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Study of Wastewater Distribution near the Heraclean Peninsula (Crimea) in the Upwelling Situation Based on Expedition Data and Numerical Modelling

P. D. Lomakin *, Yu. N. Ryabtsev

Marine Hydrophysical Institute of RAS, Sevastopol, Russia

* *e-mail: p_lomakin@mail.ru*

Abstract

Based on the oceanographic survey data taken by Marine Hydrophysical Institute in August 2019, the paper analyzes the structural features of the fields of temperature, salinity, concentration of total suspended organic matter and coloured dissolved organic matter in the area along the southwestern coast of the Heraclean Peninsula in the situation of wind upwelling. The structure of the fields of the studied quantities shows signs of ascending circulation and pollution due to offshore wind and the presence of two wastewater sources in the studied area. The numerical experiments performed using the 3D barotropic linear Felsenbaum model confirmed the observed upwelling and showed that the rise of anthropogenic waters from sewer sources to the sea surface was due to both alongshore and offshore winds oriented normally to the coastline. They also made it possible to trace the distribution of anthropogenic suspension in the upwelling situation. It is shown that suspension from sewer sources in the upper layer of water spread to the open sea, and in the intermediate and near-bottom layers it accumulated along the coastline. With a northerly wind, the effect of suspended matter accumulation in the coastal zone is more intense.

Keywords: water structure, upwelling, pollution, numerical modelling, Heraclean Peninsula, Crimea

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Исследование распространения сточных вод у Гераклейского полуострова (Крым) в ситуации апвеллинга на основе экспедиционных данных и численного моделирования

П. Д. Ломакин *, Ю. Н. Рябцев

Морской гидрофизический институт РАН, Севастополь, Россия
* *e-mail: p_lomakin@mail.ru*

Аннотация
На основе данных океанологической съемки, проведенной Морским гидрофизическим институтом в августе 2019 г., проанализированы особенности структуры полей температуры, солености, концентрации общего взвешенного и окрашенного растворенного органического веществ на участке вдоль юго-западного берега Гераклейского полуострова в ситуации ветрового апвеллинга. В структуре полей рассматриваемых величин выявлены признаки восходящей циркуляции и загрязнения, обусловленные сгонным ветром и наличием на рассматриваемом участке двух источников сточных вод. Численные эксперименты, выполненные с использованием трехмерной баротропной линейной модели Фельзенбаума, подтвердили наблюдавшийся апвеллинг и показали, что подъем вод антропогенного происхождения из канализационных источников к поверхности моря обусловлен как вдольбереговым, так и ориентированным по нормали к береговой линии сгонным ветром. Модельные расчеты также позволили проследить распространение антропогенной взвеси в ситуации апвеллинга. Показано, что в верхнем слое вод взвесь из канализационных источников распространялась в открытое море, а в промежуточном и придонном слоях она накапливалась вдоль береговой линии. При северном ветре эффект аккумуляции взвеси в прибрежной зоне более интенсивный.

Ключевые слова: структура вод, апвеллинг, загрязнение, численное моделирование, Гераклейский полуостров, Крым

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Introduction

Over the past decade, the water area of the Sevastopol seashore near the Heraclean Peninsula has been actively studied both on the basis of actual observations and at the theoretical level. Such interest is caused by the increasing anthropogenic pressure on the aquatic environment of this section of the coast.

To date, a rather capacious literature has been formed [1–11] devoted to the analysis of the structure and dynamics of waters based on oceanographic data, sources of pollution and hydrochemical regime of the region, modelling of local systems of currents and transport of anthropogenic suspension, as well as satellite studies of pollutant distribution.

Among the indicated publications, the articles [8, 11] devoted to the water structure of the considered water area in the wind upwelling system are of particular interest. They show that in the summer months of the year, during upwelling, the wastewater from deep horizons penetrates through the seasonal thermocline and exits to the sea surface. This phenomenon confirms the conclusions about the distribution patterns of polluted bottom waters in the situation of local wind upwelling off the coast of Crimea, presented in monographs [12, 13]. According to the opinion of the authors of the cited books, in the warm half-year period, in the usual situation of a sharply stratified environment, wastewater spreads mainly in the horizontal direction under the seasonal thermocline layer. Whereas during upwelling, which contributes to the weakening of the water column stratification, wastewater plumes can reach the sea surface.

