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Original paper

Ecological State of Waters of the Sevastopol Seashore (Western Crimea) and its Influence on the Dynamics of Plankton Communities

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Abstract

The Sevastopol seashore is influenced by a variety of anthropogenic and natural factors, which can be particularly pronounced in enclosed bays. The objective of this study is to analyse the spatial and temporal variability of hydrological and hydrochemical parameters and the modern state of plankton communities of the Sevastopol seashore. The variability of hydrochemical indicators of water, phytoplankton and meroplankton was studied in 2020–2022 in Kamyshovaya, Kazachya, Kruglaya, Streletskaya, Sevastopol and Karantinnaya Bays. The hydrochemical parameters (salinity, biochemical oxygen demand over five days (BOD_5), permanganate index, silicon content, mineral and organic forms of nitrogen and phosphorus) were determined according to generally accepted methods. The Redfield stoichiometric ratios were applied in order to ascertain the limiting nutrient factor. The species composition, abundance and biomass of phytoplankton and meroplankton were determined. In comparison to data collected 20 years ago, an increase in surface water pollution (BOD_5 and permanganate index exceeding maximum permissible values) was observed on the seashore of Sevastopol. Biogenic elements (nitrogen, phosphorus, and silicon compounds) varied widely. The study found that that limiting factor for phytoplankton vegetation was nitrogen in spring, silicon in summer, and phosphorus in summer and autumn. No phytoplankton blooms were recorded during the study period. Mass development of diatoms and coccolithophores was observed in spring. In summer and autumn, the abundance and biomass of planktonic microalgae decreased to minimum values. Relative synchrony of seasonal dynamics of meroplankton density was observed: in all Sevastopol bays minimum values were registered in the cold period of the year, whereas maximum values were recorded in the warm period when the water warmed up above 14.5°C. Comparative analyses and quantitative assessments of plankton dynamics in bays, differing in hydrological and hydrochemical environmental parameters, can contribute to the assessment of the functional response of Black Sea coastal ecosystems to anthropogenic and natural factors.

Keywords: phytoplankton, meroplankton, nutrients, biochemical oxygen demand over five days, BOD_5, Black Sea

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Экологическое состояние вод Севастопольского взморья (Западный Крым) и его влияние на динамику планктонных сообществ

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Аннотация

Севастопольское взморье испытывает постоянное воздействие антропогенных и природных факторов, которое может усиливаться в закрытых бухтах. Цель работы – проанализировать пространственно-временну́ю изменчивость гидролого-гидрохимических параметров и состояние планктонных сообществ Севастопольского взморья в современный период. Исследования изменчивости гидрохимических показателей вод, фитопланктона и меропланктона проведены в 2020–2022 гг. в бухтах Камышовой, Казачьей, Круглой, Стрелецкой, Севастопольской и Карантинной. Гидрохимические показатели (соленость, биохимическое потребление кислорода за пять суток ($БПК_5$), перманганатная окисляемость, содержание кремния, минеральных и органических форм азота и фосфора) определяли по общепринятым методикам. Для определения лимитирующего биогенного фактора использовали стехиометрические соотношения Редфилда. Определяли видовой состав, численность и биомассу фитопланктона и меропланктона. За 20 лет на взморье Севастополя отмечено повышение уровня загрязнения поверхностных вод ($БПК_5$ и окисляемость превышали предельно допустимые значения). Биогенные элементы (соединения азота, фосфора, кремния) изменялись в широких пределах. Лимитирующим фактором для развития фитопланктона в весенний период был азот, летом – кремний, летом и осенью – фосфор. За период исследования не зафиксировано случаев «цветения» фитопланктона. Массовое развитие диатомовых водорослей и кокколитофорид отмечено в весенний период. Летом и осенью численность и биомасса планктонных микроводорослей снижались до минимальных значений. Отмечена относительная синхронность сезонной динамики плотности меропланктона: во всех бухтах Севастополя минимальные значения зарегистрированы в холодный период года, максимальные – в теплый период при прогреве воды выше 14.5 °C. Сравнительный анализ и количественные оценки динамики планктона в бухтах, различающихся по гидрологическим и гидрохимическим параметрам среды, могут внести вклад в оценку функциональной реакции прибрежных экосистем Черного моря на антропогенные и природные факторы.

Ключевые слова: фитопланктон, меропланктон, биогенные элементы, биохимическое потребление кислорода, $БПК_5$, Черное море

