorine is readily soluble salts of water-bearing rocks and poorly washed pore solutions, which turn into a solution due to long-term contact of groundwater with rocks under conditions hindering the discharge of groundwater from the aquifer into the Sea of Azov and the Gulf of Syvash.

Even under the conditions of rock washing to a depth of 5 meters, which occurred thanks to the existing irrigation system and additional infiltration feeding, the proportion of saline lands in the Khersonska Oblast increased with each coming year. For instance, in 2011, they comprised 30.5% of the total area of agricultural land in the region (1969.5 thousand hectares). The salt composition of soils was dominated by sulfates and chlorides; the content of hydrocarbons remained relatively stable. Therefore, the recovery of saline soils was possible only by ensuring a washing regime and implementation of chemical land reclamation systems (gypsum treatment).

Hydrogeologist V. Shestopalov who studied the Dnipro artesian basin, discovered (in the catchment area between the left bank of the Kakhovka Reservoir, the Lower Dnipro, and the Molochna River) that vertical filtration of groundwater was an important factor in the formation of resources and the chemical composition of groundwater in areas of intensive and complicated water exchange. **Due to the vertical flow, the residual seawater is gradually replaced by atmospheric water, which entails the desalination of mineralized groundwater in the intensive water exchange area**, which was proven by the example of the confluence of the Lower Dnipro and the Molochna River.

Groundwater confined to saline sulfate rocks (which are Neogene complexes) always contains an increased content of sodium chloride, which contributes to the leaching of gypsum and anhydrites. After the drainage of the Kakhovka reservoir, caused by the explosion of the Kakhovka HPP Dam, the “flushing” factor of the water infiltrating from irrigation systems, in the estimated volume of 521 thousand $m^3$/day, was lost. These volumes represent ~39% of the total water balance of the territories. In the absence of additional sources, such as lateral filtration from the Kakhovka Reservoir and filtration from irrigation massifs, the structure of the water balance will acquire negative features with the predominant component of evaporation, which is equal to about 90% of the negative component of the water balance, i.e. 300-350 mm/year[11] on average; multiplied by the area of the main Neogene complex south of the Kakhovka Reservoir, 850 $km^2$, this amounts to 708 thousand $m^3$/day.

Under conditions of operation of all components of the water balance, the sum of positive components is equal to the sum of negative ones:

$Q_+ = Q_-$

where $Q_+$ is the positive component of the balance, thousand $m^3$/day; $Q_{--}$ – negative component of the balance, thousand $m^3$/day

In the conditions of the scenario considered above, the total shortfall in the balance is 1,223 thousand. $m^3$/day, which is 91% of the water balance flow that existed within the area of the main Neogene aquifer south of the Kakhovka Reservoir:

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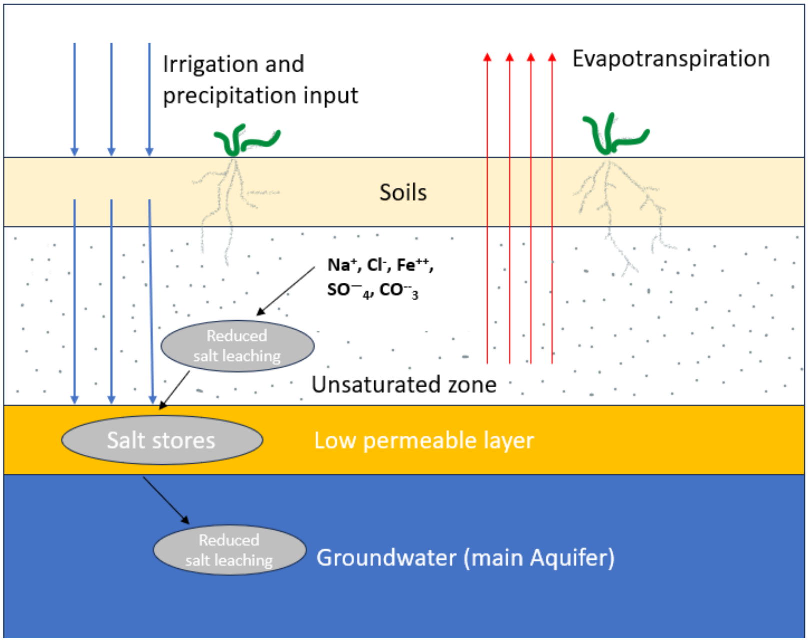
[11] A report on the assessment of the condition of forecast resources and operational reserves of groundwater in the Kherson region / SRGE Prychornomorgeologiia; supervised by Tiuremina V. G.; performed by: Bruiako A.V. et al. Odesa, 2005. – 161 pages. Geological Registry No. U-99-69/5.