In August 2019, the employees of Marine Hydrophysical Institute conducted an expedition in the area located along the southwestern coast of the Heraclean Peninsula. According to the results of expeditionary studies in the observed situation of wind upwelling and the presence of a developed seasonal thermocline, the signs indicating penetration of polluted bottom waters into the surface layer of the sea and their spread to the beach zone were revealed in the structure of oceanological value fields [11].

Aims of this article:

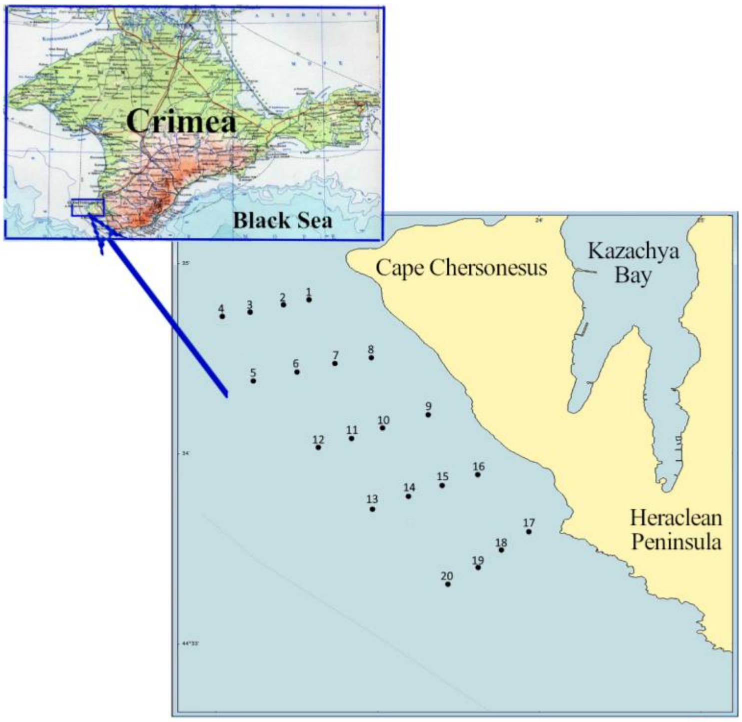
– based on the data of this expedition and numerical modelling methods, to consider the features of water circulation and the spread of anthropogenic suspension from known sources of pollution in the sea area near the southwestern coast of the Heraclean Peninsula;

– to analyse the factors that form the coastal zone of upwelling, patterns of distribution and structure of the suspended matter concentration field;

– to compare the results of expeditionary research and numerical modelling.

The studied water area is a section of the Sevastopol seaside, located along the southwestern coast of the Heraclean Peninsula. There is a well-known source of pollution of the considered region – an underwater pipeline of domestic wastewater of the *Yuzhnye* Treatment Facilities in Sevastopol [10] (Fig. 1).

The outlet head of the treatment facilities pipeline is located at a distance of ~ 3 km from the shore at a depth of 88 m. At the time of the analyzed survey, there was a leak in the pipeline, which became an additional source of anthropogenic suspended matter. The first information about the leak appeared in 2014, and in 2017 it became known that it was located at a distance of ~ 700 m from the shore at a depth of 34–37 m [5].



F i g . 1 . Geographical position of the studied water area and map of stations of the oceanological survey performed on 23 August 2019

Initial data and research methods

To analyze the structure of waters and select the parameters of the numerical experiment model, we used the data of the expedition conducted by Marine Hydrophysical Institute (Sevastopol) on August 23, 2019. Within the framework of this expedition, a complex of synchronous observations of temperature, salinity, total organic matter (TOM) and colored dissolved organic matter (CDOM) was carried out. The survey was performed according to a scheme that included 20 drift stations on five sections oriented approximately along the normal to the coastline (Fig. 1, *a*).

The station coordinates were determined using a GPS navigator. The observations were made from the board of a small vessel. The range of depths on the test site was 6–150 m. The limiting sounding horizon was 25–30 m. At each station, all four environmental parameters were synchronously recorded in the *in situ* probing mode with a depth step of 0.1 m using the Kondor measuring complex[1)].

