Numerical Modelling of the Pollution Distribution from the Underwater Discharge of the Wastewater Treatment Plant near the Heraclean Peninsula of the Crimea under Different Wind Directions

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Abstract: The present paper is focused on the numerical modelling of the pollution distribution in the coastal waters of the Crimean Peninsula from the underwater discharge of the biggest wastewater treatment plant in this area. Calculations are performed using three-dimensional σ-model of marine circulation INMOM (Institute of Numerical Mathematics Ocean Model) with high spatial resolution near the Crimean Peninsula for a one-year period, using WRF (Weather Research and Forecasting model) atmospheric forcing. Simulations are carried out according to the two experimental scenarios that differ in the presence of the leakage place in the pipeline and its absence. Simulation results are used to study temporal and spatial structure of the pollution distribution, taking into account hydrometeorological conditions and their seasonal and synoptic variation.

1 INTRODUCTION

In the case of the Crimean Peninsula, one of the largest sources of marine coastal waters' pollution is connected to the discharge from numerous wastewater treatment plants (WWTPs). The majority of these plants was constructed in the 1970's. Due to physical and technological wear, they now only produce mechanical treatment or generally untreated sewage. The current condition of these plants can significantly reduce water quality. Numerical modelling of pollution distribution from the discharge of the WWTPs makes it possible to estimate the dynamics of this distribution and its impact on coastal waters.

This paper presents simulation results of the pollution distribution from the underwater discharge of the largest WWTP on the Crimean Peninsula, which are obtained with INMOM (Institute of Numerical Mathematics Ocean Model) three-dimensional σ-model of marine circulation.

2 MODEL AND DATA

Three-dimensional σ-model of marine circulation INMOM has been developed at the INM RAS (Institute of Numerical Mathematics of the Russian Academy of Sciences) (Diansky, 2013) and based on the primitive equations of ocean hydrothermodynamics with the Boussinesq and hydrostatic approximations. A regional version of INMOM for the Black Sea (BS) with nonuniform grid near the Crimean Peninsula was developed for this study. To achieve higher horizontal spatial resolution over a specific region of interest, a spherical coordinate system with the location of one of the poles at a point with geographic coordinates 33.96^0E and 44.74^0N was used. As a result, horizontal spatial resolution varies from 200 m near the new pole to 6-8 km on the periphery of the BS (Figure 1). The grid domain in the horizontal plane contained 889×488 points along the model longitude and latitude, respectively. The vertical coordinate was represented by twenty nonuniformly distributed σ-levels to provi-

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de higher resolution near the surface.

Model depths were specified by using the GEBCO data on the Earth's topography with a high spatial resolution of 30’’ available to download from www.gebco.net. However, the initial high-resolution data were smoothed several times and limited by a minimum depth of 4 m. This is a necessary procedure for σ-models because the transformation of the vertical coordinate is used and the function describing undisturbed sea depth should be nonzero and sufficiently smooth (Diansky, 2013).

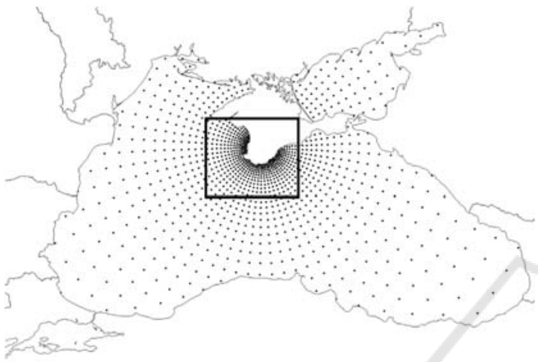


Figure 1: Grid domain of the σ-model of marine circulation INMOM with nonuniform grid near the Crimean Peninsula.

