The composition, structure and functional characteristics of macrobenthos in the coastal zone of the Primorsky Krai (Sea of Japan)

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The intense anthropogenic load and the high economic exploitation of marine biological resources in the coastal part of the Primorsky Krai (Sea of Japan) cause a comprehensive study of the marine environment and biota conditions. Macrobenthos is one of the essential components that determines the normal functioning of the marine ecosystem. We studied the composition, structure, and quantitative characteristics of macrobenthos and their functions. We grouped all coastal zones into four groups: (1) open areas subject to the influence of the prevailing river flow and minimal impact of the marine fleet; (2) open areas of the north-eastern and northern coasts, where the accumulation of organic matter (OM) is not observed; (3) water areas with naturally elevated OM content and local anthropogenic impact; and (4) the most polluted territories, subject to the intense chronic influence of factors of accumulation of OM, mainly of anthropogenic origin. The Golden Horn Bight is the water area subjected to the most significant anthropogenic impact, while the Kievka, Udobnaya, and Rudnaya Bights, on the eastern coast of Primorsky Krai, are the areas with the smallest level of anthropogenic press. The water areas of Nakhodka, Vladimira, Vostok, and Troitca Bight, enriched in organic matter, occupied the intermediate position. We revealed that the most significant components of macrobenthos-macrophytes and bivalves-cease to work as an effective biological filter, and the transformation of incoming pollution in the water area is too slow in conditions of chronic pollution of coastal marine ecosystems. The heterotrophic community feeds on a significant amount of introduced organic matter, often of toxic origin, the nature of which probably affects the functioning of mass groups of organisms, reducing the indicators of biodiversity and abundance.

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Keywords

Macrobenthos, Sea of Japan, Vladivostok, Peter the Great Bay, Golden Horn Bight, organic pollution, anthropogenic load, marine ecosystems

Introduction

Macrobenthos is an essential component of aquatic ecosystems, determined by the total production (primary and secondary) and the energy transfer and transformation of organic matter during its life. Therefore, plants and animals larger than 1 mm in size are important in shallow coastal ecosystems, where wee can define their contribution to the production and transformation processes of the ecosystem. The well-being of the functioning of ecosystems in the marine coastal zone depends on the macrobenthos status, determined by the well-being or disturbance of its composition, structure, and quantitative indices relative to anthropogenically unconverted ecosystems.

In the coastal marine zone, the most unfavorable ecological condition of ecosystems is identified due to the chronic and accidental anthropogenic impact associated with infrastructure development processes and negative changes in the water and bottom environment, leading to increased pollution and transformation of coastal and near-shore zones and anthropogenic emergencies. Human impact leads to the destruction of habitat conditions and indirect or direct disturbance of the composition, structure, and indicators of macrobenthos abundance, which affects the further functioning of the coastal marine ecosystem. The condition of macrobenthos is a sign of ecosystem changes, showing ways of its remediation, the success of which largely depends on the well-being of the functioning of the biological component. The role of macrobenthos is significant. Therefore, using up-to-date information on its actual condition allows the development of recovery programs for coastal marine ecosystems, and is sometimes the only possible way or key element to remediation success (Atkinson 1994).

This study analyzes the composition, structure, quantitative indicators and functional characteristics of macrobenthos in the waters of the coastal zone of the Primorsky Krai (the Sea of Japan), which are subject to the most significant anthropogenic impact. The objectives of the study are to determine the environment of macrobenthos on the concentration of organic carbon in sediments, to indicate species richness, biomass, and density of macrobenthos in the settlement, and to identify the peculiarities of anthropogenically transformed ecosystems by the characteristics of macrobenthos.

