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Complex control of the ecological state of the components of the environment and biota of the eastern part of the Avachinsky Gulf

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Abstract: The purpose of this work is to conduct a comprehensive assessment of the ecological status of the eastern part of Avachinsky Gulf. This assessment is based on the results of monitoring chemical and microbiological parameters of the aquatic environment and sediments, as well as biotesting the toxicity of the environment and evaluating the abundance of macrobenthos. The conditions of anthropogenic transformation of the natural ecological and chemical background are primarily observed in the inner part of the bay (Avacha Bay). Conversely, the natural climatic and oceanological processes are predominant in the open area of Khalaktyrsky Beach (the open part of the gulf). Significant differences were identified in the content of phosphorus compounds (Pmin), ammonium ions (NH_4^+), the total number of heterotrophic microorganisms, and sanitary-indicative groups of bacteria. According to biotesting results, a toxic effect was detected in the gulf environment. Despite the presence of environmental risk factors in Avacha Bay, oxygen indicators suggest a good water exchange between the bay and the open waters of the gulf, indicating a relatively strong mechanism for maintaining the stability of this water area. Additionally, the abundance of macrobenthos in the study area currently remains within normal levels, reflecting a balanced ecological condition.

Keywords: *Avacha bay, Avachinsky gulf, Biotesting, Macrobenthos, Environmental monitoring, Hydrochemical assessment, Kamchatka Peninsula, Sanitary and bacteriological assessment.*

1. Introduction

The Kamchatka Peninsula shelf is one of the most productive regions of the World Ocean. The macrobenthos of the soft bottom sediments of the Kamchatka shelf is of great forage value for valuable commercial species of marine organisms, and the coastal waters are rich in nutritious plankton and are characterized by high biological productivity [1]. Avachinsky Gulf is an area of maximum anthropogenic pressure off the coast of the Kamchatka Peninsula. The city of Petropavlovsk-Kamchatsky is located on the shore of its inner bay (Avacha Bay). The deterioration of the quality of the aquatic environment and bottom sediments in Avacha Bay began to be recorded back in the 1990s. The development of the city of Petropavlovsk-Kamchatsky against the background of natural climatic and biological processes of environmental change leaves an invariable imprint on the ecological situation of the bay. The ecological situation off the coast of Kamchatka is often complicated by massive microalgae bloom.

The monitoring of the ecological state of the Avachinsky Gulf has been carried out by Kamchatka scientists on a regular basis since the 2010s [2]. In the modern period, the growth of research aimed at assessing the ecological well-being of the Kamchatka coast [3-7] was triggered by the harmful microphytoplankton bloom (HMB) that occurred in September 2020 [8]. This HMB led to the mass death of benthic organisms in the southeastern regions of the peninsula. For the same reason, starting in 2021, the Institute of the World Ocean of the Far Eastern Federal University (IWO FEFU) conducts annual expeditions to assess the ecological well-being of coastal marine and coastal ecosystems in the

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south of the Kamchatka Peninsula. The purpose of this work is to conduct a complex assessment of the ecological status of the eastern part of the Avachinsky Gulf based on the results of monitoring the chemical and microbiological parameters of the aquatic environment and sediments, as well as biotesting the toxicity of the environment and assessing the abundance of macrobenthos.

2. Materials and Methods

The work was carried out in the eastern part of the Avachinsky Gulf (Avacha Bay and the Khalaktyrsky beach area) in September 2023 (fig. 1). Water samples for hydrochemical and microbiological analysis, as well as biotesting, were taken from the surface (0.5 m) horizon with a bathometer from aboard a small boat. Bottom sediments were collected with a dredger from the surface horizon (0.1 m) at a depth of 5 m. Samples of marine macrobenthos were taken during the flight PM 23/4 of the Scientific research vessel "Professor Multanovsky" expedition of the "Pacific Floating University" program with a box-shaped dredger with a capture area of 0.1 m^2 in the depth range of 14–106 m. Samples of all studied components of the ecosystem of the Avachinsky Gulf were selected in three repetitions. A total of 42 samples of surface waters (for hydrochemical and microbiological analysis), 42 samples of bottom sediments (for bioassay of toxicity and microbiological analysis) and 45 quantitative samples of macrobenthos were selected and analyzed.

