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## MODELING THE DISTRIBUTION OF TRANSFORMED WATERS OF THE DNIPRO RIVER IN THE BLACK SEA FOLLOWING THE ARTIFICIAL FLOOD CAUSED BY THE KAKHOVKA DAM DESTRUCTION

On the night of June 6, 2023, Russian occupying forces blew up the dam of the Kakhovka hydroelectric power plant (HPP), which is located on the Dnipro River in the Kherson region of Ukraine.

As a result of the HPP blowing up, there was an intensive leakage of water from the Kakhovsky Reservoir. As of 12.06.2023, 14.4 $km^3$ of water entered the lower Dnipro River, which formed 72% of the volume of water in the reservoir before the dam destruction (or 27% of the total volume of the average annual natural flow of the Dnipro, which makes up 53.5 $km^3$). According to rough estimates, water discharges through the dam opening in the first days after the dam destruction amounted to over 40000 $m^3/s$.

The Black Sea consequently received many different types of pollutants, which were contained in the waters of the Kakhovsky Reservoir and in the sediment at its bed, and were also washed away by the water flow from the flooded areas of the lower Dnipro River (more than 2000 ha).

Access to the coastal areas at the mouth of the Dnipro River and in the north-western part of the Black Sea (NWBS) is extremely limited due to military operations, and it is almost impossible to conduct field studies in the open sea. The main sources of information for assessing the spatial and temporal extent and specific features of contaminated river water distribution in the sea are data from remote satellite sensing of the sea surface and results of mathematical modeling.

Numerical modeling of polluted transient water spread from the Dnipro-Bug estuary to the NWBS water area after dam destruction was performed. The simulation was carried out with the use of well-known numerical hydrodynamic model Delft3D-Flow Flexible Mesh (D-Flow FM). An unstructured computational mesh was generated for the model runs. The mesh covered the entire water area of the Black and Azov Seas and contained the high-resolution area for the NWBS region. In the vertical, the terrain-following σ-coordinate system was specified, which consisted of 7 vertical layers with non-uniform layer thicknesses.

The modelling period was 30 days (06.01.2023-06.30.2023). At the lateral open boundary of the model (mouth of the Dnipro River) the boundary conditions were imposed as water level time-series based on the observation data from the hydrological post “Kherson”. Boundary conditions for water temperature were imposed on the basis of information obtained from the hydrological station “Kiev” of the Central Geophysical Observatory of Ukraine. Mineralization of river water was assumed to be 2 $mg/dm^3$. At the upper (atmospheric) open boundary the model was forced by *u*- and *v*-wind stresses and mean sea level pressure fields with the 3-hour time step and 0.25°-degree spatial resolution, obtained from the Global Forecasting System (GFS) NOMADS archive.

Modelled salinity of seawater (Fig.1) and concentration of tracer with neutral buoyancy, which entered the sea together with transformed river waters, were considered indicators of intrusion and spreading of polluted transient waters from the Dnipro-Bug estuary.

To verify the modelling results, observational data of water salinity variability at the marine hydrometeorological station “Odesa-Port” and satellite images of sea surface color were used.

According to the model results, it was found that the plume of desalinated (with salinity < 10 ppt) and polluted waters initially propagated westward along the northern coast of the NWBS towards the city of Odesa. From June 9-10, 2023 the contaminated water plume started to spread along the western coast of the NWMC. On June 14, 2023, the plume reached the northern bounds of the Danube River estuary area, near the coast of the Tuzla group of lagoons.

