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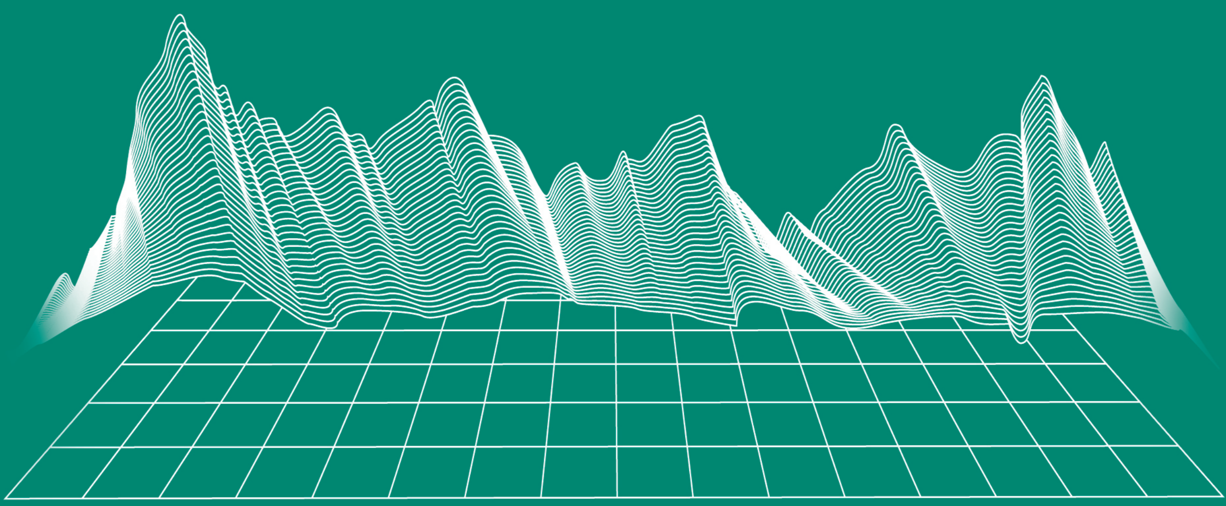

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Научно-теоретический журнал

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- 25.00.35 – Геоинформатика (географические науки),
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РЕДАКЦИОННАЯ КОЛЛЕГИЯ

CONTENTS

№ 1. 2022 January – March, 2022

СОДЕРЖАНИЕ

№ 1. 2022 Январь – Март, 2022

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Anthropogenic Impact on the Lithodynamics of the Black Sea Coastal Zone of the Crimean Peninsula

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Abstract
The dynamics of the coastal zone of seas and oceans is contingent on a complex interaction of natural processes occurring at the border of land, sea, and atmosphere. This interaction has become even more complicated due to the anthropogenic factor. The purpose of the article is to systematize information about the anthropogenic impact on the lithodynamics of the Crimean coastal zone, classify the types of impacts and map them. The authors used materials of long-term monitoring performed by Marine Hydrophysical Institute of RAS. It is shown that the greatest influence on the change in lithodynamics is exerted by hydraulic engineering. Specific examples with quantitative characteristics are given. It is found that construction of permanent facilities on the beaches leads at least to their reduction and at most to their complete disappearance, which then results in increase of coast protection costs and reduces recreational properties of the coast. It is noted that the decrease in the solid runoff of rivers due to their regulation have influenced mainly the beaches of the Western Crimea. In the same place, 25 % of the total length of the cliffs is covered with various structures, and this has reduced the flow of sediments due to cliff destruction by 16,000 m^3 per year. The paper also discusses problems of degradation and disappearance of dunes, opening of bay-bars, reduction in the number of bottom molluscs, valves of which serve as a source material for the formation of sands, etc. The paper presents coefficients of anthropogenic load on various parts of the coast as wellas maps localizing certain types of anthropogenic impact.