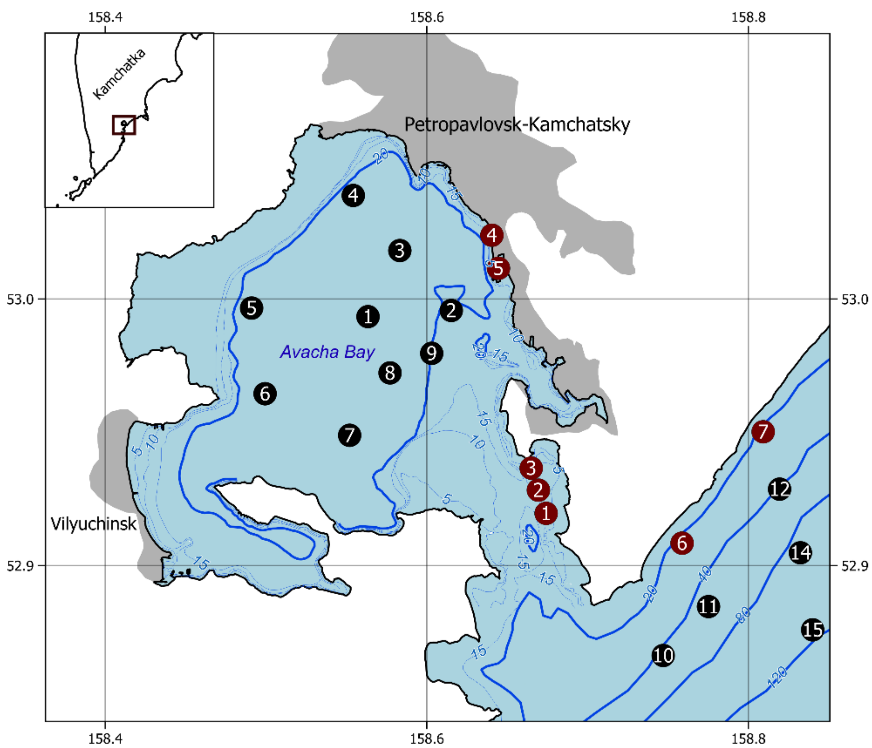

Figure 1.
A map showing the location of sampling stations.

2.1. Hydrochemical Analysis

Chemical parameters reflecting the ecological well-being of the oxygen regime and the level of organic matter in the environment of the studied water area were evaluated in surface marine waters. The dissolved oxygen content (DO) and biochemical oxygen consumption (BOC_5) were determined by the Winkler method, the concentration of phosphorus mineral compounds (phosphates) by the Morphy-Riley method, and ammonium ions (NH4+) by photometric method with Nessler reagent [9].

2.2. Sanitary and Bacteriological Analysis

Sanitary and bacteriological analysis was carried out in samples of water and bottom sediments. The total level of organic matter was assessed based on an analysis of the total number of heterotrophic microorganisms (HM), and sanitary quality was assessed by estimating the number of bacteria of *E. coli* group (BECG), *Enterococcus* bacteria (EB), and pathogenic enterobacteria (PE). The total number of HM in bottom sediments and surface sea waters was determined on a breeding ground for marine microorganisms (BGMM) by direct surface seeding on agarized ground (Koch cup method). BECG were detected using a selective Endo ground. Catalase-positive and oxidase-negative gram-negative bacteria were identified [10]. Fecal bacterias (*Enterococcus*) were detected on an azide medium by membrane filtration. Pathogenic enterobacteria were cultured on Ploskirev's ground and XLD agar.

2.3. Biotesting

Water extracts from bottom sediments were prepared for biotesting. The toxicity of bottom sediments was assessed by changes in the number of cells of the cultured microalgae *Phaeodactilum tricornutum* in the prepared suspension. Biotesting was performed under standard conditions under illumination by fluorescent lamps with a light-dark period of 16 h light: 8 h dark at a temperature of 20 ± 2 ° C. Acute toxicity of microalgae extracts was assessed after 48, 72, 96 hours from the start of the experiment, chronic – after 7 days [11]. The calculation of the number of cells and the degree of inhibition of microalgae growth in the experiment was performed in relation to the control. Bottom sediment extraction was considered non–toxic if, at the end of the study, the number of algae cells in it was ≥ 90%, slightly toxic – 65-89%, medium toxic - 50-64%, highly toxic – 0-49% of the control [12]. The chlorophyll a content was determined by the standard method of extraction from cells with acetone, followed by measurement on a Shimagzu-UV 2550 spectrophotometer.

