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DREDGED MATERIAL DISPOSAL IN OPEN WATER – CALCULATION OF SUSPENSION DIFFUSION

Gorun V. **Obliczanie dyfuzji zawieny w środowisku wodnym podczas zrzucania gruntów.** W artykule przedstawiono metody obliczeń rozprzestrzeniania się materiału zawieszonego w środowisku wodnym, w tym powstającego podczas zrzutu gruntu z pogłębiania dna do wód morskich. Omówiono opracowaną metodykę niestałej dyfuzji turbulencyjnej zawiesiny w przestrzeni trójwymiarowej.

Горун В. **Расчет диффузии взвеси в водной среде при дампинге грунтов.** В статье рассмотрены методики расчета распространения взвешенных веществ в водной среде, в том числе при сбросе в морскую среду грунтов дноуглубления. Приведена разработанная методика неустановившейся турбулентной диффузии взвеси в трехмерном пространстве.

Keywords: mathematical model, unsteady turbulent diffusion, suspended matter, water environment

Abstract

The article considers methods for calculation of suspension diffusion in water environment, including the sea disposal of dredged soil. The developed method of unsteady turbulent diffusion of suspended matter in three dimensions is offered.

INTRODUCTION

Worldwide, the morphology in near-coastal areas is subject to continuous short- and long-term changes on various spatial and temporal scales. These changes are due to the reworking and redistribution of sediments. Consequently, many seaports and shipping channels have substantial sedimentation problems, which lead to a constant need for dredging to maintain the necessary water depths. Furthermore, they have to be adapted to the increasing size of vessels.

Some of the dredged material is reused for beach nourishments or infrastructural projects, but the most of it is dumped on designated offshore dumping sites. This is also the case for the shipping channels in the Azov-Black Sea Basin.

The content of suspended matter in the water environment increases under dumping of soils, which results in its secondary pollution with substances, accumulated in soils.

There are many models describing suspended material spreading after disposal. However, at present there are no reliable techniques on which to carry out the forecast suspension diffusion for short distances (to control points) after dumping.

This study focuses on the analysis of the existent methods for calculation of the suspension diffusion in the water environment, including the disposal of dredged material, and development of a new method for calculation of unsteady turbulent diffusion of a suspended matter in a three-dimensional space.

CALCULATION OF SUSPENSION DIFFUSION IN WATER ENVIRONMENT: A REVIEW

Analytical methods

Analytical methods are used for assessment of the suspended matter diffusion in the water environment under dumping of dredged material for practical purposes. In this case the time required to obtain basic data and calculations is, as a rule, short. Therefore such methods can be applied in operative practice. For example, E. D. MOLDOVANOVA (1987) suggested a method for assessment of the diffusion of suspended matter concentration under dredging, but nonregistering a sedimentation. S. L. BELENKO and A. N. NAUMOV (1988) considered optimization problem in the context of the dumping of dredged material. S.V. KIRILCHIK (2010) performed research into prognostication of suspended matter diffusion under extraction of ferromanganese concretions.

One of the analytical methods for calculation is an application of radially symmetric diffusion models.

A. GONCHAROV (1986) and A. PROZOROV (2000) technique by can be considered as an example of this approach for assessment of the suspension diffusion under dumping of dredged material.

Goncharov formula for general calculation by has the following form

$$\overline{C}(r,t*)=\frac{q}{2\pi(pt*)^2}\exp\left(-\frac{r}{pt*}-\frac{Wt}{D}\right), \quad (1)$$

where: $\overline{C}$ (r,t^*) is the average concentration of the diffusing material (dredged soil), g/m^3, evenly distributed within the layer of thickness D, m;

q – is a mass of the dumped suspension, g, per depth unit within the layer of thickness D, m;

p – is a rate of suspension diffusion, m/s;

t^* – is a fictitious time, considering the effect of dynamic expansion of the initial suspension spot under point-to-point approximation of the source, s;

r – is a distance from the spot center, m;

t – is a real time counted from the moment of dumping, s;

W – is an effective velocity of suspended matter sedimentation, m/s.

Real time t, counted from the moment of dumping, is associated with model time t^* by ratio

$$t = t^* - t_0, \quad (2)$$

where: t_0 – correction to the real time (s) due to the influence of a dynamic effect at the initial dilution, calculated by the formula

$$t_0 = r_0 / p\sqrt{3}, \quad (3)$$

where: r_0 – an equivalent radius of the initial suspension spot, m.

