The Application of Computational Fluid Dynamic Models for Research of Wastewater Marine Outfalls in Ice Cover Periods

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Abstract. The research of pollutant transfer process in ice-covered marine water areas has a great practical interest. The understanding of pollution transfer and transformation processes in freeze-up period is necessary in conditions of active development of the Arctic Coast and in design a long-term prediction of water quality. The detailed research of wastewater transfer in ice-covered marine water areas in Russia factually not been produced despite the fact, that in practice all type of coastal outfalls realized in the Far Eastern seas, which freeze-up period during from 4 to 6 months.

The submitted research shows the results of field studies of wastewater outfalls of Vladivostok city. The field studies results was compared with results of wastewater transfer calculations, making by engineering methods and results of simulation, produced by CFD (Computational Fluid Dynamic) models which implemented in the Ansys Fluent application software package.

As a result of a comparison of the field study data and calculation results, was found that the official recommendations for calculating wastewater dilution give a significant error in calculating wastewater dilution in case of discharged into ice-covered marine water areas. A positive result was obtained for application of CFD models for research of marine outfalls in periods of water freezing.

1. Introduction
The research of pollutant transfer process in ice-covered marine water areas has a great practical interest. The understanding of pollution transfer and transformation processes in freeze-up period is necessary in conditions of active development of the Arctic Coast and in design a long-term prediction of water quality. In addition, the calculation of treatment degree in the design of wastewater treatment plants, in the absence of data on the processes during the freezing period, can lead to negative environmental consequences. The importance of the problem is confirmed by the special attention paid to the organization of sewage discharge into the ice-covered water areas in some international agreements [2, 10]. The detailed research of wastewater transfer in ice-covered marine water areas in Russia factually not been produced despite of the fact, that in practice all type of coastal outfalls realized in the Far Eastern seas, which freeze-up period during from 4 to 6 months.

2. Previous studies
The quality characteristics of sea water in discharge place in Russia calculated according the official recommendations of “Calculation manual of standards for discharges of substances and microorganisms into water bodies for water users // Approved by Ministry of Natural Resources of Russia of December 17, 2007 N 333” [5].
Traditionally, the wastewater discharge standard, which includes the flow of wastewater and pollutants concentration, is determined by the dilution degree. The dilution, in turn, is divided into the initial (jet), which the excess jet momentum is responsible, and the diffusion, associated with the turbulence of the receiving stream. Jet dilution forms a concentration field in the local zone near the outlet and depends on its design and, therefore, is controllable. Diffusion dilution is determined by sea turbulence, which is characterized by a turbulent diffusion coefficient. A sufficiently large volume of calculations of dilution in shallow seas showed that jet dilution is 3-4 times higher than the main one and is the dominant factor determining the degree of wastewater treatment and the cost of construction of wastewater treatment plants (WWTPs).

The work [5] does not contain recommendations for calculation the discharge standard in ice-covered marine water areas, however, given the references to the works [12, 14]. The work [14] contains information about the impossibility of using active nozzles in case of using scattering outfalls in a reason of the possibility of their mechanical damage by the ice field. More interesting is the work [12] which it is noted that during ice formation in water areas are created the conditions that are favorable for the accumulation of pollutant in the places of discharge. As a calculation method for determining the concentration of pollutants in discharge area in [12] was proposed a finite-difference scheme for calculating the turbulent diffusion equations in cylindrical coordinates.

It is worth noting that although [5] does not contain the recommendations for the calculation dilution in ice-covered marine water areas, in part, the issues of wastewater discharge during periods of ice cover have been resolved for other water bodies. In particular, for rivers there is a decrease the coefficient of turbulent diffusion due to friction of water on the lower surface of ice.

The original method for determining the normative-permissible load on the marine areas during periods of freeze-up was proposed in [13]. Taking the methodology [5] as a basis, the author adapts the calculated dependencies for the conditions of the western sector of the Russian Arctic. As an optimal discharge point author designated marine waters with well developed tidal currents of 0.5-0.7 m/sec or more, a depth of more than 3 m. Calculation of the dilution is make for the worst conditions, in which the author designates a 2nd half winter - the presence of extensive land fast ice and great cohesion of ice.

A large amount of data about marine outfalls in freeze-up period was accumulated by foreign researchers during realization of the Arctic programs.

The environmental impact assessment of the treated wastewater discharge from the polar station Davis, Australia is given in [16]. Pollution spread along the coastline, pollutants were recorded at a distance of 50 m to 2 km from the place of discharge. In the work, the authors noted an insufficient initial and main dilution of wastewater.