The initial conditions of temperature and salinity were constructed using three-dimensional monthly mean climatic fields of the Azov and the BS. The data from the Atlas were taken as climatic fields of temperature and salinity of the Azov Sea. In the case of the BS, the data were provided by the Marine Hydrophysical Institute of the Russian Academy of Sciences (INM RAS) with a horizontal resolution of 0.1°x0.0625° and with 36 vertical levels, from 0 to 2150 m (Ivanov et al., 2011). All described data were interpolated to the model grid domain.

The calculation of atmospheric forcing for a numerical modelling period of 2011 year was performed using the bulk formulas (Gill, 1986) based on characteristics that were obtained by non-hydrostatic atmosphere model WRF (Weather Research and Forecasting model) with a spatial resolution of 10 km and with a time resolution of 1 hour.

The discharge of the most significant rivers flowing into the BS was specified according to the climatological runoff data (Jaoshvili, 2002).

3 RESULTS AND DISCUSSION

The regional version of INMOM with high spatial resolution near the Crimean Peninsula described above was used to calculate the distribution of pollution from the underwater discharge of the WWTP KOS-1 “Yuzhnye” near the Heraclean Peninsula according to two experimental scenarios. In the first scenario (I), the entire sewage discharge occurred through the pipe head at a depth of 80 m. The length of the pipeline itself was considered to be 3.300 m. In the second scenario (II), we assumed the presence of a leakage in the pipeline at a distance of 500 m from the entrance of the pipeline into the sea and at a depth of 33-35 m, through which half of all sewage was discharged (Figure 2).

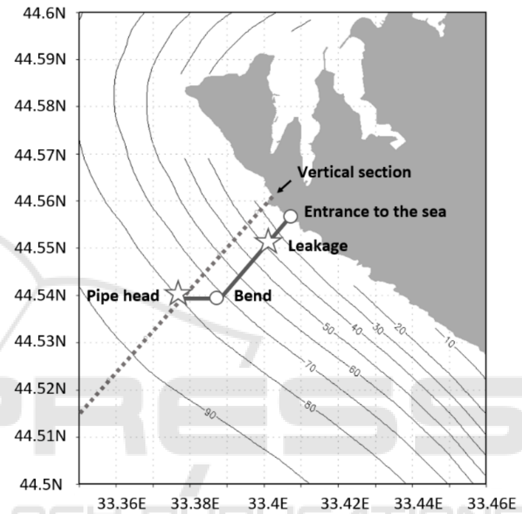


Figure 2: The location of the pipeline is indicated by a solid line. The location of the pipe head and leakage are marked with stars. The entrance of the pipeline into the sea and the location of its bend are indicated by circles. The vertical cross-section to the coast is marked by a dotted line.

The pollution distribution in the case of both experiments was calculated for a period of one year – 2011 – and the annual discharge volume of sewage of 38.300 thousand cubic meters was taken into account. To perform the calculations, the volume concentration of the conditional pollutant in the sewage was assumed to be completely polluted and equal to 1. It was taken into account that sewage affected the distribution of salinity. Therefore, at each model time step, the flow of pollutants into the nearest model cells was calculated according to the volumetric flows of pipes received for this model step, multiplied by the corresponding concentration, and instantaneous dilution of pollutants in the volumes of the corresponding cells. A similar method of calculating the pollution distribution was previously used for the coastal waters of Big Sochi and described in Diansky et al., 2013.

Graphs representing change in the volume concentration of conditional pollutant on the sea surface were drawn at points corresponding to the pipe head location and the location of the leakage place for both experiments and the entire 2011-year calculation period.