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Introduction

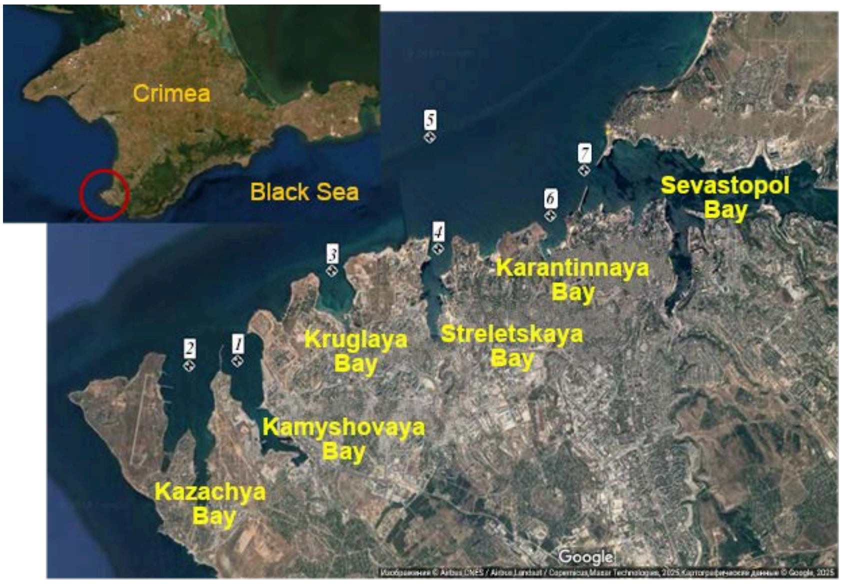
The basis of pelagic food chains in aquatic systems is phytoplankton, with its dynamics of abundance, species diversity and productivity influenced by various environmental factors. In this regard, structural and functional parameters of phytoplankton can serve as indicators of changes in bay ecosystems. One of the links of the food chain in the pelagial ecosystem is meroplankton (pelagic larvae of bottom-dwelling invertebrates). On the one hand, larvae consume a large amount of phytoplankton, and on the other hand, they themselves are part of the food of many marine invertebrates and fish. At the same time, the representatives of meroplankton are most vulnerable to the impact of various toxicants and domestic sewage [1].

The Sevastopol seashore is considerably influenced by a variety of anthropogenic factors which can be particularly pronounced in enclosed bays [2, 3]. The bays have different configuration, size and depth. Most of them are elongated and run deep into the shore (Sevastopol, Karantinnaya, Streletskaya, Kamyshovaya and Kazachya bays), except for Kruglaya Bay [4]. The formation of the hydrochemical regime of the Sevastopol seashore is influenced by river and storm water runoff as well as domestic sewage with a high content of mineral nitrogen, which exceeds the content of phosphorus compounds by one to three orders of magnitude and is a determinant in the eutrophication of water bodies [2]. The impact of river runoff and anthropogenic pollution increases from west to east. The most unfavourable location is Karantinnaya Bay while Kazachya Bay is the least unfavourable. Simultaneously, research conducted in certain bays of the Sevastopol seashore in recent years has revealed the emergence of novel anthropogenic pollution hotspots and a substantial increase in the concentration of total suspended solids, dissolved organic matter and petroleum hydrocarbons. These concentrations exceeded the maximum permissible concentration (MPC) frequently [5–7].

The objective of this study is to analyse the spatial and temporal variability of hydrological and hydrochemical parameters and the state of plankton communities of the Sevastopol seashore according to the data obtained in 2020–2022.

Materials and methods

The study was conducted from October 2020 to November 2022. Six one-day surveys were carried out in spring (May 2021), summer (July 2021, August 2022) and autumn (October 2020, November 2021 and 2022). Samples were taken at the traverse of Kamyshovaya (station *1*), Kazachya (station *2*), Kruglaya (station *1*), Streletskaya (station *4*), Karantinnaya (station *6*) and Sevastopol (station *7*) bays as well as at a station in the open part of the seashore (station *5*) 2 km offshore (Fig. 1). The depth in the study area was mainly 12–20 m, except for the control station (station *5*), where it reached 50 m.



F i g . 1 . A map-scheme of the study area (*1–7* are station numbers). Adopted from Google Maps (URL: https://www.google.ru/maps)

Samples were taken in the surface and bottom layers using a BM-48M bathometer. Salinity (a GM-65 electrosalinometer with regular calibration by titration with $AgNO_3$ solution), biochemical oxygen demand over five days (BOD_5), permanganate index in alkaline medium, silicon content as well as content of mineral and organic forms of nitrogen and phosphorus were determined according to generally accepted methods [1), 2)]. The Redfield stoichiometric ratios (PR_{at}) [3)] were used in order to ascertain the limiting nutrient factor, which had the following form for known concentrations of inorganic compounds of nitrogen, phosphorus and silicon:

$$PR_{at}\,(N/P) = 1.53\,(1.35\,NO_2 + NO_3 + 3.44\,NH_4)\,/\,PO_4,$$

$$PR_{at}\,(Si/N) = SiO_4\,/\,(1.47\,(1.37\,NO_2 + NO_3 + 3.77\,NH_4)),$$

$$PR_{at}\,(Si/P) = 1.03\,SiO_4/PO_4.$$

1) Guideline Documents РД 52.24.420-2019; РД 52.24.383-2018; РД 52.24.380-2017; РД52.24.381-2017; РД 52.24.382-2019; РД 52.24.432-2018; РД 52.10.805-2013; РД 52.24.387-2019 (in Russian).

2) *On the Approval of Water Quality Standards for Water Bodies of Commercial Fishing Importance, Including Standards for Maximum Permissible Concentrations of Harmful Substances in the Waters of Water Bodies of Commercial Fishing Importance*: Order of the Ministry of Agriculture of Russia dated December 13, 2016, No. 552 (in Russian).

3) Redfield, A.C., Ketchum, B.H. and Richards, F.A., 1963. The Influence of Organisms on the Composition of Sea-Water. In: N. M. Hill, ed., 1963. *The Sea: Ideas and Observations on Progress in the Study of the Seas*. New York: Wiley Interscience, Vol. 2, pp. 26–77.