2.4. Quantitative Assessment of Macrobenthos

Macrobenthos samples were washed on the ship on the day of sampling with seawater on a washing table equipped with a sieve system with the smallest mesh size of 1 mm. The washed samples were fixed with a 4% formaldehyde solution (formalin) and delivered to the laboratories of the IWO FEFU. In the laboratory, the sample was washed from formalin, the organisms were sorted by species, the current name and systematic position of the species were checked using the WoRMS database (Word Register of Marine Species), the abundance and biomass were determined. All results are recalculated by 1 m^2.

3. Results and Discussion

3.1. Chemical and Ecological Parameters of Surface Waters

The temperature range of surface waters in the studied water area corresponded to the climatic norm typical for the beginning of September and was 3–11.6 °C. The water temperature within the Avacha Bay was 6-7 degrees higher than in the open part of the Avachinsky Gulf. The salinity level varied within 28.5–33.5 ‰ (Table 1). Thus, the main hydrological parameters formed the natural thermohaline background of the aquatic environment of the gulf, which is a temperate warm-water eugaline water area of the Pacific Ocean.

The dissolved oxygen content at all stations corresponded to the norm and reflected sufficient oxygen saturation of the surface waters of the eastern part of the Avachinsky Gulf (the minimum was 9.82 mgO_2/l and 131%). However, the biochemical oxygen consumption (BOC_5), indicating its consumption for the decomposition of easily-oxidized organic substance, exceeded the norm at almost all stations. This substance in surface sea waters can be natural metabolites of marine organisms, as well as decomposition products of municipal wastewater entering the sea from settlements and port areas. An increase in the level of BOC_5 may indirectly indicate the presence of phytoplankton outbreaks [13]. The spatial distribution of ammonium ion concentrations indicates a significant influence of Petropavlovsk-Kamchatsky effluents on the formation of organic matter levels in Avacha Bay. Exactly on station 5 near the city center, the concentration of NH4+ exceeded the permissible norm, indicating the flow of fecal effluents from the urban sewer system. The eutrophic status of the waters in the area of the city embankment is confirmed by the concentration of mineral phosphorus compounds (phosphates) exceeding 0.2 mg/l at station 5.

Table 1.
Main hydrological and hydrochemical characteristics of the coastal waters of the eastern part of the Avachinsky Gulf in September 2023.

Station	**T. °C**	**S. ‰**	**DO**		**BOC_5. mgO_2/l**	**NH_4^+. mg/l**	**P_{min}. mg/l**
			mgO_2/l	**%**			
1	9.4	28.5	9.95±0.09	149	2.21±0.09	0.07±0.01	0.089±0.002
2	9.9	29.8	10.56±0.06	161	3.69±0.03	0.24±0.02	0.096±0.005
3	11.1	29.8	12.47±0.07	195	11.91±0.20	0.09±0.01	0.061±0.003
4	11.6	28.5	13.43±0.12	211	13.33±0.13	0.30±0.17	0.103±0.001
5	10.6	29.4	13.50±0.09	208	13.40±0.09	0.61±0.17	0.260±0.004
6	3.8	33.5	9.82±0.01	133	1.72±0.92	0.31±0.02	0.180±0.001
7	3	33.5	9.84±0.05	131	2.14±0.38	0.12±0.01	0.165±0.001

Note: the rate of DO at least 6 mgO_2/l, BOC_5 – not more than 2.1 mgO_2/l, NH4+ – no more than 0.5 mg/l; concentration P_{min}, less than 0.05 mg/l – oligotrophic water, 0.06–0,15 – mesotrophic, 0,16–0,20 – eutrophic; violation of regulations is highlighted in bold.

