Suspended particle transport process modeling based on 2D and 3D models

Chistyakov A E¹, Protsenko E A², Kuznetsova I Y³ and Nikitina A V³

¹Department of Mathematics and Informatics, Don State Technical University, 1, Gagarin Square, Rostov-on-Don, 344000, Russia
²Department of Mathematics, A.P. Chekhov University of Taganrog (branch of Rostov State University of Economics), 48, Initiativevaya str., Taganrog, 347936, Russia
³Department of Intelligent and Multiprocessor Systems, Southern Federal University, 105/42, Bolshaya Sadovaya st., Rostov-on-Don, 344006, Russia

E-mail: cheese_05@mail.ru, eapros@rambler.ru, ikuznecova@sfedu.ru, nikitina.vm@gmail.com

Abstract. In this paper, suspended particles transport mathematical model is proposed and investigated. The considered model includes the following factors: the aquatic environment movement; variable density depending on the suspension concentration; multicomponent suspension; change in the bottom geometry as suspension sedimentation result. The 3D diffusion-convection equation approximation based on splitting schemes into 2D and one-dimensional problems. In the paper, convective and diffusive transfer operators’ discrete analogs in the case of partial fullness of the cells are used. Based on the fullness function, the calculated area geometry is described. The difference scheme, which is linear combination of the Upwind and Standard Leapfrog difference schemes with weight coefficients obtained from the condition of minimizing the approximation error, is used. This scheme is designed to solve the impurity transfer problem at large grid Peclet numbers. Based on the results of numerical experiments, conclusions are drawn about the advantages of the 3D model of suspended particle transport over the 2D model. The results of numerical experiments on modeling the multicomponent suspension deposition are presented.

1. Introduction

In recent decades, we should note the significant pollution of water bodies of our planet, caused primarily by active human activity. In terms of surface water resources, the Russian Federation occupies a leading position in the world. A significant amount of pollutants enters aquatic ecosystems from river flows and air. Under the influence of natural and man-made transformations, turbidity and secondary pollution of water occur, which leads to a significant deterioration of the production and destruction processes of aquatic ecosystems. Observation of natural mechanisms of hydrodynamic processes with daily variability of meteorological data allows us to choose the right strategy for preventing water pollution. Historically, the development of methods for predicting the state of water bodies has been a priority and a crucial task of hydrochemical and ecological research [1]. Special attention in hydrochemistry and hydrobiology was paid to the study of the processes that form the biological productivity of natural waters and determine the dynamics of chemical elements and their compounds,
as well as the biological and physical parameters of the aquatic environment [2]. In [3], which describes mathematical modeling of suspended matter transport on the ocean shelf, an empirical model of horizontal dispersion of pollutants on the ocean shelf is proposed and investigated. A meshless stochastic numerical algorithm is developed that implements a combination of known methods, including the discrete cloud method and the stochastic discrete particle method. In [4], the transformation of bottom zoocenoses in the soil dumping area is studied. Projects aimed at transforming the bottom surface and the coastline during dredging and construction of various technical structures in water bodies should necessarily include preliminary fishery monitoring, which allows assessing the impact on hydrobionts [5]. The risk and harm assessment of transforming the bottom surface and the coastline should be determined based on normative documents. For example, in [6], the experimental simulation of zoobenthos collapse during soil dumping is described. After the conducted environmental monitoring, the use of mathematical modeling methodology allows conducting experiments in a wide range of input data. The development of software makes it possible to develop mechanisms for optimal environmental management, as well as significantly reduce the negative impact on hydrobioncenes and harm caused by various types of hydraulic transformations. After the research based on mathematical models of hydrophysical processes, the projects should be adjusted [7]. Thus, in the work [8], the fishery researches of the Ural water bodies and the influence of suspended solids of drainage waters on the bottom fauna of small rivers are described. The project for dredging in the White Sea included the calculation of the impact on aquatic biological resources based on a mathematical model of suspension transport [9]. In the study [10], a new stochastic Lagrangian model is proposed for constructing the trajectory of sediment particles, and the effect of turbulence on the spatial distribution of impurity is studied. The paper [11] is devoted to modeling the concentration and transport of suspended sediments in the Mittivakkat Glacier and Southeast Greenland. Empirical equations calculate the erosion and sedimentation within a permanent idealized glacier drainage system. The model is based on the energy balance, meteorological observations, and the calculation for the summer period shows that the cumulative transport of suspended sediments differs within 3% compared to the observed values. Despite the significant number of publications devoted to this problem, some issues require additional comprehensive analysis.

