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Key aspects of seawater intrusion in the Dniester River during storm surges

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ABSTRACT

Introduction. This article explores the potential for saline water from the Dniester Estuary to travel upstream into the mouth of the Dniester River, a critical area where the "Dniester" station supplies potable water to Odesa City and where the intake point of the Lower Dniester Irrigation System is located. The study is urgent due to the risk that saline water poses to the quality of drinking and irrigation water at these intake points. The primary objective of this research was to utilize hydrodynamic modeling to determine the specific hydro-meteorological conditions under which saline, transformed sea water from the estuary could penetrate the mouth of the Dniester River.

Material and methods. To address this task, a simplified version (without considering the thermal factor) of the numerical 3-D non-stationary hydrodynamic model MECCA (Model for Estuarine and Coastal Circulation Assessment), supplemented with a block for the transport of a conservative tracer, was used. The input data for the model included observations of wind condition variability and corresponding sea level fluctuations at the marine boundary of the Dniester Estuary, as well as observations of water level fluctuations in the mouth section of the Dniester River.

Results and Discussion. The findings of the study identified two key conditions necessary for such an event: (1) a significant reduction in the average daily river discharge to below 100 m³/sec, and (2) the occurrence of a strong surge wind from the south or southeast at speeds exceeding 15 m/sec, sustained for several consecutive days. Under these conditions, transformed sea water from the estuary can travel upstream through the right arm of the river, the Glybokyi Turunchuk. From there, it reaches the point where the Dniester River divides into two arms. The saline water is then drawn into the left arm, the Dniester, and eventually returns to the estuary. This process represents a significant threat to the region's freshwater resources, especially during periods of low river discharge and adverse wind conditions. The penetration of brackish estuarine waters into the Dniester River's mouth branches, namely the Dniester and Hlybokyi Turunchuk branches, occurs over some time of 12 to 24 hours. It has been concluded that due to the presence of two mouth branches through which the Dniester River flows into the Dniester Estuary, considering their location in the northeastern part of the estuary and the characteristics of water level rises in the estuary during wind surges, the penetration of estuarine waters with increased salinity (up to 7 ‰) into the main channel of the Dniester River (above the point where the river splits into two mouth branches) is unlikely, even when river discharge falls below 100 m³/s.

Conclusion. The case study presented in the article can serve as a valuable reference for experts tasked with designing hydro-engineering solutions. One proposed solution is the construction of a second estuarine canal (branch) to prevent the intrusion of transformed sea water into the river mouth, thereby safeguarding the quality of drinking and irrigation water in the region.

***Keywords**: Dniester Estuary, Dniester River mouth, transformed sea water penetration, up and down surge.*

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Introduction. An important problem faced by the population in the estuarine areas of many rivers is the deep penetration of saline seawater into the river mouths, which poses a risk to the stable fresh water supply for drinking, communal, and agricultural purposes.

The distance over which the transformed seawater penetrates the estuarine part of rivers is determined by two conditions: a decrease in the flow of water in the estuarine part of the river for one reason or another, and a rise in the sea level, which occurs on different time scales. In the works [15, 30, 31] using hydrodynamic models, changes in the intrusion of salty seawater into river estuaries in seasons with minimal river runoff were determined, caused by a long-term trend of increasing the average annual sea level due to climate change.

The impact of storm surges on the intrusion of salt water into the mouth of the river was studied in the work [21, 32]. Although storm surges occur at short intervals of a few days, combined with the rise in mean sea level caused by climate change, they can significantly increase the overall risk of saltwater intrusion into the estuary.

In addition to the peculiarities of the nature of sea level changes on different spatio-temporal scales and the temporal variability of the river flow, the penetration of salty seawater into the estuarine part of the river is influenced by other factors, such as the morphological structure of the river mouth and estuary (the number of estuarine branches, channels; the shape and size of the estuary, strait), anthropogenic regulation of the river flow, changes in the relief of the bottom due to natural processes and engineering measures [16, 17, 21, 22, 31, 32].

Therefore, the features of saltwater intrusion into the mouth of the river have a very individual character and should be studied separately. Accordingly, effective measures to prevent significant intrusion of saltwater into river estuaries or to mitigate their consequences will be different. It can be artificially regulating river runoff, building dams of various designs, reservoirs, and underground drainage networks [16, 23, 26, 32].

Four big European rivers flow into the north-western Black Sea: Danube, Dniester, Dnipro, and Pivdennyi Bug. The waters of the three last-mentioned rivers enter the sea through the Dniester Estuary and the Dnipro-Bug Estuary which are formed in their mouth areas. The conditions under which saline water penetrates the estuarine arms of the Danube have been considered in the work [4]; and in the Dnipro-Bug Estuary in the works [14, 25].

The Dniester Estuary is an expanded Dniester River valley stretching from the north-west to the south-east. The estuary is 44 km long, its maximum width is 12 km, average depth – 1.5-2.0 m, maximal depth – 2.6 m. The estuary is connected to the sea through the Dniester-Tsaregradske Mouth, about 300 m wide and 16 m deep. The estuarine mouth is connected to Bilgorod-Dnistrovskyi Port with a 14.5 km navigable canal. The estuary and the sea are divided by a 60 to 500 m wide and 11 km long sand and shell spit [9].

Black Sea tides are very low and are therefore categorized as non-tidal. The wind-induced up and down surges play a dominant role in the formation of the level fluctuations in the coastal zones on the time scales of a natural synoptic period [12]. The wind regime and the Dniester River discharge volume determine the water exchange between the Dniester Estuary and the adjacent north-western Black Sea.

The Dniester River is the main source of drinking water for Moldova and South-Western Ukraine [3]. The lower part of the catchment basin located in the arid zone is especially dependent on the water level in the river. The Lower Dniester is a part of the river from Dubăsari (Moldova) down to the mouth (342 km). The lower part of the Dniester can be considered a transit one as the tributaries entering this river segment produce no significant influence on its water content. Most of those tributaries are drying up in the 21st century due to climate change [29]. The Dniester divides into two arms, the Dniester and the Shvydkyi Turunchuk, near the Moldavian village Cioburciu (140 km from the mouth), which converge near the Bile Lake (22 km far from the mouth). There is a Ukrainian water gauging station Nezavertaylivka on the Shvydkyi Turunchuk Arm and a Moldavian water gauging station Olanesti on the Dniester Arm. Downstream from the Bile Lake begins the Dniester Delta, which is entering the northeastern part of the Dniester Estuary. Three kilometers downstream from the village Maiaky the Dniester divides again into two estuarine arms (Fig.1a). The right arm called the Glybokyi Turunchuk is a man-made canal, which is ca. 100 m long and ca. 8-10 m deep; the other arm retains the name of the main river – the Dniester.

The “Dniester” Station (the intake structures abstracting water from the river to supply potable water to Odesa) is located five-six km upstream of Maiaky village near the town Biliaivka. Another intake is situated in Maiaky – this one is supplying water to the Lower Dniester Irrigation System watering the area of 20.0 thousand hectares [8].

The salinity regime of the Dniester Estuary is formed under the influence of freshwater discharge of the Dniester River and seawater inflow through the Tsaregradske Mouth. Sea water inflow gets more intensive during up and down surges caused by storm winds. In connection with the above the following question becomes topical: is it possible, and under which circumstances, that the water with increased mineralization will rise from the Dniester Estuary high upstream and reach the water intake structures, which could deteriorate the tap water quality in Odesa and restrict water abstraction for irrigation?