Thus, the anthropogenic impact on the eastern part of the Avachinsky Gulf (namely Avacha Bay) significantly increases the natural background of organic matter, determining the eutrophic status of waters in the area adjacent to the urban area. High concentrations of organic matter are a risk factor for the development of outbreaks of pathogenic bacterial flora, harmful blooming of microalgae, the binding of toxic pollutants into heavy organic complexes and their deposition within the bay, as well as a decrease in the dissolved oxygen content in the aquatic environment. However, due to the good water exchange of Avacha Bay with the waters of the open sea, its surface waters are characterized by a high oxygen content (despite the high level of organic matter in the environment), which indicates a fairly stable mechanism of self-purification of this water area.

3.2. Microbiological Parameters of Surface Waters and Bottom Sediments

We also assessed the ecological well-being of the anthropogenic-laden part of the Avachinsky Gulf using microbial indication methods. The number of heterotrophic microorganisms (HM) is an important indicator of the state of the marine environment and characterizes the gross organic matter content. In the study area, it changed in September 2023 from $1.1*10^3$ to $8.7*10^5$ colony-forming units (CFU)/ml, generally characterizing surface waters as mesosaprobic, i.e. enriched in organic matter (Table 2). This is obviously due to intensive recreational activity on the beaches near the city of Petropavlovsk-Kamchatsky, as well as the formation of the natural background of the organic matter of the bay of autochthonous origin, supplemented by household wastewater. According to the data obtained, the highest levels of the number of HM (>1*105 CFU/ml) were recorded opposite the Central Embankment of Petropavlovsk-Kamchatsky (stations 4 and 5). A low number of HM (<1*103 CFU/ml) was observed in the open part of Avachinsky Gulf in the area of Khalaktyrsky beach (stations 6-7), where there are no domestic wastewater outlets. At 6 of the 7 stations, bacteria of *E. coli* group (BECG) were detected, indicating fecal (sewage and recreational) biological contamination of waters. Moreover, *E. coli*, a direct marker of fecal pollution, was detected at half of the stations. The largest amount of *E. coli* was detected in surface waters at stations 4 and 5 (Central Embankment of Petropavlovsk-Kamchatsky). Swimming in such waters is dangerous to health. Fecal *Enterococcus* and pathogenic enterobacteria have not been identified.

Table 2.
Sanitary and bacteriological characteristics of the surface sea waters of the eastern part of the Avachinsky Gulf (CFU/ml of water).

Station	HM	BECG / *E. coli*	EB	PE
1	(3.8±0.3)*10^3	(1.5±0.3)*10/0	0	0
2	(1.2±0.4)*10^4	(6.2±0.5)*10^2/(1.1±0.2)*10	0	0
3	(8.9±0.2)*10^4	(4.3±0.3)*10^2/(8.2±0.7)*10	0	0
4	(8.1±0.7)*10^5	(5.8±0.2)*10^3/(2.2±0.1)*10^2	0	0
5	(8.7±0.4)*10^5	(1.2±0.5)*10^4/ (4.7±0.2)*10^3	0	0
6	(1.1±0.3)*10^3	(1.0±0.1)*10/0	0	0
7	(4.8±0.4)*10^3	0/0	0	0

The total number of heterotrophic microorganisms in bottom sediments was 10^4-10^6 CFU/g (Table 3). The maximum number (as well as in sea waters) was recorded near the central embankment of Petropavlovsk-Kamchatsky in Avacha Bay. Of the sanitary-indicative microorganisms, only BECG were sown at all stations. *E. coli* was detected at more than half of the stations, which indicates fecal contamination. Fecal EB and PE have not been detected. Bottom sediments from two stations (stations 4 and 5) are classified as "extremely dangerous" pollution.

Table 3.
Sanitary and bacteriological characteristics of bottom sediments of the eastern part of the Avachinsky Gulf (CFU/g of soil).

Station	HM	BECG /E. coli	EB	PE	Category of pollution of bottom sediments
1	(1.8±0.51)*10^4	(1.5±0.3)*10/0	0	0	Moderately Dangerous
2	(8.2±0.4)*10^4	(6.2±0.48)*10^2/ (1.1±0.2)*10	0	0	Dangerous
3	(3.9±0.82)*10^5	(4.3±0.32)*10^2/ (8.2±0.7)*10	0	0	Dangerous
4	(6.6±0.32)*10^6	(5.8±0.25)*10^3/ (2.8±0.1)*10^2	0	0	Extremely Dangerous
5	(8.9±0.62)*10^5	(6.2±0.32)*10^4/ (4.7±0.19)*10^3	0	0	Extremely Dangerous
6	(2.0±0.2)*10^4	(0.5±0)*10/0	0	0	Clean
7	(4.4±0.4)*10^4	(1.0±0)*10/0	0	0	Clean

Thus, the microbial indication showed that the most disadvantaged area is the Central Embankment of Petropavlovsk-Kamchatsky, where the highest number of sanitary-indicative microorganisms is noted, which makes it possible to classify bottom sediments in this area as extremely dangerous.