Prozorov equation describes the distribution of the suspended matter content in the diffusing spot with regard to its sedimentation and has a form of

$$C(r,t)=\frac{Q}{4\pi HDt}\exp\left(-\frac{r^2}{4Dt}-\frac{W}{H}t\right), \quad (4)$$

where: $C(r, t)$ is an depth-averaged concentration of suspended matter g/m^3;

r – is a distance from the suspension spot center, m;

D – is a horizontal turbulent diffusion coefficient, m^2/s;

H – is a depth of the studied layer, m;

W – is an effective velocity of suspension sedimentation, m/s;

Q – is a quantity of suspended matter in the studied water layer after dumping of dredged material, g.

An amount of dredged material Q, passing into a suspended state under dumping, is calculated by the formula (PROZOROV, 2000)

$$Q = K \cdot p \cdot V\frac{\gamma-\gamma_B}{\gamma_T-\gamma_B}\gamma_T, \quad (5)$$

where: K is a coefficient of soil transition into suspension state under dumping, expressed as a decimal, being determined by the formula

$$K = 6{,}214\frac{\sqrt{H-h}}{c}\left(\frac{1}{b}+\frac{1}{l}\right), \quad (6)$$

c – is a unit adherence of the damped soil with regard to its desintegration (dilution) in the process of excavation and stowing into barges, Pa;

H – is a depth in the area of dumping site or a thickness of the upper quasihomogeneous layer, m;

H – is a load draught, m;
L – is a length of the bottom door, m;
B – is a width of the bottom door opening, averaged for unloading time, m;
P – is a content of silt and clay particles in the soil smaller than 0.1 mm and forming a true suspended matter, expressed as a decimal;
V – is a discharged volume, m^3;
Γ – is a volume weight of soil in a barge hold taking an account of its desintegration, t/m^3;
γ_B – is a volume weight of water, t/m^3;
γ_T – is a volume weight of soil particles, t/m^3.

Formula (6) makes it possible to assess an amount of soil passing into the suspended matter under damping with regard to the main influences: the properties of dumped soil, stratification and depth in the area of dumping site and technological parameters of dumping.

The idealized calculation techniques, suggested by A. Goncharov and A. Prozorov, are schematic and used to assess averaged integral characteristics of contamination spot on various depths at a certain volume. However, this approach is based on sufficiently simple calculation dependencies, which give a chance to reliably identify such quantitative characteristics: the time for spot occurrence limited by a preassigned value of suspension concentration; specific dimensions and area of the spot.

A three-dimensional transport and diffusion equation is used to simulate suspended diffusion in the case when the spread area is considerably larger than the depth of the water body. However, Yu. S. Yurezanskaya and V. N. Koterov (2009) believe that even if the vertical turbulent exchange has material effect, a three-dimensional problem of the transport and diffusion of polydisperse suspended matter, produced by an instantaneous point source, can be reduced to the integration of two-dimensional (depth-averaged) equation for a monodisperse suspension with time-dependent velocity of sedimentation. In this case the authors suggest using the depth-averaged transport-diffusion model for calculation of suspension diffusion. They suggested and tested a gridless hybrid stochastic method of discrete clouds to implement this model (Yurezanskaya, Koterov, 2009). It combines two techniques, namely the discrete cloud method and the discrete particle stochastic method. The technique, on the one hand, provides calculation of suspension concentrations at large distances from the source, where the concentration of suspended matter is small, and on the other – makes it possible to calculate pollutant diffusion in the case of strongly inhomogeneous flow fields.

In the Yurezanskaya and Koterov (2009) method the diffusion of suspended matter in the water body is a set of 'elliptical' discrete clouds with the following Gaussian distribution of the depth-averaged suspension concentration

$$C = \frac{m(t)}{2\pi H(x_0(t))\sigma'_{1C}(t)\sigma'_{2C}(t)} \exp\left(-\frac{x_1'^2}{2\sigma_{1C}'^2(t)} - \frac{x_2'^2}{2\sigma_{2C}'^2(t)} \right), \tag{7}$$

where: m is the current mass of suspended matter in the cloud;
x_0 – is the coordinates of the cloud center in the global coordinate system.

