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Estimation of the extent of marine pollution as a consequence of the Kakhovka reservoir dam destruction based on simulation results

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ABSTRACT

Problems Statement and Purpose. In June 2023, as a result of the Kakhovka reservoir dam destruction, pollutants from the Dnipro River entered the Black Sea. This paper discusses the problem of determining the possible accumulation zones of these pollutants in the bottom sediments of the north-western Black Sea water area. The urgency of the problem is determined by the fact that these accumulation zones are potential long-term sources of secondary pollution of the marine environment. Preliminary identification of these zones is necessary for assessing damage done to the natural resources of the sea, as well as for the preparation of marine environment monitoring after the end of military operations. Numerical modelling is used to determine zones of marine pollution, since contact studies in the open sea and in the coastal areas are currently impossible. The hypothesis is accepted that the zones of pollutant accumulation in bottom sediments correspond to those sea areas where the concentration of conservative spill of neutral buoyancy was high in the bottom water layer.

Data and Methods. The numerical hydro- and thermodynamic model Delft3D Flow Flexible Mesh (D-Flow FM), developed by an independent institute for applied research Deltares (Delft, the Netherlands), was used to solve the above problem. The distribution of conservative spill of neutral buoyancy and mineral suspended matter coming with polluted transitional waters from the Dnipro-Bug estuary during June 2023 was modelled. Near the mouth of the Dnipro River an open lateral boundary was set in the model. Based on the data from the hydro-meteorological station "Port Kherson", boundary conditions in the form of water level time-series were imposed. During the simulation, the concentration of the conservative spill of neutral buoyancy was assumed to be equal to 1 conditional unit at the open boundary. The mineral suspended matter concentration was set equal to 100 conventional units. The gravitational settling velocity of suspended particles was assumed to be $5 \times \cdot 10^{-5}$ m s^{-1}. The variability of meteorological parameters (zonal and meridional components of wind speed, atmospheric pressure reduced to mean sea level, air temperature, relative air humidity, percentage of total cloudiness) was set at the upper boundary of the computational domain based on data from the forecast archive of the global weather model GFS (Global Forecast System).

Results and Discussion. The simulation results allowed us to estimate the spatial extent and relative level of pollution of the sea water in the north-western Black Sea area both in the surface and near the seabed. This estimation would not be possible using remote sensing methods only. Areas with possible significant level of sediment contamination and potential sources of secondary marine pollution (due to resuspension) were highlighted. It is recommended to conduct a verificatory monitoring of water and sediment contamination levels for these areas after the end of military operations.

Keywords*: dam destruction, the Kakhovka reservoir, the Dnipro River, the Dnipro-Bug estuary, the Black Sea, north-western part, pollution, primary and secondary, modelling.*

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Introduction

After the destruction of the Kakhovka reservoir dam on June 6, 2023, river water from the Dnipro River was flowing into the Black Sea for two weeks. The volume of river water that entered the sea as a result of this catastrophic event amounted to 16.4 km^3 [19], which corresponds to approximately 40% of the annual flow of the Dnipro River.

According to the observation data collected on hydrological post "Kherson", the water level in the lower reaches of the Dnipro River in the morning of June 8 had increased by 5.37 meters compared to the water level of June 5. As a consequence, more than 600 km^2 of land was flooded between June 6 and 9.

After dam destruction, the flood flow intensity was 24,500-29,000 m^3 s^{-1} [19]. Together with the flood flow, the sea received a large amount of different types of pollutants contained in the water and in sediments of the Kakhovka reservoir and which were washed away from the flooded areas of the Lower Dnipro.

Various aspects of the impact of artificial flooding resulted from the Kakhovka reservoir dam destruction on water quality of the north-western Black Sea were discussed in [1, 6, 8, 10, 19, 23].

Impact on biotic components of the marine ecosystems caused by the influx of large volumes of polluted and desalinated transitional waters from the

Dnipro-Bug estuary in June 2023 was discussed in [4, 14, 15].

Although two years have passed since the Kakhovka reservoir dam destruction in early June 2023, the consequences for the ecosystem of the north-western Black Sea (NWBS) shelf zone have not been fully explained yet. While an access to the shoreline during 2022-2024 was very limited, conducting field research outside the coastal zone was not possible at all due to outbreak of hostilities.

Therefore, only remote sensing data and results of numerical modelling can be used to form a single holistic picture of the Dnipro River polluted transitional waters spread across the sea and their impact on the water quality of open sea areas. Observation data collected in coastal areas is used to verify and understand this information.

The above-mentioned studies used observation data collected in shallow coastal areas, as well as satellite-derived data on the spatial and temporal variability of sea colour, chlorophyll *a* concentration, and total suspended solids concentration in the surface layer of the sea. The results of numerical modelling of pollutant spread in the north-western part of the Black Sea, shown in papers [8, 10], also refer to the surface layer of the sea. At the same time, the spread of pollutants in the deeper area of the north-western Black Sea will obviously have its own characteristics, different from those in the sea surface layer [7]. This article is devoted to this previously unconsidered part of the problem.

It was noticed in [1, 8, 10] that pollutants delivered with the extreme flood flow of the Dnipro River in June 2023 were partially accumulated in bottom sediments as a result of sorption, hydrolysis and gravitational settling processes, which caused transfer of pollutants from the water column to the bottom sediments.

It was found that the disappearance of a water reservoir will increase the intensity of natural floods in the Lower Dnipro areas [19]. During this period of year, the amount of pollutants in bottom sediments can be increased as a result of small particles of previously polluted sediments being washed away from the drained areas of the Kakhovka reservoir bottom.

As a result of resuspension processes, toxic contaminants accumulated in bottom sediments can re-infiltrate to water column during storms and, therefore, cause secondary pollution of sea water.

In the warm season, areas of accumulation of allochthonous detrital matter could contribute to algal bloom occurrences and to hypoxia and anoxia processes in the bottom layer.

The urgent problem is the determination of areas where the abovementioned processes can strongly happen and affect the quality of marine waters substantially. The only feasible solution to this problem for the time being lies in numerical modelling of the pollutant spread in the sea due to the extreme flood runoff of the Dnipro River. This will enable us to plan the perspective verificatory monitoring of marine environment aimed at assessing the damage done to marine natural resources and identifying measures for their restoration.

The purpose of the work is to estimate the spatial scale and pollution level of north-western part of the Black Sea (including the near-bottom layer) as well as to identify potential areas of secondary contamination of sea water due to Kakhovka reservoir dam destruction based on simulation results.

We hypothesize that zones of pollutant accumulation in bottom sediments correspond to those marine areas where concentration of pollutants in near-bottom layers of water was high after the Kakhovka Reservoir dam destruction.

Material and methods. Numerical modelling of sea water dynamics, spatio-temporal variability of water thermohaline structure and transport of tracers with different properties was used for this study.

A widely acclaimed hydrodynamic model Delft3D-Flow Flexible Mesh (D-Flow FM) developed by Deltares (Delft, the Netherlands) was applied [11]. The D-Flow FM model simulates one-dimensional (1D), two-dimensional (2DH, depth-averaged) or three-dimensional (3D) unsteady flow and transport phenomena resulting from tidal and meteorological forcing, including the effect of density differences due to a non-uniform temperature and salinity distribution (density-driven flow). A combination of 1D, 2D and 3D modelling (1D2D3D) can be applied [13]. D-Flow FM is flexible by using an unstructured grid in the horizontal plane. In the vertical direction D-Flow FM offers two different vertical grid systems: a so-called σ coordinate system (σ-model) introduced by [18] for ocean models and the Cartesian z-coordinate system (Z-model).