Material and methods

We used complex survey data, including information on the composition, structure, and quantitative characteristics of macrobenthos and their spatial distribution in the ecosystems of bays and bights of the marine coastal zone in the Primorsky Krai (Sea of Japan) collected between 2000 and 2017. The study was carried out in the water areas of Troitca Bight, Vostok Bay, Nakhodka Bay, Golden Horn Bight, Kievka Bight, Rudnaya Bight, Vladimira Bay and Udobnaya Bight. Divers quantitatively took macrobenthos samples on hard bottoms using a hydrobiological frame of 1 m2 and a soft diver’s driedger with a capture area of 0.025 m2 lowered from a small vessel Van-Vin grab sampler with a capture area of 0.25 m2. We selected data on macrobenthos at each station in triplicate and recalculated them for a specific unified area of 1 m2. Furthermore, we included the complex of parameters studied, information on the granulometric composition of the bottom substrates (determination of the dimensional composition) and the content of organic matter (Corg,%) in a soft component of the substrates/bottom sediments (Shatrova et al. 2016).

Furthermore, we applied previously obtained data and scientific publications describing the characteristics of the aquatic environment and macrobenthos indicators along the marine coastal zone of the Primorsky Territory of Russia outside of Peter the Great Bay (Galysheva 2010). Below we presented the amount of data analyzed on macrobenthos (Table 1) and the arrangements of the sites and sampling stations (Figure 1).

We analyzed 265 quantitative samples of macrobenthos in eight marine areas of the the coastal zone of Primorsky Krai.

Sea area	Number of samples	Number of stations	Number of samples	Period of work
The east and north-east coasts of Primorsky Krai				
Udobnaya Bight	2	11	66	2008–2009
Rudnaya Bight	2	18	108	2007–2009
Kievka Bight	6	20	360	2004–2006
Vladimira Bay	1	33	99	2014
Peter the Great Bay				
Troitca Bight	2	22	126	2007
Vostok Bay	14	32	1344	2000–2004
Nakhodka Bay	7	22	462	2003–2005
Golden Horn Bight	1	18	90	2017

Table 1. *The number of macrobenthos samples collected from the coastal marine zone of the Primorsky Krai.*

