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Original article

Mathematical Model of a Flooding Process in the Don Delta during Extreme Surges

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Abstract
Purpose. The work consists in developing a mathematical model to study the flooding processes in the Don delta during the extreme surges.
Methods and Results. The level fluctuations in the Taganrog Bay are calculated based on solving a system of equations for long waves in a homogeneous incompressible fluid in the Coriolis force field. The problem is solved by the finite-difference methods on high-performance computing systems. The algorithm for determining the area of the Don delta flooding in the process of a surge is given. It is based on comparing the heights of the delta area to the water level and on taking a decision whether to flood or drain a computational cell. The calculation results are compared to the water level values observed at the gauging station, and are also displayed as a map diagram of the flooded area.
Conclusions. The proposed model should be applied in case of the extreme surges when a significant delta area is flooded. The model makes it possible to calculate accurately the hydrodynamic parameters of a flow including the magnitude of water level difference. The proposed algorithm determining whether flooding or draining is required for a computational domain, permits to reveal the areas in the Don delta where flooding depends on the wind conditions.

Keywords: shallow water equations, surge oscillations, computational experiment, flooding

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Introduction

The Don water level surge oscillations are essentially manifested in its mouth area, which extends from a conventional line connecting the Dolzhanskaya and Belosarai spits in the Taganrog Bay in the west, to the village of Razdorskaya in the east [1] [1]. Catastrophic floods have recently become more frequent in the Taganrog Bay and the Don River delta, which is caused by the extreme activity of the Black Sea cyclones [2–4]. An analysis of extreme natural phenomena (the inflow of salty transformed Black Sea waters into the Don delta, ice invasion

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[1] Simov, V.G., 1989. [*Hydrology of the Mouths of the Rivers of the Sea of Azov*]. Moscow: Gidrometeoizdat, 328 p. (in Russian).

from the Sea of Azov into the Kerch Strait, etc.) observed in the Sea of Azov waters in recent years is presented in [5]. It discusses public safety problems that appear during surge processes in the Don delta.

In late March 2013, a large area in the Don delta was flooded with water extremely quickly as a result of a strong storm surge; more than 2 thousand households and over 5 thousand people were affected by flooding in 21 settlements. Material losses for the population and economy of the region are estimated at more than 500 million rubles. Significant damage was also caused to the scientific expedition base of the Southern Scientific Center of the Russian Academy of Sciences, located on the Swinoye mouth shore. According to preliminary estimates, the flood area in the lower Don was 40 km wide and 50 km long (up the Don to Aksai).

Level rises dangerous for the Don delta can be caused by wind fields over the sea with significant pressure gradients and wind speeds (10–15 m/s or more). Southwestern winds over the entire Sea of Azov are especially dangerous, causing the greatest level rise in the Taganrog Bay and the Don delta [3].

The methods based on the construction and study of mathematical models of natural systems represent one of the ways for objective analysis of these problems.

Many works have been devoted to calculating the Don water level oscillations. In paper [2], it is proposed to calculate the free surface levels for the Don main channel using the formula, where the desired upsurge in a given section depends on the upsurge near the town of Azov. This method gives satisfactory results only in the years when the Don water flow is close to normal.

Based on observation data from a standard hydrometeorological network, surges in the Don estuary area were studied and a catalog of maximum annual and dangerous surges was compiled at observation points on the coastal estuary and the Don estuary from the beginning of observation period to 2014. The possibility of forecasting surges was identified according to the synoptic situation over the Sea of Azov with the advance time of three days using hydrodynamic models. It made it possible to create a prognostic scheme for calculating the transformation of surges [6, 7].

A robust system for forecasting coastal river floods is presented in [8]. The technique combines statistical and hydrodynamic models to determine the probability of floods caused by multiple factors. The method includes extreme value analysis, assessment of dependencies and interactions among flood factors, multivariate joint dependency-based probability estimation, hydrodynamic modeling of flood scenarios derived from multivariate statistical analysis and flood mapping as the final result [8].