Earlier this matter was considered in the papers [2, 5, 9] in the context of peculiarities of the wind-driven rises and drops of water level in the Dniester mouth area. In particular, it was pointed out that intensive variations of water level with big amplitude take place in the mouth area on condition of river discharge decreases down to 100-130 m3/sec and stormy winds develop over the north-western Black Sea and the Dniester Estuary in the directions that are effective to cause strong up or down surge of waters in the estuary [2]. At that, with the increase of the Dniester discharge, the surges become less intensive. The paper [2], concerning P.Z. Ryabkov (1896), A.M. Befani (1998), V.M. Gontarenko

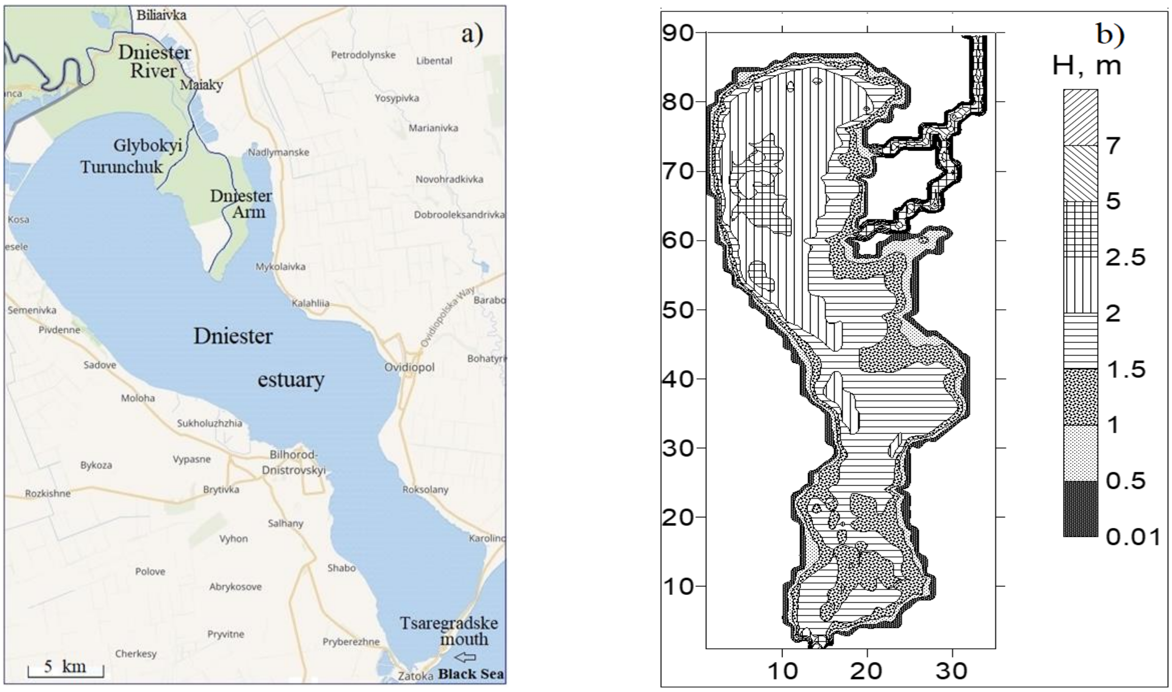

Fig. 1. Schematic map of the Dniester River mouth area and Dniester Estuary (a). Horizontal calculation grid and bathymetrical map of the Dniester Estuary with the adjacent Dniester River mouth area (the numbers of the calculation grid nodes with the horizontal step of 500 m are specified on the coordinate axes) (b)

(1992, 1993) mentions the possibility of the transformed sea water reaching the river intake structures (‘Odesa Drinking Water Station’). However, it is our opinion that this is mostly an assumption based on the observations of water level in the river mouth in 1985 and 1986 (before the Dniester Reservoir was built) rather than on direct measurements of water mineralization. At the same time there is a conclusion in [13] that though the wind-driven water level fluctuations can be registered even near Olanesti (84 km from the mouth), saline water is not entering the river mouth. Water mineralization in the lowest segment of the river mouth near Maiaky is the same as in the upstream area (village Olanesti – town Bender).

The purpose of the work is to establish, using hydrodynamic modelling, the hydro-meteorological conditions under which the transformed sea water from the Dniester Estuary could enter the mouth part of the Dniester River and impact the quality of water used for drinking and irrigation.

Material and methods. The probability of transformed sea water backflow penetration into the Dniester arms depends significantly on the dryness of a year. With river flow increase, the probability of saline water tongue penetration from the estuary into the river mouth area becomes lower. In connection with the above, it is important to establish the real level possible of decrease in the Lower Dniester water discharge resulting from the joint impact of climatic change [6, 7] and water management activities.

Due to the increase in air temperatures against the background of almost constant precipitation, climate changes negatively affect the water content of the Middle and Lower Dniester tributaries. According to estimates [10], for the RCP4.5 scenario, the water resources of Nizhny Dniester should decrease by 30% by 2050 compared to the period before the onset of climate change (the 90s of the XX century), and under the RCP8.5 scenario - by 60%.

Seasonal runoff regulation is carried out by the Upper Dniester (Dniester) reservoir for hydropower purposes, located at a distance of 677.7 km from the mouth, after the way out of the main river from the Ukrainian Carpathians.The reservoirs are operated by the "Operation Rules", which should regulate water releases including the minimum guaranteed flow required for fish spawning and the Dniester reed-beds functioning. These rules state that the minimum average daily water discharge in all seasons should be not less than 100 m^3/sec. The work [11] gives the minimum average monthly and daily flow values in front of the city Bender under natural conditions (Table 1). It can be seen from the Table that water discharges in the volume of 100 m^3/sec should ensure a better mode of the minimum river flow formation than it was under natural conditions.

The average daily discharge of 100 m^3/sec, guaranteed through water discharges of the Upper Dniester hydropower plant, maintains the water content of the river during the low-water season. However, in arid years a contradiction may arise between meeting the operational conditions of the

Table 1

Minimal, monthly average and daily discharge (m^3/sec) in front of city Bender (Lower Dniester) under the natural conditions

Period	Summer			Winter		
Probability of exceeding a given value, %	75.0	95.0	99.0	75.0	95.0	99.0
Average monthly water discharge, m^3/sec	116.0	89.5	82.5	117.0	87.5	65.0
Average daily water discharge, m^3/sec	91.5	78.0	62.5	61.0	47.0	30.0

reservoir (water reserves in it) and the guaranteed water releases to meet the needs of the Lower Dniester. To determine the possibility of such situation occurrence, the data of the average monthly and daily Dniester flow observations at Olanesti village (1959-2016) and the Shvydkyi Turunchuk flow observations at Nezavertailivka village (1971-2017) were considered. Both gauging stations are located upstream of the Biliaivka water intake.

Analysis of the results shows that the minimum values of the average monthly flow at those gauging stations are observed in January and July. The average long-term runoff for January at the Olaneshti measuring station is 93.3 m^3/sec. This parameter is almost the same for the periods before and after the construction of the Upper Dniester hydropower station. The minimum average daily value for the entire observation period was 14.0 m^3/sec; it was observed in 1962 (04.01.1962) before the Upper Dniester hydropower station was built.