The model system of equations consists of the horizontal equations of motion, the continuity equation, the equation of state and the transport equation for conservative constituents. The flow is forced by currents and discharges at the open boundaries, wind stress at the free surface, pressure gradients due to free surface gradients (barotropic) or density gradients (baroclinic). Source and sinks or laterals are included in the equations to model the discharge and withdrawal of water and of constituents and substances [13]. A k-ε turbulence closure model to account for the vertical turbulent viscosity and diffusivity was used for 3D hydro- and thermodynamic modelling.

D-Flow FM solves the Navier Stokes equations for an incompressible fluid, under the shallow water and the Boussinesq assumptions. In the vertical momentum equation, the vertical accelerations are neglected, which leads to the hydrostatic pressure equation. The set of partial differential equations in combination with an appropriate set of initial and boundary conditions is solved on an unstructured finite volume grid.

The momentum equations in *x*- and *y*-direction are given by:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}-fv = -\frac{1}{\rho_0}\frac{\partial P}{\partial x}+F_x+\frac{\partial}{\partial z}\left(\nu_V\frac{\partial u}{\partial z}\right)+M_x, \quad (1)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+fu = -\frac{1}{\rho_0}\frac{\partial P}{\partial y}+F_y+\frac{\partial}{\partial z}\left(\nu_V\frac{\partial u}{\partial z}v\right)+M_y, \quad (2)$$

where u, v, and w are the fluid velocities in the *x*-, *y*-, and *z*-directions, respectively; t is the time; f is the Coriolis parameter, which depends on the geographic latitude ϕ and the angular speed of rotation of the earth Ω ($f = 2\Omega \sin \phi$); ρ_0 is the initial density of the water; $\partial P/\partial x$ and $\partial P/\partial y$ are the baroclinic pressure terms, which represent the pressure gradients; forces F_x and F_y represent the unbalance of horizontal Reynolds stresses; ν_V is the vertical eddy viscosity coefficient; M_x and M_y represent the contributions due to external sources or sinks of momentum (external forces by discharge or withdrawal of water, wave stresses, etc.).

The vertical velocity w in the adapting σ co-ordinate system is computed from the continuity equation:

$$\frac{\partial h}{\partial t}+\frac{\partial uh}{\partial x}+\frac{\partial vh}{\partial y}+\frac{\partial w}{\partial z}=h(q_{in}-q_{out}), \quad (3)$$

where q_{in} and q_{out} are the local sources and sinks of water per unit of volume (1 s^{-1}), respectively, and h is the total water depth ($h = d + \zeta$; with d the depth below some horizontal plane of reference (datum), positive upward; ζ the water level above some horizontal plane of reference (datum).

Under the shallow water assumption, the vertical momentum equation is reduced to a hydrostatic pressure equation. Vertical accelerations due to buoyancy effects and due to sudden variations in the bed topography are not taken into account.

$$\frac{\partial P}{\partial z}=-\rho g h, \quad (4)$$

where P is the hydrostatic pressure; ρ is the water density; $g \approx 9{,}81$ m s^{-2} is the acceleration due to gravity.

In case of a non-uniform density, the modelled water density is related to the values of water temperature and salinity by the equation of state.

The forces F_x and F_y in the horizontal momentum equations represent the unbalance of horizontal Reynolds stresses which are modelled using the eddy viscosity concept:

$$F_u=\nu_H\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right), \quad (5)$$

$$F_v=\nu_H\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right), \quad (6)$$

with ν_H the horizontal eddy viscosity coefficient.

The horizontal eddy viscosity coefficient is defined by:

$$\nu_H=\nu_{SGS}+\nu_V+\nu_H^{back}, \quad (7)$$

where ν_{SGS} is the sub-grid scale (SGS) horizontal eddy viscosity, that are not resolved by the horizontal grid ("sub-grid scale turbulence") and which is computed by a dedicated SGS-turbulence model; ν_H^{back} is the background horizontal viscosity, user-defined through the input file.

The vertical eddy viscosity coefficient is defined by:

$$\nu_V=\nu_{mol}+max\left(\nu_{3D},\ \nu_V^{back}\right), \quad (8)$$

where ν_{mol} is the kinematic viscosity of water; ν_{3D} is the 3D part computed by a 3D-turbulence closure model (k-ε turbulence model); ν_V^{back} is the background or "ambient" vertical turbulent mixing coefficient.

D-Flow FM solves the depth-averaged continuity equation, derived by integration the continuity equation for incompressible fluids over the total depth, taken into account the kinematic boundary conditions at water surface and bed level, and is given by:

$$\frac{\partial h}{\partial t}+\frac{\partial Uh}{\partial x}+\frac{\partial Vh}{\partial y}=Q, \quad (9)$$

with U and V the depth averaged velocities. Q is representing the contributions per unit area due to the discharge or withdrawal of water, precipitation and evaporation:

$$Q=\int_0^h(q_{in}-q_{out})\ dz+R-E, \quad (10)$$

with R the non-local source term of precipitation and E non-local sink term due to evaporation.

The transport equation here is formulated in a conservative form in Cartesian co-ordinates in horizontal and vertical directions:

$$\frac{\partial c}{\partial t}+\frac{\partial uc}{\partial x}+\frac{\partial vc}{\partial y}+\frac{\partial wc}{\partial z} = \frac{\partial}{\partial x}\left(D_h\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_h\frac{\partial c}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_v\frac{\partial c}{\partial z}\right)+s, \quad (11)$$

with c the mass concentration of the transported substance; D_h the horizontal diffusion coefficient; D_v the vertical diffusion coefficient and s the source and sink term per unit area due to the discharge (q_{in}) or withdrawal (q_{out}) of water and the exchange of heat through the free surface Q_{tot}:

$$s = h(q_{in}c_{in} - q_{out}c_{out}) + Q_{tot}. \quad (12)$$

The total horizontal diffusion coefficient D_h is defined by:

$$D_h = D_{SGS} + D_V + D_h^{back}, \quad (13)$$

with D_{SGS} the diffusion due to the sub-grid scale turbulence model, $D_h^{back}$the user defined background horizontal diffusion coefficient.

The vertical diffusion coefficient D_v is defined by:

$$D_V = \frac{\nu_{mol}}{\sigma_{mol}} + max\left(D_{3D},\ D_h^{back}\right), \quad (14)$$

with D_{3D} the diffusion due to turbulence model in vertical direction and ν_{mol} the kinematic viscosity of water and σ_{mol} is either the (molecular) Prandtl number for heat diffusion or the Schmidt number for diffusion of dissolved matter.

The boundary conditions for the momentum equations (1) and (2) at the bed ($z = z_b$) are:

$$\frac{\nu_V}{h}\frac{\partial u}{\partial \sigma}\bigg|_{\sigma=0} = \frac{1}{\rho_0}\tau_{bx}\ , \quad (15)$$

$$\frac{\nu_V}{h}\frac{\partial v}{\partial \sigma}\bigg|_{\sigma=0} = \frac{1}{\rho_0}\tau_{by}\ , \quad (16)$$

with τ_{bx} and τ_{by} the components of the bed stress in x- and y-direction, respectively.