Hydrophysical processes can be described in the form of complex systems of initial-boundary value problems for nonlinear partial differential equations, including the equations of hydrodynamics, transport of heat, salts, and suspended matter. These processes are spatially inhomogeneous, three-dimensional, and non-stationary. Methods for solving the diffusion-convection equation are used to solve this class of problems. A separate task is the development of difference schemes for discretization and numerical solution of hydrophysical problems in the case of the prevalence of the convective operator over the diffusion one, which is typical for the occurrence of natural and man-made hazards, including storm surge, the transport of hazardous pollutants in the reservoir.

2. Statement of the problem

The initial equations of the shallow water bodies hydrodynamics are:

- the motion equations (the Navier – Stokes equations):

\[
\begin{align*}
    u_t + uu_x + vv_y + wu_z &= -\frac{1}{\rho} P_t + \left( \mu u_x \right)_x + \left( \mu v_y \right)_y + \left( \nu u_z \right)_z, \\
    v_t + uv_x + vv_y + wv_z &= -\frac{1}{\rho} P_t + \left( \mu v_y \right)_y + \left( \nu v_z \right)_z, \\
    w_t + uw_x + vv_y + wv_z &= -\frac{1}{\rho} P_t + \left( \mu w_z \right)_z + \left( \nu w_y \right)_y + g,
\end{align*}
\]

(1)

- the continuity equation in the case of variable density:
\[ \rho'_t + (\rho u'_t) + (\rho v'_t) + (\rho w'_t) = 0, \]  

(2)

where \( \mathbf{V} = \{u, v, w\} \) are the components of the velocity vector [m/s]; \( P \) is pressure [Pa]; \( \rho \) is density [kg/m³]; \( \mu, \nu \) are horizontal and vertical components of the turbulent exchange coefficient [m²/s]; \( g \) is gravitational acceleration [m/s²].

The system of equations (1) – (2) is considered under the following boundary conditions:

– inflow boundary

\[ u = u_0, \quad v = v_0, \quad P'_u = 0, \quad V'_n = 0, \]

– side boundary (coastal zone and bottom)

\[ \rho \mu u'_n = -\tau_s, \quad \rho \nu u'_n = -\tau_s, \quad V'_u = 0, \quad P'_n = 0, \]

– upper boundary

\[ \rho \mu u'_n = -\tau_s, \quad \rho \nu u'_n = -\tau_s, \quad w = -\omega - P'_l / \rho g, \quad P'_n = 0, \]

where \( \omega \) is the rate of liquid evaporation; \( \tau_s, \tau_v \) are components of tangential stress.

The components of the tangential stress for the free surface are determined from the equation

\[ \{\tau_x, \tau_y\} = \rho_a C_d \left[ \mathbf{w}\{w_x, w_y\} \right], \quad C_d = 0.0026, \]

where \( \mathbf{w} \) is the vector of wind speed through water; \( \rho_a \) is atmospheric density; \( C_d \) is the dimensionless coefficient of surface resistance, which depends on the wind speed and is considered in the range from 0.0016 to 0.0032.