After 1987, the long-term average value of the minimum daily winter runoff was 59.2 m^3/sec; the lowest value was 35 m^3/sec (1991). The lowest daily flow rates in the Shvydkyi Turunchuk Branch measured at Nezavertailivka were registered in the 1970s and made ca. 43-45 m^3/sec. At the beginning of the 21st century, the average daily flow at the Nezavertailivka gauging station was about 79 m^3/sec throughout the year. Thus, it was established that according to the data on total discharge of the Dniester Branch (Olaneshti gaging station) and the Shvydkyi Turunchuk Branch (Nezavertailivka gauging station), the minimum flow rate of the water coming from the main channel to the point where it divides into the Glybokyi Turunchuk and Dniester arms can be assumed as ca. 50 m^3/sec - 120 m^3/sec.

To solve the task mentioned in the objective of the article, a simplified variant (disregarding thermal factor) of the numerical non-stationary 3-D hydrodynamic MECCA model (Model for Estuarine and Coastal Circulation Assessment) [18-20] was applied. This model allows calculating water dynamics and distribution of an admixture in marine basins that have areas with smaller (sub-grid) sizes than the step of the computational grid in one of the horizontal directions (for example a connecting channel). The initial set of equations of the model is defined as follows.

The equations of motion in Boussinesq approximation in Cartesian coordinates:

$$\partial_t u + B_x^{-1}\partial_x(B_x uu) + \partial_y(uv) + \partial_z(uw) = -\alpha_0\partial_x P + fv + B_x^{-1}\partial_x(2B_x A_h \partial_x u) + \\ +(1-\beta_c)\partial_y[A_h(\partial_x v + \partial_y u)] + \partial_z(A_v\partial_z u) - \beta_c C_{ws} B_x^{-1} u|u|, \quad (1)$$

$$\partial_t v + \partial_x(vu) + B_y^{-1}\partial_y(B_y vv) + \partial_z(vw) = -\alpha_0\partial_y P - fu + B_y^{-1}\partial_y(2B_y A_h \partial_y v) + \\ +(1-\beta_c)\partial_x[A_h(\partial_y u + \partial_x v)] + \partial_z(A_v\partial_z v) - \beta_c C_{ws} B_y^{-1} v|v|. \quad (2)$$

The continuity equation:

$$B_x^{-1}\partial_x(B_x v) + B_y^{-1}\partial_y(B_y v) + \partial_z(w) = 0. \quad (3)$$

The equation of salt conservation:

$$\partial_t S + B_x^{-1}\partial_x(B_x uS - B_x D_h \partial_x S) + B_y^{-1}\partial_y(B_y vS - B_y D_h \partial_y S) + \partial_z(wS - D_v\partial_z S) = 0. \quad (4)$$

The hydrostatic equation:

$$\partial_z P = -\rho g. \quad (5)$$

The equation of state:

$$\rho = \rho_0[1 + F_\rho(S)]. \quad (6)$$

Here u, v, and w are the components of the current velocity vector $\vec{v}$ in directions x, y, *and* z, respectively; t is the time; f is the Coriolis acceleration; P is the pressure; g is the gravitational acceleration; ρ is the water density; $\alpha_0 = 1/\rho_0$ is the reference specific volume of water; S is the water salinity; A_h and A_v are the horizontal and vertical momentum diffusivity, respectively; D_h and D_v are the coefficients of horizontal and vertical mass diffusivity; B_x and B_y are the dimensionless (relative to the sizes of a cell of the computational grid) widths of flow in the x and y directions, respectively. The ∂_x, ∂_y, ∂_z, and ∂_t, represent the corresponding partial derivatives (e.g. $\partial F/\partial t = \partial_t F$).

The set of modelling equations written above takes into account the presence of a channel with a sub-grid scale in one of the horizontal directions and was obtained from the original set of equations formulated in standard form for the 3D hydrodynamical model [18]. The original initial set of equations of hydrodynamics was integrated in the direction normal to the flow in the horizontal plane. The resulting set of equations was compared with the initial one and a new set of equations was defined. The new set of equations corresponded to the initial one in the absence of a channel (three-dimensional flow) and to the equations integrated across the flow (two-dimensional flow) in the presence of a channel. In Eqs. (1)–(2), the multiplication factor β_c equals 0 in the absence of a channel and 1 in the presence of a channel; C_{ws} is the drag coefficient between the channel and the side. Equations (1)–(4) automatically turn into the corresponding traditional equations for $\beta_c = 0$ and $B_x = B_y = 1$. The equation of state and the hydrostatic approximation to the vertical momentum equation are unchanged. With such modifications, the model permits to calculation of currents and transfer of an admixture in river mouths or channels where the width of flow is less than the step of the computational grid (i.e. sub-grid scale) in one of the horizontal directions.

Model equations were transferred to the σ–vertical coordinate system to improve the computational properties of the model and to obtain a more precise description of water's vertical dynamic and thermohaline structure in the region of small depths. The method for solving the hydrodynamic problem envisages the decomposition of the total current velocity into the velocity averaged over depth (barotropic component) and deviations from this velocity at each depth used for computations (baroclinic component).

The vertical turbulent viscosity is described by the semi-empirical theory of turbulence with the use of mixing length arguments. The instantaneous viscosity is described as the function of a mixing length, the local vertical velocity shear, and the water column stability [18-19].

$$A_v = A_{v0} + A_z[C_{R0}(1 + C_{R1}\mathrm{Ri})^{-C_{R2}}]; \qquad (7)$$

$$D_v = D_{v0} + A_z[C_{R3}(1 + C_{R4}\mathrm{Ri})^{-C_{R5}}]; \qquad (8)$$

where

$$A_z = [\kappa z(1 - z/H)]^2\sqrt{(\partial_z u)^2 + (\partial_z v)^2}; \qquad (9)$$

$\kappa = 0.4$ is the Kármán's constant; A_{V0} is the reference viscosity; D_{V0} is the background vertical mass diffusivity; C_{R0}, C_{R1}, C_{R2}, C_{R3}, C_{R4}, and C_{R5} are the constants equal to 1.0, 10.0, 0.5, 1.0, 3.33, and 1.5, respectively [24]; and Ri is the Richardson number.

The coefficients of horizontal turbulent exchange are calculated from the value of the local horizontal shift of the barotropic component of current velocity and the pace step ΔL of the horizontal finite-difference grid [27]:

$$A_h = A_{h0} + C_{AH}(\Delta L)^2\sqrt{2[(\partial_x U)^2 + (\partial_y V)^2] + (\partial_y U + \partial_x V)^2}; \qquad (10)$$

$$D_h = A_h, \qquad (11)$$

where U and V are the components of the vector of the vertically-integrated horizontal current velocities; C_{AH} is the coefficient for horizontal diffusivity and A_{h0} is the background value.

The boundary conditions for the set of Eqs. (1)–(6) are defined as follows.

(i) At the sea surface ($z = 0$):

$$(\tau_{sx}, \tau_{sy}) = \rho A_v(\partial_z u, \partial_z v); D_v\partial_z S = 0;$$
$$w = \frac{dh}{dt};\ P = P_a, \qquad (12)$$

where h is the deviation of the sea level from the unperturbed state; C_w is the specific heat capacity of water; P_a is the atmospheric pressure; τ_{sx}, τ_{sy} are the wind stresses at the upper (air-water) interface are given by the formulas:

$$\tau_{sx} = (C_{aw1} + C_{aw2}W_{10})W_{10}W_x,$$
$$\tau_{sy} = (C_{aw1} + C_{aw2}W_{10})W_{10}W_y,$$

where W_x and W_y are the components of the wind velocity at a height of 10 m over the sea level along the x- and y- axes, respectively, W_{10} is the modulus of wind velocity at a height of 10 m, and C_{aw1} and C_{aw2} are the friction coefficients set equal to 0.0008 and 0.000065 sec/m, respectively.