The bed shear stress in 3D is related to the current just above the bed:

$$\vec{\tau}_b = \frac{g\ \rho_0\ \vec{u}_b\ |\vec{u}_b|}{c_{3D}^2}, \quad (17)$$

with $\vec{u}_b$ the flow velocity vector in the first layer just above the bed.

The 3D-Chezy coefficient c_{3D} can be expressed in the roughness height z_0 of the bed:

$$c_{3D} = \frac{\sqrt{g}}{\kappa} ln\left(1 + \frac{\Delta z_b}{2z_0}\right), \quad (18)$$

with $\kappa \approx 0.41$ the Von Karman constant, z_0 the roughness height andΔz_b the distance to the computational grid point closest to the bed.

At the free surface ($\sigma = 1$; $z = \zeta$) the boundary conditions for the momentum equations are:

$$\frac{\nu_H}{h}\frac{\partial u}{\partial \sigma}\bigg|_{\sigma=1} = \frac{1}{\rho_0}|\vec{\tau}_s|\ cos(\theta)\ , \quad (19)$$

$$\frac{\nu_H}{h}\frac{\partial v}{\partial \sigma}\bigg|_{\sigma=1} = \frac{1}{\rho_0}|\vec{\tau}_s|\ sin(\theta)\ , \quad (20)$$

where θ is the angle between the wind stress vector and the direction in the local coordinate system.

Without wind, the stress at the free surface is zero. The magnitude of the wind shear-stress is determined by the following widely used quadratic expression:

$$|\vec{\tau}_s| = \rho_a c_d U_{10}^2, \quad (21)$$

where ρ_a is the density of air, U_{10} is the wind speed 10 meters above the free surface (time and space dependent), c_d is the wind drag coefficient, dependent on U_{10}.

In order to specify the wind shear stress in the model, a drag coefficient is required as well as the wind field in terms of velocity magnitude and wind direction. The user can select how the wind drag coefficient should be computed, by choosing from the various types of wind drag formulation: constant, linearly varying, piecewise linearly varying [20], etc.

In D-Flow FM the heat exchange at the free surface is modeled by taking into account the separate effects of solar (short wave) and atmospheric (long wave) radiation, and heat loss due to back radiation, evaporation and convection. The heat losses due to evaporation and convection are functions of the wind speed.

The total heat flux through the free surface reads:

$$Q_{tot} = Q_{sn} + Q_{an} - Q_{br} - Q_{ev} - Q_{co} - Q_{ev\ free} - Q_{co\ free}, \quad (22)$$

where Q_{sn} is the net incident solar radiation (short wave), Q_{an} is the net incident atmospheric radiation (long wave), Q_{br} is the back radiation (long wave), Q_{ev} is the evaporative heat flux (latent heat), Q_{co} is the convective heat flux (sensible heat), $Q_{ev\ free}$ is the evaporative heat flux (free convection latent heat), $Q_{co\ free}$ is the convective heat flux (free convection sensible heat).

At "horizontal" closed boundaries zero-flux conditions are applied. At "horizontal" open boundaries the following boundary conditions are applied, with or without diffusion on the open boundary:

1) salt, temperature and tracers:
   - inflow: user-specified Dirichlet condition;
   - outflow: homogeneous Neumann condition;
2) suspended sediment.

The model was set up to simulate the Kakhovka reservoir dam destruction and a consequent spread of polluted transient water flowing from the Dnipro-Bug estuary into the north-western Black Sea (NWBS).

In previous years, a modernized forecasting complex for real-time prediction of oceanographic conditions in the Black Sea and Azov Sea basins was developed and validated [3, 5, 22]. A model applied in this study should became an integrated part of this complex, replacing a Delft3D-FLOW model [12] as a new hydro-thermodynamic block. This enables a forecasting complex to determine the characteristics and estimate the spatial and temporal scales of the transformed and polluted waters of the Dnipro River spread across the sea [6].

Simulation was performed on unstructured computational grid, which consisted of 22494 nodes and covers the whole Black Sea area (Figure 1). The grid has a variable resolution: from ≈ 500 m (near-shore) to 6500 m (offshore). In the vertical direction, the terrain-following σ-coordinate system with 7 non-uniform layers was applied. The bottom topography of the NWBS is shown in Figure 2.

