ISSN 2413-5577, Ecological Safety of Coastal and Shelf Zones of Sea, 2023, No. 4, pp. 101–115.

Original article

Self-Purification Capacity of Sevastopol Bay Ecosystems in Relation to Inorganic Forms of Nitrogen and Phosphorus from 2012 to 2020

I. V. Mezentseva [1], E. E. Sovga [2]*, T. V. Khmara [2]

[1] *Sevastopol Branch of the N. N. Zubov State Oceanographic Institute, Sevastopol, Russia*
[2] *Marine Hydrophysical Institute of RAS, Sevastopol, Russia*
* *e-mail: science-mhi@mail.ru*

Abstract
The paper uses the 2012–2020 joint oceanographic database of MHI RAS and SB FSBI SOI to estimate the self-purification capacity of Sevastopol Bay ecosystems in relation to biogenic nitrogen and phosphorus. The assimilation capacity and its specific value were calculated using the balance method. The paper estimates the average and maximum concentrations of inorganic phosphorus (PO_4) and nitrogen (NO_2, NO_3, NH_4), as well as the average and maximum rates and time of removal of these nutrients from the bay ecosystems. The paper shows changes in the percentage of forms of inorganic nitrogen (NO_2, NO_3, NH_4) in the water area of all parts of Sevastopol Bay for two periods (1998–2012 and 2012–2020). These changes had a greater impact on the content of the reduced form of ammonium nitrogen which has increased in all ecosystems of the bay in recent years. Changes in the self-purification capacity of the bay ecosystems were manifested as a spread of data on the assimilation capacity of the study ecosystems in relation to nutrients. At the same time, the lowest self-purification capacity was observed for the ecosystem of the eastern part of the bay. The paper assesses possible causes of the observed situation, which are associated with changes in the wind regime over the bay water area in the last decade and the resulting formation of the system of surface currents. The surface currents in the bay under prevailing easterly winds were calculated using the computational modeling method. The paper shows that an increase in the frequency of such winds contributes to increased ventilation of the waters of Yuzhnaya Bay and a more intense input of pollutants in the westerly direction. The paper analyzes the reasons for deterioration in the self-purification ability of the eastern part of the bay in the last decade in relation to all inorganic forms of nitrogen and phosphates. It was shown that changes in the self-purification ability of ecosystems throughout the Sevastopol Bay waters were associated with an increase in the recreational load on the bay coast.

Keywords: Sevastopol Bay, biogenic nitrogen, biogenic phosphorus, ecosystem, self-purification ability, assimilation capacity, surface currents

Acknowledgements: The study was performed under state assignment of MHI RAS on topic no. 0827-2020-0004 “Coastal research”.

For citation: Mezentseva, I.V., Sovga, E.E. and Khmara, T.V., 2023. Self-Purification Capacity of Sevastopol Bay Ecosystems in Relation to Inorganic Forms of Nitrogen and Phosphorus from 2012 to 2020. *Ecological Safety of Coastal and Shelf Zones of Sea*, (4), pp. 101–115.

Самоочистительная способность экосистем Севастопольской бухты в отношении неорганических форм азота и фосфора в период с 2012 по 2020 год

И. В. Мезенцева [1], Е. Е. Совга [2]*, Т. В. Хмара [2]

[1] *Севастопольское отделение Государственного океанографического института им. Н. Н. Зубова, Севастополь, Россия*
[2] *Морской гидрофизический институт РАН, Севастополь, Россия*
* *e-mail: science-mhi@mail.ru*

Аннотация
На основе сводной базы океанографических данных МГИ РАН и СО ФГБУ ГОИН за 2012–2020 гг. выполнены оценки самоочистительной способности экосистем Севастопольской бухты в отношении биогенных элементов – азота и фосфора, рассчитанные балансовым методом по величине ассимиляционной емкости и ее удельной величине. Оценены средние и максимальные концентрации неорганических форм фосфора (PO_4) и азота (NO_2, NO_3, NH_4) за указанный период, а также значения средней и максимальной скорости и времени удаления этих биогенных элементов из экосистем бухты. Показаны изменения в процентном соотношении форм неорганического азота (NO_2, NO_3, NH_4) в акватории всех частей Севастопольской бухты за два периода (1998–2012 гг. и 2012–2020 гг.). Эти изменения в большей степени отразились на содержании восстановленной формы азота аммония, которое за последние годы увеличилось в экосистемах всей бухты. Изменения самоочистительной способности экосистем бухты проявились в разбросе данных об ассимиляционной емкости исследуемых экосистем в отношении биогенных элементов. При этом наиболее низкая самоочистительная способность наблюдается в экосистеме восточной части бухты. Оценены возможные причины наблюдаемой ситуации, которые связаны с изменениями ветрового режима над акваторией бухты в последнее десятилетие и формирующейся под его влиянием системой поверхностных течений. Методом математического моделирования рассчитаны поверхностные течения в бухте при преобладающих ветрах восточных направлений. Показано, что увеличение периодичности действия таких ветров способствует усилению вентиляции вод Южной бухты и более интенсивному поступлению загрязняющих веществ в западном направлении. Проанализированы причины ухудшения самоочистительной способности восточной части бухты в отношении всех неорганических форм азота и фосфатов в последнее десятилетие. Показано, что изменения самоочистительной способности экосистем всей акватории Севастопольской бухты связаны с ростом рекреационной нагрузки на побережье бухты.