3.3. Biotesting of Environmental Toxicity

In samples of bottom sediments from the coastal part of Petropavlovsk-Kamchatsky, during the first four days of the biotesting experiment using a laboratory culture of the microalgae *Phaeodactylum tricornutum*, an inhibition of crop population growth was observed. Then, by day 7, the number of cells in the tested extracts reached the control level (Figure 2). In almost all water extracts, the degree of inhibition in the acute experiment exceeded the level of 20% (Figure 3), confirming the significant toxic effect of the studied bottom sediments on microalgae. The only exception was the sample from station 7 (Khalaktyrsky beach, near the surfer camp) in the open part of Avachinsky Gulf, where water extracts from bottom sediments do not have a toxic effect on the test culture.

The content of chlorophyll *a* in microalgae cells is an indicator of the physiological state of the test object. Thus, in an acute experiment in microalgae cells exposed in water extracts from Avacha Bay stations (stations 1, 4, 5 and 6), by 72 hours this indicator was minimal and did not reach the control level (Figure 2). In general, according to the results of the acute experiment (72 hours), samples from stations 1, 4, 5, 6 are classified as highly toxic, 2 and 3 are medium toxic, 7 are slightly toxic. In the chronic experiment, by day 7, in most samples, after a long period of culture adaptation, there was an active increase in the number of microalgae to the control level, which is a manifestation of the launch of compensatory mechanisms that partially or completely neutralize the toxic effect over time. Thus, according to the results of biotesting, the unfavorable ecological situation in the Avacha Bay is confirmed, where conditions are formed in the sediments for the accumulation of pollutants capable of having a toxic effect on living organisms.

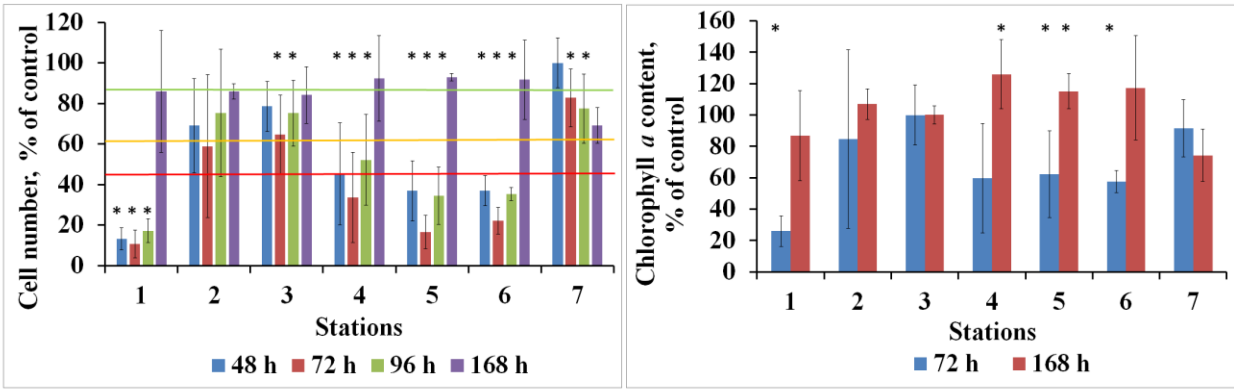

Figure 2.
The dynamics of the abundance and content of chlorophyll *a* in the cells of *P. tricornutum* microalgae in water extracts of bottom sediments (*– the difference from the control is significant at $p < 0.05$).