[1)] HYDROoptics Ltd. *Complex Hydrobiophysical Multiparametric Submersible Autonomous "CONDOR"*. 2023. [online] Available at: http://ecodevice.com.ru/ecodevice-catalogue/multiturbidimeter-kondor [Accessed: 04 June 2023].

It should be noted that TOM and CDOM belong to the group of the best indicators of pollution (including bacterial one) of coastal marine areas, as well as other natural water bodies [14–16].

At present, there is no maximum allowable standard for TOM and CDOM as a numerical indicator of water pollution. Therefore, to assess the significance of the anthropogenic component in the concentration field of these substances, their actual content was compared with the concentration characteristic of the open waters of the Black Sea off the coast of Crimea, which, according to [11], is equal to 2 mg/L for CDOM and 0.8 mg/L for TOM.

These values are conditionally accepted by us as a natural norm for the concentration of these quantities in the Black Sea coastal waters near the Crimean Peninsula. They were used to identify areas with an anthropogenic component in the fields of TOM and CDOM concentrations and to assess the degree of contamination of the considered water area with these substances.

The atmospheric synoptic situation during the survey was determined by the southeastern periphery of the anticyclone with the centre over Belarus [2)].

The survey was accompanied by a fresh and strong wind, the average daily velocity of which was 6 m/s, and the direction changed in the sector from north to northeast. At sea, the wind gusts reached 12–15 m/s. The excitement of the sea reached 3–4 points [3)].

Numerical modelling methods were used to understand the origin of the identified features in the water structure and the distribution of pollutants in the water area near the Heraclean Peninsula.

Due to the comparative shallowness of the considered area, the currents here are mainly determined by the wind. We will assume that the impurity transfer is carried out by steady currents. To calculate them, we use the 3D barotropic linear Felsenbaum model [17, 18] generalized to the case when Rayleigh friction is taken into account.

The 3D character of suspension propagation was taken into account in this work. The process of passive suspension propagation due to currents and turbulent diffusion is described by an equation in a divergent form, which has the following form [19, 20]

$$C_t + (uC - \mu C_x)_x + (vC - \mu C_y)_y + ((w + w_c)\cdot C - \kappa C_z)_z = 0,$$

where $C(x, y, z, t)$ is suspension concentration; κ is vertical, μ is horizontal turbulent diffusion coefficient; w_c is own velocity of the suspension.

At the initial moment of time, the suspension concentration is equal to zero. We consider that at the given points the suspension is ejected. At the side boundaries and at the bottom, conditions are also set for the absence of suspended matter flows.

The problem of impurity transfer is solved numerically. A conservative scheme is used, which has the property of transportability and positive definiteness. This scheme is described in detail in [17].

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2) Wetterzentrale. *Top Karten: Archiv Reanalysis – Eiropa*. 2023. [online] Available at: http://smtp.pilzepilze.de/topkarten/fsreaeur.html [Accessed: 04 June 2023].

3) Raspisanie Pogody, Ltd. *Weather Archive at the Chersonesos Lighthouse*. 2023. [online] Available at: https://rp5.ru/Архив_погоды_на_Херсонесском_маяке [Accessed: 04 June 2023].

A uniform grid with steps $\Delta x = \Delta y = 40$ m was used. An uneven grid was applied vertically Δz_k = 1, 2, 4, 6, 14, 16, 27, H – 70 m. The middle layers are at depths: 0.5, 2, 5, 10, 20, 35, 56.5 m. The kinematic coefficient of vertical viscosity is constant $A = 30$ cm^2/s; Coriolis parameter $f = 10^{-4}$ s^{-1}, $\kappa = 0.1$ cm^2/s, $\mu = 100$ cm^2/s, $w_c = -2$ cm/s. The value of shear stresses at the upper boundary was assumed to be equal to 1 cm^2/s^2, which corresponds to a wind speed of 8 m/s.

The integral water circulation is determined by the bottom topography and wind direction. The numerical experiments were carried out for two main wind directions that accompanied the survey, north and northeast, with real bottom topography and parameters of pollution sources.