To determine the species composition, abundance and biomass of phytoplankton, samples (V = 2.0 L) were collected from the upper layer of seawater (0–1 m). Seawater was filtered through nuclear-track membranes with a pore diameter of 1 μm (JINR, Dubna) on a reverse filtration unit. Then, it was concentrated to a volume of 40–50 mL and fixed with Utermel solution. The identification of microalgae species was conducted using a light microscope at magnifications of 200× and 400× (Olympus BX43) with the help of identifiers [4), 5)]. Phytoplankton abundance and biomass were calculated using the Gloria software developed at the IBSS [8]. Taxonomic names are given according to the AlgaeBase (available at: https://www.algaebase.org) and World Register of Marine Species (available at: https://www.marinespecies.org) databases.

Sampling of meroplankton during the study period was carried out at coastal stations with a depth of up to 13 m. The material was collected with a Juday net with an inlet diameter of 36 cm and a silk bolting cloth mesh size of 135 μm. The water layer 0–10 m from bottom to surface was considered under study. Live material was processed by total counting of larvae in a Bogorov type chamber under an MBS-9 binocular; a MIKMED-5 light microscope was used to clarify the species affiliation of larvae [3].

A total of 96 samples for hydrological and hydrochemical analysis and 23 phyto- and meroplankton samples each were processed and analysed.

Mathematical and statistical calculations were performed in Excel 2016. Estimates of minimum, maximum, mean values and standard deviations were obtained.

Results

Spatial and temporal distribution of thermohaline and hydrochemical parameters

Temperature and salinity. Surface layer temperature varied from 14.4 (May) to 26.1°C (August) decreasing to 13.1°C as a result of autumn cooling (November). During the period of thermocline formation (May–August), water stratification was observed: the maximum temperature difference between the surface and bottom layers at the control station reached 16.2°C while at the shallow station (Kamyshovaya Bay), stratification was minimal, with the temperature difference not exceeding 0.9°C. During the autumn months, convective mixing resulted in vertical equilibrium of temperatures.

The spatial structure of the surface layer thermohaline fields was characterised by insignificant gradients. It was demonstrated that the range of variability of sea water surface layer temperature was 0.3–1.4°C and that of salinity – 0.08–0.21 PSU. It is important to note the elevated salinity levels observed at the control station

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[4)] Proshkina-Lavrenko, A.I., 1955. [*Diatom Algae of the Black Sea Plankton*]. Moscow, Leningrad: Izd. AN SSSR, 224 p. (in Russian).

[5)] Tomas, C.R., ed., 1993. *Marine Phytoplankton: A Guide to Naked Flagellates and Coccolithophorids*. Academic Press, 263 p.

in comparison to the bays. Extremely low salinity values were recorded in November 2021 (17.63–17.84 PSU). During the periods of other surveys, the surface layer salinity values varied in the range of 18.02–18.54 PSU. Salinity increased from the surface to the bottom, the maximum difference in salinity values was recorded in the 0–50 m layer (0.42 PSU on 17.11.2021 and 0.33 PSU on 09.07.2021).

BOD_5 and permanganate index. BOD_5 values varied over a wide range of 0.57–3.87 mg/dm^3 (Table). Values close to water quality standards for water bodies of fishery significance and exceeding them ($\geq$ 2.1 mg/dm^3) were observed in spring (Kamyshovaya, Kruglaya, Karantinnaya, Sevastopol bays) and during summer surveys (Kamyshovaya, Kazachya, Kruglaya, Streletskaya bays). Furthermore, autumn BOD_5 values did not exceed the normative values at all stations, except for the survey in autumn 2021 at the station in Kamyshovaya Bay (3.84 mg/dm^3).

Permanganate index varied from 1.62 to 5.49 mgO/dm^3 during the period under consideration (Table). Exceedance of this index standard (> 4.0 mgO/dm^3) was observed in all bays and in different seasons of the year. Mean values of permanganate for the observation period in the bays were below the water quality standards.

Nutrients. Nitrite nitrogen concentration (NO_2) was low and did not exceed 3.5 μg/dm^3 in the surface layer (Table) and 4.6 μg/dm^3 in the near-bottom one (Streletskaya Bay). Nitrate concentration in the surface layer varied from 4.6 (May 2021, Sevastopol Bay) to 267.5 μg/dm^3 (August 2022, Karantinnaya Bay). The near-bottom layer demonstrated the nitrate concentration variation from 3.8 to 86.8 μg/dm^3 (August 2022). Mean values of nitrate in the surface layer varied in the bays from 12.7 in Kruglaya Bay to 58.1 μg/dm^3 in Karantinnaya Bay. Of note is the August 2022 survey when high nitrate values were recorded at all stations and reached 267.5 μg/dm^3 in the Karantinnaya Bay surface layer. Elevated concentration values in the same survey were also recorded in the bottom layer (39–59 μg/dm^3) while the maximum (86.8 μg/dm^3) was observed at the control station near the bottom. Ammonium nitrogen concentration on the Sevastopol seashore was low and ranged from 0.6 μg/dm^3 (Kruglaya Bay, May 2021) to 32.4 μg/dm^3 (Kamyshovaya Bay, August 2022). August 2022 was characterised by NH_4 increased concentration at all stations. Organic nitrogen concentration (N_{org}) varied over a wide range: from 331 μg/dm^3 in May 2020 to 1375 μg/dm^3 in Streletskaya Bay in August 2022 (Table). High N_{org} concentration values were recorded also in Kruglaya, Kazachya and Kamyshovaya bays.