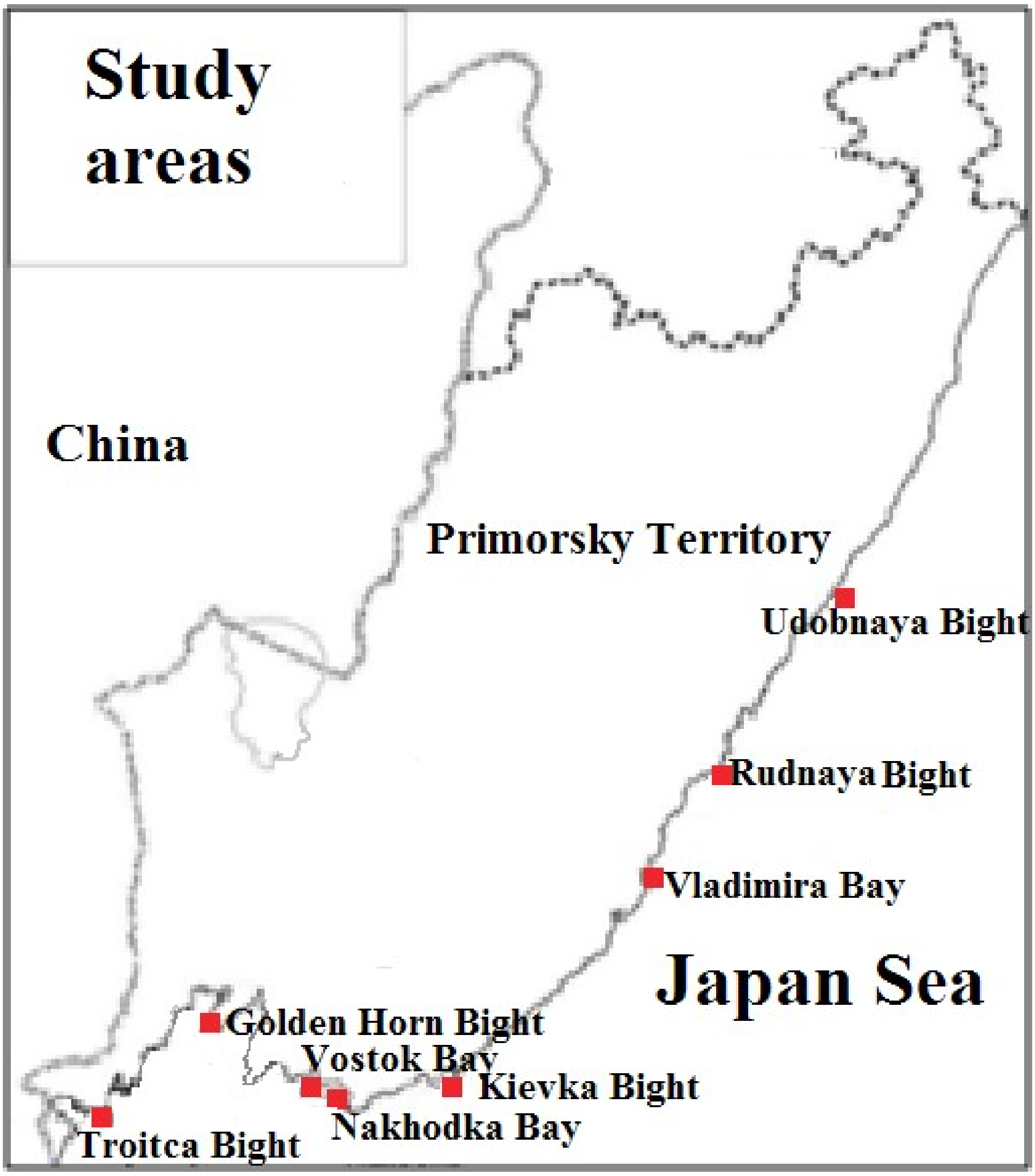

Figure 1. *Sampling sites*

Results

In the surveyed areas, the maximum values of organic carbon are different. The most enriched in organic matter are the bottom sediments of the Nakhodka Bay, the Vladimir Bay, and especially the Golden Horn Bight. The average abundance of species varies from 8.1 ± 4.3 (in Golden Horn Bight) to 20.1 ± 9.7 (in Nakhodka Bay) species per station. The mean biomass values in the water areas studied ranged from 204.2 ± 50.1 to 4523.9 ± 9324.2 g/m2. We define the minimum in the Golden Horn Bight and maximum in the Udobnaya Bight. The average population density of macrobenthos varies from 17.4 ± 12.3 to 250.6 ± 365.4 ind./m2 (Table 2). The average biomass of the Golden Horn Bight macrophytes was approximately 18 g/m2 and 2% of the total average biomass, including marine invertebrate animals (Figure 2).

Thus, the area of water on the Golden Horn Bight was more polluted with organic matter and characterized by the lowest abundance of species, the general biomass of macrobenthos, and the biomass of marine macrophytes.

Most urbanized coastal areas and areas with developed infrastructure have complex chronic effects on the marine environment and contribute to the introduction of mixed organic pollution and various forms of heavy metals into coastal areas. Different regions of the Russian coast of the Sea of Japan are abundant with irregular levels and the nature of anthropogenic impact, leading to different levels of pollution and set of pollutants.

Sea area	Max C org , %	Average species abundance, species/station	Average biomass, g/m 2	Settlement density ind./m 2
Udobnaya Bight	0.50	11.8±6.4	4523.9±9324.2	108.5±90.3
Rudnaya Bight	1.97	12.0±6.7	1173.5±1268.6	77.0±54.4
Vladimira Bay	3.64	11.04±5.7	841.2±583.0	17.4±12.3
Kievka Bight	1.16	16.6±9.1	1634.9±954.5	159.1±124.6
Nakhodka Bay	3.20	20.1±9.7	1014.9±825.2	250.6±365.4
Vostok Bay	2.87	14.2±8.3	864.5±662.0	170.2±762.0
Troitca Bight	2.60	18.5±8.6	473.7±627.1	93.7±80.4
Golden Horn Bight	9.66	8.1±4.3	204.2±50.1	115.0±4.9