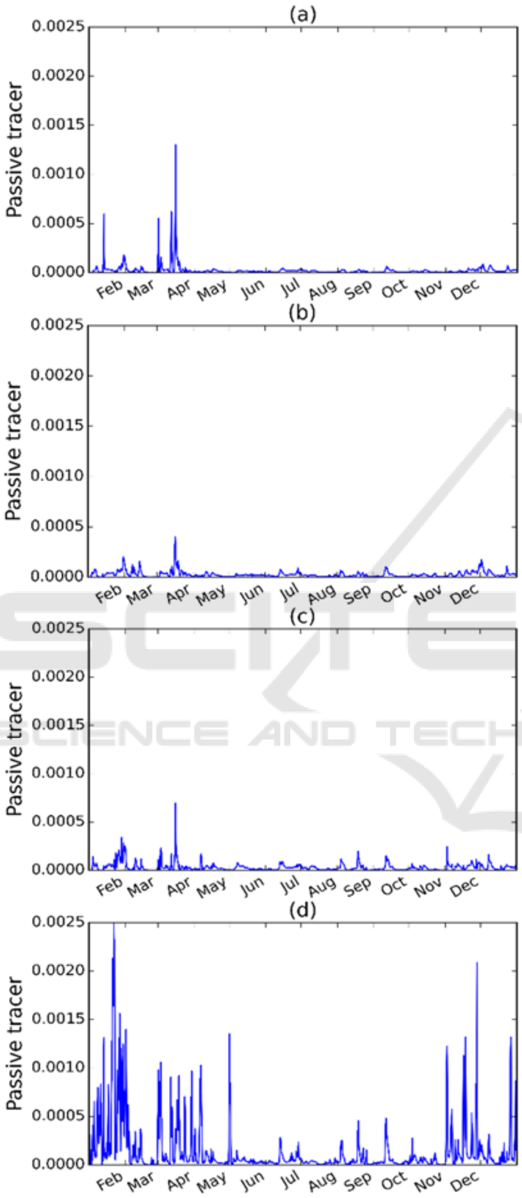


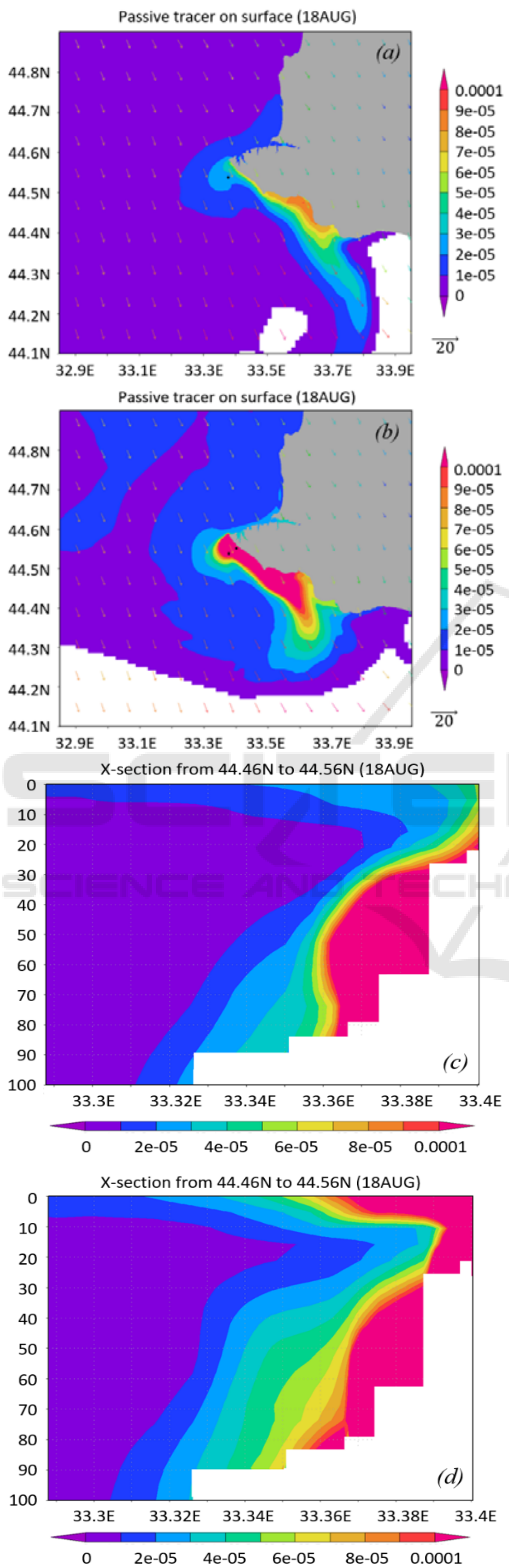
Figure 3: Volume concentration of the conditional pollutant on the sea surface for 2011 year at the points corresponding to the location of the pipe head (a, c) and leakage place (b, d) for two experiments: in the case of the entire sewage discharge through the pipe head (I) (a, b) and the sewage discharge through the pipe head and through the leakage place in equal proportions (II) (c, d). The concentration scale of conditional pollutant is presented in dimensionless units and marked along the y axis.