Mineral phosphorus (PO_4) concentration varied from 1.1 to 15.9 μg/dm^3. Minimum content was observed in autumn 2022 at the control station, maximum – in spring 2021 in Kamyshovaya Bay (Table). The mean value of PO_4 in the Sevastopol seashore water area for 2020–2022 is 6.3 μg/dm^3. Organic phosphorus (P_{org}) content varied from 3.7 to 34.9 μg/dm^3. Maximum values were recorded in summer in Kazachya Bay. Mean values of P_{org} for all the period under study varied from 15.3 to 22.1 μg/dm^3. In general, P_{org} concentration values were low and uniform. No seasonal variability was recorded.

Hydrochemical parameters in the surface layer of the water area under study (2020–2022)

Bays	Value	BOD_5, mg/dm^3	PI, mgO/dm^3	Content, μg/dm^3						
				NO_2	NO_3	NH_4	N_{org}	PO_4	P_{org}	Si
Kazachya	mean	1.63	3.23	0.9	24.3	8.7	696	4.0	17.8	44.5
	min	0.70	1.75	0.4	4.7	2.1	378	1.4	3.7	12.4
	max	**2.72***	**4.37**	1.3	90.3	15.0	1131	12.3	34.9	72.6
Kamyshovaya	mean	**2.61**	3.92	1.3	24.6	13.5	645	6.5	21.0	60.3
	min	1.31	2.30	0.9	5.3	1.7	331	2.4	5.0	14.8
	max	**3.87**	**5.49**	1.6	70.4	32.4	1188	15.9	26.7	98.6
Kruglaya	mean	1.40	3.24	0.8	12.7	8.2	645	3.7	17.6	40.0
	min	0.57	2.01	0.1	5.4	0.6	372	1.4	4.3	17.9
	max	**2.23**	**4.11**	1.2	44.5	17.4	1235	10.9	26.4	63.7
Streletskaya	mean	1.38	3.37	1.4	24.2	8.6	660	3.9	19.2	81.2
	min	0.60	1.98	0.7	5.1	1.8	412	1.1	4.1	23.8
	max	**2.21**	**4.50**	2.1	40.9	19.1	1375	10.5	33.4	118.1
Karantinnaya	mean	1.43	3.22	1.4	58.1	8.8	545	5.1	17.1	64.8
	min	0.66	1.62	0.8	6.5	1.9	411	1.8	4.6	15.1
	max	**2.72**	**4.73**	3.5	267.5	17.8	824	11.5	27.3	152.4
Sevastopol	mean	1.45	3.51	1.7	14.1	8.7	670	6.3	22.1	47.4
	min	1.10	2.39	1.2	4.6	2.6	459	3.5	15.0	19.8
	max	**2.32**	**4.63**	2.3	22.2	12.9	838	11.2	34.2	75.0
Control	mean	1.50	3.89	0.8	14.3	7.7	618	4.2	22.8	31.0
	min	1.26	3.28	0.5	6.5	2.2	370	1.8	14.2	14.3
	max	**2.02**	**4.42**	1.0	29.1	13.6	801	9.5	29.1	58.7

Note: values exceeding maximum permissible concentrations (MPC) [2)] and limits for water quality of fisheries [2)] are given in bold. PI – permanganate index. MPC of NO_2 – 20 μg/dm^3, NO_3 – 9,000 μg/dm^3, NH_4 – 390 μg/dm^3. BOD_5 limit value – under 2.1 μg/dm^3, PI limit value – 4.0 μg/dm^3.

Silicon (Si) content was characterised by great variability. Thus, Si concentration in the surface layer varied from 12.4 µg/dm^3 (July 2021) in Kazachya Bay to 152.4 µg/dm^3 (August 2022) in Karantinnaya Bay (Table). High Si concentrations were recorded in all bays in August 2022 in the surface (64–152 µg/dm^3) and near-bottom layers (100–153 µg/dm^3). No silicon concentration seasonal variability was recorded.

Ratio of nutrients

Fig. 2 shows the results of calculations of the Redfield ratio (PR_{at}) for nitrogen, phosphorus and silicon to determine the limiting factor for phytoplankton. A wide range of relative N/P values was observed – from 1 to 53. The minimum values were observed in spring (1–3), indicating significant nitrogen limitation. The ratio was close to the classical Redfield ratio in summer (except for Kazachya and Karantinnaya bays), autumn 2020 in Karantinnaya and Sevastopol bays and autumn 2021 in Kamyshovaya Bay. In other cases, the ratio of N/P values exceeded 16 which corresponded to phosphorus-induced limitation.