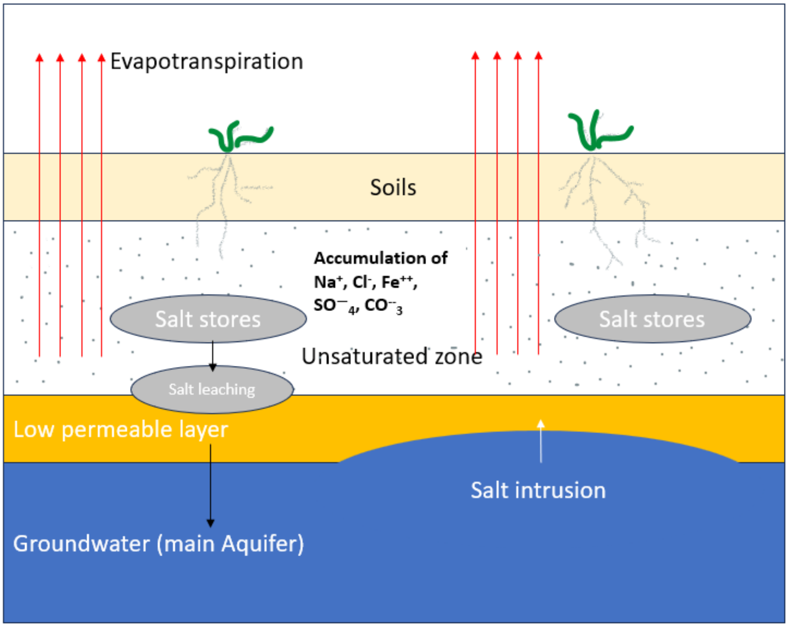
1343.12-521.5 = 1336.92+708*

**see the balance table in the text*

Such indicators in the loss of water balance create negative conditions that will contribute to the retention of salts in the soil cover of the aeration zone due to the intensification of evaporation (see figure below). The drop in the level of groundwater and the subsequent depletion of resources in the Upper Pliocene aquifers, which are higher than the middle Neogene and have low mineralization, make it impossible to flush groundwater from the aquifer complexes of the main Neogene, which have increased mineralization (1.5-3.0 mg/dm$^3$). Under such conditions, the formation of salt intrusions in the near-surface layers should be expected, since mineral-enriched salty or mineralized waters have a higher pressure than fresh waters – it is created by the pressure of water in the pore medium.