Ключевые слова: Севастопольская бухта, биогенные элементы, биогенный азот, биогенный фосфор, экосистема, самоочищение, самоочистительная способность, ассимиляционная емкость, поверхностные течения

Благодарности: работа выполнена в рамках государственного задания ФГБУН МГИ по теме № 0827-2020-0004 «Прибрежные исследования».

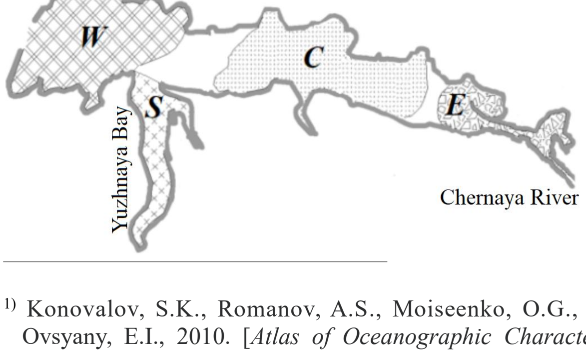
Для цитирования: *Мезенцева И. В., Совга Е. Е., Хмара Т. В.* Самоочистительная способность экосистем Севастопольской бухты в отношении неорганических форм азота и фосфора в период с 2012 по 2020 год // Экологическая безопасность прибрежной и шельфовой зон моря. 2023. № 4. С. 101–115. EDN MQUMMV.

Introduction

Sevastopol Bay is one of the city-forming factors of Sevastopol, and it serves as an indicator of the ecological health of the region. The bay is a semi-enclosed estuarine-type water area with a length of about 7 km, a maximum width of up to 1 km, and a mirror area of over 7 km^2. Water exchange in the bay is hindered, besides, it is constantly under active anthropogenic impact. Systematic studies of water quality in Sevastopol Bay began in 1975 after the introduction of the programme of the National Environmental Monitoring and Control Service [1]. The results of hydrological and hydrochemical studies of Sevastopol Bay [1)] have been repeatedly reviewed in the literature (e.g., [2, 3]). These works show that depending on the localisation of pollution sources, bottom shape and hydrometeorological conditions, both relatively clean zones and those with a persistent high-pollution level (e.g., Yuzhnaya Bay) are formed in Sevastopol Bay. According to the pollution level, the bay water area was divided into four areas [3] (Fig. 1).

Ecological well-being of shallow-water marine ecosystems, irrespective of environmental protection measures, is determined primarily by their self-purification capacity, the intensity of which depends on a number of mutually causal factors. The capacity of shallow water area ecosystems for self-purification can be assessed by calculating their assimilation capacity (AC) in relation to a priority pollutant or a complex of pollutants.

Sevastopol Bay is a water body with complex geographical and hydrological-hydrochemical characteristics. This implies the presence of fresh water sources and zones of their mixing with sea waters, as well as heterogeneity of the anthropogenic load. Therefore, the water area should be zoned and the self-purification capacity (AC of the ecosystem) should be calculated for each zoned area.



F i g. 1. Zoning of Sevastopol Bay according to the anthropogenic influence level: *W* – western area, *E* – eastern area, *C* – central area and *S* – southern area (from work [3])

1) Konovalov, S.K., Romanov, A.S., Moiseenko, O.G., Vnukov, Yu.L., Chumakova, N.I. and Ovsyany, E.I., 2010. [*Atlas of Oceanographic Characteristics of Sevastopol Bay*]. Sevastopol: ECOSI-Gidrofizika, 320 p. (in Russian).

The article analyses the self-purification capacity of the eastern, central, western parts of the bay and Yuzhnaya Bay, as well as the water area of the entire Sevastopol Bay. Several works [4–7] consider the self-purification capacity of the Sevastopol Bay ecosystem in relation to all forms of inorganic nitrogen and inorganic phosphorus. They study the ecosystem of the entire bay or its separate parts (western, central, eastern ones and Yuzhnaya Bay) using calculated data on the hydrodynamics of the bay waters. Thus, [4] compared the ecosystem self-purification capacity for the western part of the bay bordering the open sea in relation to all forms of inorganic nitrogen and that for the southern, most polluted part of the bay. The work [5] estimates the self-purification capacity of ecosystems of the whole Sevastopol Bay in relation to reduced forms of nitrogen (nitrites and ammonium).

In [6], the self-purification capacity of the bay ecosystems in relation to all inorganic forms of nitrogen is compared, and trophic state indices for the studied ecosystems are given. The work [7] studies the self-purification capacity for the ecosystems of Yuzhnaya Bay and the eastern part of Sevastopol Bay (which is under the influence of the Chernaya River runoff during flooding and low water periods) in relation to phosphates under changes in the hydrodynamic regime of the bay. The works [4–7] share the fact that the self-purification capacity of the Sevastopol Bay ecosystems was calculated based on the oceanographic database of MHI RAS for 1998–2012.

Seasonal water dynamics in some parts of Sevastopol Bay was calculated using the hydrothermodynamic module of the numerical three-dimensional nonstationary model MECCA (Model for Estuarine and Coastal Circulation Assessment) [8]. The results obtained for the eastern part of the bay and Yuzhnaya Bay are presented in [7], and those for the central part of the bay are given in [5].

The study aims to calculate the self-purification capacity of the ecosystems for all parts of Sevastopol Bay in relation to inorganic nitrogen and phosphorus using the database of MHI RAS and SB FSBI SOI for 2012–2020, taking into account changes in the hydrometeorological situation in the last decade.