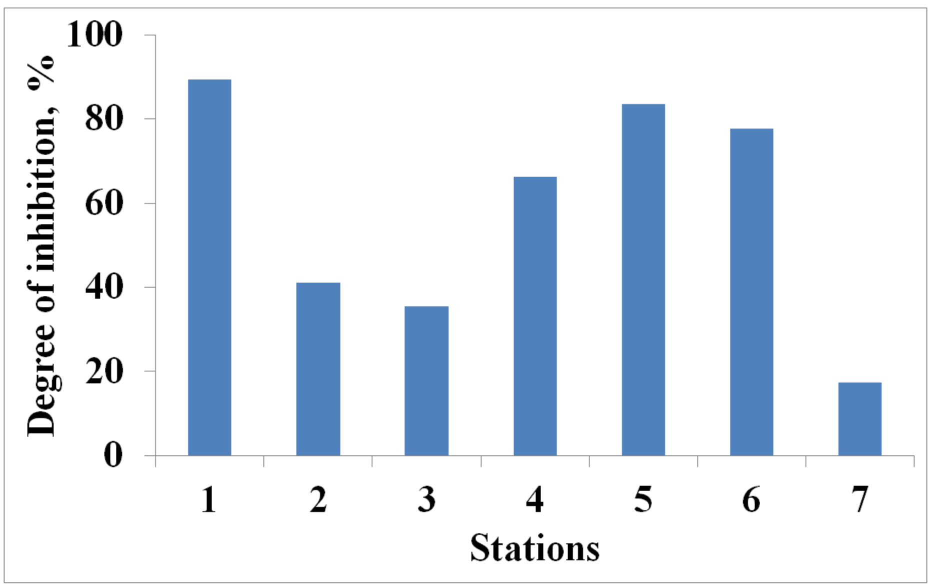

Figure 3.
Deviation of the abundance of *P. tricornutum* from the control (degree of inhibition).

3.4. Quantitative Assessment of Macrobenthos

In the studied area, macrobenthos was characterized by a relatively low species diversity – the maximum indicator was found in the open part of the gulf, where 29 species were recorded at station 10 and 29 species at Station 14, respectively (Figure 4). The inner part of the gulf (the Avacha Bay) is characterized by a lower species abundance of macrobenthos than the open area. The frequency of occurrence is dominated by bivalves *Macoma calcarea* (56.90% occurrence) and *Ennucula tenius* (32.76%), polychaetes *Ampharete* sp. (41.38%), *Asychis gotoi* (25.86%), *Nephthys* sp. (22.41%), echiura *Echiurus echiurus* (32.76%), ophiura *Ophiura leptoctenia* (48.28%), marine flat sea urchin *Echinorachnius parma* (36.21%). The biogeographic composition is formed by five zonal biogeographic groups, as well as species of the cosmopolitan group. In terms of the number of species (40%), the Arctic-boreal group and the Boreal-Arctic group (31%) dominate. Most of the macrobenthos species belong to the trophic group

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of sorting detritophages (45%, ophiura, polychaetes and flat sea urchins) and omnivorous animals (22% decapod crustaceans, amphipods, polychaetes).

In terms of biomass and the number (density) of the bottom population, Avacha Bay, on the contrary, is characterized by higher abundance values of macrobenthos compared to the open waters of the bay. The open eastern part of the Avachinsky Gulf is characterized by a high level of hydrodynamics (waves and surf), which affects the stability of bottom sediments and the deposition of organic detritus in them, which is a nutrient resource for many benthic groups. As hydrochemical and microbiological data show, an increased (but not critical) level of organic matter is formed in Avacha Bay and, as a result, higher levels of biomass and benthos abundance. The values of the Shannon index (H) for the area covered by the research ranged from 0.5 to 1.82, characterizing a generally low degree of biological diversity in the eastern part of the Avachinsky Gulf.