The components of the tangential stress for the bottom, depending on the movement of water, can be written as follows

\[ \{\tau_s, \tau_r\} = \rho C_d \left[ \mathbf{V}\{u, v\} \right], \quad C_d = g n^2 / h^{1/3}, \]

where \( n = 0.04 \) is the group roughness coefficient in the Manning formula and is considered in the range from 0.025 to 0.2; \( h \) is water area depth [m].

To describe the transport of multicomponent suspended particles, we use the diffusion-convection equation, which can be written in the following form:

\[ \frac{\partial c_r}{\partial t} + \frac{\partial (uc_r)}{\partial x} + \frac{\partial (vc_r)}{\partial y} + \frac{\partial \left[(w+w_s) c_r\right]}{\partial z} = \frac{\partial}{\partial x}\left(\mu \frac{\partial c_r}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu \frac{\partial c_r}{\partial y}\right) + \frac{\partial}{\partial z}\left(v \frac{\partial c_r}{\partial z}\right) + F_r, \]

(3)

where \( c_r \) is the concentration of the \( r \)-th suspension fraction [mg/l]; \( w_s, r \) is the rate of settling of the \( r \)-th suspension fraction [m/s]; \( F_r \) is a function describing the intensity of the \( r \)-th suspension fraction sources distribution [mg/l·s].

On a free surface, the flow in the vertical direction is zero:

\[ (c_r)'_z = 0. \]

Near the bottom surface the flow is

\[ D_v (c_r)' = w_s c_r. \]

There is no flow on the side surface.
\[ (c_r)'_n = 0, \text{ if } (V, n) \geq 0, \]

and the suspension goes beyond the boundary of the computational domain

\[ D_h (c_r)'_n = V_n c_r, \text{ if } (V, n) < 0, \]

where \( V_n \) is the normal component of the velocity vector; \( n \) is the normal vector directed inside the computational domain.

The density of the aquatic environment is calculated according to the formula

\[ \rho = \left(1 - \sum_{r=1}^{g} V_r\right) \rho_0 + \sum_{r=1}^{g} V_r \rho_{r,c}, \quad c_r = V_r \rho_{r,c}, \]  

where \( V_r \) is the volume ratio of the \( r \)-th suspension fraction; \( \rho_0 \) is density of fresh water at standard conditions; \( \rho_{r,c} \) is density of the \( r \)-th suspension fraction.

The sediment transport equation in the case of a multicomponent suspension is written as

\[ (1 - \varepsilon) \frac{\partial H}{\partial t} + \text{div} \left( \sum_{r=1}^{g} V_r k \tau_b \right) \frac{\text{grad} H}{\sin \varphi_0} \right) + \sum_{r=1}^{g} \frac{w + w_{r,c}}{\rho_{r,c}} c_r \]  

where \( \varepsilon \) is the fraction-averaged porosity of bottom sediments; \( \tau_b \) is the vector of tangential stress at the bottom of the reservoir; \( \tau_{bc,q} \) is the critical value of tangential stress for the \( r \)-th suspension fraction, \( \tau_{bc,q} = a_q \sin \varphi_0 \); \( \varphi_0 \) is the angle of friction of the soil in the reservoir; \( k_q = k_q \left( H, x, y, t \right) \) is the non-linear coefficient defined by the ratio

\[ k_r \equiv \frac{A \overline{\omega} d_r}{\left( \rho_r - \rho_0 \right) g d_r} \left( \frac{\tau_b - \tau_{bc,q} \text{grad} H}{\sin \varphi_0} \right)^{\beta-1}, \]

where \( \rho_r \) is solid particles density of the \( r \)-th suspension fraction; \( d_r \) is typical size of particles of the \( r \)-th suspension fraction; \( \overline{\omega} \) is averaged wave frequency; \( A \) and \( \beta \) are dimensionless constants.