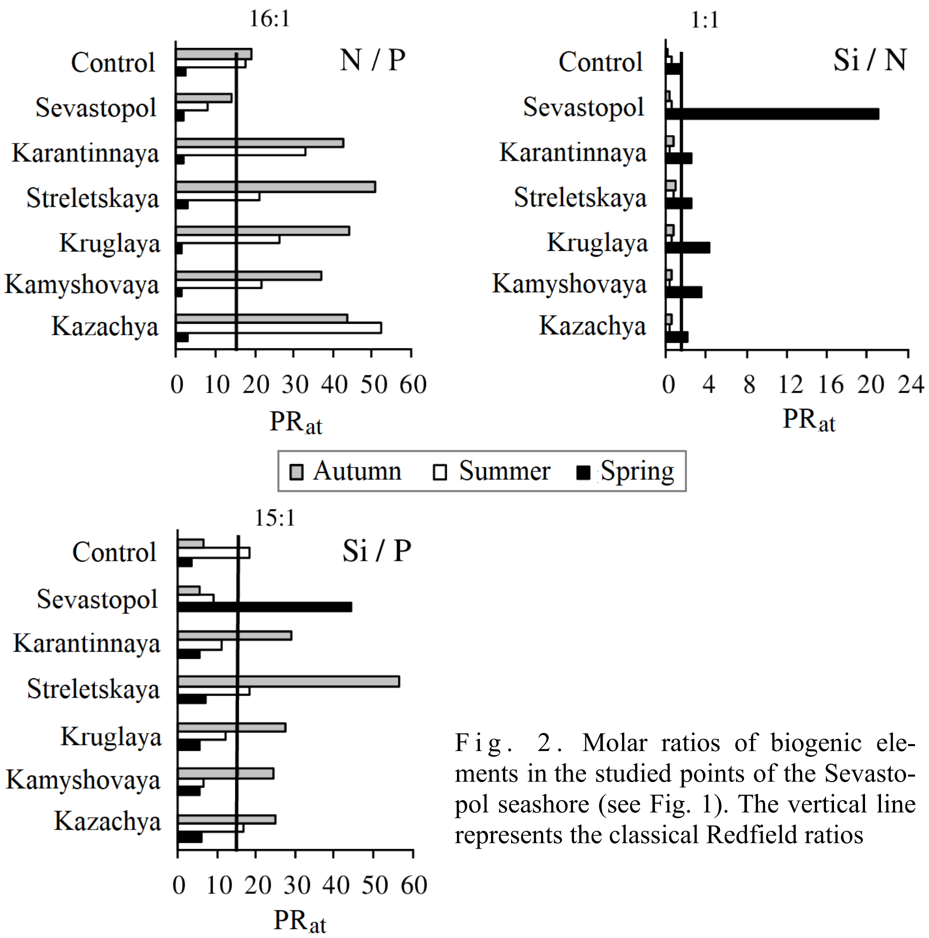


Fig. 2. Molar ratios of biogenic elements in the studied points of the Sevastopol seashore (see Fig. 1). The vertical line represents the classical Redfield ratios

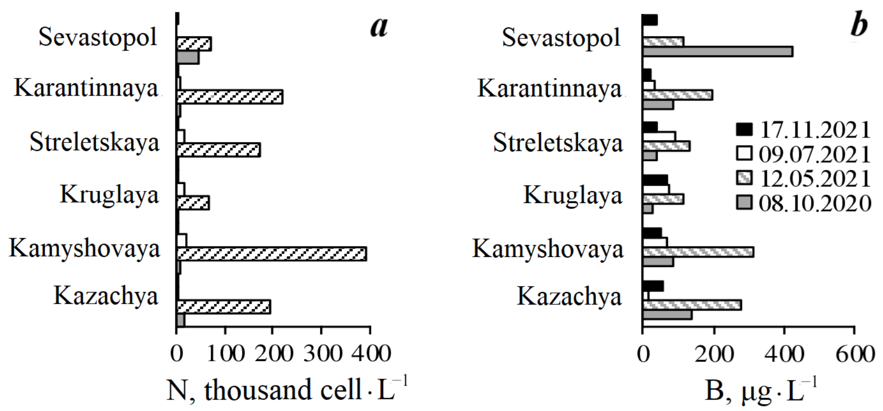
The Si/N ratio varied from 0.2 to 21. The Si/N value greater than one was recorded in spring and also in autumn 2020 in Streletskaya Bay. The Si/P ratio varied from 3 to 56. In autumn 2020 and 2021 this ratio exceeded the classical values. In spring and summer, lower values of the Si/P ratio were observed.

Taking the ratio of all three elements (N/Si/P) into account, the values close to the classical Redfield ratio were observed only in autumn 2020 in Karantinnaya Bay (18/17/1). Significant deviations were noted at other times.

Phytoplankton: dynamics of taxonomic composition and density

A total of 75 species of microalgae were recorded in phytoplankton samples, 35 of which belong to diatoms and 32 to dinophytes. The remaining species belong to such phyla as Haptophyta, Euglenozoa, Ochrophyta, Cercozoa. The maximum values of phytoplankton abundance and biomass in all bays were observed in spring (Fig. 3). The exception was the autumn period of 2020 in Sevastopol Bay, when the biomass of planktonic microalgae exceeded 400 mg·L^{-1}, with low abundance of phytoplankton. Phytoplankton abundance was also low during summer and autumn 2021.

The spatial and temporal variability of the abundance of the main phytoplankton groups indicates high variability of the community composition. In autumn 2020 and 2021, diatoms were absolutely dominant in terms of both abundance (75–100%) and biomass (64–100%). In spring, diatoms and coccolithophores dominated in abundance (98–99%) in Kamyshovaya, Kruglaya and Sevastopol bays and in biomass – at all stations. In summer, diatoms dominated in abundance (52–80%), but were inferior to dinoflagellates (57–91%) in biomass. In autumn 2020 at all stations, large-celled diatom alga *Proboscia alata* was the main contributor (57–97%) to total abundance and biomass, while in autumn 2021, it was *Pseudosolenia calcar-avis* (87–99%). Coccolithophore *Emiliania huxleyi*



F i g . 3 . The total abundance *N* (*a*) and biomass *B* (*b*) of phytoplankton in Sevastopol bays (see Fig. 1) dominated almost at all stations in May 2021 (37–58% of total abundance), and in Kamyshovaya Bay, diatoms *Pseudo-nitzschia calliantha* and *Chaetoceros wighamii* made a significant contribution to abundance (23 and 45% of the total number, respectively) along with coccolithophores.