Study methods and materials

The authors used the joint database of archival materials of MHI RAS and SB FGBU SOI for 2012–2020, including 8277 determinations of phosphate, nitrite, nitrate and ammonium content. To assess the AC of the selected areas of Sevastopol Bay, 5567 concentration values of the above indicators were selected (Table 1).

The AC of ecosystems of the selected areas of Sevastopol Bay was calculated using the balance method [9]. When using this method, to calculate the integral time of pollutants staying in the studied ecosystem is the most complicated part. This time is largely determined by physical and chemical properties of a particular pollutant, hydrodynamic parameters of the water area and a complex of processes (physical, chemical, microbiological) responsible for the destruction of pollutants or their removal from the studied water area.

T a b l e 1. Concentration of inorganic phosphorus and nitrogen compounds in different parts of Sevastopol Bay (according to database of MHI RAS and Sevastopol Branch of SOI) in 2012–2020

Compounds	Mean content for the period, μM/L	Concentration range, μM/L	Standard deviation	Number of determinations
Phosphates	0.10	0–3.65	0.082	1520
Nitrites	0.24	0–7.67	0.711	1354
Nitrates	5.70	0–67.28	1.765	1355
Ammonium	1.40	0–40.66	1.021	1338

The final formulae for estimating the mean value $\overline{A}_{mi}$ and standard deviation $\sqrt{D[A_{mi}]}$ of the AC of a marine ecosystem (*m*) in relation to the *i*-th pollutant are as follows:

$$\mathrm{AE}_{mi} = \overline{A}_{mi} \pm \sqrt{D[A_{mi}]},$$

$$\overline{A}_{mi} = \frac{Q_m \cdot C_{\mathrm{thr}i}}{C_{\max i}} \cdot \overline{v}_i, \quad D[A_{mi}] = \left(\frac{Q_m \cdot C_{\mathrm{thr}i}}{C_{\max i}}\right)^2 \cdot D[v_i],$$

where Q_m – water volume in the calculation area; $C_{\mathrm{thr}i}$ – threshold concentration of a pollutant; $C_{\max i}$ – maximum concentration of a pollutant in the ecosystem; v_i – rate of pollutant removal from the ecosystem, the mean value $\overline{v_i}$ and dispersion $D[v_i]$ of which are determined by the original algorithm [10].

Results and discussion

Comparison of relatively new data for 2012–2022 with the materials of previously published studies (1998–2012) showed a significant change in the content of biogenic forms of nitrogen and phosphorus in the waters of the selected areas of Sevastopol Bay. Table 2 presents the mean and maximum values of the concentration of inorganic phosphorus and nitrogen compounds in different parts of the bay in 2012–2020.

Thus, over the study period 2012–2020, the mean **phosphate** content either remained unchanged (the eastern part of the bay) or decreased by 0.02–0.06 μM/L (in all other water areas). Maximum concentration values increased significantly in the eastern part (2.6 times) and decreased slightly in the rest of the bay.

T a b l e 2. Content (μM/L) of inorganic phosphorus and nitrogen compounds in different parts of Sevastopol Bay in 2012–2020

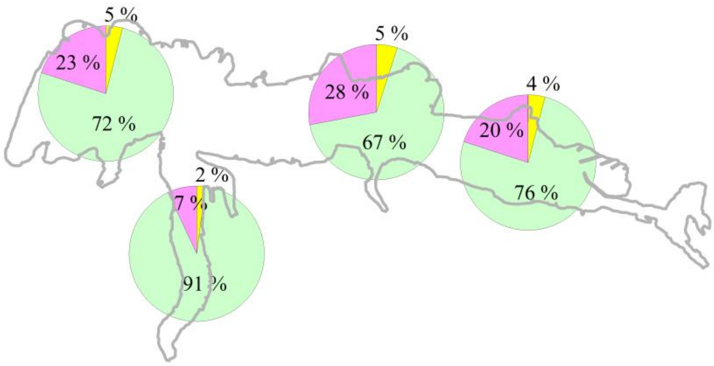
Area	(PO_4^{3-}) / Phosphates		(NO_2^-) / Nitrites		(NO_3^-) / Nitrates		(NH_4^+) / Ammonium	
	Mean	Max	Mean	Max	Mean	Max	Mean	Max
Yuzhnaya Bay	0.10	0.95	0.23	2.54	14.79	286.40	1.59	16.02
Eastern part	0.15	3.65	0.30	7.06	3.71	67.28	2.25	40.66
Central part	0.07	0.66	0.19	5.18	2.08	14.67	1.05	9.94
Western part	0.07	0.77	0.23	7.67	2.22	8.29	0.72	9.09

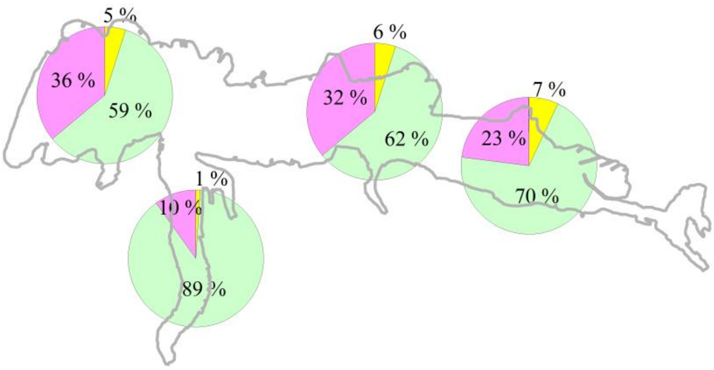
The **nitrite** content increased in all parts of the bay: the maximum concentration in the eastern part was 7.06 μM/L, in the western part – 7.67 μM/L.