Equation (5) is considered with the following initial and boundary conditions:

– initial condition

\[ H(x, y, 0) = H_0(x, y), \]

– boundary condition

\[ H'_n = 0. \]

3. Suspended particle transport problem approximation

Consider the approximation of the three-dimensional diffusion-convection equation

\[ \frac{c_x' + uc_x' + vc_x' + wc_x'}{x} = \left( \frac{\mu c_x'}{x} \right)' + \left( \frac{\mu c_y'}{y} \right)' + \left( \frac{\mu c_z'}{z} \right)' . \]  

Let's construct a uniform grid \( \omega_i \) in time with a step \( \tau \): \n
\[ \omega_i = \{ t_n = n \tau, n = 0, N; \quad N \tau = T \}. \]

For equation (7), we use the splitting schemes into two-dimensional and one-dimensional problems:
\[
\frac{c^{n+1/2} - c^n}{\tau} + u(c^n)'_x + v(c^n)'_y = \left[ \mu(c^n)'_x \right] + \left[ \mu(c^n)'_y \right],
\]
\[
\frac{c^{n+1} - c^{n+1/2}}{\tau} + w(c^{n+1/2})'_\zeta = \left[ v(c^{n+1/2})'_\zeta \right].
\]

For the numerical implementation of the discrete mathematical model of the problem, we introduce spatial grid:
\[
w_n = \{ x_i = ih_x, y_j = jh_y; i = 0, ..., N_x; j = 0, ..., N_y; N_\tau = T, N_\Sigma h_x = l_x, N_\Sigma h_y = l_y \},
\]
where \( \tau \) is time step; \( h_x, h_y \) are space steps; \( N_x \) is the upper time bound; \( N_x, N_y \) are space bounds; \( l_x, l_y \) are size of the computational domain.

To approximate the homogeneous equation (8), we will use the splitting schemes in spatial coordinate directions:
\[
\frac{c^{n+1/2} - c^n}{\tau} + u(c^n)'_x = \left[ \mu(c^n)'_x \right],
\]
\[
\frac{c^{n+1} - c^{n+1/2}}{\tau} + v(c^{n+1/2})'_y = \left[ \mu(c^{n+1/2})'_y \right].
\]

Introduce coefficients \( q_0, q_1, q_2, q_3, q_4 \), describing the volume of fluid (VOF) of the corresponding control areas located near the cell. The value of the coefficient \( q_0 \) characterizes the filling area \( D_0 \) where
\[
\begin{aligned}
\{ x \in (x_{i-1/2}, x_{i+1/2}), y \in (y_{j-1/2}, y_{j+1/2}) \},
q_1 - D_1: D_0 \cup \{ x \geq x_i \}, q_2 - D_2: D_0 \cup \{ x \leq x_i \},
q_3 - D_3: D_0 \cup \{ y \geq y_j \}, q_4 - D_4: D_0 \cup \{ y \leq y_j \}.
\end{aligned}
\]

The filled part of the regions \( D_m \) will be called \( \Omega_m \), where \( m = 0, ..., 4 \). By this, the coefficients \( q_m \) can be calculated from the equations [12-15]:
\[
\begin{aligned}
(q_m)_{i,j} = \frac{S_{i,j}}{S_{n,0}}. (q_0)_{i,j} = \frac{a_{i,j} + a_{i+1,j} + a_{i+1,j+1} + a_{i,j+1}}{4}, (q_1)_{i,j} = \frac{a_{i+1,j} + a_{i+1,j+1}}{2},
(q_2)_{i,j} = \frac{a_{i,j} + a_{i+1,j+1}}{2}, (q_3)_{i,j} = \frac{a_{i+1,j} + a_{i,j+1}}{2}, (q_4)_{i,j} = \frac{a_{i,j} + a_{i+1,j+1}}{2}.
\end{aligned}
\]