Based on the results presented in Figure 3 (a-d), the most adverse period of the pollution spread from deeper layers to the surface occurred during the cold autumn-winter and subsequent spring seasons, when the BS vertical water exchange increased and when vertical stratification was weakened due to convective cooling and turbulent mixing (the last one also occurred due to the increased intensity of winds during these seasons). Due to the upper layers warming, as well as the wind speed decrease after the beginning of the summer season, a density jump layer was formed, which usually prevented the release of pollution from deeper layers to the sea surface.

However, in the case of the upwelling, which is found to be a rather common phenomenon in the coastal area of the Crimean Peninsula in the summer season, the polluted water from deeper layers can reach the surface. For the entire period of performed calculations, several similar situations were identified. We conducted an analysis of one of them, dated 18.08.2011, and present it below (Figure 4).

Figure 4 (a, b) shows the pollution concentration on the sea surface on 18.08.2011 under two scenarios (I, II). These maps were reconstructed in a geographic coordinate system by interpolating numerical modelling results on the uniform 1 km grid area. The scale of volume concentrations is presented in dimensionless units, as in Figure 3. The results of numerical modelling confirmed that, depending on the experimental conditions, the most significant differences in the pollution concentration were observed at the sea surface. According to the graphs (Figure 3), the highest concentration of the pollution was noted in the experiment with the sewage discharge through the pipe head and through the leakage place in equal proportions. This was quite predictable because of the closer location of the leakage to the surface (~33-35 m) than the pipe head itself (~80 m).

Figure 4 (c, d) shows pollution concentration maps on the vertical cross-section to the shore (shown in Figure 2) on 18.08.2011, also for both scenarios (I, II). The map data was based on the calculation results, transformed into a geographic coordinate system by interpolating model data on the uniform 1-km grid area, followed by interpolation on 36 vertical levels from 0 to 2150 m and on the vertical cross-section itself. Therefore, vertical coordinates are measured in meters. The scale of volume concentrations, as in the case of the pollution concentration on the surface, is presented in dimensionless units.



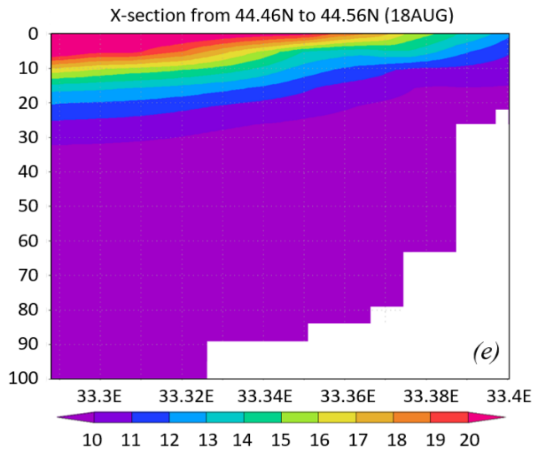


Figure 4: Volume concentration of the conditional pollutant on the sea surface on 18.08.2011 in the case of the entire sewage discharge through the pipe head (I, a) and the sewage discharge through the pipe head and through the leakage place in equal proportions (II, b). The concentration scale of conditional pollutant is presented in dimensionless units and shown on the right. The vectors of wind velocity near the sea surface with the scale of arrows in cm/s are also indicated on the right of the figures and are additionally marked on the maps. The volume concentration on the vertical section, the position of which is shown in Figure 2 on 18.08.2011 in the case of two different scenarios: (I, c); (II, d). The concentration scales in dimensionless units are shown below. (II, e) - temperature distribution on the vertical cross-section to the shore on 18.08.2011. The scale in °C is shown below. Vertical coordinates are measured in meters.