A time period for the simulation was set to be

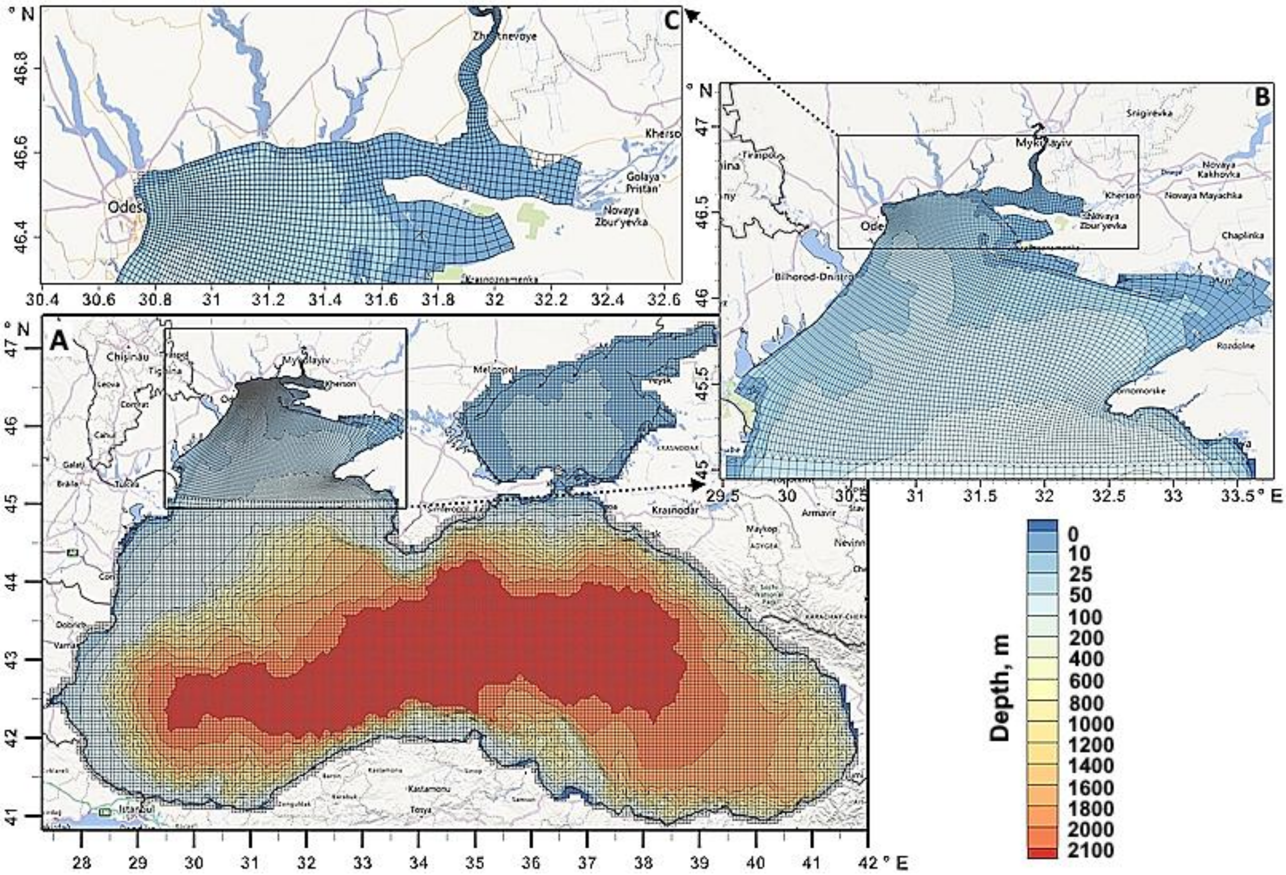

Fig. 1. Computational grid generated for the Black Sea model (A). Insets show parts of the grid in the northwestern area of the Black Sea (B) and in the Dnipro-Bug estuarine area (C)

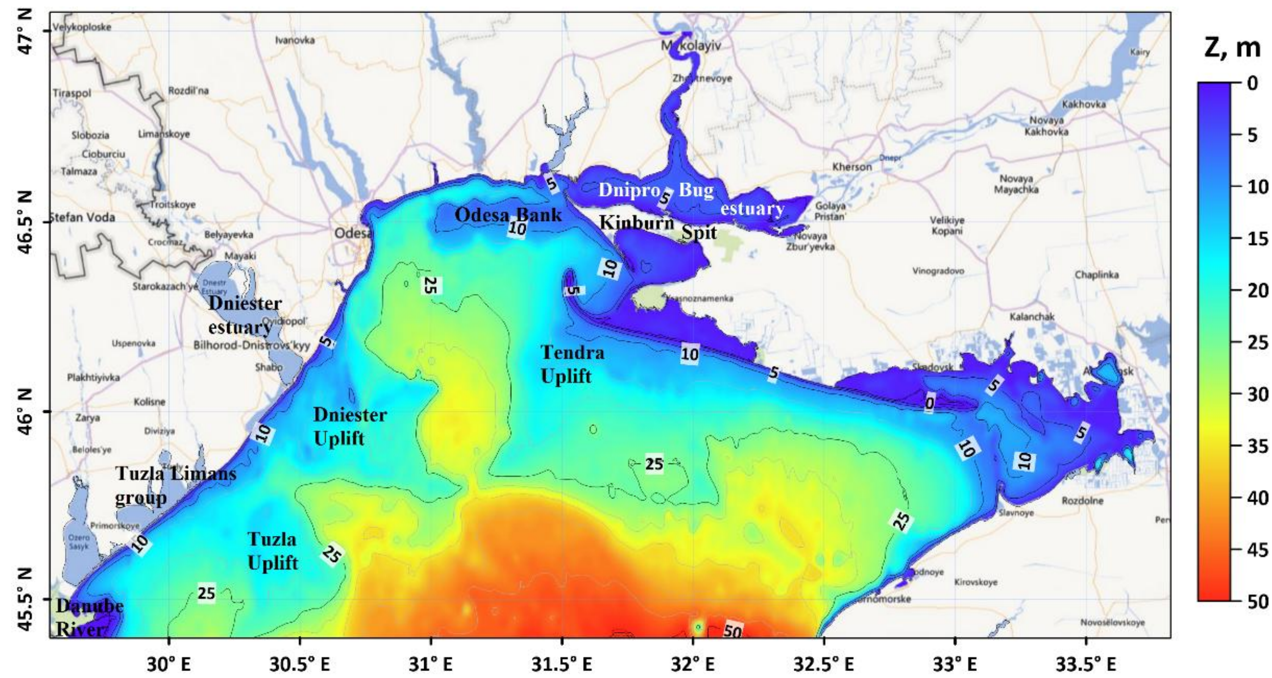

Fig. 2. Bottom topography of the north-western part of the Black Sea

from June 1 to June 30, 2023. A model time step was determined automatically based on the CFL stability criterion, within the range of time steps specified by user. The initial time step for the model was set to 1 second, and the maximum allowed time step was 30 seconds.

The model was forced by the meteorological data obtained from the NOMADS archive (National Operational Model Archive and Distribution System) of GFS Global Forecasting System for the Black Sea area [17, 21, 22].

The discharge of the Dnipro River was computed in the model from the "water level" type open boundary, imposed near the mouth of the Dnipro. The boundary conditions were set in the form of water level time-series based on observation data at the "Kherson" hydrological post (Figure 3).

Boundary conditions for water temperature were set on the basis of data obtained from the "Kyiv" hydrological station, a subdivision of Central Geophysical Observatory of Ukraine. Salt content in the riverine water was assumed to be constant (2 mg·dm^{-3}).

The freshwater discharge of the Dniester and Danube rivers, which flow into the north-western part of the Black Sea, was not taken into account in the model.

Spatially non-uniform initial fields of temperature, salinity and water level (at t = 0) were specified on the model computational grid. Historical data with a spatial resolution of 1/40°, obtained from Copernicus Monitoring Environment Marine Service (CMEMS) archive [9], was used for creating these initial conditions.

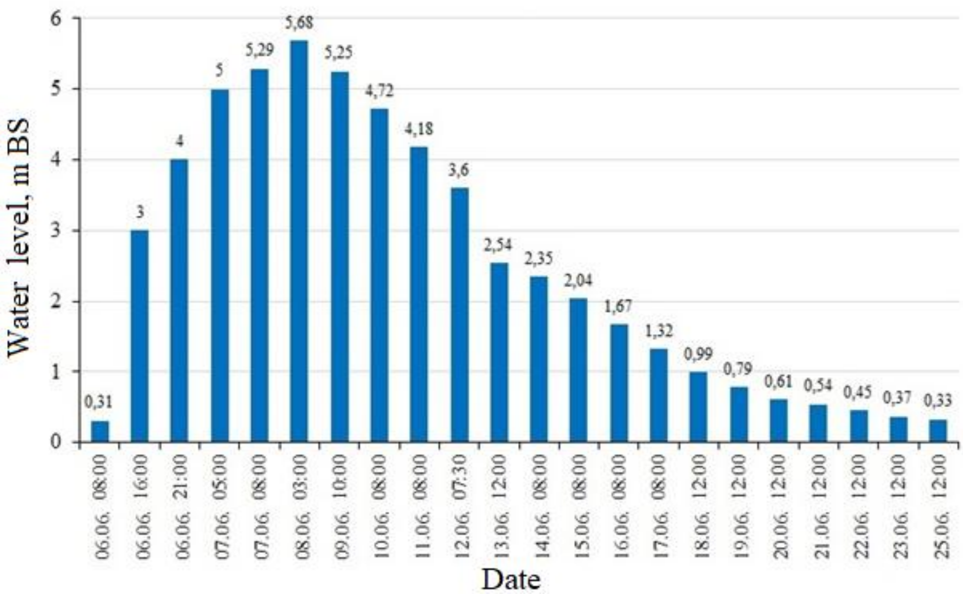

Fig. 3. Water level at the Kherson hydrological station

The model results were verified against the observational data for water salinity at the "Odesa-Port" hydro-meteorological monitoring station and satellite-derived data on sea surface colour variability and concentration of Chlorophyll *a* [6].