Discussion of the results

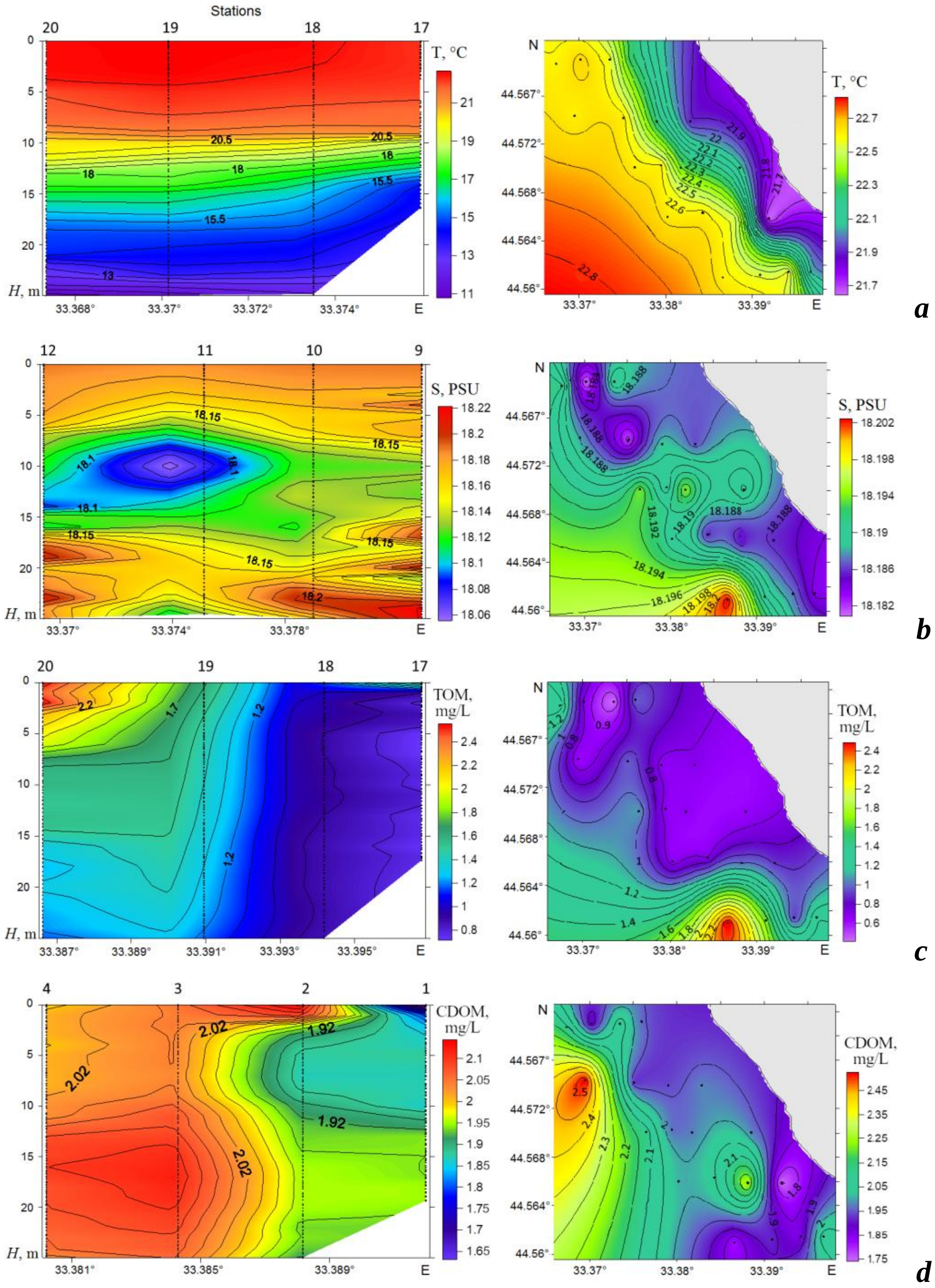
Analysis of the results of expeditionary research showed the following. In the considered section, the direction of the actual wind changed in the sector from approximately 0° to 45°. Judging by the structure of the temperature, salinity, TOM and CDOM concentration fields, this wind situation was accompanied by the rise of water from near-bottom horizons to the sea surface in the ascending wind upwelling circulation system. Moreover, these waters had clear signs of pollution. This is evidenced by the following characteristic properties (Fig. 2).