Many works using neural networks and machine learning methods to model floods have appeared [9]. In [10], the identification of flood-prone areas in an urban environment is shown with the help of neural networks. Such models can be used to

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[2] Mikhaylov, V.N., Rogov, M.M. and Chistyakov, A.A., 1986. [*River Deltas: Hydrological and Morphological Processes*]. Leningrad: Gidrometeoizdat, 280 p. (in Russian).

map flood-prone urban areas which hydraulic models are not suitable for due to the lack of data. In addition, the combination of artificial neural networks and HEC-RAS hydrodynamic model makes it possible to determine the hydrodynamic parameters of currents, as well as to map floods in channels [11, 12]. To train and test the model, both weather station data and topographic humidity index are used.

Papers [13, 14] study the magnitude of storm surge oscillations in the Sea of Azov level based on the analysis of observational data and modeling results. These storm surge oscillations lead to extreme floods in the coastal areas of the Sea of Azov and the Taganrog Bay, when atmospheric cyclones become effective generators of significant sea level rises.

Paper [15] studies "surge oscillations in the Sea of Azov level, which occur during long-term atmospheric impacts of the same type and are the cause of floods/drying in coastal areas. Based on the analysis of the results of the three-dimensional hydrodynamic Princeton Ocean Model, spatial maps and reference data sets of the extent of flooding/drying of the Sea of Azov coast were created" [15, p. 185]. Flood areas are considered with a flat bottom of constant slope. It is assumed that there are no channels, eriks or ravines in the flood area.

A geometric approach to modeling flood areas using e-vector maps of territories is given in [16]. One of the intermediate stages of generating auxiliary cartographic data based on the use of pseudoposts is considered, and a 2D fragment of a map with a flood area is shown.

In [17], a numerical study of the process of flooding of the Lower Don floodplain as a result of high floods is presented. This model is based on 2D Saint-Venant differential equations using digital 3D terrain models. In addition, a similar model was used to clarify the hydrodynamic dependencies of the watercourse and estimate the impact of the Don floodplain transformation [18].

Long-term observations have shown that the Don delta flooding occurs not only because of seasonal floods, but as a result of extreme surges from the Taganrog Bay influenced by westerly winds. The present paper is aimed at numerical study of exactly this phenomenon. The use of a mathematical model based on the equations of motion of an incompressible fluid makes it possible to obtain the Don delta pictures in the process of its flooding. In this case, a digital terrain model of the delta is used, taking into account branches, erics and creeks.

Materials & methods

Downstream after Rostov-on-Don, the Don channel is divided into creeks and branches. The Don delta is characterized by intersected riverbed branches and numerous eriks, where delta islands rise low above the water level. Taking into account these features, the proposed model is used in the case of extreme surges, i.e., when the entire floodplain is flooded and it is necessary to apply 2D equations of water movement. In the case when the water level rises only in the Don branches, it is necessary to consider a model containing the equations of water movement in an open channel.

Mathematical modeling of hydrophysical processes in the Don delta region was carried out according to the classical scheme as follows:

- expression of the most important relations and laws inherent to a natural object (water body) under study in mathematical terms;
- development of model implementation algorithms on a modern computer;
- creation and debugging of software necessary for carrying out a large number of calculations and implementing selected mathematical models and algorithms on high-performance computing systems;
- establishing the adequacy of the constructed model to the original object;
- carrying out computational experiments allowing to obtain all the required qualitative and quantitative properties and characteristics of the object [3].

Calculations of the Taganrog Bay level oscillations are based on solving a system of equations for long waves in a homogeneous incompressible fluid in the Coriolis force field [19]:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}-\Omega v=-g\frac{\partial \zeta}{\partial x}+\frac{\tau_{sx}}{H}-\frac{\tau_{bx}}{H},$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+\Omega u=-g\frac{\partial \zeta}{\partial y}+\frac{\tau_{sy}}{H}-\frac{\tau_{by}}{H},$$

$$\frac{\partial \zeta}{\partial t}+\frac{\partial (Hu)}{\partial x}+\frac{\partial (Hv)}{\partial y}=0,$$

where $H=h+\zeta$; $h=h(x,y)$ is water body depth; $u=u(x,y,t)$, $v=v(x,y,t)$ are velocities; τ_{sx},τ_{sy} are projections of the wind friction force on the water surface on the *OX* and *OY* axes; τ_{bx},τ_{by} are projections of the fluid friction force on the bottom on the *OX* and *OY* axes. These values depend on wind speed $\overline{W}_B=\{W_x;W_y\}$ and current $\overline{W}_T=\{u;v\}$ and are defined as follows [20]:

$$\overline{\tau}_s=\gamma\left|\overline{W}_B\right|\overline{W}_B,\qquad \overline{\tau}_b=\beta\left|\overline{W}_T\right|\overline{W}_T,$$

where $\left|\overline{W}_B\right|=\sqrt{W_x^2+W_y^2}$, $\left|\overline{W}_T\right|=\sqrt{u^2+v^2}$, $\beta(x,y)$ is friction coefficient of fluid on the bottom; γ is coefficient of wind friction on the free water surface.