Discrete forms of the convective \( uc'_x \) and diffusion transfer operators \( \left[ \mu c'_x \right] \) in the case of partial filling of cells can be written as follows:
\[
\begin{aligned}
(q_0)_{i,j} uc'_x \square (q_1)_{i,j} u_{i+1/2,j} - \frac{c_{i+1,j} - c_{i,j}}{2a} + (q_2)_{i,j} u_{i-1/2,j} - \frac{c_{i,j} - c_{i-1,j}}{2a},
(q_0)_{i,j} \left[ \mu c'_x \right] \square (q_1)_{i,j} \mu_{i+1/2,j} - \frac{c_{i+1,j} - c_{i,j}}{h^2} - (q_2)_{i,j} \mu_{i-1/2,j} - \frac{c_{i,j} - c_{i-1,j}}{h^2} - \left| (q_1)_{i,j} - (q_2)_{i,j} \right| \mu_{i,j} \alpha_{i,j} + \beta_{i,j}.
\end{aligned}
\]
To approximate the model (7), we will use the scheme obtained as a linear combination of the Upwind and Standard Leapfrog difference schemes, with the VOF of cells [16-20]:

- difference scheme for the equation (10), describes the transfer along the Ox direction, we write in the form:

\[
\frac{2q_{2,i,j} + q_{0,i,j}}{3} \left| \begin{array}{c}
\frac{c_{i,j}^{n+1/2} - c_{i,j}^n}{\tau} + 5u_{i+1/2,j}q_{2,i,j} - c_{i+1,j}^n - c_{i,j}^n + u_{i+1/2,j} \min(q_{i,j,0}, q_{2,j,i}) \left( c_{i+1,j}^n - c_{i,j}^n \right) + \\
+ \Delta \frac{c_{i+1,j}^n + \Delta c_{i,j}^n q_{0,i,j}}{3}
\end{array} \right| + 2\Delta \frac{c_{i+1,j}^n}{3} - 2\Delta \frac{c_{i,j}^n}{3} = 2\mu_{i+1/2,j}q_{2,i,j}^n - \frac{e_{i,j}^n - e_{i+1,j}^n}{h_x^2} - 2\mu_{i+1/2,j}q_{2,i,j}^n - \frac{e_{i,j}^n - e_{i+1,j}^n}{h_x^2} - \\
- |q_{i,j,0} - q_{2,i,j}| \frac{h_x}{h_x}, \quad u_{i,j} \geq 0, \quad \text{where} \quad \Delta t c_{i,j}^n = \frac{c_{i,j}^n - c_{i,j}^{n-1}}{\tau};
\]

- difference scheme for the equation (10), describes the transfer along the Oy direction, we write in the form:

\[
\frac{2q_{2,i,j} + q_{0,i,j}}{3} \left| \begin{array}{c}
\frac{c_{i,j}^{n+1/2} - c_{i,j}^{n-1/2}}{\tau} + 5v_{i,j+1/2}q_{4,i,j} - c_{i,j+1/2}^{n-1/2} - c_{i,j}^{n-1/2} + v_{i,j+1/2} \min(q_{3,i,j}, q_{4,i,j}) \left( c_{i,j+1/2}^{n-1/2} - c_{i,j}^{n-1/2} \right) + \\
+ \Delta \frac{c_{i,j+1/2}^n + \Delta c_{i,j}^n q_{0,i,j}}{3} - \Delta \frac{c_{i,j+1/2}^n}{3} = 2\mu_{i,j+1/2}q_{4,i,j}^n - \frac{e_{i,j+1/2}^n - e_{i,j}^n}{h_y^2} - 2\mu_{i,j+1/2}q_{4,i,j}^n - \frac{e_{i,j+1/2}^n - e_{i,j}^n}{h_y^2} - \\
- |q_{3,i,j} - q_{4,i,j}| \frac{h_y}{h_y}, \quad v_{i,j} \geq 0, \quad \text{where} \quad \Delta t c_{i,j}^n = \frac{c_{i,j}^n - c_{i,j}^{n-1/2}}{\tau}.
\]

To obtain difference schemes for the equation (10) in cases \( u_{i,j} < 0 \) and \( v_{i,j} < 0 \) from the presented approximations, it is necessary to direct the corresponding coordinate axes Ox and Oy in opposite directions. Equation (9) is solved by the elimination method [15, 21].