(ii) At the bottom ($z = -H$):

$$(\tau_{bx}, \tau_{by}) = \rho A_v(\partial_z u, \partial_z v);\ D_v\partial_z S = 0. \qquad (13)$$

where τ_{bx}, τ_{by} are the bottom friction stresses at the lower (water-bottom) interface have the form:

$$\tau_{bx} = \Phi u_b \text{ and } \tau_{by} = \Phi v_b;$$
$$\Phi = \left[C_{wb1} + C_{wb2}\left(u_b^2 + v_b^2\right)^{1/2}\right],$$

u_b and v_b are the components of the bottom current velocity; C_{wb1} and C_{wb2} are the friction coefficients whose typical values are equal to 0.001 and 0.0026 m/sec, respectively.

At the point of entry of the river bed into the computational domain, boundary conditions have the following form:

$$h_t = \frac{Q_r}{B_x B_y \Delta L^2},\ (HS)_t = 0, \qquad (14)$$

where Q_r - river discharge, m^3/sec.

At the open sea border, we specify the perturbations of the sea level caused by wind action, $h = h_m(x, y, t)$. The following conditions are formulated for S: if the flow enters into the computation region, then baseline values (S^*) characteristic of the open sea are assigned to the border with the open sea; otherwise, values of modeled variables are extrapolated from the region of computation with the help of simplified advection equations

$$S_m = S^* \text{ if } \vec{v}\vec{n} \leq 0; \qquad (15)$$

$$\partial_t S_m = -\vec{v}\vec{n}\partial_{\vec{n}} S \text{ if } \vec{v}\vec{n} > 0, \qquad (16)$$

where $\vec{v}\vec{n}$ is the projection of the vector of current computed at the boundary points of the domain onto the outer normal to that boundary.

The model's structure permits to assimilation of new information on the variability of meteorological and hydrological parameters with a given time resolution for (i) speed and wind direction at the sea surface; (ii) water salinity, sea level at the open sea border; (iii) water discharge, mineralization of river waters at the on the lateral liquid boundary. The linear interpolation in time is done between discrete input values.

The following values were used for modeling parameters: $C_{ws} = 0.008$; $A_{h0} = 1.0$ m^{2}sec^{-1}; $C_{AH} = 0.01$; $A_{v0} = D_{v0} = 10^{-6}$ m^{2}sec^{-1}.

Previously, the model was successfully used to determine effective ways to stabilize the hydrological and hydroecological regimes of the Tiligulsky, Dofinovsky, and Tuzlovsky estuaries of the north-western Black Sea region [1, 20, 28].

During calculations, the estuary's water area together with the adjacent estuarine section of the Lower Dniester was covered with a horizontal calculation grid of 35x90 nodes, its step was 500 m (Fig. 1b). Six vertical calculation levels in the σ - s-coordinate system was used.

The probability of the transformed seawater penetration from the Dniester Estuary up into the Dniester mouth area increases when the small values of the river discharge coincide with strong (storm) surge-driving winds. Those winds contribute to sea waters' rising into the estuary and further to the Dniester River arms; they also contribute to water level rises in the area of the estuary, which is the mouth seaside of the Dniester River. That is why in the first set of numerical experiments with the model the winds of different directions and forces were combined with low-water period discharges in the Dniester River main channel (upstream of the intake structures) that were set artificially decreased starting with 175 m^3/sec (175, 150, 125, 100, 75, 50). During that stage, we did not take into account the wind-induced sea level fluctuations (up and down surges) at the open sea border of the calculation area (the Tsaregradske Mouth of the Dniester Estuary).

During the second set of digital experiments, the real wind conditions were set, and the respective sea-level fluctuations by the data from observation at the "Tsaregradske Mouth" Marine Hydrometeorological Station (MHS) and the "Bilgorod-Dnistrovskyi" Marine Hydrometeorological Station. The average daily Dniester River discharges (upstream of the intake structures) were set artificially reduced starting with 175 m^3/sec. Out of the standard observation sets for the period 1990-2010 three month-long intervals were picked up with the most favorable conditions for the transformed seawater to enter the Dniester River estuarine arms and the Glybokyi Turunchuk: strong surges with a significant increase in water level both on the border between the estuary and the sea and in the estuary, namely: October 1994, March 2007 and September 2008.

Results and discussion. The first set of numerical experiments with the model has shown that the strongest surges in the Dniester Estuary happen at southern and south-eastern winds (Fig. 2). At south-eastern wind, in case of its force growing during three days from 5 to 25 m/sec, the difference in level between the southern and the northern parts of the estuary reaches 170 cm. However, the transformed sea water enters only the Glybokyi Turunchuk Arm and this only starts under the condition that the average daily discharge in the main river is below 100 m^3/sec, which coincides with the conclusions from the previous studies [5].

It is shown in Fig. 3 how the nature of the barotropic (depth-averaged) water circulation in the estuary and the arms of the Dniester River estuarine part changes with strengthening of southern and south-eastern surge-driving winds and the river water discharge of about 75 m^3/sec. It can be seen that with the wind speed increase from 10 to 20 m/sec, during the second day, the direction of the current in the Glybokyi Turunchuk Arm changes to the opposite – the water starts to go from the estuary into this estuarine arm.

When the high wind speed (20-30 m/sec) stays during the third day of the modelling time, the water level at the point where the river divides into two arms grows so much due to hydraulic backwater that the flow of the Glybokyi Turunchuk Arm towards the estuary is restoring.

The described features of water flow directions variability in the Dniester River estuarine branches are explained by the fact that, as can be seen in Fig. 2, with given surge winds the water level in the estuary near the Glybokyi Turunchuk Arm mouth is 15 cm higher than the water level in the estuary near the entrance to the Dniester Arm. Therefore, it is natural that the estuarine water enters the river mouth through the Glybokyi Turunchuk Arm.

When the speed of a storm surge wind stays the

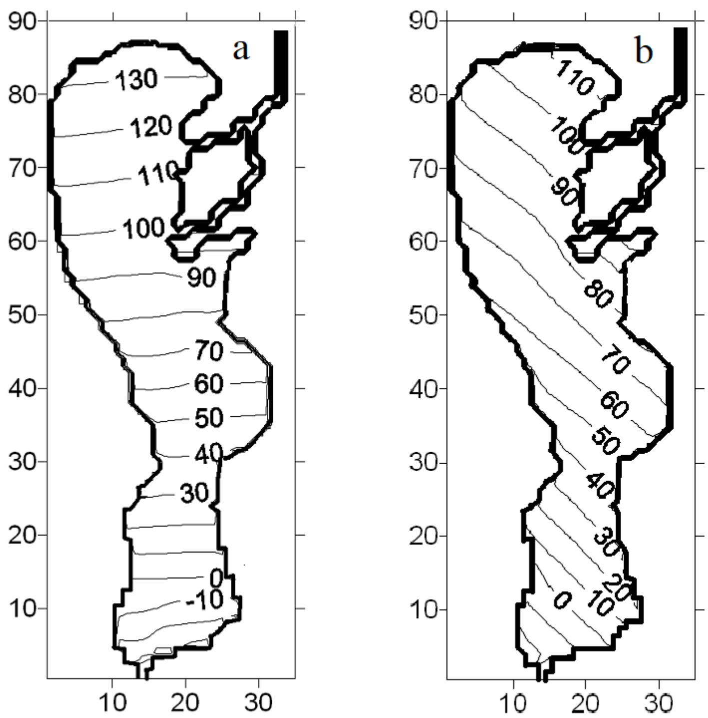

Fig. 2. Denivelation of water level in the Dniester Estuary (cm) with strengthening of the south-eastern (a) and southern (b) winds up to 20-25 m/sec

same or gets somewhat weaker, as the result of water level increases in the place where the main flow of the Dniester River splits into two arms, the Glybokyi Turunchuk and the Dniester, due to the river water backing up by the estuarine, the flow from the estuary into the Glybokyi Turunchuk Arm first gets weaker and then changes for the usual, in direction to the estuary, but its intensity is lower than before (Fig. 3c).