Slip conditions are specified on the solid boundary $\partial\Omega_b$:

$$\mathbf{V}_n\big|_{\partial\Omega_b}=0,\qquad \left.\frac{\partial \mathbf{V}_\tau}{\partial \overline{n}}\right|_{\partial\Omega_b}=0,$$

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[3] Chikin, A.L., 2009. [*Development and Implementation of a Two-Layer Mathematical Model of Hydrophysical Processes in Reservoirs with Vast Areas of Shallow Water on High-Performance Computing Systems*]. Thesis Dr. Phys.-Math.Sci. Moscow, 233 p. (in Russian).

and in places where water flows in or out, $\partial\Omega_r$, the corresponding velocity values are set:

$$u\big|_{\partial\Omega_r} = u_1, v\big|_{\partial\Omega_r} = v_1,$$

where $\mathbf{V}_n$ is normal component of the velocity vector; $\mathbf{V}_\tau$ is tangential component of the velocity vector.

As initial data, any known velocity distribution can be set:

$$u = u^0,\ v = v^0,\ \zeta = \zeta^0 \ -$$

or considered these velocities to be zero.

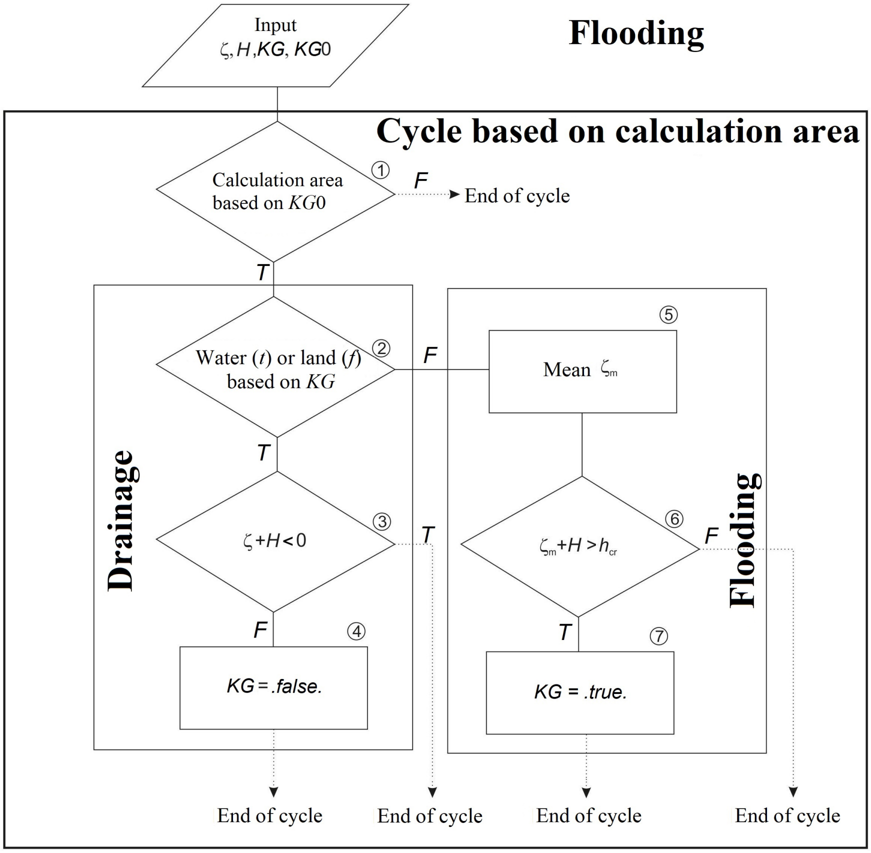
The algorithm of the coastline change as a result of drainage or flooding of the calculation area is quite simple and is based on determining whether the calculation cells belong to land or water.