The spill of passive conservative contaminant with neutral buoyancy spreading across the water area of the NWBS was simulated. The concentration of contaminant was considered to be a pollution tracer which enters the sea with transitional waters from the Dnipro-Bug estuary.

Toxic pollutants dissolved in seawater, as well as mineral and organic compounds of biogenic elements can be considered as passive contaminants with neutral buoyancy at a first approximation.

In general, nutrients are not conservative, as they take part in chemical and biological processes that occur in the aquatic environment. However, taking into account large volumes of nutrient inflow into the sea with transformed transitional waters from the Dnipro-Bug estuary within a short period of time and the fact that both utilization of mineral forms of biogenic elements by phytoplankton and their regeneration due to mineralization of organic matter occur simultaneously, the concentration of the conditional contaminant can be considered as an integral indicator of the relative concentration of nutrients, at a first approximation.

The concentration of a conservative contaminant with neutral buoyancy in the Dnipro River water at the "Kherson" station was assumed to be equal to one conventional unit. Therefore, the simulation results show the concentration of conventional contaminant in the model grid cells in fractions of its concentration at the mouth of the Dnipro River, near the city of Kherson.

Additionally, the dynamics of the suspension concentration, which enters the sea with the transformed river waters from the Dnipro-Buh estuary was simulated. The concentration of mineral suspension in the waters of the Dnipro River at Kherson city was assumed to be 100 conventional units. The silt particles with a diameter of 0.01 mm and density of 2000 kg·m^{-3} were considered. The rate of gravitational sedimentation of the suspension, estimated using the well-known formula for the fall speed of a sedimenting single particle under gravitational force provided by Stokes' law, was taken as ≈ $5 \cdot 10^{-5}$ m s^{-1}.

Results and discussion. The concentration of the conventional contaminant at the surface layer and at the bottom is shown on Figs. 4 and 5, respectively. These figures demonstrate that the concentration of the conventional contaminant in seawater decreases gradually due to the action of hydrodynamic factors (basic dilution).

It can be seen from the figures that the flow of polluted transitional waters from the Dnipro-Bug estuary covers the entire water column (from surface to 15-20 m depth) not only the sub-surface layer

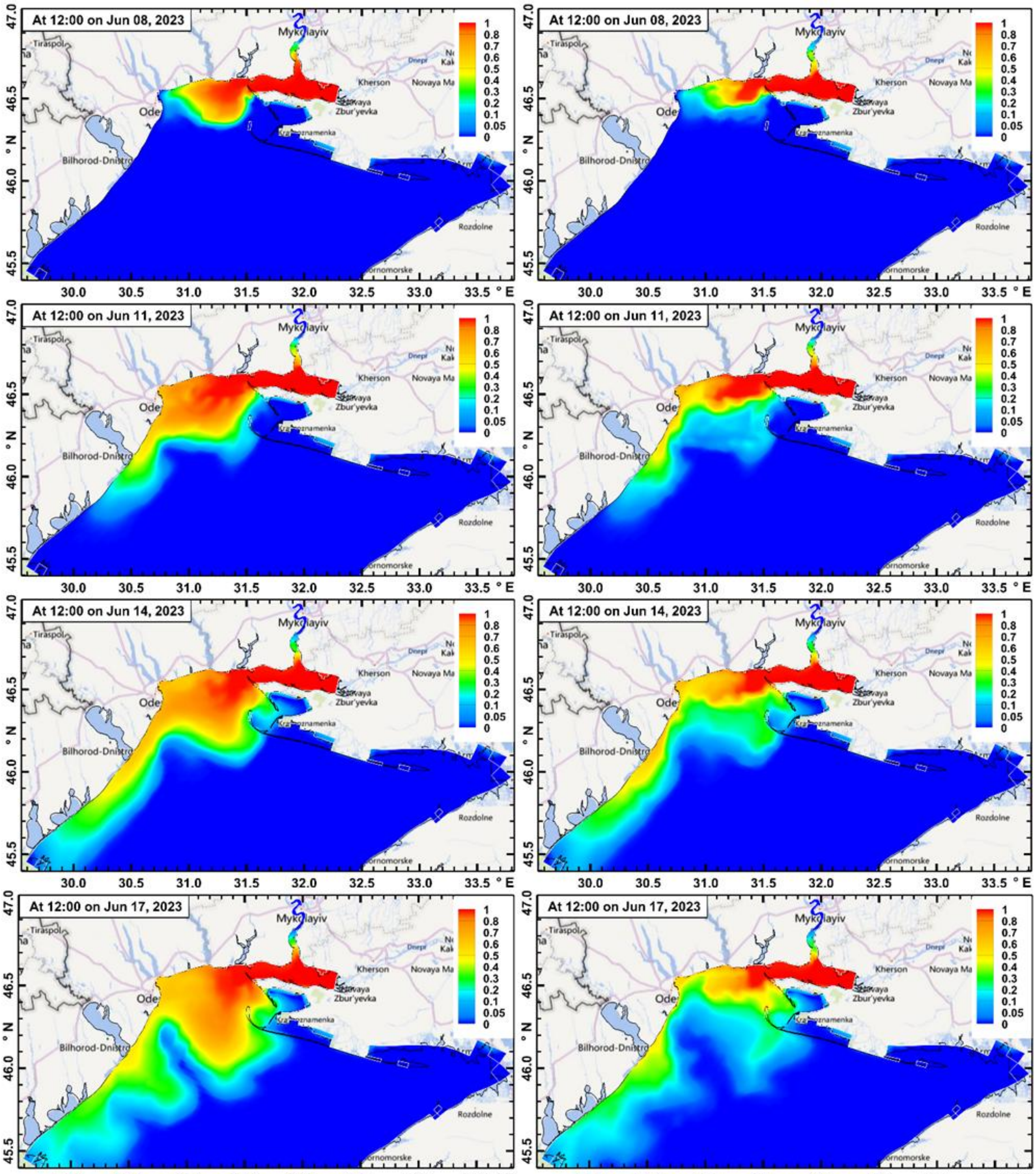

Fig. 4 Concentration of the conventional contaminant with neutral buoyancy (in conventional units; where 1 is the maximum concentration of polluted river waters) at the surface (left) and in the bottom layer (right) of the NWBS area, from June 08 to 17, 2023