P. alata formed the basis of biomass (40–58% of the total biomass) of spring phytoplankton in all bays. In summer, dinophytes of genus *Prorocentrum* gave peak abundance in Kazachya and Streletskaya bays. In Kamyshovaya Bay, diatoms *Chaetoceros tortissimus*, *Leptocylindrus danicus* and *P. alata* accounted for more than 68% of the total abundance, while diatoms *P. calliantha* and *P. alata* dominated in Kruglaya Bay (more than 50% of the total abundance). The basis of biomass was formed by large-celled diatom *P. alata* and dinoflagellates of genus *Prorocentrum*.

Meroplankton: dynamics of taxonomic composition and density

During the study period, larvae of 41 species of benthic invertebrates belonging to the following taxa were identified in plankton: type Annelida, class Polychaeta – 16 species; type Mollusca, classes Bivalvia – 7, Gastropoda – 9 species; type Arthropoda, subtype Crustacea: infraclass Cirripedia – 2 species and order Decapoda – 7 species. Planulae Coelenterata (Type Cnidaria), larvae Kamptozoa (Type Entoprocta) and Bryozoa (Type Bryozoa) not identified to species, were encountered sporadically.

The minimum number of larvae of benthic invertebrates was recorded in the cold period of the year in the whole water area of the Sevastopol seashore. In November 2021 the total density of meroplankton did not exceed 29 ind./m^3 (Fig. 4). Veliconchae of such bivalves as mussel *Mytilus galloprovincialis* Lamarck, 1819 and surf clam *Spisula subtruncata* (Da Costa, 1778), gastropod veligers not identified to species, polychaete larvae (*Spio decorata* Bobretzky, 1870) and barnacle nauplii *Amphibalanus improvisus* (Darwin, 1854) were found in the plankton.

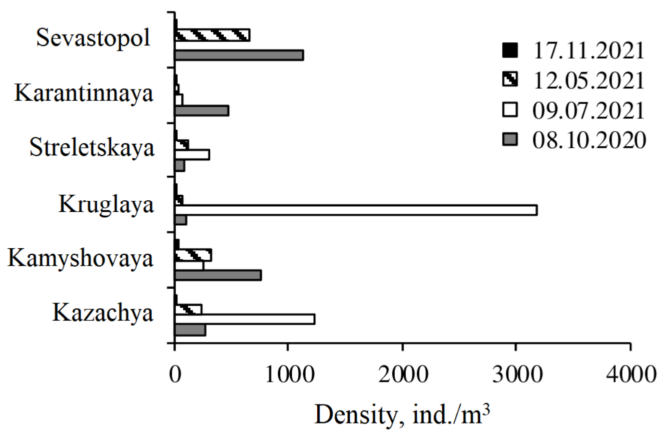


Fig. 4. Dynamics of meroplankton density in Sevastopol bays (see Fig. 1)

A substantial increase in the number of larvae in the plankton was observed during the warm period of the year when a multitude of species of benthic invertebrates commenced their reproductive cycle. In May, the maximum plankton density (661 ind./m^3) was recorded in Sevastopol Bay, it reached 322 ind./m^3 in Kamyshovaya Bay and ranged from 26 ind./m^3 (in Karantinnaya Bay) to 227 ind./m^3 (in Kazachya Bay) in other areas (Fig. 4).

The species composition of meroplankton underwent an increase in diversity. Among mollusks, with the exception of mussel larvae, veliconchae of the bivalve mollusks of family Cardiidae, gastropod veligers of family Rissoidae were observed to occur in the plankton. The density of mussel larvae was low – up to 15 ind./m^3, while that of veligers Gastropoda reached 147 ind./m^3 (in Kamyshovaya Bay). Larvae of polychaetes *Harmothoe reticulata* (Claparède, 1870), *Pholoe inornata* Johnston, 1839, *Polydora cornuta* Bosc, 1802, *Alitta succinea* (Leuckart, 1847) and larvae of family Nereididae not identified to species appeared in the plankton. Larvae Decapoda (*Hippolyte leptocerus* (Heller, 1863), *Upogebia pusilla* (Petagna, 1792)) were recorded sporadically. In terms of abundance, all bays were dominated by larvae of barnacle *A. improvisus,* from their maximum of 597 ind./m^3 (in Sevastopol Bay) to 227 ind./m^3 (in Kazachya Bay).

In July, the maximum meroplankton density (3180 ind./m^3) was recorded in Kruglaya Bay. It was stipulated by high density of gastropods larvae (2173 ind./m^3). Veligers of bittium (*Bittium reticulatum* (Da Costa, 1778)) and representatives of family Rissoidae dominated in the plankton. With their density not exceeding 135 ind./m^3 in other bays, it reached 373 ind./m^3 in Kazachya Bay only. During this period, an increase in the density of barnacle larvae was also noted in all bays but the plankton was dominated by nauplii of another species, *Verruca spengleri* Darwin, 1854.