The upwelling center was clearly distinguished in the temperature field in the form of a strip of coastal waters with a temperature lowered by ~ 1 °C against the ambient background. The temperature field was well stratified with a pronounced (vertical gradient ~ –1 °C/m) seasonal thermocline elevated near the coast, which was located between 10 and 15 m horizons and was clearly visible on the extreme southern section between stations 17–20 (Fig. 1; 2, *a*).

In the vertical structure of the salinity field, individual desalinated water lenses with salinity decreased by 0.05–0.17 PSU relative to the background were found. The vertical and horizontal dimensions of these formations were estimated to be about 10 and 300 m, respectively. The most significant inhomogeneities in the haline field were noted in the plane of the median section between stations 9–12 (Fig. 1; 2, *b*).

In the extreme southern area of the test site in the surface layer of the sea, against the background of a low-gradient field of TOM content, a lens with a vertical size of 5–7 m and a maximum concentration of 2.3–2.5 mg/L within the entire considered area was clearly distinguished, which was three times higher than the natural norm (extreme southern section, stations 17–20). In addition, smaller formations with the content of this substance of anthropogenic origin were noted (Fig. 1; 2, *c*).

In the northwestern part of the test site, a lens with a maximum CDOM concentration (up to 2.4 mg/L) was observed, and it was traced throughout the entire water column at the extreme northern section between stations 1–4. In the vertical structure of the CDOM concentration field, as well as in the structure of the fields of salinity and TOM content, smaller heterogeneities were recorded with an increase in the content of this substance by about 1.5 times relative to the natural norm (Fig. 1; 2, *d*).



F i g . 2 . Vertical (*left*) and horizontal in the surface layer (*right*) distribution of oceanological environmental parameters: *a* – temperature, °C; *b* – salinity, PSU; *c* – total organic matter concentration, mg/L; *d* – colored dissolved organic matter concentration, mg/L, near the wastewater outlet according to the data of the August 2019 expedition

Model experiments confirmed the wind upwelling observed during the oceanographic survey and the exit of anthropogenic waters to the sea surface. In addition, these experiments showed a number of interesting effects associated with water circulation and temporal dynamics of the spread of anthropogenic suspension, which can be applied in practice.

The calculated fields of current vectors along the given horizons for the north and northeast winds revealed a two-layer kinematic structure and a coastal cell of transverse water circulation typical of upwelling (Fig. 3).

The currents in the upper layer are directed downwind towards the sea, while the compensation current near the bottom is directed towards the shore. Near the shore on the sea surface, the current velocity was about 10 cm/s. The bottom layer was dominated by weak currents with a velocity of 1÷2 cm/s.

With a northerly wind whose vector was directed at an obtuse angle to the coastline, and the eastward-oriented alongshore component was well pronounced (Fig. 3, *a*, *b*), the upwelling was determined by the Ekman effect. In the situation of the northeast wind, whose vector was directed approximately along the normal to the coastline, a typical upwelling was observed, caused by the wind surge (Fig. 3, *c*, *d*).

When modelling the distribution of suspended matter, the total volume of the pipeline outlet is assumed to be Q = 43,800 m^3/year (according to 1998 data [10]). Let us assume that 0.8 Q passes through the outlet head, and 0.2 Q passes through the emergency outlet (leakage). Positions of the sources are indicated by dots in Fig. 4.