It should be pointed out that in case of southern and south-eastern storm winds that cause the highest surge in the upper part of the estuary, the water level mark at the outlet of the Dniester Arm is always lower than those of the Glybokyi Turunchuk Arm and the place where the main river channel divides into the two arms. At the same time, in different temporal periods of wind surge development, the level in the Glybokyi Turunchuk Arm can be both higher and lower than that at the point of the main river channel division into the two mouth arms.

Variability of salinity spatial distribution obtained for the hydrometeorological conditions described above using the model is presented in Fig. 4. As the southern and south-eastern surge winds intensify, the transformed sea water of higher salinity rises up along the estuary's eastern shore to the mouthes of Glybokyi Turunchuk and Dniester Arm. Penetration of waters having a salinity of 4-7 ppt into the Glybokyi Turunchuk is visible. The front of estuarine brackish water penetrates this branch up to the point where the Dniester main channel divides into two branches, the Glybokyi Turunchuk, and the Dniester Arm, after which the brackish estuarine water mixes intensively with the fresh river water and returns to the estuary through the Dniester Arm with the river flow.

The process of brackish estuarine water penetration in the Glybokyi Turunchuk Arm develops in a period of one day. Preliminary analysis of results of the second series of numerical experiments with the model for three selected monthly samples of real variability of the wind conditions and the corresponding sea level fluctuations in the Tsaregradske Mouth showed that penetration of transformed sea waters into the Dniester River estuarine arms occurred only in the case of the storm observed in March 2007. Wind conditions variability in March 2007, according to the data from the Tsaregradske Mouth MHS, is shown in Table 2.

The variability of sea level deviations from its initial undisturbed state during the period of calculation (March 2007) is shown in Figure 5a. It can be seen that in the period from 18 to 23 March a wind-caused rise in water level happened at the seaward edge of the estuary in the Tsaregradske Mouth, as well as in the part of the estuary near the river mouth. At the same time, the wind-induced water level rise in the estuary near the mouth of the Dniester River exceeds that at its sea border significantly (by 1.2 m during the period of maximal surge). During the mentioned period of intense surge, the conditions established under which the water level mark in the estuary near the mouth of the Glybokyi Turunchuk Arm exceeded the level mark at the point

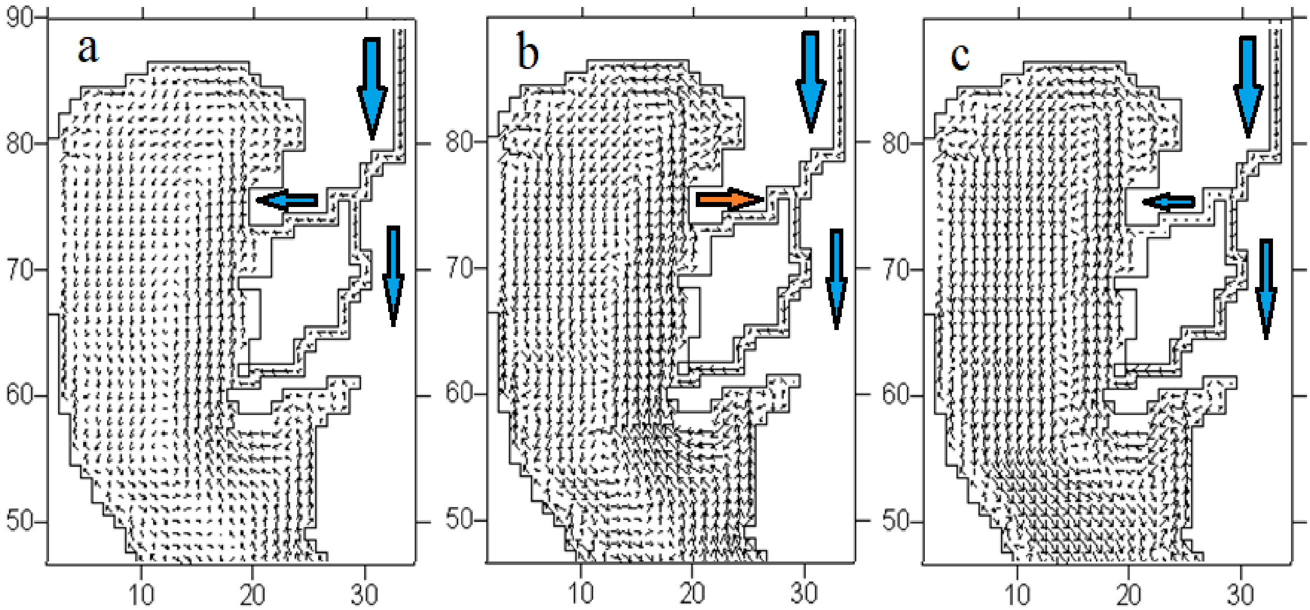

Fig. 3. Variability of barotropic (average in depth) circulation of water at strengthening of the south-eastern wind from 5 to 25 m/sec and the Dniester discharge of 75 m^3/sec: a) the first modeled day; b) the second day; c) the third day of wind speed growth

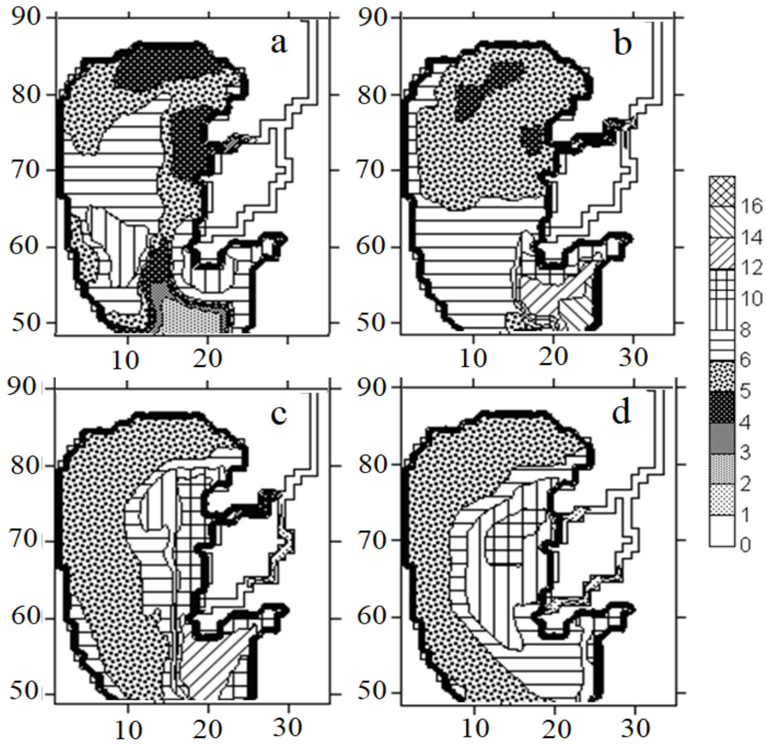

Fig 4. Variability of water salinity (ppt) spatial distribution obtained from the model at growing southern wind speed from 5 to 25 m/sec and the Dniester discharge of 75 m^3/sec: a) in 1 day at 10-15 m/sec southern wind; b) in 1.5 days at 20 m/sec southern wind; c) in 2 days at 25 m/sec southern wind; d) in 2.5 days at 20 m/sec southern wind

where the main channel of the Dniester River divided into two branches - the Glybokyi Turunchuk and the Dniester Arm (Figure 5b).