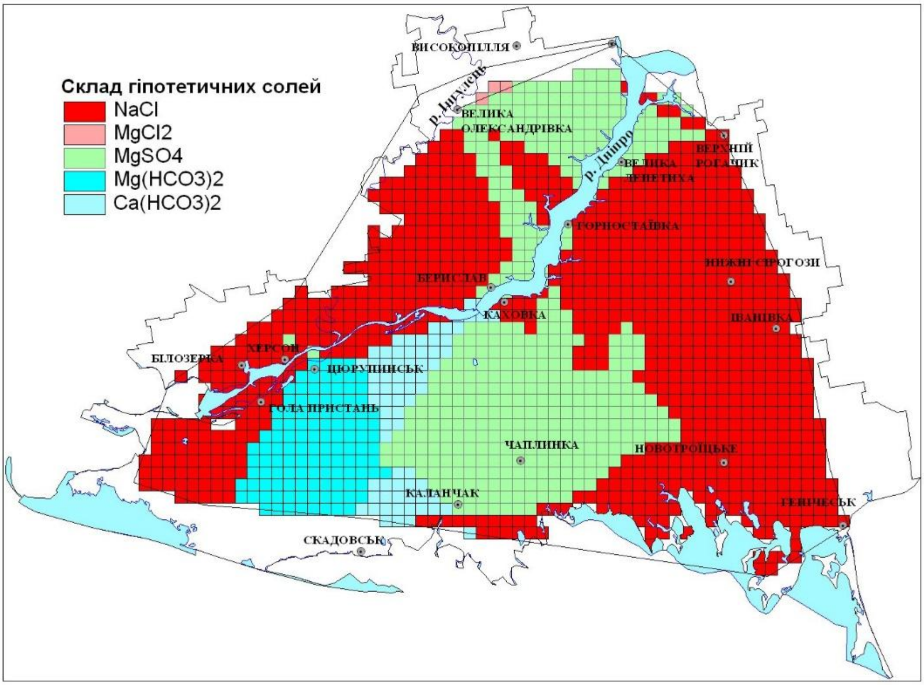


The scheme of salt transport and accumulation in soils and aquifers under normal infiltration conditions (sufficient infiltration created on irrigation massifs)



The scheme of salt transport and accumulation in soils and aquifers under the water deficit conditions caused by the Kakhovka irrigation canal system disabling

According to O. V. Shcherbak’s model of the distribution of the composition of the main hypothetical salts in the drinking groundwater of the main Neogene aquifer, it is possible to identify and estimate the area of the predicted territories, within which in the future, as a result of the decommissioning of the Kakhovka irrigation complex and depletion of underground water resources, salinization of soils and the upper layer of the geological section will occur to the depth of the first non-pressure aquifer.



Distribution of the composition of the main hypothetical salt in drinking groundwater of the Neogene (by Shcherbak O.V.)*

*areas marked by red are potential areas of coming salination

Active salinization of the upper zone of the water exchange was noticeable in the very first months after the shallowing of the Kakhovka Reservoir.

In the course of field research, groundwater samples were taken and their chemical analysis was performed. The results of the analysis indicate a sharp deterioration in the quality of groundwater in terms of mineralization.

According to the table, all water samples tend to increase in acidity, and in most of them, the pH does not meet the drinking water requirements. Most of the samples do not meet the required parameters for salt content; half of them don't meet the required parameters for dissolved oxygen.

Thus, water from underground sources, which is used by the population of the surveyed settlements (the right bank of the Kakhovka Reservoir, Dnipropetrovska, and Khersonska Oblasts), does not meet the requirements established for drinking water. Further use of such water will also entail soil salinization during irrigation.

## Results of field tests of water samples from surface waters and groundwater observation points

| No | Sampling point | t, °C | pH | δ, μSm[12]/m | Mineralization, mg/$dm^3$ (ppt[13]) | TDS[14], mg/$dm^3$ (ppt) | Dissolved Oxygen mg/l$O_2$ |
|---|---|---|---|---|---|---|---|
| 2 | The village of Maryanske | 20.9 | **6.1** | 3370 | - | - | **3.8** |
| 15 | The village of Maryanske, borehole, 18 m | 16.3 | **6.4** | 5190 | **2900** | 2590 | 6.2 |
| 17 | The village of Novovorontsovka (Khersonska Oblast), borehole 15 m | 13.6 | **6.32** | 2520 | **1360** | 1260 | **2.6** |
| 18 | The village of Novovorontsovka, well 6 m | 14.9 | **6.25** | 3730 | **2030** | 1960 | **3.3** |
| 19 | The village of Hrushivka (Leninske), borehole 35 m | 20.5 | **6.37** | 5440 | **3400** | 2720 | 7.1 |
| 20 | The village of Hrushivka (Leninske), well 2.35 m | 12.6 | 6.6 | 490 | 250 | 244 | 5.2 |
| 21 | The village of Naberezhne, drillhole 28 m | 15.9 | 6.54 | 1310 | 680 | 650 | **4** |
| 22 | The village of Naberezhne, drillhole 30 m | 17 | 6.6 | 1300 | 680 | 680 | **3.5** |
| 23 | The village of Pokrovske, drillhole 31 m | 21.3 | **6.3** | 6590 | **3720** | 3290 | 4.8 |
| 24 | The village of Pokrovske, drillhole 29 m | 15.3 | **6.46** | 5370 | **2900** | 2680 | **4** |
| **Threshold value** | | | **6.5-8.5** | | **1000** | | **≥4** |