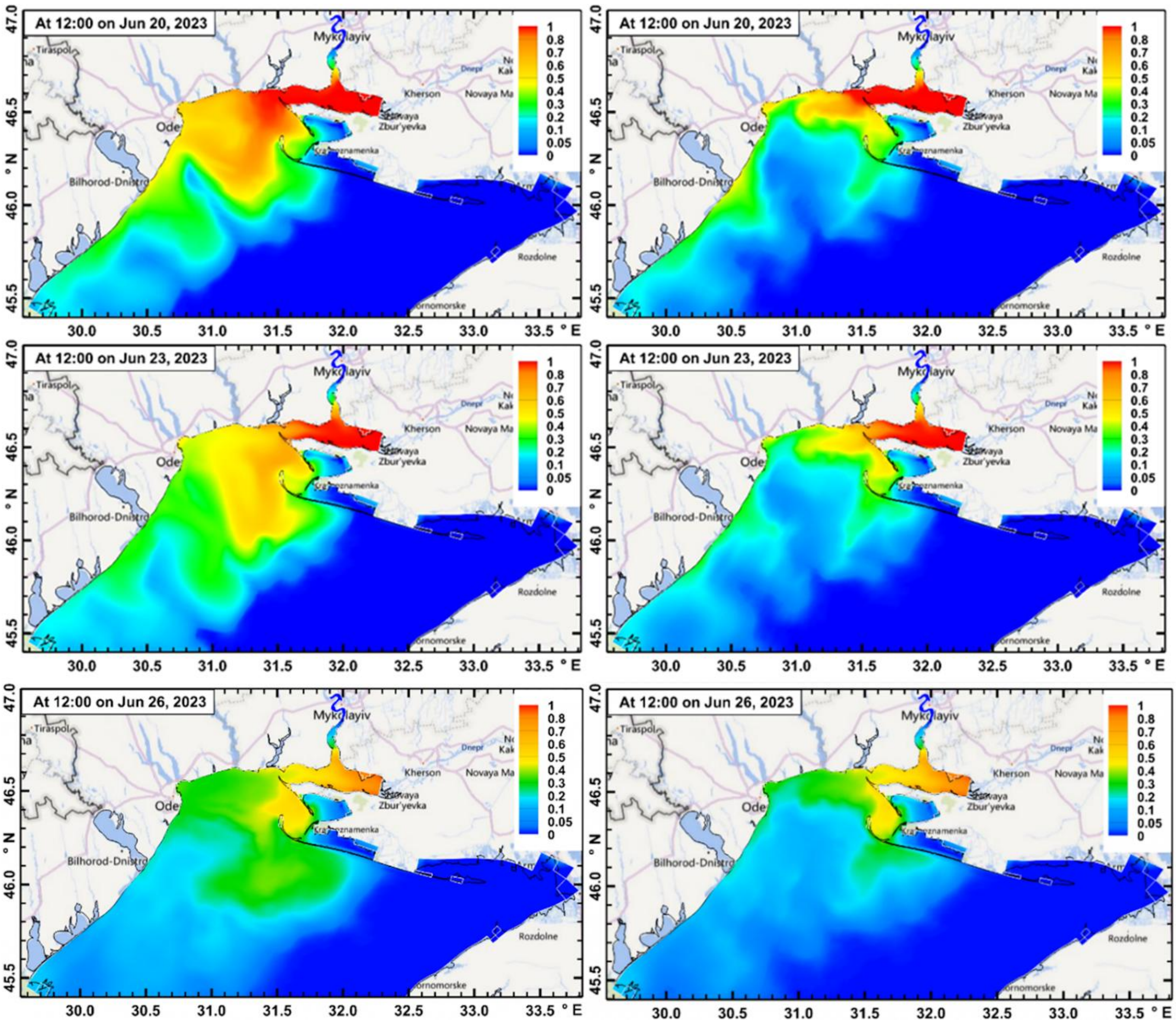

Fig. 5 Concentration of the conservative contaminant with neutral buoyancy (in conventional units; where 1 is the maximum concentration of polluted river waters) at the surface (left) and in the bottom layer (right) of the NWBS area, from June 17 to 23, 2023

(down to 5 m depth).

This was facilitated by the extra large volumes of transformed river water flown from the Dnipro River within a short period of time after dam failure. Intensive gradient currents and mixing caused by spatial velocity shifts of generated currents also contributed to this process [7].

Transformed river waters with high levels of pollutants were in contact not only with planktonic, but also with bottom sediments and benthic organisms in the water areas of the Dnipro-Bug area of the NWBS within the specified depths.

As a result, they could worsen the conditions of existence of benthic organisms, cause their suppression or death, as well as lead to accumulation of pollutants in bottom sediments due to adsorption and bioaccumulation.

The width of the plume of polluted waters and, accordingly, its area, as one could expect, is smaller in the bottom layer than at the surface. The plume of polluted waters is washed out in the near-bottom layer much more intensively than at the surface layer as well.

Analysis of modelling results indicate that the highest level of sea water pollution took place at the mouth of the Dnipro-Buh estuary and above the Odesa Bank. For example, on 11 June 2023 the concentration of conventional contaminant in these areas varied from 0.7 to 1.0 conventional unit, i.e. was equal to 70-100 % of its initial value at the mouth of the Dnipro River. A clearly visible accelerated transport of contaminant flowing along the shallow waters of the northern coast of the NWBS towards the city of Odesa is highlighted. As a result of accelerated flow of contaminant towards the Odesa Bay, a zone with increased (relative to the surrounding waters) pollution level was formed and remained there for quite a long time.

In the period from 10 to 14 June 2023, the plume with increased concentration (0.2-0.6 conventional unit) of conventional contaminant can be traced along the western coast of the NWBS area: from Odesa city to the coastal sea zone adjacent to the spit of the Tuzla Limans group (near Lebedivka village). Later on, this plume narrows to the width of the longshore current flow at the coastal area near the city of Chernomorsk (17 June 2023, Figure 4). On 17-19 June, a longshore plume with concentrations of 0.1-0.2 conventional unit reaches the Danube River mouth sector. At the same time, a broad local zone of high concentration of contaminant is formed on the Dniester site of seabed rise, which can be traced until 20 June 2023 (Figure 5).

Starting from 17 June, another plume of increased concentrations of conservative contaminant (0.2-0.6 conventional unit) was formed primarily in the sea surface layer. This plume can be observed to the south of the Odesa Bank and Kinburn Strait, along with the Tendra Uplift of bottom.

As of 26 June 2023, plumes of contaminated water at the Dniester and Tuzlivskyi sectors of seabed rise had been completely washed out. The plume located at the Tendra sector of seabed rise was still remaining, and the concentration of conditional contaminant was in range of 0.2-0.3 unit fractions there (Figure 5).

The above-described characteristics of the plume of contaminated water flowing from the Dnipro-Buh estuary were determined by water dynamics at the NWBS area, which is described in detail in the paper [7].

The obtained results of modelling the transport of contaminant with neutral buoyancy are consistent with satellite information on the colour of the sea surface, shown in Figure 6, and with those cited in [2].