In such periods the water from the estuary enters the Glybokyi Turunchuk Arm. The water level mark in the estuary near the Dniester Arm mouth is always lower than the mark at the point where the Dniester River main channel splits into two arms. Therefore, no transformed marine (estuarine) water enters the Dniester Arm from the estuary.

Wind conditions during the period of intensive surge development in the estuary were characterized

Table 2

Wind Speed and Direction Variability in March 2007 According to the Data of Observations at the Tsaregradske Mouth MHS

Date	Time, Hour	Wind Direction, Rhumbs	Wind Speed, m/sec	Time, Hour	Wind Direction, Rhumbs	Wind Speed, m/sec	Time, Hour
17.03.07	6	NW	3	22.03.07	6	SE	7
	18	S	6		18	E	9
18.03.07	6	NW	14	23.03.07	6	E	12
	18	Calm	0		18	E	25
19.03.07	6	S	5	24.03.07	6	E	22
	18	NE	10		18	N	6
20.03.07	6	S	14	25.03.07	6	N	7
	18	S	14		18	NE	8
21.03.07	6	S	14	26.03.07	6	NE	11
	18	SE	15		18	W	7

Notes: S – southern; N – northern; E – eastern; W – western; SE – south-eastern; SW – south-western; NE – north-eastern; NW – north-western.

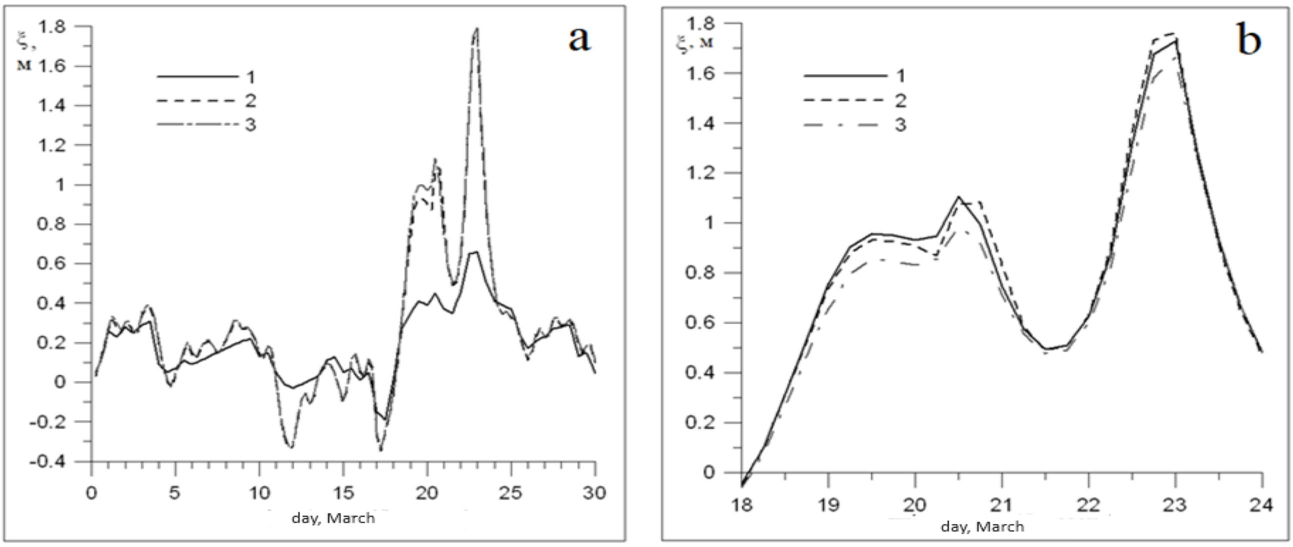

Fig. 5. Water level denivelation (m) in March 2007:a) 1 – according to the data of observations in the Tsaregradske Mouth; calculated by the model: 2 – at the entrance to the Glybokyi Turunchuk Arm from the estuary; 3 – in the Dniester River at the water gauging station in Maiaky village; b) calculated by the model: 1 – at the point where the Lower Dniester splits into branches, grid point (28.76); 2 – at the exit of the Glybokyi Turunchuk Arm into the estuary, grid point (21.73); 3 – at the exit of the Dniester Arm into the estuary, grid point (19,61)

by the dominance of the southern and southeastern winds at a speed of 5-15 m/sec for 3.5 days from 03/19 to 03/22/2007 (Table 2). At that, the storm winds with the speed of 14-15 m/sec lasted for 2 days.

The variability of the spatial distribution of water level deviations from the initially set sea level mark (as of March 1, 2007) during the period of intense water surge in March 2007, calculated using the model, is shown in Figure 6. It can be seen that at the maximal surgeon 22.03.2007, the skew of the water level between the southern and northern ends of the estuary reaches 1.5 m. The water level mark in the estuary near the Glybokyi Turunchuk Arm mouth is 15-20 cm higher than the level mark near the mouth of the Dniester Arm.

Schemes of the depth-averaged (barotropic) water circulation in the estuary and estuarine segment of the Dniester River, with stationary average daily discharge of 50 m^3/sec during the wind surge development period are shown in Figure 7. The formation of the current directed from the estuary into the Glybokyi Turunchuk Arm during the 21st and 22nd days of calculations (March 21-22) is visible. The discharge flow from the Dniester Arm into the estuary continues during the entire period of the surge.

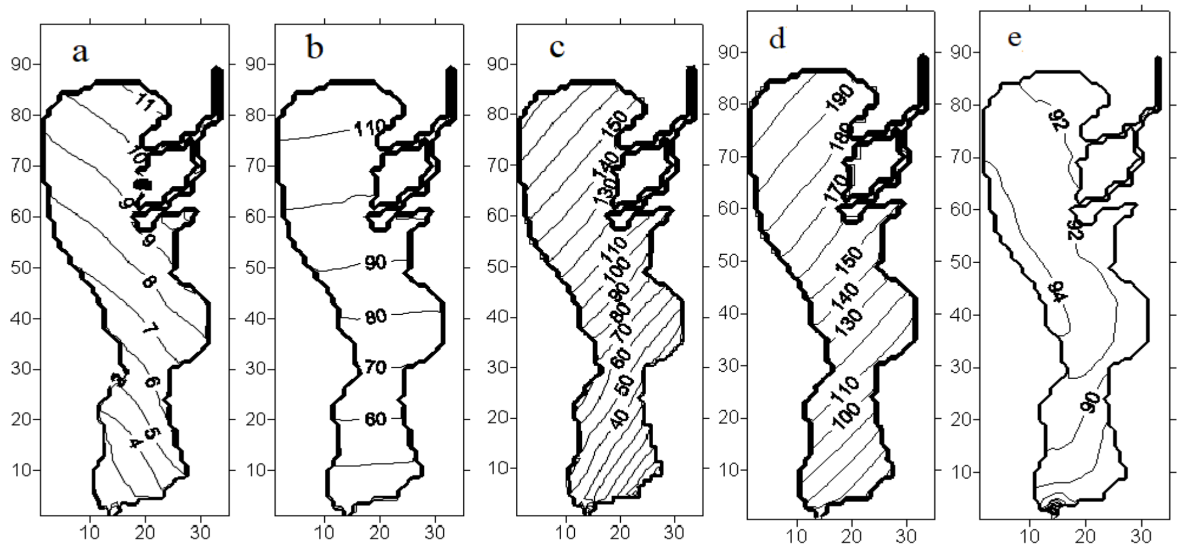

Fig. 6. Model-calculated variability of the spatial distribution of water level deviations (cm) in the estuary from the initially set level in March 2007 (as of March 1, 2007): a) 18th day, 0:00; b) 20th day, 0:00; c) 22nd day, 12:00; d) 23rd day, 0:00; e) 23rd day, 12:00