A 1.1-fold and 1.6-fold decrease in the mean and maximum **nitrate** content (to 2.22 and 8.29 μM/L, respectively) was observed in the waters of the cleaner western part of Sevastopol Bay. In the other selected water areas, an increase in concentration was observed. In the central part, the maximum value was 14.7 μM/L, in the eastern part – 67.3 μM/L, and in Yuzhnaya Bay – 286.4 μM/L.

In the ecosystem waters of all parts of Sevastopol Bay, the average **ammonium** content increased by 0.15–1.20 μM/L, while the maximum content decreased by 1.5 times in the central part of the bay and changed slightly in the western part (decreased to 9.09 μM/L). At the same time, the maximum values of this indicator doubled in Yuzhnaya Bay (up to 16.02 μM/L) and increased eightfold in the eastern part (up to 40.66 μM/L).

Fig. 2 shows that in the last decade the percentage ratio of different forms of inorganic nitrogen has changed in all parts of Sevastopol Bay. This mostly concerns the content of the reduced form of nitrogen – ammonium. In recent years, an increase in its content has been observed in all water areas of the bay, with the largest increase (from 23 to 36%) in the western part of the bay. Apparently, the presence of Khrustalny Beach in this part of the bay and the growth of recreational load on the water area have an impact. At the same time, the nitrate content decreases (Fig. 2). In the western part of the bay their content decreased from 72 to 59%. The smallest changes in the content of inorganic forms of nitrogen are observed in the water area of Yuzhnaya Bay.





F i g. 2. Distribution of content shares for mineral forms of nitrogen in the Sevastopol Bay in 1998–2012 (*a*) [6] and 2012–2020 (*b*). Yellow colour – NO_2; green – NO_3; pink – NH_4

A comparative analysis of the removal rate and time for inorganic forms of nitrogen and phosphorus in the Sevastopol Bay ecosystem in 2012–2020 and in the previous period 1998–2012 showed different trends of changes in these parameters in the water areas of the selected areas. Thus, the time of **phosphate** removal from the ecosystems of all parts of the bay has decreased in recent years, but still remains maximum in the eastern part of Sevastopol Bay (Table 3). Obviously, the decrease in the time of phosphate presence is due to an increase in the average elimination rate everywhere except in Yuzhnaya Bay, where this rate decreased from 0.007 to 0.005 μM/(L·day). The maximum estimated phosphate removal rate (0.039 μM/(L·day)) was recorded in the central part of the bay, while in the other areas, the removal rate did not exceed 0.023–0.024 μM/(L·day).

In the eastern and central parts of Sevastopol Bay, an increase in the average nitrite removal rate by 2.3–2.5 times was observed. The maximum values of the indicator were determined for the eastern and western parts of the bay (0.085 and 0.097 μM/(L·day), respectively). In the central part, the removal rate decreased from 0.126 μM/(L·day) in 1998–2012 to 0.062 μM/(L·day) in 2012–2020. Nitrite removal time decreased for all parts of the bay except the western part, for which there was an increase in the time nitrite was in the ecosystem with a relatively stable elimination rate.

T a b l e 3. Rate v_i (μM/(L·day)) and time t_r (day) of removal of inorganic phosphorus and nitrogen from different parts of Sevastopol Bay in 2012–2020

Area	(PO_4^{3-}) / Phosphates		(NO_2^-) / Nitrites		(NO_3^-) / Nitrates		(NH_4^+) / Ammonium	
	v_i	t_r	v_i	t_r	v_i	t_r	v_i	t_r
Yuzhnaya Bay	0.005	18–22	0.006	33–37	0.536	22–28	0.033	49–53
Eastern part	0.005	30–38	0.010	25–29	0.051	63–72	0.029	76–81
Central part	0.008	9–15	0.007	24–27	0.048	40–43	0.031	34–42
Western part	0.006	13–22	0.013	15–18	0.037	58–61	0.036	20–29

A clear pattern is observed for **nitrates**: even a small increase in their removal rate from Yuzhnaya Bay and the central part of Sevastopol Bay reduces the elimination time. On the contrary, when the removal rate of nitrates from the water area of the eastern and western parts of the bay significantly decreases (by 2.7 and 7.5 times, respectively), their elimination time considerably increases (by 2.3 and 7.4 times, respectively). The maximum removal rate (2.098 μM/(L·day)), as in the previous period, was observed in Yuzhnaya Bay, while in the other areas it did not exceed 0.396 μM/(L·day).

During the study period in all parts of the Sevastopol Bay water area, as shown above, the **ammonium** content increased. Its average removal rate decreased threefold in the Yuzhnaya Bay water area and 5.8 times in the western, cleanest part of Sevastopol Bay. The maximum removal rate in all selected areas did not exceed 0.181 μM/(L·day) compared to the maximum of 0.940 μM/(L·day) observed in the previous calculation period (1998–2012, western part of the bay [5]). The drop in the rate of ammonium removal caused an increase in the time required for self-purification of the ecosystems. Thus, the staying time of ammonium in the waters of Yuzhnaya Bay and in the eastern part of Sevastopol Bay increased by 2.8 and 2.3 times, respectively. As for the water area of the western part of the bay, the estimated time increased more than eight times.

Of particular interest is the information on specifying the ability of ecosystems of all parts of Sevastopol Bay to self-purification according to the AC value for the last decade (Table 4), in particular by its specific, i. e. calculated per fixed unit of volume (in our case per 1 litre), value ($AC_{spec.}$), which allows levelling the differences in the volume of different parts of the Sevastopol Bay water area.