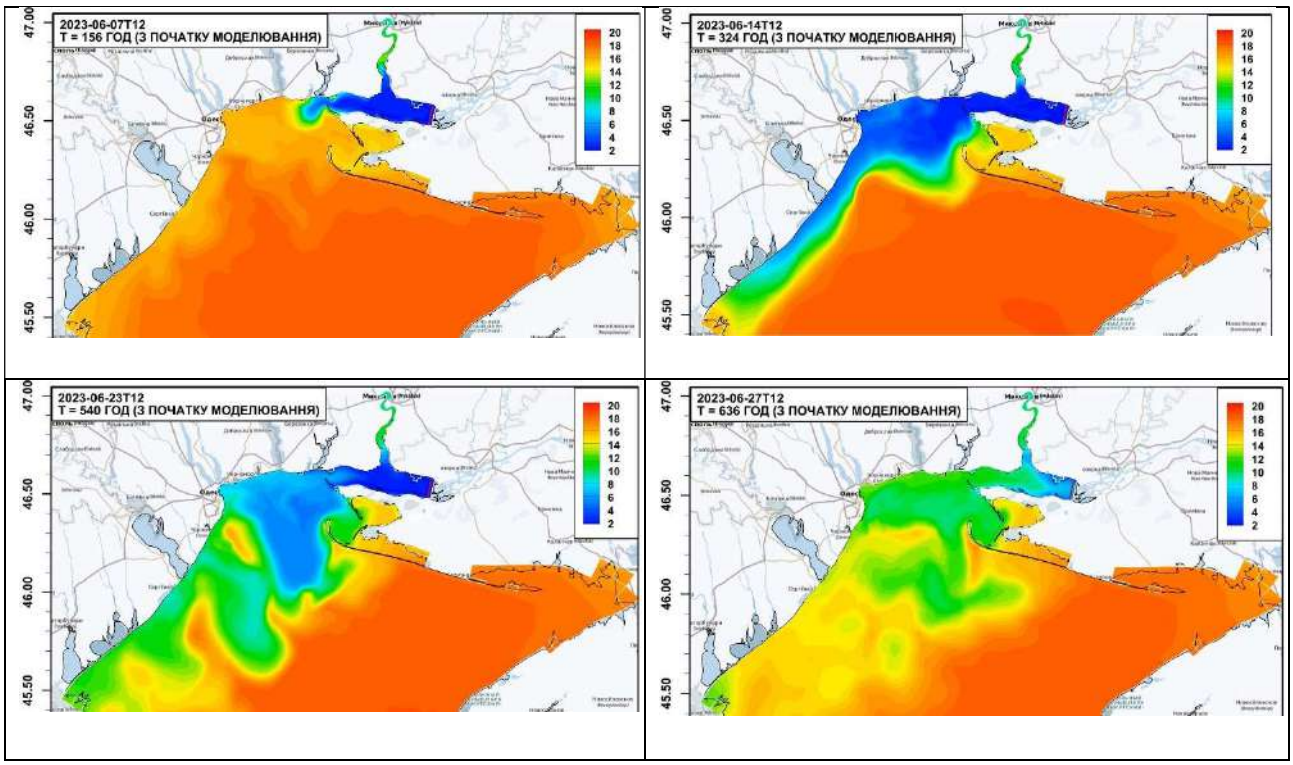


*Fig. 1.* **Changes in the spatial distribution of water salinity in the northwestern part of the Black Sea from June 7 to June 27, 2023, based on modeling results [1].**

This narrow plume of contaminated fresh water subsequently diffused in the direction of the open sea, with the formation of so-called “tongues” of water with reduced salinity, which were spotted in the areas of the Dniester and Danube-Dniester seabed rises. In addition, the plume of desalinated water spread southward from the Odessa Bank towards the open sea, flowing over the Tendrovsky bottom uplift. The simulation results are in good agreement with satellite information about sea surface color, clarifying and supplementing them with additional data.A conservative spill of neutral buoyancy, whose concentration at the open boundary of the model was 100%, was modeled as a tracer of pollution spreading with transient waters from the Dnipro-Bug estuary. A simulation showed that in the Odessa area of the NWBS the pollution level is reduced to 60% of the initial level due to hydrodynamic dilution. At the Danube-Dniester mouth area, the concentration of polluted waters decreases to 30% of the initial one.

It is shown that in the first days after the dam breach, significant sea level gradients were formed in the Dnipro-Bug estuary, which were caused by the inflow of large volumes of desalinated transient waters. At the hydrological front, density currents emerged between the transformed river waters and the surrounding sea waters, significantly influencing the formation of water circulation and, consequently, the distribution of the plume of desalinated waters and conditional pollutants.

The behavior of the plume of desalinated transient waters, spreading from the Dnipro-Bug estuary, and the position and configuration of the hydrological front were affected by wind conditions. Though wind currents were not dominant in the water area, they influenced water dynamics and distribution of spill concentrations, e.g. chlorophyll-a. They contributed to the intrusion of transformed river water towards Odesa along the coastal shallow waters.

Thus, the application of the numerical hydrodynamic model D-Flow FM in combination with the satellite data allowed us to determine the characteristics of the distribution of large volumes of desalinated and polluted transient waters from the Dnipro-Bug estuary, which entered the north-western part of the Black Sea as a result of the destruction of the Kakhovka HPP dam in June 2023.

1.*Tuchkovenko, Y. S., Kushnir, D. V., Ovcharuk, V. A., Sokolov, A. V., & Komorin, V. N. (2023).* Characteristics of Black Sea dispersion of freshened and polluted transitional waters from the Dnipro-Bug estuary after destruction of the Kakhovka Reservoir dam. Ukrainian Hydrometeorological Journal, (32), 95-114. https://doi.org/10.31481/uhmj.32.2023.07