Detailed research of wastewater outfalls were carried out as part of the implementation of the Antarctic program at Mc Murray Station, USA [8]. Here, the most interesting are the results of pollution transport modeling made by using the CORMIX software package [9]. During the simulation were realized 2 scenarios - the discharge of treated wastewater and a mixture of wastewater and brine from a desalination station. For all cases, the model predicts that the wastewater stream rises to the bottom of the ice and gradually spreads horizontally. Further modeling shows that the pollutants will spread along the coastline. Although there are known the cases of successful application of the CORMIX for describing the pollutions in rivers during the periods of ice cover, the authors of [9] note that the results may not correspond to the reality, since the CORMIX models do not describe the effects of wastewater density changes during their cooling.

In general, it can be argued that ice cover at the outfall point has an impact on pollution transport, which can be divided into two types: in the presence of an ice field, there is no wind mixing, can formed a special conditions in water areas, which contributing to the accumulation of pollution or the displacement of pollution by new portions of waste water; the bottom surface of the ice creates a roughness similar to the roughness at the bottom, which changes the nature of the ice flows. The authors of [15] come to similar conclusions by adding to these effects the structure of the lower surface of the ice and the effects of jet sticking to the lower surface of the ice.
3. Excremental research

3.1. Field study

To identify the spread of pollution in the local area at the place of discharge of sewage into the ice-covered areas was made a series of field studies. As the objects of the research was chosen marine outfalls of WWTPs of Vladivostok City. As of 2019, wastewater discharges in Vladivostok City are carried out in the Amursky and Ussuriysky gulfs through 29 outfalls. Some of this outfalls use only for emergency discharge or for discharge of storm waters and don’t use in a cold period of the year. Discharge from Vladivostok WWTP carried out in the north part of the Amursky Bay and the Bay of the Kirpichny Plant; discharge of treated wastewater from the "The South" WWTP carried out in the non-freezing Ussuriysky Bay. So, as the objects of our research was chosen "The North" and "The Central" WWTPs. The brief description of the research objects is given below.

The "The North" WWTP includes structures for mechanical, biological, deep treatment and disinfection. In 2017, carried out works to modernize the station in a complete biological treatment plant with remove biogenic elements, which consist in setting up an anaerobic treatment zone based on primary sedimentation tanks and separating the anoxide treatment zone in the total aeration tank volume (A2O purification scheme).

"The Central" WWTP estimated capacity of 160 000 m3/day, is located in the valley of the Second River, in proximity to the MUP "Special Plant № 1". The technological scheme of cleaning without primary settler includes mechanical cleaning (grates, horizontal sand traps), aeration tanks, secondary horizontal settlers, after-treatment filters and ultraviolet disinfection.

The characteristics of outfalls are summarized in table 1.

| Characteristic                          | “The Northern” WWTP | “The Central” WWTP |
|----------------------------------------|----------------------|--------------------|
| Constructive                           | Multiport            | Multiport          |
| Material                               | Steel                | Steel              |
| Diameter, mm                           | 830                  | 1600               |
| Length, m                              | 1300                 | 1200               |
| Ports number                           | 3                    | 5                  |
| Ports pitch                            | 4                    | 5                  |
| Port diameter, mm                      | 300                  | 800                |
| Depth, m                               | 2.5                  | 10.4               |
| Flow rate, m/s                         | ≈ 0                  | ≈ 0                |
| Wastewater flow, m3/day                | 14231                | 79032              |
| WWTP design capacity, m3 / day         | 57000                | 160000             |
| Wastewater temperature, ° C            | 4                    | 15                 |

To identify the spread of pollution in the local area at the place of discharge of sewage into the ice-covered offshore areas in the period from 2015-2019, were conducted a series of field studies.

The difference in salinity of sewage and seawater made it possible to use the method of indicators to identify the pattern of pollution formed during the long-term discharge of sewage. The essence of the method is to establish the distribution of pollutants to change the conductivity of sea water. The technique of experiment is described in [6].

Samples were taken from ice from the drilled hole. Samples were taken with a bathometer from three water horizons (at the bottom, in the middle water and in the upper (under-ice) layer). During the field research, the depth, water temperature, ice thickness were recorded. Sampling locations were recorded using GPS. After sampling, the samples were delivered to the laboratory and immediately analyzed. Samples were analyzed on the basis of the laboratories of the Institute of Chemistry of the
Far Eastern Branch of the Russian Academy of Sciences. With the help of a conductivity meter, the conductivity of water was determined, which was converted into salinity based on known dependencies. The background salinity of sea water was determined to remove at least 500 m from the place of release.

As the results of field studies was made a diagrams of salinity of sea water at the discharge point that is shown in Figures 1 and 2.