T a b l e 4. Characteristics of capacity of the study water areas of Sevastopol Bay to self-purification $AC_{spec.}$ (μM/(L·day)) and AC of water area (t/year) in 2012–2020

Area	(PO_4^{3-}) / Phosphates		(NO_2^-) / Nitrites		(NO_3^-) / Nitrates		(NH_4^+) / Ammonium	
	AC_{spec}	AC	AC_{spec}	AC	AC_{spec}	AC	AC_{spec}	AC
Yuzhnaya Bay	0.0076	0.89	0.0046	0.24	1.524	79.86	0.389	20.39
Eastern part	0.0017	0.25	0.0029	0.19	0.565	37.37	0.142	9.41
Central part	0.0111	2.89	0.0026	0.30	2.315	269.75	0.519	60.43
Western part	0.0070	2.69	0.0034	0.58	3.003	519.04	0.571	98.69

In the period under consideration 2012–2020, in relation to **phosphates**, the minimum $AC_{spec.}$ value was observed in the eastern part of the bay – 0.0017 μM/(L·day). According to the calculated AC of this water area, up to 0.25 tonnes of phosphorus per year can enter the ecosystem without damage to the latter. In the previous calculation period 1998–2012, this value was 0.64 tonnes of phosphorus per year, i. e. the permissible level threshold decreased by 2.6 times [7]. For the Yuzhnaya Bay ecosystem, the value was 0.0076 μM/day or 0.89 t/year, indicating a slight decrease in the permissible level threshold (0.93 t for 1998–2012 [7]). The western part of the bay is also characterised by a similar value of $AC_{spec.}$ The increased self-purification capacity of the central part is offset by the difference between the volumes of its water area and that of the western part, so the AC values of these parts are close (2.89 and 2.69 tonnes of phosphate per year, respectively). For comparison, in 1998–2012, the difference was more significant – 1.17 and 2.00 tonnes of phosphate per year [7], indicating an improvement in the current situation.

In relation to **nitrites**, it is important to note a significant decrease in the self-purification capacity of the western part of Sevastopol Bay. Thus, in comparison with the previous calculation period (1998–2012), the $AC_{spec.}$ decreased 14.3 times, which resulted in a 12.6-fold decrease in the AC of this water area (7.38 and 0.58 tonnes of nitrite per year, respectively). The ecosystem of the central and eastern parts of the bay also showed a decrease in AC, but it was not so sharp – up to 0.30 and 0.19 tonnes of nitrite per year, respectively, against 0.48 and 0.39 tonnes of nitrite per year in the previous period [6]. In the southern part of the bay, no changes were observed in the two periods: $AC_{spec.}$ was 0.005 μM/(L·day), AC of the water area was 0.24–0.25 t/year.

The $AC_{spec.}$ value in relation to **nitrates** in the ecosystem of the eastern part of the bay did not change significantly in comparison if compared with the previous calculation period. In the last decade, the ecosystem of this area has been characterised by the weakest self-purification capacity. The self-purification capacity of the Yuzhnaya Bay ecosystem more than doubled, reaching the nitrates removal limit of 79.86 t/year. The AC of the central part of Sevastopol Bay changed even more, reaching a value of almost 270 tonnes of nitrates per year, $AC_{spec.}$ increased from 0.614 to 2.315 µM/(L·day) compared to the previous calculation period. As in the case of nitrites, the western part of the bay bordering the open sea has experienced a decrease in self-purification capacity, with 519 tonnes of nitrates per year over the last decade, compared to 882 tonnes per year for 1998–2012. [6].

With respect to **ammonium**, the minimum $AC_{spec.}$ value was observed in the ecosystem of the eastern part of the bay – 0.142 µM/(L·day), which corresponds to an AC of 9.41 tonnes of ammonium per year. High values of $AC_{spec.}$ are observed for the ecosystems of the western and central parts of the bay – 0.571 and 0.519 µM/(L·day), respectively, which corresponds to an AC of the water area of 98.69 and 60.43 t/year. For comparison, based on the data from 1998–2012, these values were 6.90 tonnes of ammonium per year for Yuzhnaya Bay, 8.36 t for the eastern part of the bay, 9.33 t for the central part of the bay, and 93.40 t for the western part of the bay [5]. Thus, for the water areas of the eastern and western parts of the bay, the changes in self-purification capacity in relation to ammonium are insignificant. However, despite a significant increase in ammonium concentration in the central part of the bay, the self-purifying capacity of its ecosystem has improved. Apparently, the relevant hydrometeorological conditions and hydrodynamics of waters in the bay may have played a significant role. A slightly less significant improvement of the self-purification capacity took place in Yuzhnaya Bay, where the $AC_{spec.}$ increased from 0.132 to 0.389 µM/(L·day).

Thus, there is a large spread of data on the AC of the ecosystem in relation to both a particular nutrient and each separate part of the water area of Sevastopol Bay. The distribution of nutrient concentrations between different parts of Sevastopol Bay is somewhat inconsistent with the changes in the AC value. This is due to the complexity of AC, which is determined by processes of different nature.

The information presented in Table 4 allows us to assess the current situation for each specific water area with respect to all nutrients by the value of their specific assimilation capacity.

Thus, the obtained results made it possible to assess the general state of Sevastopol Bay ecosystems by the AC value:

Yuzhnaya Bay. For phosphates – slight decrease in $AC_{spec.}$; for nitrates and ammonium – increase in $AC_{spec.}$, and for nitrites – no change. In general, the situation has improved.