On the surface of the studied water body, together with the expected flooding area, a 2D rectangular grid, being uniform in each direction, with h_1 and h_2 steps, is constructed. Depth values are entered into the nodes of a flat rectangular difference grid covering the water area, and height values are entered into the grid nodes covering the expected flooding area.

Taking into account the depth values at the flat grid nodes, cells located in water or on land are determined. Logical array *KG*0, which characterizes the type of cells (“water”, “land”), sets the initial configuration of the entire computational domain and does not change until the end of the calculation.

During the calculation process, some cells with shallow depths may dry out due to the downsurge and become classified as “land”. This happens when the value $H + \zeta$ ceases to be positive. Cells that have passed into the “land” category due to the downsurge, can return to the “water” category. The “water” category may also include “land” cells in the probable flood area. This occurs if there is an increase in the water level and the average depth over neighboring cells is not less than set critical value h_{cr}. The depth value in the current cell is set taking into account the law of conservation of mass. Logical array *KG* can change during the calculation process and characterizes the type of cells (“water”, “land”) that can be drained or flooded.

Fig. 1 shows a block diagram of the algorithm for determining the water body shoreline in the case of surges. The algorithm is based on determining the water body depth depending on the value of the water surface level difference. When iterating over all calculation cells based on the values of logical variable *KG*0, those that are obviously not included in the calculation area are immediately discarded (*KG*0 = *false*). Then, *KG* variable makes it possible to determine which process is taking place in the cell: drainage, flooding, or none.



F i g. 1. Block diagram of the algorithm for calculating the area of flooding and drainage [4]

If the cell was in a water body (*KG* = *true*), then in case $H + \zeta \leq 0$ this cell goes into the “land” category, and the *KG* variable takes the value *false*. Otherwise, drainage does not take place in this cell.

If a cell located in the calculation area (*KG*0 = *true*) is currently land (*KG* = *false*), then it can be flooded. This will happen if $\zeta_m + H \geq h_{\text{cr}}$, where ζ_m is the average value of the water level difference over neighboring cells. In this case, the cell goes into the “water” category, and the *KG* variable takes the value *true* [4].

In all cases of changes in the nature of difference cells, it is necessary to re-index the entire computational area. When indexing, it should be taken into account that the tape width in the matrix obtained after approximating a system of linear algebraic equations depends on the enumeration order of the indices. To narrow the tape, it is

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[4] Chikin, A.L. and Chikina, L.G., 2021. Numerical Study of Flooding of the Don Delta during Surges. In: SSC RAS, 2021. *Regularities of Formation and Impact of Marine and Atmospheric Hazardous Phenomena and Disasters on the Coastal Zone of the Russian Federation under the Conditions of Global Climatic and Industrial Challenges* («*Dangerous Phenomena - III*»): Proceedings of the III International Scientific Conference in Memory of RAS Corresponding Member D.G. Matishov (Rostov-on-Don, 15-19 June 2021). Rostov-on-Don: SSC RAS Publishers, pp. 142-145 (in Russian).

necessary to start enumerating nodes with the index corresponding to the smallest dimension of the calculation area and end with the index corresponding to the largest dimension.

The problem is solved using finite difference methods. The algorithm for calculating the parameters of water flow on the $(n + 1)^{\text{th}}$ time layer is based on the principle that each equation is “defining” for its unknown. All other variables are considered to be known and are taken from the n^{th} layer.

The 1st step, the level difference at the $(n+1)^{\text{th}}$ time layer, is calculated according to the following scheme:

$$\frac{\zeta_{i,j}^{n+1}-\zeta_{i,j}^{n}}{\Delta t}=-\left[\frac{u_{i+1,j}\dfrac{f_{i,j}+f_{i+1,j}}{2}-u_{i,j}\dfrac{f_{i-1,j}+f_{i,j}}{2}}{\Delta x}+\frac{v_{i,j}\dfrac{f_{i,j}+f_{i,j+1}}{2}-v_{i,j-1}\dfrac{f_{i,j-1}+f_{i,j}}{2}}{\Delta y}\right]^{n},$$

where $f_{ij}=H_{ij}+\zeta_{ij}$.