Local coordinates, measured from the cloud center, are marked with hachures (x_1' – along the water course direction, x_2' – in a perpendicular direction). Every cloud is characterized by the moment of its emergence t_0 and initial dispersions $\sigma_{1C0}'^2$ and $\sigma_{2C0}'^2$. Cloud centers x_0 at every temporal step $\Delta t = t_{n+1} - t_n$ move together with the water and undergo stochastic walks, distributed by normal law, with a total dispersion $\sigma_X^2(t)$ (a dispersion of the random increments of coordinates at each step of the process makes up $\sigma_X^2(t_{n+1}) - \sigma_X^2(t_n)$ respecttively).

A. V. Maslakov (2005) made an attempt to apply the concept of 'a near-field zone', which dimensional scale is correlated with the size of the object, polluting an aquatorium, and the 'a far-field zone', including control points, for calculation of pollution transport from a coastal source (waste-water of a biological treatment plant).

The aforementioned analytical techniques reduce the problem of calculating suspension diffusion to a plane formulation (a depth-averaged suspended matter concentration is considered) with the use of an exponential distribution in space and time. This does not enable us to calculate a turbulent exchange of suspended matter in the water column vertically and simulate secondary peaks of the content of fine suspended matter in the upper layers after dumping (see below).

Numerical methods

A semi-empirical theory of turbulence is most widely used to describe the diffusion of suspended matter in real water bodies. The numerical methods are most common for modelling pollutant diffusion in water bodies.

Numerical models for prognostication of the short-term diffusion of dredged material have been developed by the following authors: R. C.Y. Koh and Y. C. Chang (1973), M. G. Brandsma and D. J. Divoky (1976), Johnson (1990).

The data concerning the 'fate' of dumped dredged soil after the lapse of considerable period upon the dumping are quite scanty. Study of the movement of natural bottom deposits are used for assessment of the nature of these processes and their possible simulation. Two-dimensional models implementing this problem numerically are developed by R. Ariathurai and R. B. Krone (1976).

The models for calculation of the concentration of suspended matter in the pollution cloud generated by the persistent discharge of dredged material with remote pipeline are presented in publications (Shubel, Carter, 1978; Wilson, 1979).

Suspended matter diffusion has been studied by the following Ukrainian and Russian specialists: G. Y. Shkudova (1977) – the models of pollutant transport in a shallow barotropic and a deep baroclinic sea, S. V. Afanasiev (1986) – the model of turbulent diffusion of suspended matter, and L. Y. Trukshane (1992) – conducted research into the dispersion of pollutants in dredged material. S. A. Lonin (1994) and D. V. Alekseev (2008) dealt with suspension diffusion at the North-Western shelf of the Black Sea.

The mentioned models provide satisfactory prognostic estimates of suspension distribution on basin-wide scale, since they study the large-scale fields of pollution with a grid size of several kilometers. During assessment of the water environment quality, under rate setting for pollution discharges and evaluation of various types of damage it is necessary to know the maximum concentration of suspended matter in a control point, located 250–500 m from the pollution source. Unfortunately, in the viewed publications the authors did not mention dependences, which can help to perform the calculations.

An optimization numerical model to select dumping sites was suggested by A. A. Goncharov (1988). The model is built on a three-dimensional turbulent diffusion equation and makes it possible, on the basis of the adjoint problem through exhaustive search of a source functional, to obtain the source coordinates, ensuring a minimal impact (concentration of suspended matter) in this area.

In Eco-Express-Service (2012) an equation of suspension diffusion in the sigma-coordinate system has the following form:

$$\frac{\partial C_i}{\partial t}+\frac{\partial C_i UD}{\partial x}+\frac{\partial C_i VD}{\partial y}+\frac{\partial C_i(\omega+\omega_c)}{\partial\sigma}=\frac{\partial}{\partial\sigma}\left[\frac{K_c}{D}\frac{\partial C_i}{\partial\sigma}\right]+$$

$$+\frac{\partial}{\partial x}\left[DA_c\frac{\partial C_i}{\partial x}\right]+\frac{\partial}{\partial y}\left[DA_c\frac{\partial C_i}{\partial y}\right]+Q(x,y,\sigma), \tag{8}$$

where: x, y, σ, t define the coordinate system;
C_i – is a concentration of fraction of suspended particles, g/m^3;
U, V – is the horizontal components of flow velocity, m/s;
Ω – is the vertical component of velocity, normal to the sigma-surface, m/s;
ω_{ci} – is an own gravitational vertical velocity of a fraction of suspended particles, m/s;

$$D=H+\eta, \tag{9}$$

H – is a depth, m;
H – is a level, m;
K_c and A_c are horizontal and vertical turbulent diffusion coefficients, m^2/s;
Q – is the source of pollution, g/(m^3*s).