Central part of the bay. For phosphates – significant increase in $AC_{spec.}$; for nitrates and ammonium – significant increase; for nitrites – decrease. In general, the situation has significantly improved.

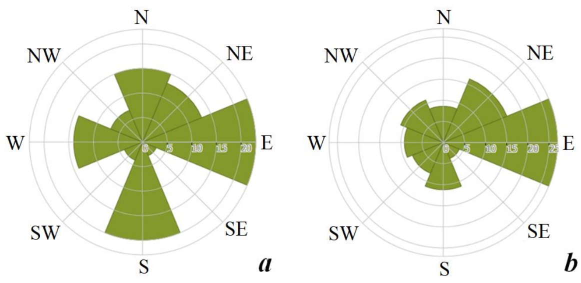
Eastern part of the bay. For phosphates – decrease in $AC_{spec.}$; for nitrates – insignificant decrease; for ammonium – insignificant increase; for nitrites – significant decrease. In general, the situation has deteriorated.

Western part of the bay. For phosphates – increase in $AC_{spec.}$; for nitrates – significant decrease; for ammonium and nitrites – decrease. In general, the situation, as in the eastern part, has recently deteriorated.

To provide the reasons for this situation, it is necessary to consider the changes in the hydrometeorological situation for the last decade.

Due to the zonally elongated orientation of the bay surrounded by high shores, the prevailing wind directions are easterly (23.1%) and southerly (19.6%) [11]. The changes in wind recurrence by direction for two periods (1998–2012 [11] and 2012–2020 [2]) are presented in Fig. 3.

Fig. 3, *b* shows that in the modern period, the duration of easterly winds increased to 35%, and the share of southerly winds significantly decreased compared to the previous decade (Fig. 3, *a*). As is known from the data of [7], it is the southerly winds that complicate the water exchange in Yuzhnaya Bay with the water area of the entire Sevastopol Bay. To establish the reasons for the differences in the $AC_{spec.}$ values in the ecosystems of different parts of the bay, let us consider the features of their hydrodynamic situation calculated using the hydrothermodynamic module of the numerical three-dimensional non-stationary model MECCA [8] at prevailing winds of eastern directions (Fig. 3, *b*). The results of the currents calculation obtained for the water area of Sevastopol Bay are presented in Fig. 4.



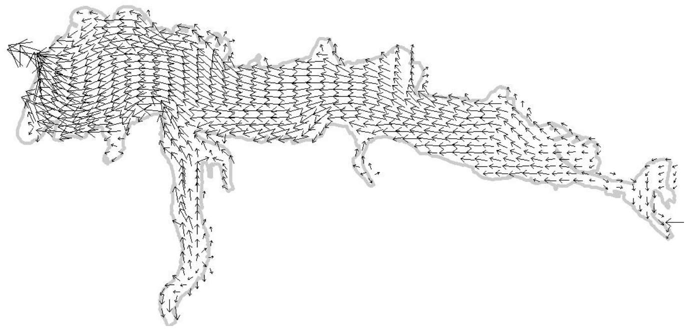
F i g. 3. Wind rose for the Sevastopol water area in 1998–2012 (*a*) and 2012–2020 (*b*)

Fig. 4 shows that the increase in the easterly wind recurrence observed in the last decade contributes to increased ventilation of the Yuzhnaya Bay waters and their transfer to the western part of the bay. Yuzhnaya Bay is characterised by a hindered water exchange with the adjacent water area. The waters of the bay receive record volumes of residential and storm water runoff, moreover, there are berths in its water area.

When northerly and northeasterly winds prevail over the bay water area, a surface drift current directed along the bay axis to the west is formed. This favours more intensive water inflow into Yuzhnaya Bay both in the surface and bottom layers. The northerly and northwesterly winds cause a surge effect and the corresponding compensatory rise of water from the bottom horizons to the surface of the middle part of Yuzhnaya Bay [7].

---

[2] Raspisanie Pogody, Ltd. [Weather Archive Sevastopol]. 2023. [online] Available at: https://rp5.ru/Архив_погоды_в_Севастополе [Accessed: 10 December 2023] (in Russian).



F i g. 4. Map of surface currents in Sevastopol Bay under an easterly wind of 5–10 cm/s

Let us focus on the peculiarities of the dynamic regime in the central part of the bay as a possible reason for the increase in the self-purification capacity of its ecosystem in the last decade. Due to the location of the central part of the bay, the currents here are determined mainly by the wind. Under the influence of the easterly wind, a direct flow of the west direction is formed in the surface water layer, which also persists under the northerly and southerly winds and contributes to the transfer of pollutants to the western part of the bay (Fig. 4).

According to the work [5], in the central part of Sevastopol Bay there are two counter flows – one from east to west from the Chernaya River and the other from the open part of the sea. This contributes to the formation of a buffer zone in the central part of the bay, in which multidirectional flows carrying pollutants are "closed". This is explained by the orientation and morphometric characteristics of the bay, as well as by the inflow of river water from the east, which creates a slope of the water surface and causes runoff currents.