**Figure 1.** Salinity diagrams of sea water in a local area near "The North" WWTP outfall, northern part of Amursky Bay, DeFreeze peninsula region.

An analysis of the field study results of "The North" WWTP discharge point shows that:
- Spread of wastewater take place in the upper horizons of water without mixing with sea water;
- Sea flow in the place of discharge practically absent, the spread of the pollution spot take place in the radial direction;
- The temperature of waste water in the place of discharge does not exceed 1 °C, which is connected with the length of outfall and the mode of operation of the treatment plant;
- Changes in ice thickness and wastewater temperature have a southern direction. This is explained by the availability of free water surface and the northern direction of the prevailing wind of the cold season.

**Figure 2.** Salinity diagrams of sea water in a local area near the outfall of “The Central” WWTP, Amursky Gulf, Kirpichny Plant Bay.

The picture formed by the deep-water outfall of “The Central” WWTP differs from “The North” WWTP.

At the place of discharge in an ice field, was observed a large area of open water, having an ellipse shape extending from the north-west to the south-east. The size of the area is 350x150 m, the area is located symmetrically relative to the axis of outfall. The maximum sea temperature at the place of release was recorded in the upper horizons of water at a distance of 250 m from the place of release and was 0.4 °C. The thickness of the ice in both studied sections decreased from 0.2 m at the boundaries of open water to 0.3–0.4 m at a distance of 600–1300 m. The density of sea water in depth
at each sampling point is not significantly different from the background, which suggests that the mixing process ends within the boundaries of the open water zone, and the spread of contamination occurs by displacement.

The results of comparing the field studies data and results of the calculations, made in accordance with the recommendations of the official methodology [5] are shown in Figure 3.

![Figure 3](image)

**Figure 3.** The comparison of field studies results and calculations data: left - “The North” WWTP: right - “The Central” WWTP.

As can be seen, the expected value of dilution significantly exceeds the real. And in both cases, the value of the full dilution exceeds the initial. The dilution diagram, constructed from field data, is close to straight path which indicates the absence of diffusion mixing, or that extrusion the pollutants by new portions of wastewater.

Very indicative the results obtained for "The Central" WWTP. In the discharge point there is a large area of open water. In this area the behavior of the jet is very good described by official methodology. Further spread of contamination occurs by extrusion.

### 3.2. Numerical experiment

To establish the reasons for the significant deviation of the calculated dilution values and field data during wastewater discharge in period of ice cover, were carried a series of numerical experiments using the ANSYS Fluent application software package. The CFD solvers in the ANSYS program are based on the finite volume method, in which the computational domain is divided into many cells, for each of which is written a system of laws of conservation of mass, momentum and energy, which in integral form having the form

\[
\frac{\partial}{\partial t} \int_V \rho \Phi \, dV + \oint_A \rho \Phi U \, dA = \oint_A \Gamma_\Phi \nabla \Phi \, dA + \int_V S_\Phi \, dV \tag{1}
\]

where \( V \) - the cell volume; \( A \) – its surface; \( U \) - the speed; \( \Phi = 1 \) for the law of conservation of mass, \( \Phi = U_i \) for the law of conservation of angular momentum in the i-th direction, \( \Phi = h \) (enthalpy) for the law of conservation of energy. Further, the integral dependences are transformed into a system of algebraic equations, the total number of which depends on the physics of the problem and boundary conditions are introduced that specify the values of the desired parameters at the boundaries of the computational domain. After setting the boundary conditions, choose a method for solving the problem and initiate its solution.
Although the CFD models have some drawbacks and limitations [4,17], they are successfully used to research a pollution of marine water areas or their local areas [1,3,9]. In our research, the assignment of boundary conditions and the choice of a model for describing the flows of liquids with different densities were carried out according the recommendations of [7, 11].

In the modeling, a two-dimensional problem was solved. For the calculation were taken the symmetrical axes of the port and the perpendicular axes of outfall. The calculation was made for areas with a length of 500 m away from the place of discharge. In the experiment, an unsteady flow pattern was considered; the time step value was set to 0.01 seconds. The accuracy of the solution at each time interval is 0.001% for all indicators. The convergence of the solution was achieved at each time interval. The total estimated time was 3600 s. The density of sea and waste water was taken according the results of the field study - 999 and 1025 kg/m3, respectively. The conditions at the lateral boundaries were set based on the conditions for ensuring unhindered outflow of water without the formation of back flows.

In case of research the effect of roughness on the lower ice surface, the roughness coefficient was set twice as much that specified in the recommendations [5] for rivers (0.05 - 0.25). The bottom roughness was taken 0.5 mm.