Table 2. *Values of the maximum concentration of Corg in bottom sediments, species abundance, average biomass, and settlement density of macrobenthos in different water areas of the coastal zone of the Primorsky Krai (Sea of Japan). Data presented as mean ± SD.*

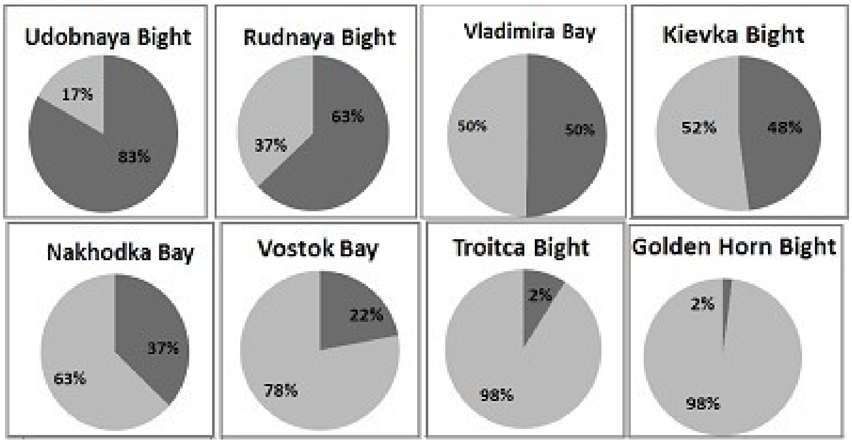

Figure 2. *The ratio of the average biomass of macrobenthic animals (invertebrates) and plants (macrophytes) in the coastal marine zone of the Primorsky Krai.*

The southern coast part of the Primorsky Krai is affected by severe anthropogenic impact, where marine areas with a favorable state of the environment are found together with anthropogenically transformed areas. Due to the ecological situation of the observed water areas, characterized by accumulating OM in the aquatic environment and bottom sediments, one can group the water areas of the coastal zone of Primorsky Krai into four clusters:

1. Open areas influenced by dominant river flow and minimal impact of the maritime fleet;
2. Open areas of the north-eastern and northern coast of Primorsky Krai, where the accumulation of OM is not evident;
3. Aquatories with an elevated natural level of OM content and local anthropogenic impact;
4. The most polluted areas are influenced by an intensive chronic impact of OM accumulation factors, mainly of anthropogenic origin.

The water areas of the Kievka, Udobnaya and Rudnaya Bights on the east coast of the Primorsky Krai were affected by the least polluted OM (confirmed by the data on Corg in the soils). The water areas of the Nakhodka, Vladimira, Vostok, and Troitca Bight were enriched with organic matter. Chronic organic pollution characterized the bottom sediments of the Golden Horn Bight at extreme levels (Table 2).

We determined these aspects because of the different economic activities carried out in the waters of the Bight. These are the zones of ports and floats exposed by the most powerful pressure from Vladivostok. The quality of the aquatic environment and the bottom sediments of this area were considerably disturbed. At this rate, various indices, including those representing the level of organic pollution, the maximum allowable concentration, and the maximum permissible level devices, were exceeded several times (up to dozens). Therefore, the total content of Corg in the bottom sediments of the Golden Horn Bight could reach more than 9.66% of the dry residue. This value is extremely high for the natural background of the Peter the Great Bay ecosystem because of the accumulation of heavy OM fractions on the bottom surface and various organic inclusions of anthropogenic nature.

According to the results of the benthic investigation, the maximum abundance of species in the soft sediments in the Golden Horn Bight varied from zero (st.1, the apex of the bight) to 18 species per station. In the clean water areas of the Primorsky Krai, it can reach several tens or even hundreds of species per square meter (for example, in Vostok Bay). The average abundance of species per station (Table 2) in Golden Horn Bay is the minimum among the water areas and is only 8.13±4.3.