The calculations were carried out on the second day. Fig. 4 shows the distribution of suspended matter concentration in isolines with a step of 10 % of

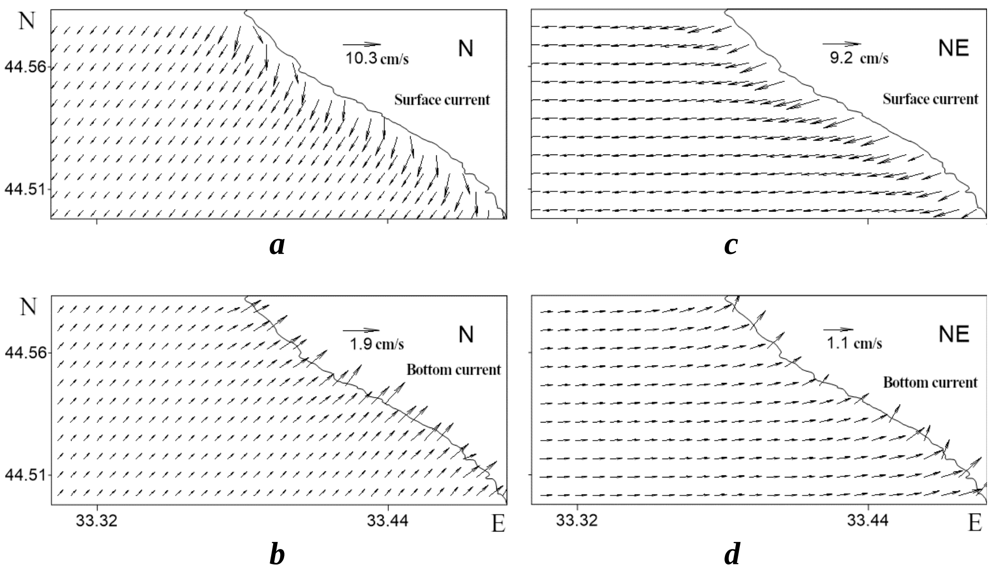
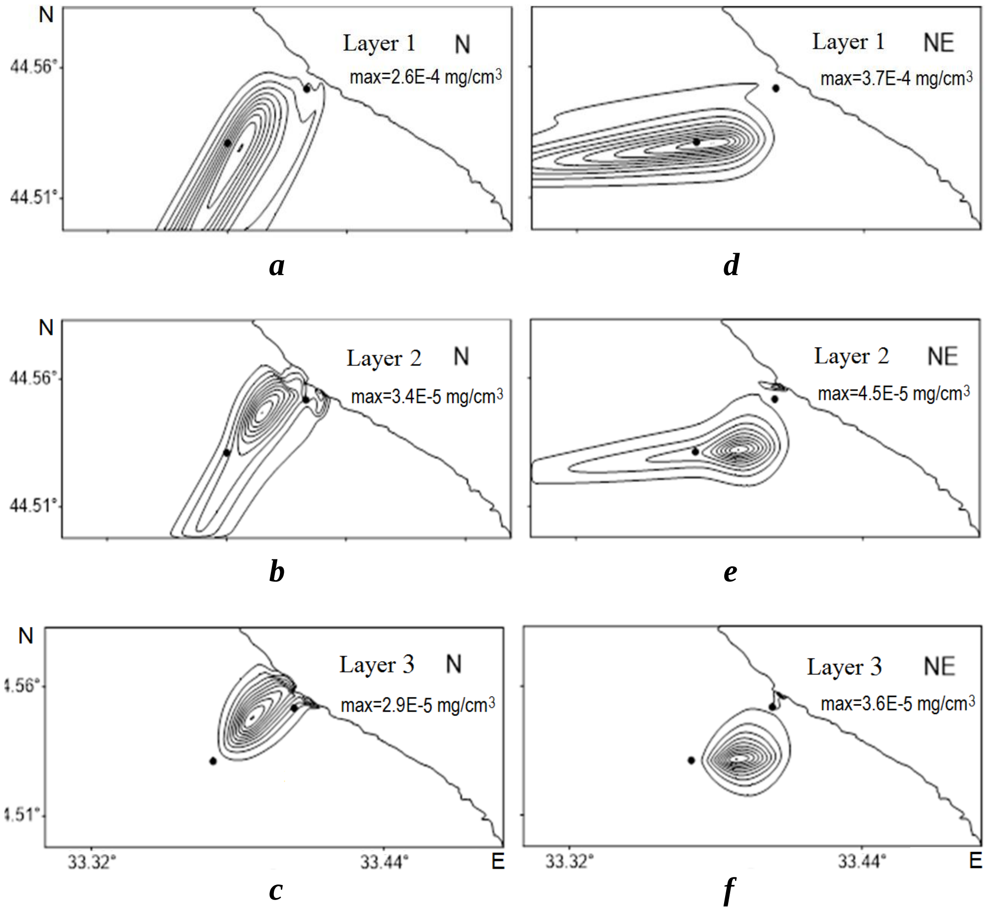