The model-calculated variability of the water salinity spatial distribution in the estuary's water area and the Dniester River mouth, at the unchanged average daily discharge (Maiaky water gauging station) of 100, 75, and 50 m^3/sec, is presented in Figure 8-9. It can be seen that the lower the Dniester River flow under the same wind conditions, the more intensively and in larger volume brackish estuarine water penetrates the river mouth. Thus, in case the Dniester River discharge is set as 100 m^3/sec for the period of maximal surge development during the 22nd day of the month, brackish estuarine water rises only to the middle of the northern arm (Glybokyi Turunchuk).

When the discharge is 75 m^3/sec, the estuarine water penetrates the river mouth almost up to the place where it divides into two estuarine arms, while in case the average daily discharge of the Dniester River drops down to 50 m^3/sec (Figure 9) the brackish estuarine water reaches the point where the Dniester divides into two branches (Glybokyi Turunchuk and Dniester Arm) and is drawn by the discharge flow into the Dniester Arm increasing its water salinity to 3-4 ppt. At that, the time of brackish estuarine water stay in the river mouth area also increases.

It can be seen from (Figure 9**)** that by the middle of the 23rd day, during the stage of the surge termination and water level decrease in the estuarine area, when the estuarine water is already pressed out by the discharge flow from the Glybokyi Turunchuk Arm into the estuary, the brackish water is still present in the Dniester Arm and its salinity makes several ppm.

In conclusion, we have to note that the results obtained in the first and second series of numerical experiments with the model are in good agreement with each other and allow us to generalize the conclusion on the conditions and nature of the penetration of transformed sea water (brackish, estuarine) into the Dniester River mouth.

Conclusion. It was established based on hydrodynamic modeling results that the most favorable conditions for saline seawater penetration in the Dniester Estuary and then, after transformation into brackish estuarine waters, the estuarine arms of the Dniester River, are the storm surge-causing winds of southern and south-eastern directions.

The following circumstances should coincide for the transformed seawater penetration of the Dniester Estuary: average daily discharge of the Dniester should go down to 100 m^3/sec or below; surge winds from the south or southeast at a speed of 14-20 m/sec should prevail for several days.

The transformed sea water penetrates the estuarine arms and further, the Dniester River main channel from the estuary through the right estuarine arm, the Glybokyi Turunchuk, and then, having reached the point where the Dniester River channel divides into two estuarine arms, the water from the estuary is drawn into the left branch (the Dniester Arm) by the discharge flow and returns via the Dniester Arm back to the estuary.

The process of brackish estuarine water penetration in the Dniester and the Glybokyi Turunchuk estuarine arms takes place over 12-24 hours.

Since water level in the estuary at the entrance to the Glybokyi Turunchuk Arm at surge winds from the sea will always be higher than at the entrance into the Dniester Arm, is unlikely that estuarine water of higher salinity (up to 7 ppt) could penetrate the main channel of the Dniester River (that is high-

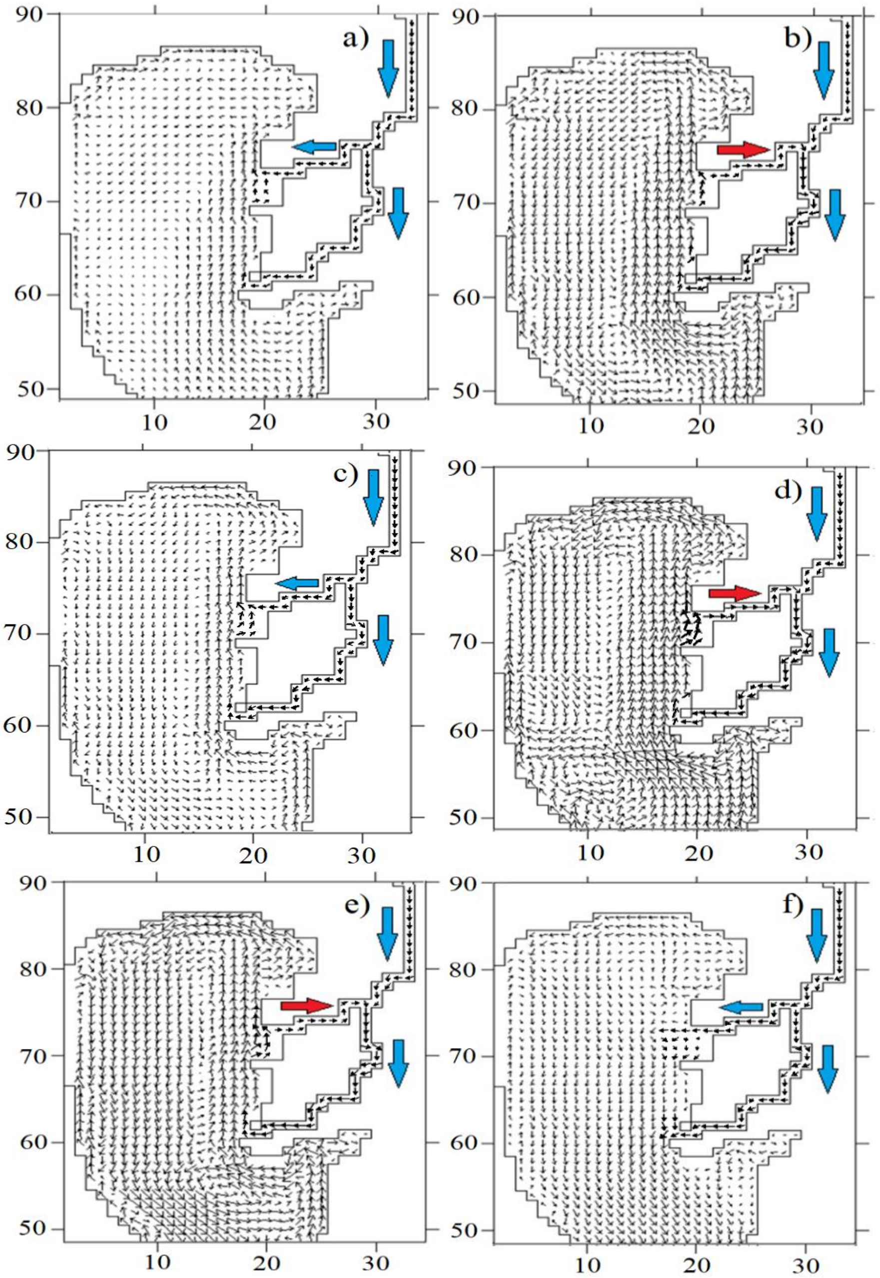

Fig. 7. Variability of barotropic (depth-mean) water circulation in March 2007 at the Dniester River average daily discharge of 50 m^3/sec: a) 18th day, 0:00; б) 21st day, 0:00; c) 22nd day, 0:00; d) 22nd day, 12:00; e) 23rd day, 0:00; f) 23rd day, 12:00

