Numerical simulation of hydrological and ecological regime of Siberian rivers' estuaries in the Russian sector of the Arctic

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Abstract. Numerical simulation of hydrological and hydro-chemical regimes is performed using the mathematical model of water quality, developed at Lavrentyev Institute of Hydrodynamics SB RAS. This method is based on the one-dimensional Saint-Venant equations and the transfer equation of heat, oxygen and other impurities. The paper presents examples of numerical simulation.

1. Introduction

Global warming and intense development of the Arctic requires a thorough investigation (study) of the changes taking place in this region. In this regard, the problems of the water quality, protection of water bodies against pollution entering during the construction and operation of industrial enterprises, water resources utilization systems, hydraulic structures, etc., built on the waterways and adjacent territories are of particular relevance.

In some cases, there may be thermal pollution of water bodies caused, for example, by emergency discharges of hot water by industrial enterprises, thermal and nuclear power plants. Assessment of the severity of exposure of a pollution source on the aquatic environment requires considering the resulting hydrodynamic, physical, chemical and biological processes.

2. Material and methods

Numerical modeling of possible changes in hydrological regimes in open water flows and their systems, as well as occurring hydrochemical processes in the case of an unsteady flow, is carried out using mathematical models and numerical methods developed at Lavrentyev Institute of Hydrodynamics SB RAS. To calculate the hydraulic characteristics, we used a system of one-dimensional shallow water equations (Saint-Venant equations) with various alternative options for taking into account surface runoff from the areas adjacent to the watercourse [1, 2]

\begin{align*}
B \frac{\partial Z}{\partial t} + \frac{\partial Q}{\partial x} &= q, \\
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{Q^2}{\omega} \right) &= -g \omega \left( \frac{\partial Z}{\partial x} + \frac{Q|Q|}{K^2} \right) + R_w,
\end{align*}

where \( t \) is the time; \( x \) is the coordinate, counted along the axis of the watercourse; \( Z(x,t) \) is the level of the free surface; \( Q(x,t) \) is water flow rate; \( q(x,t) \) is the lateral inflow distributed along the length
of the watercourse; \( B(h, x) \), \( \omega(h, x) \), \( K(h, x) \) are the width of the free surface, the cross-sectional area, and the module of flow rate at a depth \( h \); \( R \) are external factors (for example, wind upsurge (negative surge), the barometric pressure gradient); and \( g \) is the acceleration of gravity.

To calculate the water quality characteristics we used single-type transfer equations of heat, oxygen and other substances, namely: the heat balance equation, the equation of biochemical oxygen demand, and the equation of dissolved oxygen. The latter can be written in a general form

\[
\frac{\partial}{\partial t} (\omega Y) + \frac{\partial}{\partial x} (Q Y) = \frac{\partial}{\partial x} \left( \omega E \frac{\partial Y}{\partial x} \right) + q Y + F, 
\]

Using the continuity equation, this equation is reduced to:

\[
\omega \frac{\partial Y}{\partial t} + Q \frac{\partial Y}{\partial x} - \frac{\partial}{\partial x} \left( \omega E \frac{\partial Y}{\partial x} \right) = F + q(y - Y). \tag{1}
\]

Here \( Y(x, t) \) means either water temperature \( T(x, t) \), or biochemical oxygen demand (BOD) per unit volume of water \( L(x, t) \), or the concentration of dissolved oxygen \( c(x, t) \) or salt \( S(x, t) \) (or concentration of any dissolved substance); \( y \) is the characteristic of water quality: \( T_q(x, t), L_q(x, t), c_q(x, t) \) or \( S(x, t) \), coming together with the distributed inflow (outflow) of water per unit length of the watercourse; at that, \( q \leq 0 \), then \( y = Y \), otherwise \( y \) should be set; \( E(h, x) \) is the longitudinal dispersion coefficient calculated by the Harleman formula [3]:

\[
E = 20.2 \cdot \sqrt{g \cdot |\nu| \cdot R / C},
\]

where \( R \) is the hydraulic radius, \( C \) is the Chezy coefficient; depending on \( Y \) the value \( F \) is determined as follows:

\[
- k_T B(T - T_E), \text{ if } Y \equiv T, \\
- k_\omega L, \text{ if } Y \equiv L, \\
k_\omega (c^* - c) - k_\omega L, \text{ if } Y \equiv c, \\
0, \text{ if } Y \equiv S.
\]

Here, \( k_T \) is the heat transfer coefficient with the environment; \( T_E \) is the equilibrium (or so called “natural”) temperature, i.e. the water temperature at which, in given quasi-stationary meteorological conditions, the heat exchange between the water mass and the atmosphere would cease; \( c^* \) is the concentration of oxygen at saturation; \( k_1(T) \) is the coefficient of mineralization, characterizing the rate of oxygen consumption due to the oxidation of organic contaminants (coefficient de-aeration); \( k_2(T) \) is the coefficient of re-aeration, characterizing the rate of oxygen income from the atmosphere [4].