4. Discussion of results

As a result of the simulation, it was not possible to obtain a picture similar to the results of the field studies obtained for “The Central” WWTP outfall. As a possible reason, one can point out the presence of a large area of open water at the discharge point and, as a consequence, the difficulties of modeling wind induced flows. Below are the results obtained for "The North" WWTP outfall.

![Image](Image.jpg)

Figure 4. The effect of the ice surface roughness on the density distribution of the mixture of sea and waste waters at the discharge point of "The North" WWTP. Calculation duration 360 sec. The roughness coefficient of the lower surface of ice: a) 0.05; b) 0.5.

Figure 4 shows that the roughness of the ice surface practically have not affected on the size of the mixing layer, but only affects the distribution of pollutants inside the waste water jet.

These results have a good agreement with the general theory of ice hydraulics, in particular, used in the recommendation [5] for calculating the diffusion coefficients of rivers during the ice cover periods. Specific conditions under the ice cover lead to a decrease in the coefficient of vertical diffusion and a more pronounced stratification effect.

Interesting results were obtained in simulation of the discharge regime (Figure 5). In the process of wastewater discharge are formed epy circulation zones which prevent the initial dilution. These results are confirmed by the data of [18] in which, on the basis of experimental research, in the case of the formation of circulation zones, they recommend excluding initial dilution from the calculation, assuming that the stream of wastewater is evenly distributed vertically and the concentration will decrease due to background turbulence. The condition for the absence of initial dilution in jets with circulation zones according to [18] follows from the continuity condition. In case of the stationary problem, then what volume of water is attached to the jet, the same volume of water should give the jet into the circulation movement. However, field study results and results of simulation do not show
the expected picture. A field of pollutants do not participating in the circulation movement, it localized on the surface of the water area and under ice. Consequently, the impurity is propagated by the flow of a radial stream of wastewater, and a stationary state is not formed in the absence of carrying flows. Figure 5 shows that the uniform distribution of the flow along the depth does not really occur.

![Image of Figure 5 showing the effect of discharge duration on the distribution pattern of the density of the mixture of sea and waste waters in the discharge point of "The North" WWTP. Calculation duration 3600 sec. The roughness coefficient of the lower surface of the ice is 0.05.](image)

**Figure 5.** Effect of discharge duration on the distribution pattern of the density of the mixture of sea and waste waters in the discharge point of "The North" WWTP. Calculation duration 3600 sec. The roughness coefficient of the lower surface of the ice is 0.05.

The results of field studies and computer simulations shows, that the recommendation [5] give overestimated results in the calculation of dilution and, therefore, underestimate the requirements for wastewater treatment. The real picture of the pollutants spread indicates the formation under ice of a zone of increased concentration of undiluted wastewater, which is unacceptable from the environmental safety point of view. This position is noteworthy, since under current legislation under any conditions of discharge, even within the city, it is not necessary to clean to the maximum permissible concentrations (MPC). The situation is further aggravated by the fact that purification to MPC is impossible, primarily for economic reasons.

5. **Conclusions**
   - The official recommendations [5] give a significant error in calculating the dilution of wastewater in case of discharge into ice-covered marine water areas. In such water areas formed undiluted wastewater fields, which cannot predict by recommendations [5]. This situation can lead to an underestimation of the environmental hazard and the wrong choice of the technological scheme in a design of wastewater treatment plants;
   - The main factors preventing effective dilution in ice-covered marine water areas are the absence of flows and a reduction in the depth of the stream. The ice cover prevents wind mixing and creates the prerequisites for the formation of stable multi density flows. In this case, the physical characteristics of ice (roughness, ice hummocks and other) do not significantly affect the nature of pollutants transfer;
• The open water area, which is formed at the place of discharge due to a difference on temperature of marine and waste waters, has a positive effect on dilution, also, the actual dilution values are in good agreement with calculated according to the official recommendations [5, 19];
• An important factor that has a significant impact on the wastewater distribution is the regime of discharge. In stagnant water areas (water under ice, stagnant lakes, etc.) the advective transfer of pollutants is carried out by a stream of wastewater, while the condition of mass conservation is not fulfilled, therefore, the task in such cases is not stationary;
• The CFD models give a fairly accurate picture of wastewater dilution in ice-covered marine water areas and can be successfully used to research this process. This is due to the fact that the main difficulties arising in open water simulation (variable wind flows, waves on the surface of the water, etc.) are absent during periods of ice cover. However, further research is needed to correctly define the conditions of uniqueness;
• To understand the processes of pollutants transfer in shallow water areas, additional studies are needed to explain the formation of multi density flows.

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