The 2nd step is as follows: the values of the velocity components u and v are found from the difference momentum equations [5]

$$\frac{u_{s_{i,j}}^{n+1}-u_{s_{i,j}}^{n}}{\tau}+\frac{u_{s_{i,j}}^{n}+\left|u_{s_{i,j}}^{n}\right|}{2}\frac{u_{s_{i,j}}^{n+1}-u_{s_{i-1,j}}^{n+1}}{h_1}+\frac{u_{s_{i,j}}^{n}-\left|u_{s_{i,j}}^{n}\right|}{2}\frac{u_{s_{i+1,j}}^{n+1}-u_{s_{i,j}}^{n+1}}{h_1}+$$

$$+\frac{v_{s_{i,j}}^{n}+\left|v_{s_{i,j}}^{n}\right|}{2}\frac{u_{s_{i,j}}^{n+1}-u_{s_{i,j-1}}^{n+1}}{h_2}+\frac{v_{s_{i,j}}^{n}-\left|v_{s_{i,j}}^{n}\right|}{2}\frac{u_{s_{i,j+1}}^{n+1}-u_{s_{i,j}}^{n+1}}{h_2}-\Omega\tilde{v}_{s_{i,j}}=$$

$$=-g\frac{\zeta_{i,j}^{n}-\zeta_{i-1,j}^{n}}{h_1}+\left(\frac{\tau_{sx}}{H_{ij}}-\frac{\tau_{bx}}{H_{ij}}\right)\Bigg|_{i,j}^{n},$$

$$\tilde{v}_{s_{i,j}}=\frac{1}{4}\left(v_{s_{i,j}}^{n}+v_{s_{i-1,j}}^{n}+v_{s_{i-1,j-1}}^{n}+v_{s_{i,j-1}}^{n}\right).$$

$$\frac{v_{s_{i,j}}^{n+1}-v_{s_{i,j}}^{n}}{\tau}+\frac{u_{s_{i,j}}^{n}+\left|u_{s_{i,j}}^{n}\right|}{2}\frac{v_{s_{i,j}}^{n+1}-v_{s_{i-1,j}}^{n+1}}{h_1}+\frac{u_{s_{i,j}}^{n}-\left|u_{s_{i,j}}^{n}\right|}{2}\frac{v_{s_{i+1,j}}^{n+1}-v_{s_{i,j}}^{n+1}}{h_1}+$$

$$+\frac{v_{s_{i,j}}^{n}+\left|v_{s_{i,j}}^{n}\right|}{2}\frac{v_{s_{i,j}}^{n+1}-v_{s_{i,j-1}}^{n+1}}{h_2}+\frac{v_{s_{i,j}}^{n}-\left|v_{s_{i,j}}^{n}\right|}{2}\frac{v_{s_{i,j+1}}^{n+1}-v_{s_{i,j}}^{n+1}}{h_2}-\Omega\tilde{u}_{s_{i,j}}=$$

$$=-g\frac{\zeta_{i,j+1}^{n}-\zeta_{i,j}^{n}}{h_2}+\left(\frac{\tau_{sx}}{H_{ij}}-\frac{\tau_{bx}}{H_{ij}}\right)\Bigg|_{i,j}^{n},$$

$$\tilde{u}_{s_{i,j}}=\frac{1}{4}\left(u_{s_{i,j}}^{n}+u_{s_{i+1,j}}^{n}+u_{s_{i,j+1}}^{n}+u_{s_{i+1,j+1}}^{n}\right).$$

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[5] Chikin, A.L., 2009. The Two-Layer Mathematical Model of the Wind Currents in the Basin with Different Level of Deep. *Mathematical Modeling*, 21(12), pp. 152-160 (in Russian).

Then, these steps are repeated on a new time layer until the counting end condition is met. Such a condition can represent a certain time period (in hours, days, etc.) during which the calculation should be carried out.

An analytical study of the presented algorithm stability has not been carried out. However, numerical studies have shown that a stable count is observed at time step $\tau \le 120$ s.

The software is coded in FORTRAN, the numerical implementation of the model was carried out on high-performance computing systems in the MPI environment using the Aztec package of parallel routines.

Calculation results and discussion

In the study area, which includes the Sea of Azov, the Taganrog Bay and the Don delta, a grid of depths and heights was constructed in the Baltic height system. The grid step was $\Delta x = 660$ m, $\Delta y = 685$ m with the number of nodes 550×342, which gave about 190,000 cells. After indexing, the number of cells in the computational domain with unknown hydrodynamic parameters became approximately 84,000.