4. 2D and 3D models for solving suspended particles transport problems application

The initial data for the simulation: reservoir depth is 10 m; source intensity is 6.27 kg/s; flow speed is 0.2 m/s; deposition rate (Stokes) is 2,042 mm/s; soil density is 1600 kg/m³; the percentage of the dust particles in sandy soils (d less than 0.05 mm) is 26.83 %. Computational domain parameters: length is 1 km; width is 720 m; steps along the horizontal and vertical spatial coordinates are 10 and 1 m, respectively; the calculated interval is 2 hours. Figure 1 shows the distribution of the concentration of suspended particles (g / l). The values of the suspension concentration field in the cross-section of the calculated area in the plane passing through the discharge point formed by vectors directed vertically and along the flow are given. The water flow is directed from left to right.

The average effective sedimentation rate \( w_i \) of suspensions in the dredging area is 2.042 mm/s. The average distance from the discharge point to the bottom of the reservoir in the dredging area is 5.5 m. Therefore, the average time of the suspended particle (settling time) is approximately 2693 s (approximately 45 min). The simulation of the suspension transport process was performed on a calculated area of 1 km × 720 m, with the grid step over the space \( h = 10 \) m. The current velocity at depths from 4 to 10 m is 0.075 m/s. Based on the input data of the model, it can be concluded that during the sedimentation period, due to convective transfer, the suspension will be distributed approximately 202 m along the flow (which is about 20 grid steps). Diffusion transfer will also contribute to the sediment spreading, but the spreading of sediments due to diffusion transfer will not exceed 200 m.
Figure 1 shows that the suspension is deposited at a distance of 100-300 m from the discharge point, which is consistent with the expected result.

![Figure 1. The suspended particles concentration distribution.](image1)

Figure 2 shows the suspended particles concentration (g/l) averaged over the depth of the reservoir.

![Figure 2. The suspended particles concentration averaged over the reservoir depth.](image2)

Modeling of the space-time structure and variability of the suspension concentration fields based on 2D models was performed without reference to distribution of the suspension concentration along the vertical component. In dredging areas, the maximum concentration can be more than 50 g/l, but the permissible exposure limit is less than 50 mg/l, so the model error should not exceed 0.1 %. According to the 2D model, the suspension deposits much more slowly. For example, suppose that the suspension is uniformly distributed with depth. Take a time step equal to half of the settling time. According to 2D model, 1/2 of the suspension is deposited in the first step, and 1/4 of the suspension is deposited in the second step. After two time steps, no particles should remain in suspension, but according to calculations, 1/4 of the suspension has not yet settled. If the time step $\tau$ is small and the calculation is made for the settling time, the simulation results will show that $1/e$ or 37% of the particles remain in a suspended state in the reservoir. According to the model, it takes $\ln\left(\frac{N_f}{N_e}\right)$ times more period for
the suspension concentration to fall from $N_1$ to $N_2$, where $N_2$ is significantly less than $N_1$, at small steps $\tau$.

Make a comparison of the results of experimental calculations based on 2D and 3D models of the test problem of soil dumping described above. Figure 3 shows comparative graphs of the distribution of particles level 2 hours after discharge, obtained based on 2D and 3D models for different sedimentation rates and different fraction composition. The vertical axis shows the concentration of suspended particles (in figure 3 b), a logarithmic scale is used for clarity). The horizontal axis passes through the dredging area and is directed along the flow.

![Figure 3: Suspended particle concentrations distribution 2 hours after dumping based on 2D and 3D models.](image)

The experimental results are consistent with the theoretical calculations given above. Figure 3 shows that the higher particles level was obtained near the dredging area based on the 2D model. At a distance of 50 meters from the work area, 2D and 3D models show identical results. The results of calculating long-distance sediment spreading based on 2D and 3D models differ widely. The results of calculations based on the 3D model showed a higher deposition rate compared to the results based on 2D.