Eco-Express-Service (2012) considers a model of steady turbulent diffusion of suspended particles. However, the use of the suggested differential equation in rectangular coordinates in three-dimensional formulation of the problem in the case of unsteady turbulent diffusion is too complicated owing to the necessity for a very large number of calculations. For example, the description of suspended matter distribution in a pollution spot at some point of time in cylindrical coordinates takes one sheet, and with the use of this model in rectangular coordinates it will take several sheets.

The numerical methods, based on a differential equation (8), enable us to perform calculation with rather complete advection-and-diffusion equations, model quite arbitrary hydrodynamic regime and complicated dependencies of the coefficients on environmental conditions, as well as to take an account of various types of source functions and boundary conditions. Their scientific value is undeniable. However, these models encounter the problem of assignment for a dimensional distribution of the current field. Typically, this model includes a hydrodynamic unit. Circulation is simulated on the basis of this unit. But this results in even greater uncertainty of assignment for initial and boundary conditions, and model parameters. Their application for quantitative assessment of real processes is limited.

METHOD OF UNSTEADY TURBULENT DIFFUSION OF SUSPENDED MATTER IN THREE DIMENSIONS

Materials and results

The suggested method for unsteady turbulent diffusion of a suspension makes it possible to calculate a field of suspended matter concentration in the pollution cloud in three dimensions at different points of time after the dumping. This method is obtained by means of solving numerically the mathematical model for unsteady turbulent diffusion of a suspended matter in a cylindrical coordinate system (Yurasov, Gorun, 2010).

The following problem was considered. There was a volley discharge of suspension with hydraulic size *u*. The pollution cloud of a cylinder shape with a height *H* was generated after dumping. The mass transport in this cloud due to the turbulent diffusion is steady in all directions from the central axis. In plan the pollution cloud looks like a circular-shaped spot with an initial radius r_0.

The pollution cloud along horizontal line is divided into rings with a step Δr, and along vertical line – into layers with a step Δy. Distribution of the suspended matter concentration in it is examined at regular time intervals Δt.

The beginning of the coordinate system is the point of crossing of the cylinder vertical axis (*OY*) with the water surface. Position of a point in the horizontal plane of the coordinate system is assigned by rotation angle ϕ and distance *r* from the vertical axis *OY*. An origin of coordinates is always in the centre of the considered cloud and moves together with it, with an average flow velocity.

Mathematical models for unsteady turbulent diffusion of a suspension with hydraulic size *u* in the plane (polar coordinates) and dimensional (cylindrical coordinate system) formulation of the problem can be written as:

$$\partial C/\partial t = D(\partial^2 C/\partial r^2) + D/r(\partial C/\partial r) - uC/H, \tag{10}$$

$$\partial C/\partial t = D(\partial^2 C/\partial r^2) + D/r(\partial C/\partial r) + D(\partial^2 C/\partial y^2) - u\partial C/\partial y, \tag{11}$$

where: *C* is a concentration of a substance, g/m^3;
t – is a time counted after the dumping, s;
D – is a turbulent diffusion coefficient, m^2/s;
H – is a water depth, m;
R – is a radius – distance from the center of a coordinate system to the required point, m.

The differential equation (11) (with the equation (10) being a special case) is based on V. M. Makkaveev general equation of suspension turbulent diffusion in a rectangular coordinate system (12) and A. V. Karaushev (1987) unsteady turbulent diffusion of nonconservative substances in polar coordinates (13):

$$\frac{\partial C}{\partial x}V_X + \frac{\partial C}{\partial y}V_Y + \frac{\partial C}{\partial z}V_Z + \frac{\partial C}{\partial t} = D\left[\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}\right] - u\frac{\partial C}{\partial y}, \tag{12}$$

$$\partial C/\partial t = D(\partial^2 C/\partial r^2) + \left[D - Q_{CT}/(\varphi H)\right]/r(\partial C/\partial r) + Ck_H, \tag{13}$$

where: V_X, V_Y, V_Z are the projection of the averaged vector of current velocity on the axis of the coordinate system, m/s;

Q_{CT} – is waste water consumption, m^3/s, equaling 0 under volley discharge;
ϕ – is an angle of the sector, which receives waste water, rad;
k_H – is a coefficient of nonconservative substances.