Fig. 3. Vectors of currents at the sea surface and near the bottom at north (*a*, *b*) and north-east (*c*, *d*) winds



F i g . 4 . Distribution of suspended matter concentration in two days in three sea layers (surface, intermediate and near-bottom) at north (*a*, *b*, *c*) and north-east (*d*, *e*, *f*) winds

the maximum value in each layer. This method of presentation was chosen to pay attention not to the quantitative characteristics of pollutants entering the water column, but to the features of the dynamics and transformation of suspension concentration distributions.

Analysis of the fields of the calculated content of suspended matter showed that from the moment of the "launch" of sources located at the bottom at given directions and wind speeds, a two-layer structure of the concentration field of the studied quantity with multidirectional currents is formed in the considered area. In the near-bottom horizons (layer 3), the suspension spread to the shore, while in the upper layers 1 and 2 it was carried out to the seaward side.

By the end of the second day, the maximum concentration of suspended matter appeared in the upper layer in the area of the main outlet, and its predominant current was directed to the sea and was traced at a distance of about 2.5 miles from the coast. In the lower layers, the maximum distribution of suspended matter shifted towards the coast and spread to shallow water. Moreover, with the north wind, the concentration of suspended matter near the coast reached 40 % of the maximum, while with the northeast wind it was only 10 % (Fig. 4).

Off the coast of Crimea, in the warm half-year period during wind surges and upwelling, wastewater plumes from the near-bottom horizon penetrate through the thermocline to the sea surface. This property, first discovered and studied by the authors of the monograph [13], is confirmed by our results of numerical modelling (Fig. 4) and *in situ* observations (see Fig. 2).

Conclusion

Based on the structure analysis of the fields of temperature, salinity, concentration of total organic and colored dissolved organic matter, which were obtained from the materials of the MHI expedition conducted in August 2019, it was found that with north and northeast winds, waters of anthropogenic origin spread from the deep horizons to the sea surface. The rise of waters was associated with wind upwelling, and its source was represented by two outlets in the pipeline of the *Yuzhnye* Treatment Facilities.

The results of model experiments confirmed the upwelling observed during the oceanographic survey and the emergence of anthropogenic waters from the existing sources to the sea surface. They also made it possible to trace the spread of anthropogenic suspension coming from the sewer sources of the *Yuzhnye* Treatment Facilities.

The calculated fields of current vectors generated by north and northeast winds revealed a cell of transverse water circulation typical of coastal upwelling. It is also shown that upwelling in the coastal area under consideration is caused by both alongshore and offshore winds oriented along the normal to the coastline.

It has been established that near the southwestern coast of the Heraclean Peninsula, due to the special structure of the current field caused by the north and northeast winds, the suspension from sewer sources in the upper layer of water spreads into the open sea, and in the intermediate and near-bottom layers it accumulates along the coastline. With a northerly wind, the effect of anthropogenic suspension accumulation in the coastal zone is more intense.

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About the authors:

Pavel D. Lomakin, Leading Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya St., Sevastopol, 299011, Russian Federation), Dr.Sci. (Geogr.), Professor, **ResearcherID: V-7761-2017, Scopus Author ID: 6701439810, IstinaResearcherID: 18321047**, *p_lomakin@mail.ru*

Yuri N. Ryabtsev, Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya St., Sevastopol, 299011, Russian Federation), **ORCID ID: 0000-0002-9682-9969, SPIN-code: 7853-4597**, *ruab@mail.ru*

Contribution of the authors:

Pavel D. Lomakin – general supervision of the study, interpretation of expeditionary data, statement of the problem and objectives, interpretation of the overall result, writing the article

Yuri N. Ryabtsev – model parameter selection, model adaptation, performance of numerical experiments and their interpretation, revision of the article

All the authors have read and approved the final manuscript.