The eastern part of Sevastopol Bay receives water from the Chernaya River, the major runoff (up to 80%) of which occurs in winter and spring. During the high-water period with weak winds, the runoff currents caused by the inflow of the Chernaya River waters become predominant. The deterioration of the self-purification capacity of this part of the bay in the last decade is associated with an increase in the flux of biogenic nitrogen and phosphorus with the runoff of the Chernaya River. This flux is especially intensified during the formation of winter and spring floods, when distributed surface flood waters spread up to the Neftyanaya Gavan area. Flood waters contain elevated levels of silicium, nitrates, ammonium and phosphorus, which enter the river and bay waters from residential waste-water in the lower reaches of the river, as well as from sewage discharges from settlements and enterprises located in the water protection zone. More detailed information on the influence of the regimes of a particular winter and spring flood and summer low water of the Chernaya River in 2015 on the self-purification capacity of the eastern part of the bay is presented in the work [12].

For this part of the Sevastopol Bay water area, the peculiarities of the bottom structure are also significant. Longer removal of phosphates in the eastern part of Sevastopol Bay (Table 3), observed by us in the last decade, may indicate their accumulation in bottom soils and increase the risk of secondary pollution of the water area. Thus, the work [13] provides data, obtained in the expedition of MHI RAS, on an artificial deepening of the bottom (depths of 19–20 m) in the area of the floating dock located near the southern shore of the eastern part of Sevastopol Bay are given. This deepening of the bottom in the eastern part of the bay resulted in reductive conditions under which, due to hypoxia, phosphorus accumulated in bottom sediments can re-enter the bottom water layer [7]. This also favours the oxidation of organic matter at the expense of nitrates with the formation of ammonium and nitrites.

Recently, some decrease in the self-purification capacity of the ecosystem of the western part of the bay has been observed, especially in relation to inorganic forms of nitrogen (Table 4). This is associated both with the hydrodynamic regime (Fig. 4), according to which the transport of pollutants, including nutrients, is carried out in the western direction, and with the growth in the number of sources of nutrient inputs as a result of increased recreational load on the bay coast.

Conclusions

Based on the consolidated database of archival materials of MHI RAS and SB FGBU SOI for 2012–2020, the authors used the balance method to calculate the value of assimilation capacity AC of the Sevastopol Bay ecosystems in relation to biogenic forms of nitrogen and phosphorus as well as its specific component $AC_{spec.}$, which allows calculating the differences in the volume of the studied parts of the bay.

Mean and maximum concentrations of inorganic forms of phosphorus (PO_4) and nitrogen (NO_2, NO_3, NH_4) for the specified period were estimated, values of mean and maximum rates of removal of the mentioned nutrients from the bay ecosystems were obtained, and the time of their removal from the bay ecosystems was calculated.

The paper presents the results of comparison of changes in the percentage of inorganic nitrogen forms (NO_2, NO_3, NH_4) in the water area of all parts of Sevastopol Bay for two periods (1998–2012 and 2012–2020). These changes mostly influenced the content of the reduced form of ammonium nitrogen. In recent years, its content has been increasing in all water areas of the bay, with the greatest increase observed in the western part of the bay – from 23 to 36%. The mean and maximum concentration of nitrites (NO_2) in the ecosystems of all parts of the bay is only increasing. The maximum concentration value was observed in the eastern and western parts of the bay (7.07 and 7.67 μM/L, respectively).

It is shown that over the last decade certain changes in the self-purification capacity of the bay ecosystems have occurred, which manifested themselves in a large variation of data on the value of assimilation capacity of the studied ecosystems with respect to both a specific nutrient and the ecosystem of each separate part of the bay water area. For all studied water areas of Sevastopol Bay, in some cases, improvement of self-purification capacity was observed, whereas in some cases, deterioration was noted.

Thus, the self-purification capacity of the Yuzhnaya Bay ecosystem improved in relation to nitrates and ammonium and deteriorated in relation to phosphates.

For the central part of the bay, an increase in the self-purification capacity for phosphates, nitrates and ammonium and a decrease only for nitrites was noted. In general, the situation has significantly improved.

For the ecosystem of the eastern part of the bay, which is under the influence of the Chernaya River runoff, a decrease in the self-purification capacity in relation to phosphates and all forms of nitrogen has been observed in the last decade. Therefore, the ecosystem condition has deteriorated, too.

For the ecosystem of the western part of the bay, a decrease in the self-purification capacity for all inorganic forms of nitrogen and a slight increase in that for phosphates were observed. In general, as in the eastern part of the bay, the ecosystem condition has deteriorated.

It is shown that the data on the state of Sevastopol Bay ecosystems, obtained in this work, can be associated with changes in the wind regime over the water area in the last decade and the system of surface currents formed under its influence in the water area of the bay. In addition, the current state of the bay ecosystems is associated with an increase in the number of sources of nutrients as a result of the growth of recreational load on the bay coast.