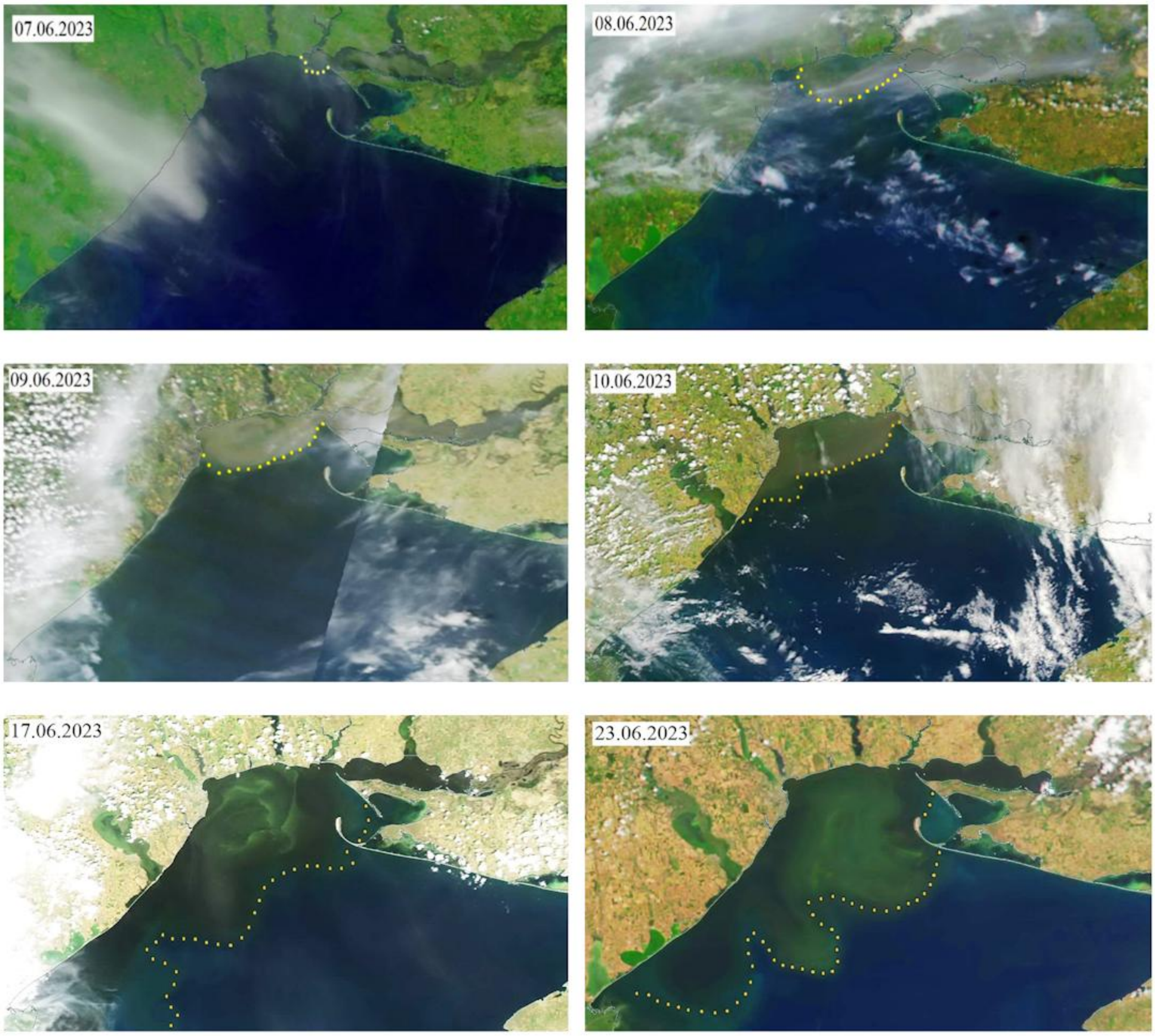

Fig. 6 Corrected colour satellite images of sea surface in the NWBS for some days in June 2023, which visualize the spread of polluted muddy waters from the Dnipro-Bug estuary. The images are constructed from multi-channel imagery by MODIS radiometer from Aqua, Terra satellites, VIIRS radiometer from Suomi NPP and NOAA-20 satellites [16]

In addition to the passive contaminant with neutral buoyancy, modelling of the dynamics of the concentration of suspended solids, which entered the sea together with transformed river waters from the Dnipro-Bug estuary, was performed.

Particles of mineral and organic sediment were stirred up from the bottom of the Kakhovka water reservoir and the Dnipro River bed by the flooding flow, which was formed after the Kakhovka dam destruction. Soils with a high humus content, industrial and household wastes, fragments of dead flora and fauna of the Dnipro River delta were washed into the lower reaches of the Dnipro and further into the sea. It should be noted that heavy metal compounds, including those that came with discharges from industrial enterprises of Zaporizhzhya and Dnipro cities, have been accumulated in the bottom sediments of the Kakhovka water reservoir for decades. Additionally, these compounds could have been adsorbed on the surface of suspended sediment particles transported with the flow of polluted river water along with hazardous chemicals of toxic action washed off from flooded areas.

The flow of muddy water with high concentration of silt particles and other suspended matter is well traced on satellite images of sea surface color on 8-10 June 2023 (Figure 6). Further, as the carrying capacity of the flow decreased, particles of organic and mineral suspended matter were deposited and accumulated in bottom sediments, together with toxic pollutants adsorbed by them, in particular, heavy metals. Because of this, in case of storm winds, bottom sediments may become a source of secondary pollution of marine waters as a result of their wind-wave resuspension.

The main objective of modelling the dynamics of mineral suspension concentration in the NWBS water area was to identify the sites with the most contaminated bottom sediment. The hypothesis was that such sites correspond to areas where the high