Figure 4 shows the graphs of changes in the bottom granulometric composition at different initial concentrations of suspended particles. In the process of modeling the transport of suspended particles, the sedimentation of two fractions was considered. The deposition rate of fraction A is 2.4 mm/s, and
the percentage of fraction A in dusty particles is 36%. The deposition rate of fraction B is 1.775 mm/s, the percentage of fraction B is 64%.

The horizontal axis in figure 4 is drawn through the dredging area and directed along the flow. In figures 4 a) and b), the vertical axis shows the depth of the reservoir (in meters), the axis $Oz$ is directed vertically down. In figures 4 c) and d), the vertical axis shows the level of bottom sediment (in millimeters), the axis $Oz$ is directed vertically upward. Figure 4 a) shows the concentration of fraction A in water. Figure 4 b) shows the concentration of fraction B in water. Figures 4 c) and d) show the percentage composition of fractions A and B in the bottom sediments, respectively.

**Figure 4.** Suspended particle concentration distribution and bottom granulometric composition: a) concentration of fraction A in water; b) concentration of fraction B in water; c) the percentage composition of fraction A in the bottom sediments; d) the percentage composition of fraction B in the bottom sediments.

Figure 4 shows that the heavier fraction A is deposited closer to the dredging zone and lies deeper in the sedimentary rocks than fraction B. The experimental results allow us to analyze the dynamics of changes in the geometry and granulometric composition of the bottom, the formation of structures and sediments, the transport of suspensions in the water, as well as the level of water pollution. This mathematical model and the developed software allow to predict the appearance of sea ridges and spits, its growth and transformation, changes in the field of suspension concentration, the drift of hydraulic structures, as well as siltation of approach shipping channels.

5. Conclusions
The hydrophysical process associated with the transport of suspended particles is described and investigated based on 2D and 3D non-stationary mathematical models. The numerical implementation of the problem of suspended particles transport is performed based on a difference scheme obtained by a linear combination of the Upwind and Standard Leapfrog difference schemes with weight coefficients obtained as a result of minimizing the order of approximation error and taking into account the fill function. The results of the experiments based on the developed mathematical models allowed us to conclude that for modelling the process of suspended particles transport in a reservoir, it is better to use a three-dimensional model with the density distribution in the vertical direction. For numerical implementation of discrete analogs of suspension transport models, it is recommended to use schemes with lower grid viscosity; after localizing the sedimentation zone, it is necessary to use a model of the hydrodynamics of water passing through the dredging zone, which will help to assess the dynamics and nature of secondary water pollution.

Acknowledgments
The reported study was funded by RFBR according to the research project № 19-07-00623.