The GIDR software package, created on the basis of the developed numerical methods and algorithms, allows implementing these computer based algorithms for solving a broad range of research and practical (applied) tasks on the hydrological and environmental justification of various water resources utilization projects, assessment of possible negative impacts on the environment, and
the development of effective protective measures in case of catastrophic phenomena on water bodies [5].

The numerical simulation was carried out using the DSIGMA software package included in the "GIDR" software package for calculation of unsteady water movements in branched systems of watercourses and channels taking into account water quality [6]. The package programs are universal, because they allow automatic adjustment for operation of any of the six modes mentioned below. In addition, they have a flexible modular structure, which allows making adjustments to blocks or replacement of some blocks with others and, if necessary, supplement the missing ones.

By means of the package programs, a wide range of one-dimensional hydraulic problems of open watercourses (channels) can be solved, for example, described in [7, 8]. These problems include the following:

- floods and releases, high water, daily and weekly regulation in the pool of hydro power plants;
- thermal pollution of water caused, for example, by emergency discharges of hot water by industrial enterprises, thermal power plants, and nuclear power plants;
- biochemical oxygen demand (BOD) of water;
- the concentration of oxygen contained in the water of rivers and reservoirs, necessary to the flora and fauna for their satisfactory habitat in the aquatic environment;
- water pollution by various impurities (water salinity or any other water-dissolved conservative substance).

3. Results.

A stream with a real morphometry consisting of 2 segments with a total length $L_{общ} = 156 \text{ km}$ is considered. At the junction of the segments (x=85 km) is the source of the contamination, occasionally discharging into a watercourse wastewater at a certain flow rate $Q^*(t)$ with characteristics of contamination $T^*(t), L^*(t), C^*(t), S^*(t)$ varying time. When calculating we used the following boundary conditions for the hydraulic equations. In the entrance range of the 1st segment: the water flow rate $Q(t)$ changing in time (3-hour rise of the flow rate from 1000 to 1500 m$^3$/s followed by further (after 9 hours) 6-hour descent to a constant value of 1000 m$^3$/s; in the main-stream station (outlet) of the system (the end of the 2nd segment) water level was constant in time $z(t)=78,75=\text{const}$. In Figure 1 at the top of the beginning of the 1st segment ($I_n$), characteristics of water quality of flow incoming through this cross section, needed for the substance transfer equations, are given. In the closing part of the 2nd segment, the boundary condition is not required, since it is produced by the transport equations themselves, assuming that at a great distance from the place of discharge of impurities (heat), the role of longitudinal dispersion becomes negligible, (i.e. $E = 0$), and the impurity concentration (temperature) at this boundary is determined mainly by advection transport. Thus, the equation (1) is reduced to the form:

$$\frac{\partial}{\partial t} (\omega Y) + \frac{\partial}{\partial x} (QY) = F,$$

The initial conditions for the hydraulic characteristics assumed a steady state condition, obtained by calculating for establishment of flow rate $Q^0=1000 \text{ m}^3/\text{s}$ and quality characteristics constant in time: temperature $T^0=200 \text{C}$, BOD=0, oxygen concentration $C^0=3 \text{ mg/l}$ and concentration of impurities $S^0=5 \text{ mg/l}$. The calculation was conducted with a time step $dt=600 \text{ s}$, which was constant throughout the estimated period of time $t=0-120 \text{ h}$. At that, the length increment on the 1st segment was equal to 2900 m, while on the 2nd segment – 3050 m. The Chezy coefficient was calculated according to the full formula of N.N. Pavlovsky, while the dispersion coefficient – according to the formula of Harleman.
The calculation results, shown in Figure 1 for the ends of the calculation segments, clearly reflect the changes in water quality characteristics, and allow tracing visually the process of distribution (restoration) of the watercourse depending on pollution (from top to bottom): water temperature (T), oxygen concentration (C), BOD (L), and the concentration of other impurities in water (S).

The analysis of the obtained results shows that in consequence of the provided operation mode of the treatment plant located at the junction of the segments, the consequences of emergency wastewater discharge can be eliminated only by the end of the 5th day, i.e. the achievement of water quality characteristics in the watercourse typical for its initial natural conditions.

![Figure 1](image.png)

Figure 1. Distribution of temperature, oxygen, BOD and impurities in time at the ends of the segments.

4. Conclusion
The results obtained show the possibility of using this mathematical model for the study and prediction of water quality in the watercourse: the restoration of water quality performance, which was worsened due to the pollutants discharged into the watercourse to environmentally friendly standards required for flora and fauna.

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