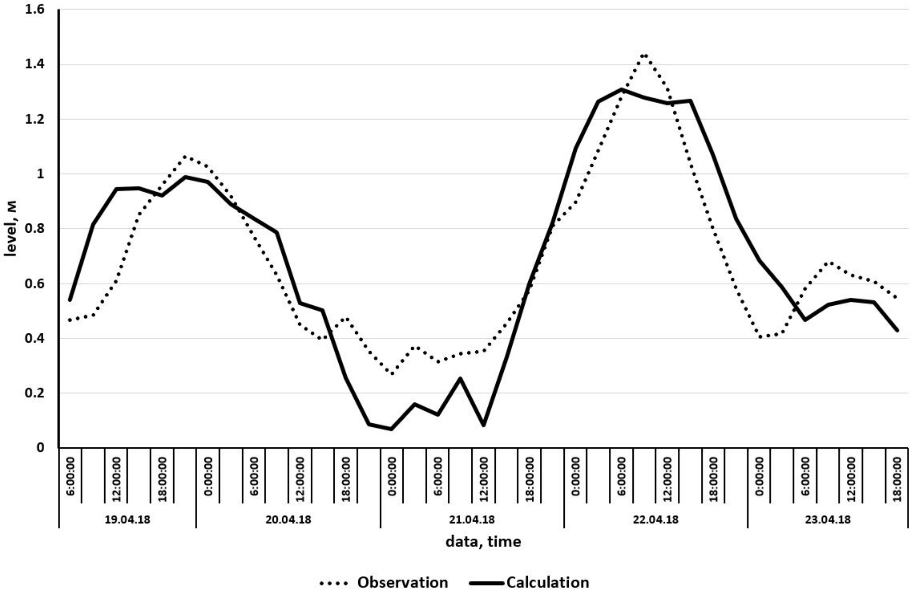
The model verification was carried out both by a numerical comparison of the calculated and measured values of the water level at observation points and by a visual comparison of the calculated and actually flooded Don delta area. Water level values were taken at the gauging station in the khutor of Donskoy, located in the Stary Don branch. Wind situations during surges in September 2014 and April 2018 were considered.

When visualizing the flooding area, a finer grid with 100 m resolution was constructed in the Don delta, onto which the results of water level calculations were transferred. This made it possible to display the flooded area landscape more clearly. Using this grid in calculations would require approximately 50 times more computer resources and computation time, so calculations were carried out on a coarser grid.

At the beginning of the period from 19 April 2018 to 23 April 2018, the wind blew from the west at a speed of 9–11 m/s. Then it changed its direction to the north and weakened to 4–6 m/s, but then strengthened again to 11–13 m/s and became southwestern. This led to a repeated increase of the surge. Fig. 2 shows the calculated and measured water level oscillations at the Donskoy gauging station from 19 April 2018 to 23 April 2018. A comparison of measured and calculated values of water level in Donskoy showed that the calculation error is 23%.

In the last third of September 2014, the wind situation developed in such a way that the eastern wind blew at a speed of 3–4 m/s on 23 September 2014, which led to some water runoff in the Taganrog Bay. Then, the wind direction changed sharply to the southwest and winds began to blow at a speed of 2–24 m/s, which led to an extreme surge into the Don delta. During the extreme surge on 24–25 September