References
[1] Bruevich S V 1966 Chemistry of the Pacific Ocean Nauka (Moscow, Russia) 360 p (in Russian)
[2] Abakumov A I 1994 Mathematical ecology Vladivostok: Publishing house of the Far Eastern State University (Vladivostok, Russia) 120 p (in Russian)
[3] Koterov V N and Yurezanskaya Yu S 2009 Simulation of suspended substance dispersion on the ocean shelf: Effective hydraulic coarseness of polydisperse suspension Comput. Math. Math. Phys. 49(7) pp 1245-1256 DOI: 10.1134/S096554250907015X
[4] Chernyavsky A V 1984 Transformation of bottom zoocenoses in the area of the Grigorovskaya landfill Dredging and problems of protection of fish stocks and the environment of fishery reservoirs pp 208-210 (in Russian)
[5] Susloparova O N 2003 Fisheries monitoring during dredging in the water area of the Oil Harbor GosNIORKh funds (in Russian)
[6] Ivanova V V 1988 Experimental modelling of zoobenthos collapse during soil dumping GosNIORKh funds 85 pp 107-113 (in Russian)
[7] Adjustment of the «Project for the development of the sand deposit «Sestreteskoye» located in the Gulf of Finland of the Baltic Sea» in connection with the reconstruction of the open pit 2012 LLC «Eco-Express-Service» (in Russian)
[8] Morozov A E 1979 Bottom fauna of small rivers and the influence of suspended solids of drainage waters on it Fisheries research of water bodies of the Urals (in Russian)
[9] Kovtun I I, Protsenko E A, Sukhinov A I and Chistyakov A E 2016 Calculation of the impact on aquatic biological resources of dredging in the White Sea Fundamental and Applied Hydrophysics 9 (2) pp 27-38 (in Russian)
[10] Tsai C W and Huang S H 2019 Modeling suspended sediment transport under influence of turbulence ejection and sweep events Water resources research 55 (7) pp 5379-5393 DOI: 10.1029/2018WR023493
[11] Fausto R S, Mernild S H, Hasholt B, Ahlstrom A P, and Knudsen N T 2018 Modeling suspended sediment concentration and transport, Mittivakkat Glacier, Southeast Greenland Arctic, Antarctic, and Alpine Research An Interdisciplinary Journal 44 (3) pp 306-318 DOI: 10.1657/1938-4246-44.3.306
[12] Sukhinov A I, Chistyakov A E and Protsenko E A 2019 Difference scheme for solving problems of hydrodynamics for large grid Peclet numbers Computer Research and Modeling 11 (5) pp 833-848 DOI: 10.20537/2076-7633-2019-11-5-833-848
[13] Samarskiy A A and Vabishchevich P N 1999 Numerical methods for solving convection-diffusion problems Mathematical Models and Editorial URSS (in Russian)
[14] Belotserkovsky O M, Gushchin V A and Shchennikov V V 1975 Application of the splitting
method to solving problems of the dynamics of a viscous incompressible fluid *Computational Mathematics and Mathematical Physics* **15** (1) pp 197-207 (in Russian)

[15] Samarskiy A A and Nikolaev E S 1978 *Methods for solving grid equations* Nauka (Moscow, Russia) (in Russian)

[16] Sukhinov A I, Chistyakov A E, Protsenko E A, Sidoryakina V V and Protsenko S V 2020 Accounting method of filling cells for the solution of hydrodynamics problems with a complex geometry of the computational domain *Mathematical Models and Computer Simulations* **12** (2) pp 232-245 DOI: 10.1134/S2070048220020155

[17] Gushchin V A, Sukhinov A I, Nikitina A V, Chistyakov A E and Semenyakina A A 2018 A model of transport and transformation of biogenic elements in the coastal system and its numerical implementation *Computational Mathematics and Mathematical Physics* **58** (8) pp 1316-1333 DOI: 10.1134/S0965542518080092

[18] Sukhinov A I, Chistyak, A E, Kuznetsova I Y and Protsenko E A 2020 Modelling of suspended particles motion in channel *Journal of Physics: Conference Series* **1479** (1) 012082 DOI: 10.1088/1742-6596/1479/1/012082

[19] Chetverushkin B N and Yakobovskiy M V 2018 Numerical algorithms and architecture of HPC systems *Keldysh Institute Preprints* **52** 12 p DOI: 10.20948/prepr-2018-52 (in Russian)

[20] Sukhinov A I, Chistyakov A E, Shishenya A V and Timofeeva E F 2018 Predictive modeling of coastal hydrophysical processes in multiple-processor systems based on explicit schemes *Mathematical Models and Computer Simulations* **10** (5) pp 648-658 DOI: 10.1134/S2070048218050125

[21] Sukhinov A I, Chistyakov A E, Filina A A, Nikitina A V and Litvinov V N 2019 Supercomputer simulation of oil spills in the Azov Sea *Bulletin of the South Ural State University, Series: Mathematical Modelling, Programming and Computer Software* **12** (3) pp 115-129 DOI: 10.14529/mmp190310