The taxonomic composition of the polluted water areas is specific, dominated by Polychaete worms. In the Golden Horn Bight, the most prevalent are detritophage polychaetes with the frequency index 86.7% (*Chaetosone* sp.), 53.3% (*Dorvillea* sp.), 60% (*Chone* sp.), 40.0% (*Ch. setosa*). The number of groups of macrobenthos (classrank taxon) appropriately increases from the apex (lifeless for macrobenthos of soft bottoms) to the exit of the bight. The absence of macroorganisms was typical for the apex of the Golden Horn Bight. The soft sediments of this part of the bight posed as a mixture of mineral particles, organic remains of shell material, tar-like addition of oil hydrocarbons and multiple anthropogenic traces (scraps of plastic, textiles, glass fragments, cigarettes butts, different metallic objects) and natural material (leaves of trees), introduced by the Obyasnenia River. Practically oxygen-free conditions in the bottom sediments formed a lifeless zone in this part of the bight for the macrobenthic community. The physiological health of marine invertebrates under conditions of increasing concentrations of toxicants was disrupted. In turn, this aspect affected the dimensional characteristics and proportions of the Golden Horn Bight organisms, characterized by disproportion and aberration of symmetry.

The biomass values of macrobenthos at sampling stations in the Golden Horn Bight varied from 0 (st. 1 – the apex of the bight, region of the Obyasnenia River influx) to 4540.70 g/m2 (st. 9 – the central part of the bay, accumulation of ascidians). The average biomass was 204.2±50.1 g/m2, putting the Golden Horn Bight in the last place in the row of water areas. The value of macrobenthos biomass in the Troitca Bight was approximately 473.7 g/m2 on average, in the Vostok Bay – 864.5 g/ m2, in Kievka Bight–1634.9 g/m2, in the north of Primorsky Territory (in the Udobnaya Bight) – up to 4523 g/m2 (Galysheva 2010).

The biomass of macrobenthos in the Golden Horn Bight was abnormally low for rigid substrates, resulting in the animals being smaller than those living in clear waters. The high turbidity of the water, disruption of natural bottom substrata, and the bight landscapes reduce the macrophyte biomass. According to this indicator, Golden Horn Bight is in the last place among the other bays.

Discussion

The problem of choosing an adequate level of biomarkers of the response of marine ecosystems to changes in environmental conditions (including anthropogenic ones) is a serious issue for ecosystem research. According to generalized publications, manifestations of stress in marine ecosystems are investigated at different levels of organization and rate: from the most rapidly occurring biochemical changes to population and biocenotic rearrangements in chronic stress. Functional changes in marine ecosystems are also termed long-term stress reactions (Patin 2015). However, some researchers argue that in almost all studies, an insufficient set of bioindicators is evaluated and their maximum complex should be used - from biochemical markers of biocenotic parameters (Shakhmatova 2012).

However, many authors have described the ecological state of the Golden Horn Bight, the most polluted in the Sea of Japan. Most of the works by different authors are devoted to the characterization of environmental conditions in the Golden Horn Bight (Buzoleva et al. 2008; Blinovskaya et al. 2010; Ermolitskaya 2012; Kalitina 2012; Ermolitskaya 2013; Zubtsova et al. 2018; Boychenko 2019; Zubtsova 2019; Pelekh et al. 2020). A particular, narrower circle of researchers describes macrobenthos, assessing the parameters of biological diversity, abundance, and distribution of the bottom population of this bay and using various indices of the ecological state of macrobenthos (Bagaveeva 1992; Davydkova et al. 2005; Moshchenko and Belan 2008; Belan 2015; Moshchenko et al. 2017; Moshchenko et al. 2018; Moshchenko et al. 2019). However, we did not describe the functional parameters (function features) of the biocenosis of the Golden Horn Bight. We did not find the functional changes that affect the macrobenthos population in this water area.