In October, Sevastopol and Kamyshovaya bays showed higher meroplankton density values – up to 1126 and 756 ind./m^3, respectively (Fig. 4). At the same time, the number of larvae in other bays ranged from 91 ind./m^3 (in Streletskaya Bay) to 463 ind./m^3 (in Karantinnaya Bay). In terms of abundance, veligers of gastropods (*Retusa truncatula* (Bruguière, 1792), *Caecum trachea* (Montagu, 1803), *Limapontia capitata* (O. F. Müller, 1774), *Rissoa parva* (Da Costa, 1778), *Rissoa* sp.) dominated. Their maximum total density (235 ind./m^3) was recorded in Kamyshovaya Bay. That period was also characterised by the increased number of mussel *M. galloprovincialis* larvae in the stage of ocellated veliconcha. Their density was 110 ind./m^3 in Kamyshovaya Bay and ranged from 9 to 62 ind./m^3 in other areas under study. The density of polychaete larvae did not exceed 29 ind./m^3. *Lysidice ninetta* Aud. et H. M. Edw., 1833 *Magelona rosea* Moore, 1907, *Malacoceros fuliginosus* (Claparède, 1870) and *Prionospio* sp. and *Phyllodoce* sp. not identified to species were observed. Barnacle nauplii *A. improvisus* (up to 782 ind./m^3) dominated in Sevastopol Bay. Larvae of decapods (*Clibanarius erythropus* (Latreille, 1818), *Pisidia longimana* (Risso, 1816), *Xantho poressa* (Olivi, 1792), *Pachygrapsus marmoratus* (Fabricius, 1787), *Athanas nitescens* (Leach, 1813) were recorded in the plankton in October but their total density did not exceed 30 ind./m^3 (Karantinnaya Bay).

The meroplankton density dynamics in all bays exhibited a high degree of synchrony. Minimum values, with a maximum of 29 ind./m^3, were observed to be characteristic of the cold period of the year when the water temperature was recorded at 14.5°C (in November). An increase in density was noted with the onset of water warming in May, July and October. In terms of abundance, the meroplankton showed the domination of barnacle nauplii *Amphibalanus improvisus*: during the cold period of the year, they occurred sporadically and dominated the plankton in May and October, which then influenced the total meroplankton density values. The maximum number of barnacle larvae was recorded in Sevastopol and Kamyshovaya bays.

Discussion

A comparison of the hydrological and hydrochemical data obtained from one station scheme in 2001–2005 and 2020–2022 is of interest [2]. In 2020–2022, an increase of salinity in the surface layer in the water area was noted. In 2001–2005, mean salinity values ranged from 17.70 to 17.94 PSU [2] while in 2020–2022, salinity values reached 18.54 PSU. The trend of salinity increase in the Sevastopol coastal area in recent years has also been indicated by other authors [3, 9]. A positive salinity trend in the surface layer was found in Karantinnaya Bay from 2001 to 2018 [9]. Studies in the shelf zone of the north-eastern Black Sea also demonstrated a progressive increase in salinity in the upper 200 m layer of the sea from 2010 to 2020 [10]. The authors attribute this primarily to fluctuations in the Black Sea climate regime.

According to the official data provided by the Crimean Service of State Statistics (available at: https://82.rosstat.gov.ru/), the population of the City of Sevastopol has increased by 33% over the last 20 years while the government estimates that the actual increase is over 40%. Urban development has expanded in the coastal zone, with a corresponding increase in the volume of domestic water and the load on sewage treatment plants. In addition, as urbanization increases, the volume of stormwater runoff also increases with the deterioration of its quality [5, 11]. All this results in an increase in the concentration of mineral and organic substances in the coastal water area and affects the level of surface water pollution which we assessed by two indicators – BOD_5 and permanganate index. The first value reflects the pollution of the environment by non-persistent organic matter; the second one indicates the degree of pollution by persistent organic matter. BOD_5 mean values obtained until 2005 on the Sevastopol seashore did not exceed 0.79 mg/dm^3 [2] while in the modern period, BOD_5 values exceeded water quality standards for water bodies of fishery significance in spring (in Kamyshovaya, Kruglaya, Karantinnaya, Sevastopol bays) and in summer (in Kamyshovaya, Kazachya, Kruglaya, Streletskaya bays), which indicates an increase in the degree of pollution of the seashore. This is also confirmed by permanganate index (exceedance of standards was observed in all bays and in different seasons) and nitrogen concentration. It should be noted that nutrient content is influenced by water dynamics, anthropogenic pollution and interactions with biota.

The dynamics of abundance, species diversity and productivity of the phytoplankton community are influenced by a complex of different environmental factors: temperature, light, nutrients, trace elements, pollutants, consumption by other components of food chains, water dynamics, etc. However, it is not possible to isolate the influence of individual factors in natural conditions. The impact of temperature and light on the reproductive capacity of diverse phytoplankton groups is a well-documented phenomenon. In order to gain a more complete understanding of the effects of trace elements and pollutants, experimental work is required. To facilitate a discussion regarding the influence of wind-wave processes, a series of long-term observations must be conducted. Nutrients represented by mineral compounds of nitrogen, phosphorus and silicon constitute the material basis for the creation of primary production in water bodies. The concentration of these substances and their ratio regulate phytoplankton vital activity and ensure biological productivity of aquatic ecosystems as a whole. In this connection, we tried to assess the relationships of nutrients with the development of phytoplankton communities in the studied water areas in different seasons.