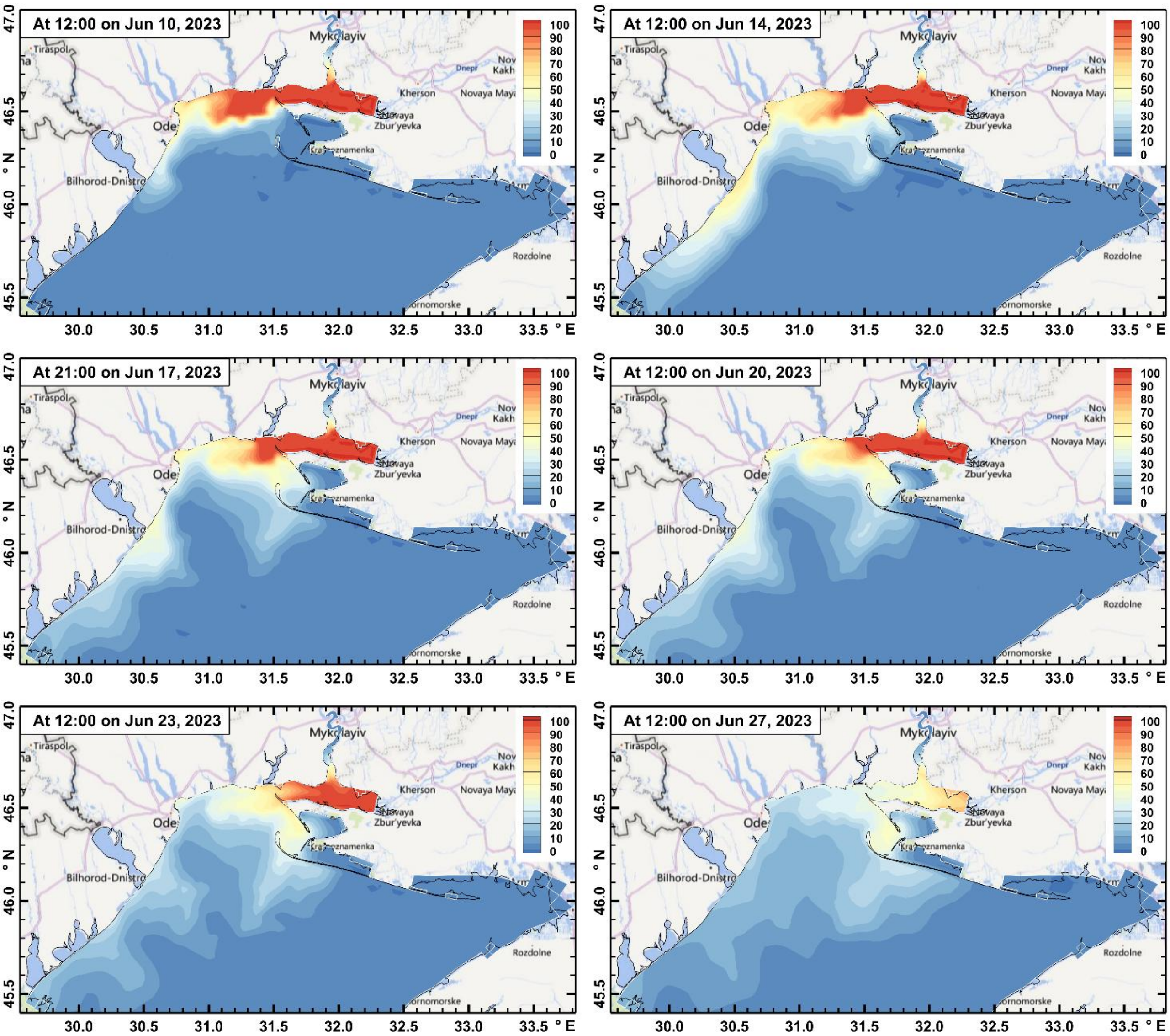

Fig. 7. Changes in the concentration of mineral suspended matter (as a percentage of its concentration at the outlet of the Dnipro River mouth in the Kherson area) in the bottom waters of the NWBS in June 2023 after the Kakhovka dam destruction

concentration of suspended solids in the bottom layer remains high for a long time.

Modelled spatial distribution of inorganic suspended matter concentration in the bottom layer of the NWBS water area is shown in Figure 7. The study of its dynamics allowed us to draw conclusions that a high level of bottom sediment pollution should be expected along the northern coast of the NWBS, on the Odesa Bank, in the Odesa Bay, along the western coast of the Odesa area of the NWBS, and in the area of the Dniester Uplift of bottom.

These conclusions are supported by data on heavy metals and petroleum products content in the bottom sediments of the coastal zone of the Odesa area in summer-autumn 2023, summarized in [19].

Conclusion. Spatial scales and relative level of sea pollution in the north-western part of the Black Sea as a result of volley inflow of large volumes of polluted transitional waters from the Dnipro-Bug estuary due to the Kakhovka dam destruction were determined. This study was performed on the basis of the analysis of mathematical modelling results, using numerical hydrodynamic model D-Flow FM.

The distribution of polluted waters was considered not only in the surface layer of the sea, which can be done on the basis of satellite information, but also in the bottom layer of the water area of NWBS.

Spreading of conservative contaminant with neutral buoyancy across the NWBS water area was simulated. It is shown that in the first week after the dam destruction the water pollution level in the Odesa area of the NWBS went down to 70% of the pollution level at the mouth of the Dnipro River near the city of Kherson. In the water area of the Danube-Dniester interfluve the water pollution reduced to a level of 20-50% of the water pollution in the mouth of the Dnipro River. These reductions of marine water pollution level were merely caused by the hydrodynamic dilution. A plume of polluted water with concentrations of the conditional contaminant 10-20% was spreading along the western coast of the NWBS and eventually reached the mouth of the Danube River.

A zone with increased (relative to the surrounding waters) pollution level is formed in the Odesa Bay and remains there for quite a long time. This ascertains the fact that the accelerated transport of contaminant along the shallow northern coast towards the city of Odesa is developed.

The results of the modelling of spatio-temporal variability of the concentration of a conservative contaminant with neutral buoyancy in the surface layer agree well with satellite images of the color of the sea surface.

The flow of contaminated water covered the entire water column from surface to bottom in the sea areas with depths down to 15 meters, which could lead to contamination of bottom sediments due to adsorption, bioaccumulation and sedimentation.

The results of modelling the dynamics of concentration of conditional contaminant with neutral buoyancy and suspended sediment in bottom layer waters allow us to make the following conclusion: higher pollution levels of sea-floor sediments should be expected along the northern and western coasts of NWBS, at the Odesa Bank, in the Odesa Bay and near the Dniester site of seabed rise. It is recommended to carry out a verificatory monitoring of water and bottom sediments contamination with toxic substances in the mentioned sea zones, especially after strong storms.

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Оцінка масштабів забруднення моря внаслідок руйнування дамби Каховського водосховища на основі результатів моделювання

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Обговорюється проблема визначення можливих зон акумуляції в донних відкладах північно-західної частини Чорного моря забруднюючих речовин, що надійшли до моря в червні 2023 року з водами річки Дніпро внаслідок руйнування греблі Каховського водосховища. Актуальність проблеми визначається тим, що ці зони є потенційними довготривалими джерелами вторинного забруднення морського середовища. Їхня попередня ідентифікація необхідна для планування моніторингу якості морського середовища після завершення воєнних дій з метою оцінювання шкоди, завданої природним ресурсам моря, та врахування під час обґрунтування шляхів для досягнення доброго екологічного стану морських акваторій. Оскільки через військові дії, що тривають, проведення контактних досліджень у відкритому морі та на деяких ділянках прибережної зони неможливе, то для визначення цих зон використовуються результати чисельного математичного моделювання. Приймається гіпотеза, що зони акумуляції забруднювальних речовин в донних відкладах відповідають тим областям акваторії моря, де їхня концентрація в водах придонного шару була високою. Для вирішення вищезазначеної задачі використовувалась гідротермодинамічна модель Delft3D-Flow Flexible Mesh (Deltares). Моделювалося поширення умовної домішки нейтральної плавучості та завісі, що надходила із забрудненими перехідними водами з Дніпровсько-Бузького лиману протягом червня 2023 року. Стік Дніпра задавався на основі спостережених у порту Херсон змін відміток рівня води. При моделюванні умовна концентрація домішки нейтральної плавучості у гирлі річки Дніпро (Херсон) приймалася рівною 1 умовній одиниці, а завісі – 100. Гравітаційна швидкість осадження частинок завісі приймалася рівною 5×10^{-5} м $с^{-1}$. Мінливість метеорологічних умов на верхній (з атмосферою) границі розрахункової області задавалася на основі даних, зчитаних з архіву прогнозів глобальної моделі прогнозу погоди GFS. Результати дослідження дали змогу оцінити просторові масштаби та відносний рівень забруднення морських вод не тільки в поверхневому шарі моря, що можна зробити на основі супутникової інформації, а й у придонному шарі акваторії північно-західної частини Чорного моря. Це дало змогу виділити зони, де забруднення донних відкладів може бути значним, і вони можуть бути потенційним джерелом вторинного забруднення морського середовища в майбутньому внаслідок ресуспендування. У таких зонах рекомендовано провести контрольний моніторинг забруднення вод і донних відкладів після завершення військових дій.

Ключові слова*: руйнування греблі, Каховське водосховище, річка Дніпро, Дніпровсько-Бузький лиман, Чорне море, північно-західна частина, забруднення, первинне і вторинне, моделювання.*

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