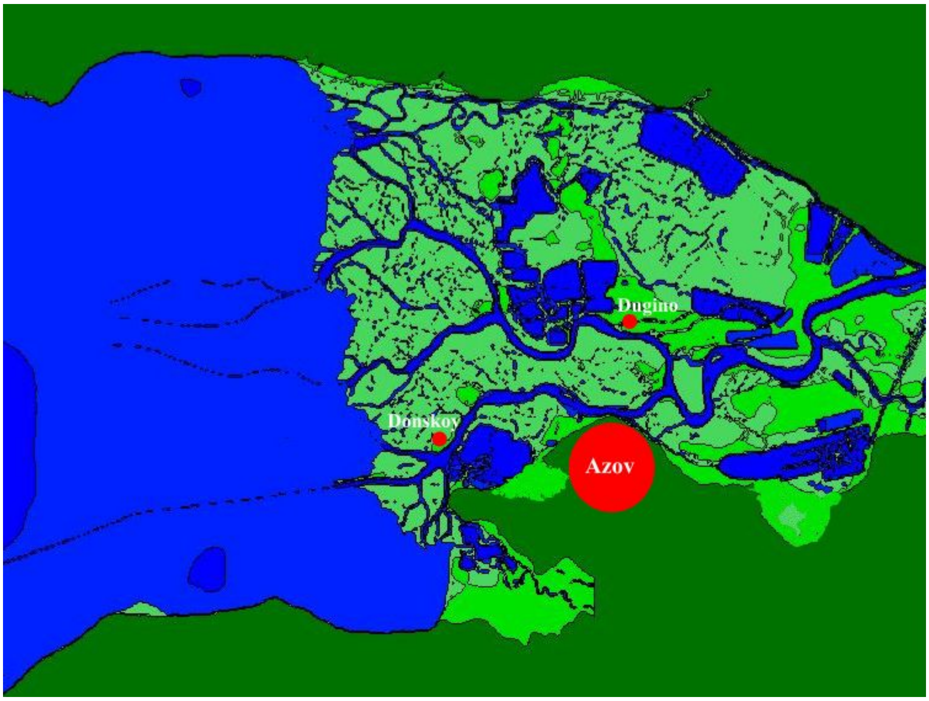
2014, not only water level oscillations were recorded, but also the flooded area in the Don delta which made it possible to visually compare the real and calculated flooding patterns. During this surge, unusually high salinity was also observed in the Azov port area (5.6 ‰) [21].



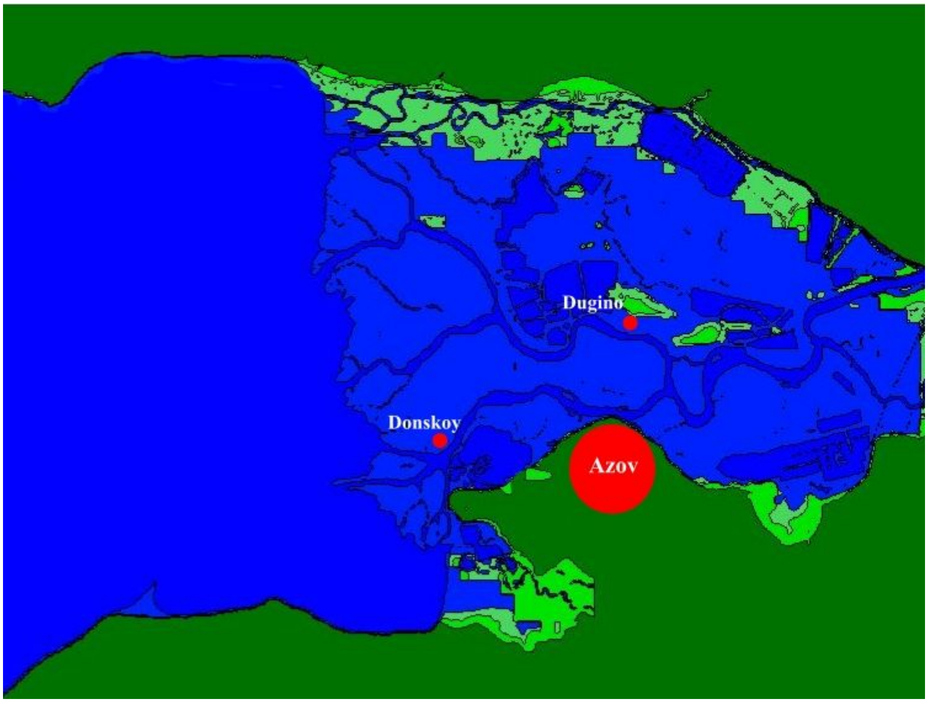
F i g. 2. Changes of water level in Donskoy from 19 April 2018 to 23 April 2018

Fig. 3 shows the Don delta region in its initial state, when level oscillations are insignificant. The water surface, including the Don branches and fish-breeding ponds, is highlighted in blue; the area with possible flooding is highlighted in light green. Fig. 4 shows the same area at the time of the maximum water level rise at 18:00 on 24 September 2014. The error in calculating the water level in the khutor of Donskoy was 17%.