This research contributes to the study of functional changes in the biota of the Golden Horn Bight. We found a dysfunction of the ‘normality’ of the biomass parameter in the Golden Horn Bight at lower values compared to other water areas of the study and the biomass dominance replacement of the zone by the dominance zone of population density. This phenomenon of reversal of the dominance of abundance indicators is a characteristic of the disturbance of the bottom cenoses under conditions of siltation, changes in hydrodynamics, and hypoxia (Stolyarov and Burkovsky 2018).

Macrobenthos biomass was abnormally low for solid substrates in the Golden Horn Bight due to the individual mass of bottom animals, which is significantly lower than in the pure waters. Their growth was probably inhibited according to the depressed economy of food resources and energy for the neutralization of toxic effects from various pollutants. A decrease in body size is the threshold for the onset of population changes. Furthermore, it can indicate a decrease in fertility and the number of populations living in areas with chronic polluted (Patin 2015). Consequently, reproductive function could be inhibited and the population acquired the "pseudopopulation" format. Therefore, the environment in the inner part of the bay is unfavorable for the development of abundant benthic settlements that impact the parameters of the biota population.

In ecologically unfavorable areas, the settlement area of large sestonophages (ascidians, bivalve molluscs and balanuses) decreases, and the dispersal area of small detritophages increases – in macrobenthos, mainly polychaetes (Stolyarov and Burkovsky 2018). Such changes in the bottom biocenoses were revealed in a rather polluted area, the Kerch Strait (Zubtsova et al. 2018) and the Sevastopol Bay (Orekhova et al. 2020).

The ecosystem of the Golden Horn Bight has undergone noticeable changes associated with defects of natural water exchange with open sea areas across the Bosphor Vostochny Strait, as well as with the arrival of contaminated flows from the Obyasnenia River, in turn, dropped into the river from the cooling system of the Vladivostok Central Heating and Power Plant (CHPP-2). The deterioration of water exchange in the bay creates hypoxia conditions in the environment, further disturbs the structure of benthic communities (Stolyarov and Burkovsky 2018).

In the structure of the Golden Horn Bight ecosystem, the supralittoral and littoral zones have practically disappeared. Dredging work and the hydrotechnical facilities have significantly altered the landscape of the upper sublittoral zone. Furthermore, due to the pollution of the Golden Horn

Bight, there is high turbidity (low transparency) of its waters. As a result, this aspect changed the structure of the natural bottom communities and the deterioration of the species composition due to macrophytes. This is a negative phenomenon with profound consequences. Macrophytes are essential biological filters (Shakhmatova 2012). They accumulate various toxicants and are the most critical link in the self-purification of water bodies. In Golden Horn Bight, due to extremely low biomass values of macrophytes, the function of the biofilter was severely impaired.

Undoubtedly, the area of macrophytes in the Golden Horn Bight, before the hydrotechnical structures were built, was much more extensive. Previously, macrophytes occupied vast shallow waters, which today are practically absent in the bay. Only small localities several hundred meters long have survived at the entrance of the bight, north of the Tigrovy Cape. Meanwhile, the bays near the Amursky and Ussuriysky bays have rich communities of macrophytes with a biomass of several kilograms (Kalita and Skriptsova 2014).

Small epiphytes in the Golden Horn Bight are widespread on the quay walls, in the fouling of piers, on sunken objects and on the bottoms of ships. Thus, they do not make a significant contribution to the production and filtration of the bight environment. The primary representatives of the epiphytes in the bight are some mass species, mostly filamentous green algae of the upper horizon. Their biomass is affected by significant seasonal changes and reaches a maximum in the uppermost horizons and a minimum in the lower ones.

Therefore, algae-macrophytes and epiphytic algae in the Golden Horn Bight incompletely perform their filter-accumulating and producing functions. The role of macrophytobenthos in the synthesis of organic matter and biofiltration should be much larger under conditions of bight environment recovery. This aspect is key to the normal functioning of the ecosystem.