No seasonal regularity in the change of nitrate and organic nitrogen concentration was observed, which confirms the influence of anthropogenic pollution as the main source of nitrogen. At the same time, the concentration of nitrate nitrogen required by the phytoplankton varied widely. NH_4^+ maximum concentrations were observed in autumn when the plankton composition was dominated by large-celled diatom algae. The phytoplankton are known to consume NH_4 during photosynthesis, with algae using less energy compared to nitrate assimilation [12]. Absorption of reduced forms of nitrogen, including NH_4^+, depends on the phytoplankton cell size. Small-cell phytoplankton assimilate ammonium nitrogen predominantly while large-cell phytoplankton are the main consumers of nitrates [13]. Mean values of mineral and organic nitrogen concentrations in Kamyshovaya, Kazachya and Kruglaya bays exceeded similar values recorded until 2005 [2].

Maximum phosphate concentrations were observed during the period of phytoplankton mass development with predominance of coccolithophores (spring 2021). The same period was characterised by minimal Redfield ratio PR_{at} (N/P) (1–3), which can indicate nitrogen limitation of the phytoplankton production. Similar data on biogenic elements in the spring period were obtained by A. S. Mikaelyan et al. [14]. The authors noted an interesting peculiarity for the Black Sea: phosphates have a positive effect on the mass development of coccolithophores under nitrogen limitation of primary production. In summer and autumn, we observed phosphorus deficiency in most cases. The importance of mineral phosphorus as the leading factor of chemical limitation of phytoplankton production along with the length of daylight hours and water temperature on the Sevastopol seashore is stated in [15].

The silicon content exhibited significant variability over the 2020–2022 period, with values gradually declining from the peak recorded in spring to lower levels in summer and autumn, attributed to the consumption of this element by the phytoplankton. It is probable that silicates did not constitute a limiting factor for the phytoplankton growth in spring, when diatom algae were predominant, in conjunction with coccolithophores. The lowest silicon content was observed in summer when the silicon-to-nitrogen ratio was less than 0.5. This period also coincided with the absence of diatoms as the dominant phytoplankton group. The observed deviation from the classical Redfield ratios (Si/N) in summer and autumn in some bays indicates higher consumption of silicates by phytoplankton compared to nitrates.

Excess nitrogen combined with a deficiency of phosphorus, and in some cases silicon, resulted in an unbalanced stoichiometry of dissolved nutrients. This imbalance is reflected in deviations from the classical Redfield ratios (N/Si/P) as well as wide variations in these ratios. The enrichment of the biosphere with nitrogen, the concentration of which in the ocean far exceeds that of phosphorus, is of concern as it can affect coastal ecosystems [16].

No direct influence of nutrients and phytoplankton on the dynamics of meroplankton density was found. The influence of phytoplankton is likely to have a delayed effect. Furthermore, the main influence of the temperature factor on mass reproduction of some meroplankton taxa cannot be excluded. At the same time, taking into account that larvae of bottom invertebrates consume phytoplankton, we can assume the opposite effect. Thus, in July 2021, in Kruglaya Bay, in the context of low phytoplankton abundance, the maximum value of meroplankton density was recorded, which can be associated with the ingestion of phytoplankton by larvae. The density of meroplankton in autumn 2020 and spring 2021 in Kamyshovaya and Sevastopol bays was high due to an increase in the number of larvae of barnacles and bivalves, which is associated with seasonal cycles of their reproduction, and did not depend on hydrochemical parameters. At the same time, a large number of quay walls, breakwaters and other hydro-technical structures in the above-mentioned bays attract larvae of these meroplankton groups as a convenient substrate for settling.

Conclusion

During the period under study, an increase in the level of pollution on the Sevastopol seashore was observed in comparison with the 2001–2005 period. The maximum BOD_5 values in all bays exceeded water quality standards for water bodies of fishery significance. According to this indicator, the bays can be arranged from the most polluted with non-stable organic substances to the less polluted in the following order: Kamyshovaya, Kazachya, Karantinnaya, Sevastopol, Kruglaya, Streletskaya. The maximum permanganate index values in all bays also exceeded quality standards. Nitrate concentration on the Sevastopol seashore increased from spring to summer and decreased by autumn. The average values of mineral and organic nitrogen concentrations in Kamyshovaya, Kazachya and Kruglaya bays exceeded similar values recorded until 2005. The minimum concentration of nitrates was recorded in Kruglaya Bay, the maximum one – in Karantinnaya Bay. Ammonium nitrogen concentrations exhibited seasonal variations, analogous to the fluctuations observed in nitrate levels. The phytoplankton community composition exhibited significant spatial and temporal variability in the abundance of the main groups. The predominance of large-celled diatom algae was observed in autumn while the spring period was characterised by the dominance of small-celled colonial diatoms and coccolithophore *Emiliania huxleyi*, diatoms dominated in summer in terms of abundance and dinoflagellates – in terms of biomass. Relative synchrony of seasonal dynamics of meroplankton density in Sevastopol bays was noted, with minimum values registered in the cold period of the year and maximum ones in the warm period. The meroplankton community was dominated by barnacle nauplii *Amphibalanus improvisus* which were found to be the most prevalent species in the fouling of hard substrates. The maximum number of larvae of this species was recorded in Sevastopol and Kamyshovaya bays.

The results obtained can be used to assess the functional response of the Black Sea coastal ecosystems to variability of anthropogenic and natural factors.

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