Equation (12) can be easily reduced to an object scheme by means of fixing the origin of a rectangular coordinate system into the center of the contamination cloud on the water surface. In this case, one last summand ($V_X = V_Y = V_Z = 0$) remains on the left side of (12). However, it is very difficult to implement a numerical experiment in a dimensional problem statement by using a differential equation in this form (see above).

The model, presented by the differential equation (11), describes, in contrast to (12) and (13), the turbulent diffusion of a suspended matter in the pollution cloud in space (in cylindrical coordinate system) and time, and makes it possible to implement the numerical experiment relatively easy.

A solution of the equations (10) and (11) by means of the method of finite differences has the following form:

$$C_{k+1,n} = (1-2a-2f)C_{k,n} + a(bC_{k,n+1} + dC_{k,n-1}), \tag{14}$$

where: $a = D\Delta t/\Delta r^2$, $b = 2n/(2n-1)$, $d = 2(n-1)/(2n-1)$, $f = u\Delta t/2H$,

$$C_{k+1,n,m} = (1-2a_1-2a_2)C_{k,n,m} + a_1(bC_{k,n+1,m} + dC_{k,n-1,m}) + \\ +(a_2 - f)C_{k,n,m+1} + (a_2 + f)C_{k,n,m-1}, \tag{15}$$

$$C_{k+1,n,1} = (1-2a_1-a_2-f)C_{k,n,1} + a_1(bC_{k,n+1,1} + dC_{k,n-1,1}) + (a_2 - f)C_{k,n,2}, \tag{16}$$

$$C_{k+1,n,M} = (1-2a_1-a_2-f)C_{k,n,M} + a_1(bC_{k,n+1,M} + dC_{k,n-1,M}) + (a_2 + f)C_{k,n,M-1}, \tag{17}$$

where: $a_1 = D\Delta t/\Delta r^2$, $a_2 = D\Delta t/\Delta y^2$, $f = u\Delta t/2\Delta y$,

Index k denotes a time step Δt; n is a number of rings Δr wide; m is a number of layers Δy thick; M is a total number of layers by depth; a non-dimentional parameter f takes an account of the exchange of a suspended matter in the flow between the layers and its removal from the water environment due to sedimentation.

The equation (14) is a solution to the problem in a two-dimensional statement, the equations (15) - (17) – in a three-dimensional statement. (15) is a solution for the water column, (16) – for the surface and (17) – for the bottom layers.

The performed numerical experiments (YURASOV, GORUN, 2010) have shown that the developed numerical model adequately responds to changes in the initial conditions:

– If the suspended matter at the initial point of time is situated only in the top layer, its amount in the pollution cloud remains constant until the moment when it reaches the bottom layer. After the moment of contact with the bottom, quantity of the suspended matter begins to decrease, due to its sedimentation on the bottom;

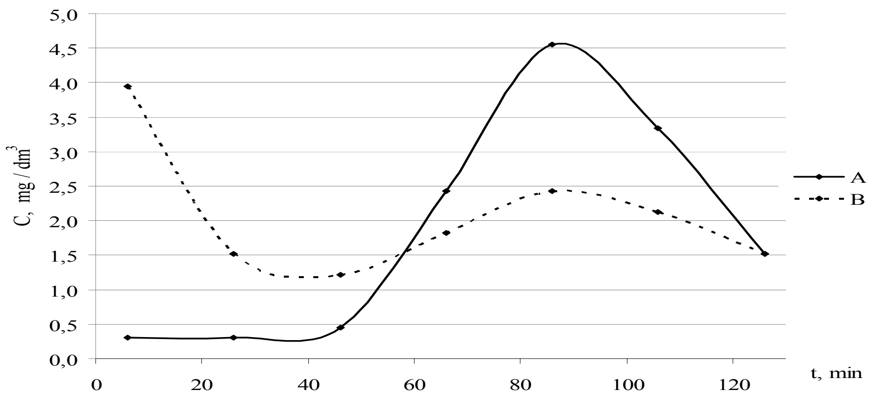
– If the suspended matter at the initial time is located only in the bottom layer, its concentration in the upper layers of the flow increases until the certain point of time, due to the vertical turbulent diffusion. In this case the total amount of suspended matter in the pollution cloud decreases due to the sedimentation on the bottom. After reaching the maximum at a certain time point, the concentration of suspended matter in the upper layers begins to decrease gradually.