The filtering organisms-inhabitants of solid substrates (mollusks, ascidians, and balanuses) have the maximum biomass in the Golden Horn Bight compared to other groups. They actively filter and assimilate the pollution in the bay. However, compared to other water areas, one can identify the reduced biomass of bivalve mollusks, ascidians, and balanus can be identified in the Golden Horn Bigh. Due to pollution, we determined a significant decrease in these taxonomic groups with almost complete disappearance in some areas in the Kerch Strait and the Sevastopol Bay of the Black Sea (Orekhova et al. 2020; Terentyev 2013).

The formation of zones of active filter and detritus feeders during the rearrangement of bottom biocenoses is a sign of functional changes in the ecosystem. The ecosystems of the Black Sea also described it (Luibimov et al. 2020). Considering the functioning of the ecosystem, bivalve mollusks are an essential taxonomy group, as well as other macrobenthos organisms. Different taxonomic groups of bivalves have their peculiarities in filtering nutrition. We showed that the value of the bivalve mollusk filtration activity was about 2000-ml water per gram of weight per hour (Konstantinov 1986). The total calculated mass of bivalves of the Golden Horn Bight was equal to 30.9 tons. Therefore, their total filtration activity will be 61.8 thousand cubic meters per hour or 1.483 million cubic meters per day. This aspect means that this group of organisms can pass through the entire water mass of the bight (62.6 million m3) in 41 days and clear the water area. However, this does not happen due to the non-stop pollution of the bight. Thus, the heterotrophic benthic community existing in the Golden Horn Bight actively consumes the organic matter entering its environment, but clearly cannot cope with the cleaning of the Golden Horn Bight.

In the first stages, eutrophication increases the food resources of the ecosystem and multiplies its productivity. In the future, this can lead to the supersaturation of the environment with organic matter and the formation of anaerobic conditions. They recorded these negative phenomena in the Baltic Se (Shatrova et al. 2016), Black Sea (Orekhova et al. 2020; Terentyev 2013) and in the Golden Horn Bight of the Sea of Japan. Previous researchers recorded the formation of anaerobic conditions at the apex of the Golden Horn Bight (Belan 2015; Moshchenko et al. 2019) and we confirm this aspect based on the data from this study. Thus, we determined that the irreversible negative transformation processes in the bay have passed and completely covered its inner part. The reason was chronic anthropogenic pollution with oil hydrocarbons and a significant weakening of the hydrodynamics. Volley oil spills (Petrenko et al. 2009) did not have this effect.

In conditions of chronic pollution in coastal marine ecosystems, the most significant components of macrobenthos-macrophytes and bivalve mollusks no longer act as biological filters. Due to the suppressed state of the biota, the conversion wheel of the substance entering the bay was too slow. Macrophytes do not contribute significantly to the accumulation of incoming substances and the creation of primary production because of the turbidity of the bight waters. The heterotrophic community is determined by a significant amount of allochthonous organic matter, whose toxic nature affects the functioning of groups of numerical organisms, reduc- ing their biodiversity and abundance indicators.

Conclusion

We found the maximum abundance of species at the station for second-order bays in the southeastern part of the coast (Vostok and Nakhodka bays). Furthermore, we determined a clear gradient of decrease in the average total biomass of macrobenthos traced from the northeast to the southwest. The minimum values of the total biomass were recorded on the Golden Horn Bight. We explain the decrease in the biomass of macrobenthos in the Golden Horn Bight due to the effect of biota crushing due to the described effects of growth disturbance as a reaction to chronic stress. The reason for this decrease is chronic pollution of the water area.

In the Golden Horn Bight, we revealed a decrease in the biomass of the primary groups that make up the biofilter of the marine area – bivalve mollusks, ascidians, balanuses and particularly macrophytes. This aspect indicates a violation of the self-cleaning mechanism of the chronically polluted water area and, consequently, a violation of the functioning of its ecosystem as a whole.

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