REFERENCES

1. Simonov, A.I. and Ryabinin, A.I., eds., 1996. [*Hydrometeorology and Hydrochemistry of Seas. Vol. 4. The Black Sea. Iss. 3. Modern State of the Black Sea Waters Pollution*]. Sevastopol: ECOSI-Gidrofizika, 230 p. (in Russian).
2. Lopukhin, A.S., Ovsyany, E.I., Romanov, A.S., Kovardakov, S.A., Sysoeva, I.V., Braynzeva, Yu.V., Rylkova, O.A., Gavrilova, N.A., Gubanov, V.V. [et al.], 2007. Seasonal Peculiarities of Hydrologic-Hydrochemical Structure of Sevastopol Bay Water, Microplankton and Distribution of its Biochemical Components (the Black Sea, Observations of 2004–2005). In: MHI, 2007. *Ekologicheskaya Bezopasnost' Pribrezhnoy i Shel'fovoy Zon i Kompleksnoe Ispol'zovanie Resursov Shel'fa* [Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources]. Sevastopol: ECOSI-Gidrofizika. Iss. 15, pp. 74–109 (in Russian).
3. Ivanov, V.A., Ovsyany, E.I., Repetin, L.N., Romanov, A.S. and Ignatyeva, O.G., 2006. *Hydrological and Hydrochemical Regime of the Sebastopol Bay and its Changing under Influence of Climatic and Anthropogenic Factors*. Sevastopol: MHI NAS of Ukraine, 90 p. (in Russian).
4. Sovga, E.E., Mezentseva, I.V. and Kotelyanets, E.A., 2017. Assimilation Capacity of the Marine Shallow Water Ecosystems with Various Anthropogenic Impacts as the Estimation Method of Its Self-Purification Ability. *Problems of Ecological Monitoring and Ecosystem Modelling*, 28(4), pp. 38-51. doi:10.21513/0207-2564-2017-4-38-51 (in Russian).
5. Sovga, E.E., Mezentseva, I.V. and Khmara, T.V., 2021. Natural-Climatic and Anthropogenic Factors Determining the Self-Purification Capacity of Shallow-Water Marine Ecosystems in Relation to Reduced Nitrogen Forms. *Ecological Safety of Coastal and Shelf Zones of Sea*, (3), pp. 23–36. doi:10.22449/2413-5577-2021-3-23-36 (in Russian).
6. Sovga, E.E., Mezentseva, I.V. and Slepchuk, K.A., 2020. Comparison of Assimilative Capacity and Trophic Index for Various Parts of the Sevastopol Bay Water Area. *Ecological Safety of Coastal and Shelf Zones of Sea*, (3), pp. 63–76. doi:10.22449/2413-5577-2020-3-63-76 (in Russian).

7. Sovga, E.E., Mezentseva, I.V. and Khmara, T.V., 2022. Simulation of Seasonal Hydrodynamic Regime in the Sevastopol Bay and of Assessment of the Self-Purification Capacity of its Ecosystem. *Fundamental and Applied Hydrophysics*, 15(2), pp. 110–123. doi:10.59887/fpg/92ge-ahz6-n2pt (in Russian).
8. Ivanov, V.A. and Tuchkovenko, Yu.S., 2008. *Applied Mathematical Water-Quality Modeling of Shelf Marine Ecosystems*. Sevastopol: ECOSI-Gidrofizika, 311 p. (in Russian).
9. Izrael, Yu.A. and Tsyban, A.V., 1989. [*Anthropogenic Ecology of the Ocean*]. Moscow: Gidrometeoizdat, 529 p. (in Russian).
10. Sovga, E., Mezentseva, I. and Verzhevskaia, L., 2015. Assimilation Capacity of the Ecosystem of Sevastopol Bay. In: E. Ozhan, 2015. *Proceedings of the Twelfth International Conference on the Mediterranean Coastal Environment MEDCOAST' 2015, 6–10 October 2015. Varna, Bulagaria*. Varna. Vol. 1, pp. 317–326.
11. Repetin, L.N., Belokopytov, V.N. and Lipchenko, M.M., 2003. Wind and Wave Perturbations in the Southwest Crimean Coast. In: MHI, 2003. *Ekologicheskaya Bezopasnost' Pribrezhnoy i Shel'fovoy Zon i Kompleksnoe Ispol'zovanie Resursov Shel'fa* [Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources]. Sevastopol: ECOSI-Gidrofizika. Iss. 9, pp. 13–28 (in Russian).
12. Sovga, E.E. and Khmara, T.V., 2020. Influence of the Chernaya River Runoff during High and Low Water on the Ecological State of the Apex of the Sevastopol Bay Water Area. *Physical Oceanography*, 27(1), pp. 28–36. doi:10.22449/1573-160X-2020-1-28-36
13. Kondratev, S.I. and Vidnichuk, A.V., 2020. Local Seasonal Hypoxia and Hydrogen Sulphide Formation in the Bottom Waters of the Sevastopol Bay in 2009–2019. *Ecological Safety of Coastal and Shelf Zones of Sea*, (2), pp. 107–121. doi:10.22449/2413-5577-2020-2-107-121 (in Russian).

Submitted 21.08.2023; accepted after review 15.09.2023;
revised 11.10.2023 ; published 20.12.2023

About the authors:

Irina V. Mezentseva, Senior Research Associate, Sevastopol Branch of the N. N. Zubov State Oceanographic Institute (61 Sovetskaya St., Sevastopol, 299011, Russian Federation), PhD (Geogr.), **ORCID ID: 0000-0001-9771-0380**, *mez-irina@mail.ru*

Elena E. Sovga, Leading Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya St., Sevastopol, 299011, Russian Federation), DrSci (Geogr.), **ORCID ID: 0000-0002-0670-4573**, **ResearcherID: A-9774-2018**, *esovga@mhi-ras.ru*

Tatiyana V. Khmara, Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya St., Sevastopol, 299011, Russian Federation), **Scopus Author ID: 6506060413**, **ResearcherID: C-2358-2016**, *xmara@mhi-ras.ru*

Contribution of the authors:

Irina V. Mezentseva – calculation of the assimilation capacity for ecosystems of parts of Sevastopol Bay, analysis of calculation results

Elena E. Sovga – study task statement, analysis of methods for calculating the assimilation capacity, comparison of assimilation capacity values for ecosystems of different parts of Sevastopol Bay, formation of the article

Tatiyana V. Khmara – calculations, discussion of the study results, data presentation in the text, data analysis, manuscript revision

All the authors have read and approved the final manuscript.