The results of field researches conducted in the dumping site at the Equi Island in the Gulf of Finland (SAARSO, GONCHAROV, 1988) were viewed to demonstrate the advantages of the suggested method. The observations showed that after the lapse of a certain time from dumping the concentration of a suspended matter in the upper layers of the water body had increased (fig. 1a). This phenomenon, according to the authors (SAARSO, GONCHAROV, 1988), may be associated with:

-firstly, the destruction of unstable aggregates composed of small particles (mostly fraction A), since these aggregates could be formed in the process of consolidation of sediments at the place of soil intake;

-secondly, the processes of suspended matter carry-over from the lower supporting layers (thermocline and bottom ones).

a) Results of field researches at the Equi Island



b) Results of the numerical experiment

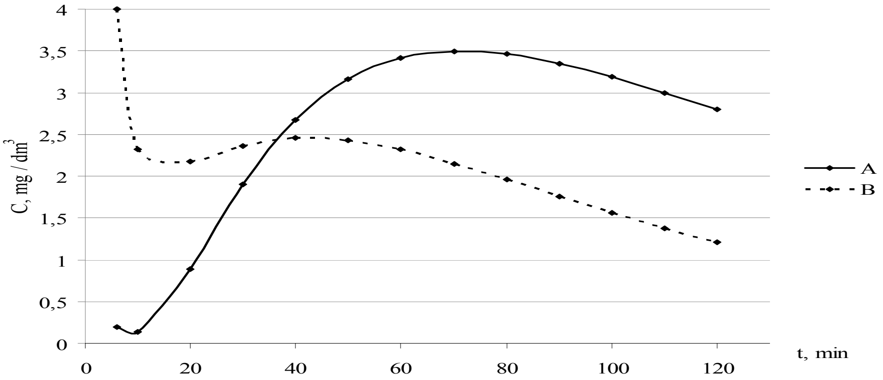


Fig. 1. Changes in the suspended matter concentration by fractions in time on 10 m horizon.
Fraction notations: A – 0.025–0.05 mm, B – 0.05–0.1 mm

Rys. 1. Zmiany w koncentracji zawiesiny według frakcji w czasie na 10 m w poziomie.
Przedziały frakcji: A – 0.025–0.05 mm, B – 0.05–0.1 mm

The second hypothesis seems more plausible. This is confirmed by the results of numerical experiments based on the suggested method: the obtained pattern for concentration dynamics of fine suspended particles in the upper layer was similar to the field observations. The secondary peak of their content appears in the case if suspended matter concentration in the lower layers just after dumping is much higher than in the upper layers (fig. 1b) (GORUN, YURASOV, 2012).

The comparison of field and calculated suspended matter concentrations was impossible to be conducted due to the lack of information on the hydrodynamic conditions in the area of dumping and the ship location on the pollution spot.

Recommendations for the calculation of suspension diffusion in the water environment and the verification of calculation accuracy were elaborated on the basis of the research.

CONCLUSION

1. A disadvantage of the analytical methods is the reduction of the problem for calculating suspension diffusion to a plane formulation. In this case a vertical turbulent diffusion of a suspended matter in the water body is not considered.
2. The existent numerical methods provide satisfactory forecasts of the suspension diffusion in the basin-wide scale, because they simulate large-scale pollution fields with the grid size of several kilometers. However, they are not applicable for assessment of suspension diffusion on short distances: from the point of soil dumping to the control point, located 250–500 m further.
3. The suggested method of unsteady turbulent diffusion of a suspension makes it possible to calculate a field of suspension concentration in a pollution cloud in a three-dimensional space at various points of time after dumping.

In contrast to the methods in a two-dimensional problem statement, the suggested model provides an opportunity to study turbulent diffusion of a suspension vertically and obtain a secondary peak of its content in the upper layer after dumping at the expense of suspension carry-over from the lower layers.

The non-dimentional parameter *f* in the model takes an account of the exchange of a suspended matter in the flow between the layers and its removal from the water environment due to sedimentation.

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