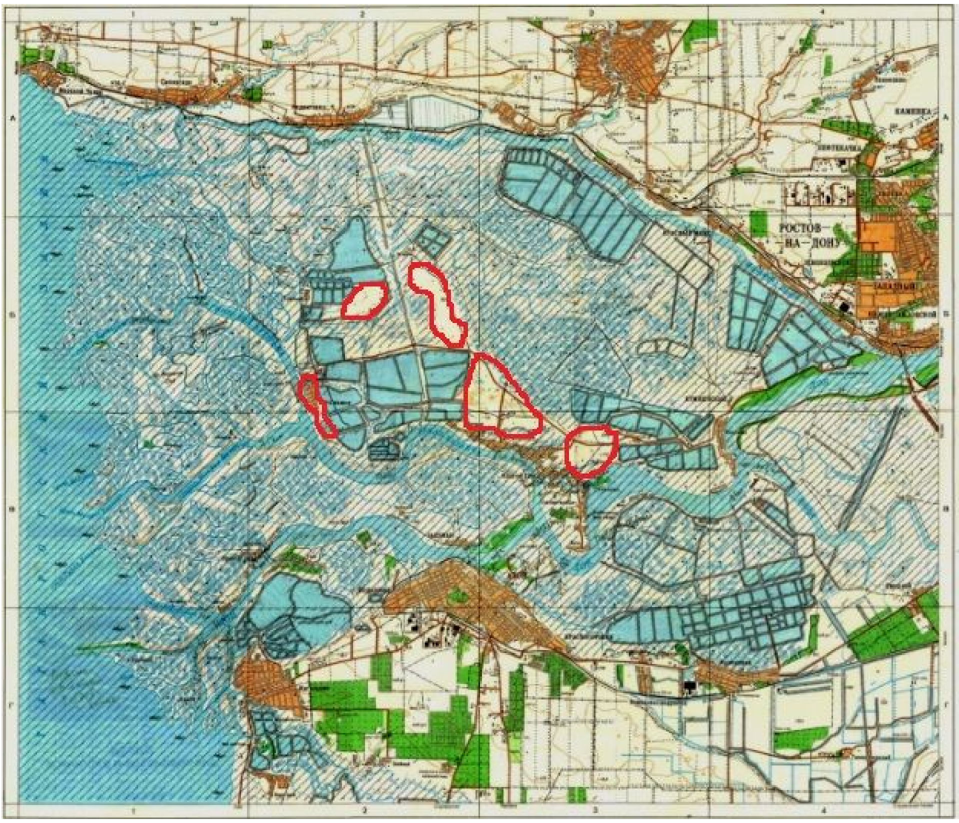
A.Yu. Moskovets, a Southern Scientific Center specialist, tracked the flooding area in the Don delta region. The real picture of flooding is shown in Fig. 5. Flooded areas are indicated by shading. Unflooded areas of the delta are highlighted in red. The flood area obtained as a result of the surge simulation agrees quite well with the real picture in the specified area, although the differences between the modeled picture and the real one have not been quantified. The existing differences in flooded areas are explained by the fact that the calculations were carried out on a fairly coarse grid, and the calculation results were transferred to a fine grid only for visualization.



F i g. 3. Region of the Don delta at the beginning of upsurge on 24 September 2014



F i g. 4. Region of the Don delta at the time of the water level maximum rise on 24 September 2014



F i g. 5. Scheme of the flooded area of the Don River delta on 24 September 2014 (highlighted by hatching) performed by A.Yu. Moskovets

Conclusions

The proposed model should be used in the case of extreme upsurges, when the water level rise in the Don branches is so great that it floods the entire delta region. In this case, it is appropriate to use 2D hydrodynamic equations. In the case of small water level oscillations in the Taganrog Bay, the water flow in the Don channel is determined by the equations for channel flows.

Calculations have shown that this model makes it possible to calculate quite accurately the hydrodynamic parameters of the wind current, including the water level drop value. The proposed algorithm for determining flooding or drainage of the computational area permits to determine the locations of the Don delta flooding depending on the wind situation. Comparison of the measured water level values at the gauging station with the calculated ones indicates the correspondence of the proposed hydrodynamic model and the algorithm for determining flood areas during extreme water upsurges in the Taganrog Bay to the real flooding picture.

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