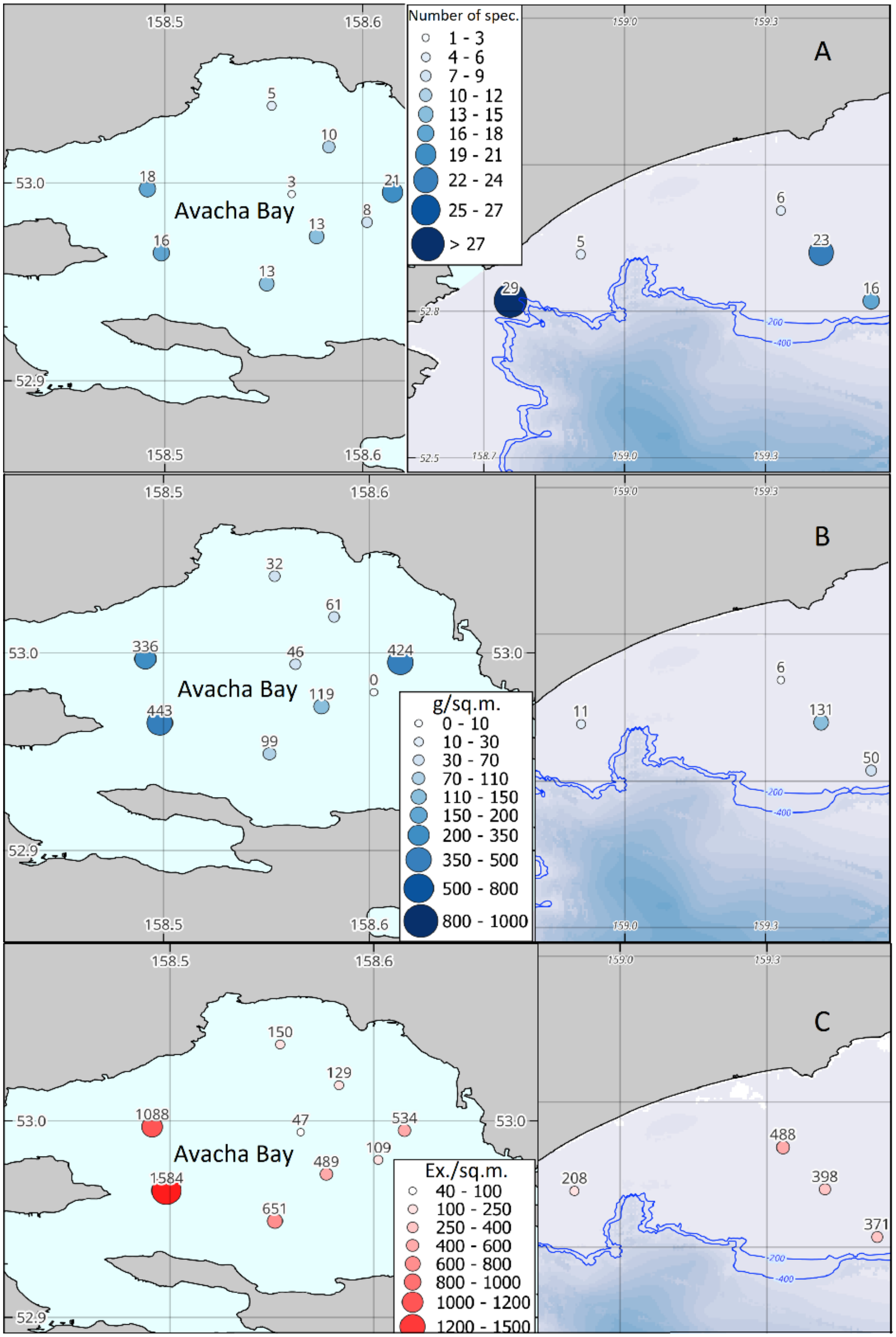

Figure 4.
Values of species abundance (A), biomass (B), and settlement density (C) of macrobenthos at sampling stations in the eastern part of the Avachinsky Gulf.

4. Conclusion

Thus, the increased level of organic matter in Avacha Bay, which is determined by hydro-chemical and microbiological parameters, causes the risk of negative processes in it. Among such processes, an increase in the number of opportunistic and pathogenic bacteria, outbreaks of planktonic microalgae (including harmful ones), binding and accumulation of toxic substances in the aquatic environment and sediments can be predicted. The toxic effect is detected by the results of the conducted biotesting and may eventually affect the well-being of reproductive processes and the growth of marine organisms. However, despite the presence of environmental risk factors in the inner part of the Avachinsky Gulf (Avacha Bay), oxygen indicators indicate a good water exchange between its environment and the open waters of the bay and a fairly high mechanism of stability of this water area. Indicators of macrobenthos abundance in the study area are normal.

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Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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