Using the presented pictures and considering the temperature distribution on the vertical cross-section in Figure 4 (e), it can be concluded that on 18.08.2011 there was an upwelling caused by the north-east wind when the coast was to the left of the wind direction. According to existing studies, this situation is found to be quite common in the coastal area of the BS (Silvestrova et al., 2017). At the same time, the integral Ekman transfer in the upper quasi-homogeneous layer was directed from the coast, which lead to a compensatory rise of the underlying, colder waters, which sometimes come to the sea surface (Silvestrova et al., 2017).

Figure 5 shows wind velocity and its direction in August 2011 at the closest point to the pipe head and the leakage place location, according to the WRF data on the wind speed at 10 m height. The time scale along the x axis is represented by the number of the day in a year. Respectively, the date of 18.08.2011 is equivalent to 230 days. According to the analyzed graph, several days before the date of interest, the wind strengthened and the north-west wind along the coastline prevailed.

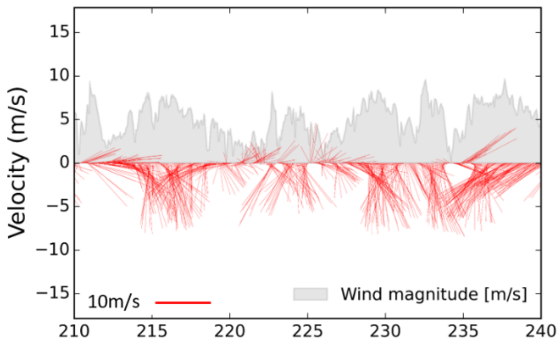


Figure 5: The wind velocity (m/s) and direction for August 2011 at the point closest to the pipe head and to the leakage place according to the WRF data. The velocity of the wind is represented by a shaded gray graph; wind direction corresponds to red vectors, measured from the north azimuth. The scale of the vectors in m/s is placed at the bottom of the picture. The timeline is represented by the numbers of days in a year.

It additionally confirmed the presence of the upwelling phenomenon and it can be concluded that because of the integral Ekman transfer arising due to the intensification of northwestern and western winds, polluted water raised from the deeper layers and reached the sea surface at the sites of sewage discharges, especially in the case of the leakage, which can seriously affect the state of the marine environment of the considered coastal area.

4 CONCLUSIONS

As part of the presented study, we developed a regional version of the INMOM for the BS with the nonuniform grid, horizontal spatial resolution of which is increasing from 200 m near the Crimean Peninsula to 6-8 km on the periphery of the BS. It allowed us to calculate the pollution distribution from the underwater discharge of the WWTP with the high spatial resolution and gave us an opportunity to study the temporal and spatial structure of the pollution distribution, taking into account hydrometeorological conditions and their seasonal and synoptic variability.

It was shown that the most adverse period of the pollution transport from deeper layers to the sea surface was occurring during the cold autumn-winter and subsequent spring seasons, because of the increasing vertical water exchange and weakening of vertical stratification. However, even after the beginning of the summer season, when a density jump layer is usually formed in the BS, due to the upwelling, the polluted water from deeper layers can reach the surface.

The analysis of the numerical modelling results from the experiments with two different scenarios showed that in the presence of a leakage place in the pipeline the release of pollution to the sea surface occurred more intensively than in the case of its absence. Therefore, the state of the pipeline also requires further research to take all necessary measures to reduce the anthropogenic load on the ecological state of the coastal area. It is also noted that the pollution distribution beyond the sea surface horizon should be researched further.

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