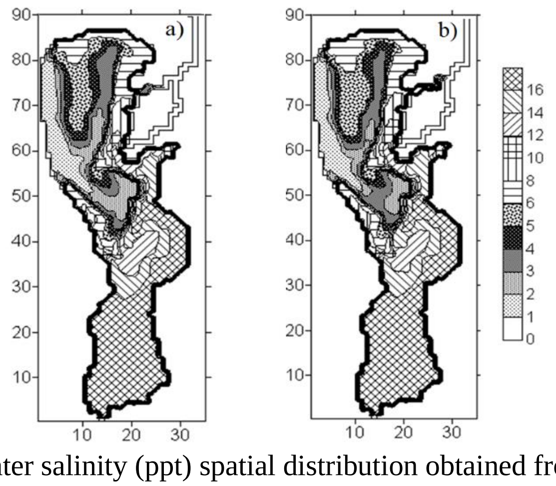

Fig. 8. Variability of water salinity (ppt) spatial distribution obtained from the model for 12:00 of 22 March 2007 at the Dniester River average daily discharge of a) 100 m^3/sec; b) 75 m^3/sec

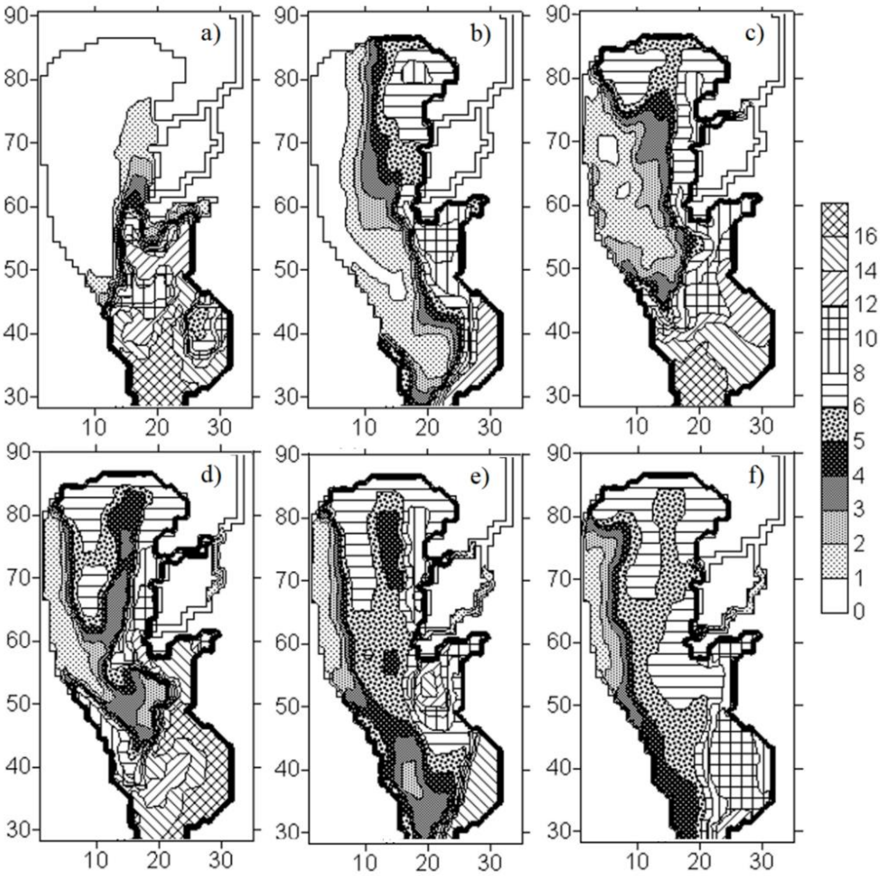

Fig. 9. Variability of water salinity (ppt) spatial distribution obtained from the model for March 2007 at the Dniester River average daily discharge of 50 m^3/sec: a) 20th day; 0:00; b) 21st day, 0:00; c) 22nd day, 0:00; d) 22nd day, 12:00; e) 23rd day, 0:00; f) 23rd day, 12:00.

er than the place where the river divides into two estuarine arms) even with flow rate going below 100 m3/sec, as evidenced by the scheme of estuarine water distribution in the Dniester River mouth area described in the paper.

The case described in the article could be used by experts as an example when identifying effective hydro-engineering measures to prevent transformed sea water penetration in river mouth by the building of a second estuarine canal (arm).

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Ключові аспекти проникнення морської води у річку Дністер під час штормових нагонів

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В статті обговорюється проблема можливості проникнення солонуватих вод з Дністровського лиману у гирлову частину річки Дністер протяжністю близько 22 км від лиману. Актуальність дослідження полягає в тому, що в цій частині р.Дністер розташована водозабірна станція «Дністер», яка живить питною водою місто Одеса, а також водозабір Нижньо-Дністровської зрошувальної системи. Мета роботи полягала у визначені шляхом застосування гідродинамічного моделювання таких гідрометеорологічних умов, за яких можливе проникнення трансформованих морських вод з Дністровського лиману в гирлову область річки Дністер. Для вирішення цієї задачі використовувався спрощений варіант (без урахування термічного фактору) чисельної 3-D нестаціонарної гідродинамічної моделі MECCA (Model for Estuarine and Coastal Circulation Assessment), доповненої блоком переносу консервативної домішки. В результаті гідродинамічного моделювання встановлено, що для проникнення трансформованих морських вод в гирлові рукави р.Дністер необхідне виконання наступних умов: (1) середньодобові витрати р.Дністер повинні зменшитись нижче 100 $м^3/с$; (2) домінування нагінних вітрів південного або південно-східного напрямків зі швидкістю більшою 15 м/с протягом декількох діб. За таких умов проникнення трансформованих морських вод з лиману до гирлових рукавів і далі до основного русла р. Дністер відбувається спочатку через правий гирловий рукав – Глибокий Турунчук, а потім, після досягнення місця розділення основного русла р. Дністер на два гирлових рукави, лиманні води залучаються стоковим потоком в русло лівого рукава – Дністер, і повертаються через нього до лиману. Процес проникнення солонуватих лиманних вод до гирлових рукавів Дністер та Глибокий Турунчук відбувається на часовому відрізку тривалістю 12-24 год. Зроблений висновок про те, що через наявність двох гирлових рукавів, якими річка Дністер впадає в Дністровський лиман, з урахуванням місця їх розташування в північно-східній частині лиману та особливостей підвищення рівня води в лимані при нагінних вітрах, проникнення лиманних вод з підвищеною солоністю (до 7 ‰) в основне русло р. Дністер (вище за місце розділення русла на два гирлові рукави) маловірогідно навіть при витратах річки менших за 100 $м^3/с$. Описаний в статті випадок може бути використаний фахівцями як приклад при визначенні ефективних гідротехнічних заходів для запобігання проникненню трансформованих морських вод в гирла річок шляхом будівництва другого гирлового каналу (рукава).

***Ключові слова**: Дністровський лиман, гирло Дністра, проникнення перетвореної морської води, підйом і спад.*

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