Keywords: Black Sea, coastal zone of Crimea, anthropogenic impact, lithodynamic, coast protection works

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Антропогенное воздействие на литодинамику черноморского побережья Крымского полуострова

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Аннотация
Динамика береговой зоны морей и океанов обусловлена сложным взаимодействием природных процессов, происходящих на стыке суши, моря и атмосферы, которое еще больше усложнилось из-за антропогенного фактора. Цель статьи – систематизация сведений об антропогенном воздействии на литодинамику черноморского побережья Крыма, классификация видов воздействий и их картографирование. Использовались материалы многолетних мониторинговых наблюдений, выполняемых Морским гидрофизическим институтом РАН. Показано, что наибольшее влияние на изменение литодинамики Западного Крыма оказывает гидротехническое строительство. Приводятся конкретные примеры с количественными характеристиками. Установлено, что строительство капитальных сооружений на пляжах ведет как минимум к сокращению пляжей, как максимум – к их полному исчезновению, что в дальнейшем приводит к увеличению затрат на защиту берега и снижению его рекреационных свойств. Отмечается, что уменьшение твердого стока рек из-за их зарегулирования повлияло в основном на пляжи Западного Крыма. Там же различными сооружениями закрыто 25 % общей протяженности клифов, что снизило поступление наносов от разрушения клифов на 16 000 м^3 в год. Обсуждаются также проблемы, связанные с деградацией и исчезновением дюн, раскрытием пересыпей, сокращением количества донных моллюсков, створки которых служат исходным материалом для образования песков и др. Приводятся коэффициенты техногенной нагрузки на различные участки побережья и карты локализации отдельных видов антропогенного воздействия.

Ключевые слова: Черное море, береговая зона Крыма, антропогенное воздействие, литодинамика, берегозащитные сооружения

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Introduction

It is becoming more and more obvious that human intervention in the environment, while increasing the comfort of existence, simultaneously leads to significant problems now and creates prerequisites for their increase in the future. The most well-known problem is global warming due to the rapid increase in emissions of CO_2 and other greenhouse gases into the Earth’s atmosphere, which is associated with the recent increase in extreme weather events [1]. Given that possible consequences, such as rising sea levels, coastal flooding, extreme heat, heavy rainfall, etc., affecting ecosystems and infrastructure around the world, used to be the subject of many years of discussion in the scientific community, now many countries have moved to practical solutions that will seriously affect their economy and, possibly, their way of life in the future.

Many areas of waterways and territories on the planet have long been experiencing negative consequences of economic activity. This applies to a large extent to the coastal zone of seas and oceans, which is characterized by a complex interaction between natural processes occurring at the junction of land, sea and atmosphere. Recently, anthropogenic impact has been added to these processes. Human activity is currently comparable to geological forces, since in some areas it has been radically transforming the natural state of the environment [2]. For example, it is believed that more than 50 % of the coastline of developed countries (USA, Australia, Japan, Denmark, the Netherlands, etc.) has been changed by engineering structures [3].

Human intervention in the natural environment with negative consequences has many aspects, such as biological (for example, the impact of pollution on marine ecosystems and bioresources), economic (withdrawal of valuable land from circulation, destruction of coastal infrastructure) and others. In this paper, we consider one of these aspects - the anthropogenic impact on the lithodynamics of the coastal zone. The object of the study is the Black Sea coast of the Crimean Peninsula. The article focuses on Western Crimea, since this region is the most promising for recreational development, but is already experiencing certain problems associated with economic activity. The Southern coast of Crimea (SCC) is currently an almost completely urbanized area with extreme anthropogenic pressure, and the eastern coast, due to natural and social reasons, on the contrary, has not been affected much by economic activity.

The purpose of the article is to systematize information about the anthropogenic impact on the lithodynamics of the coastal zone of the Crimean Peninsula within the Black Sea, to classify the types of impact and to map them.

Publication analysis and state of the issue

In the Black Sea basin, where more than 300 million people live and about 20 cities with a population of more than 50,000 people each are located, the anthropogenic pressure on the coastal zone is increasing. It is due to urbanization and expansion of economic, especially recreational activities. In [4], we reviewed the literature dedicated to the anthropogenic impact on the lithodynamics of the Turkish, Romanian, and Bulgarian coasts. It was noted that, despite the difference in natural conditions, the sources of anthropogenic impact in these countries were the same: hydrotechnical construction, regulation of rivers by reservoirs, construction of permanent structures on beaches, illegal sand mining, dredging, etc. This impact changes the natural dynamics of sediments, creates their deficiency and destroys coastal ecosystems.

The influence of various types of hydraulic structures on the coastal zone of the Russian and Georgian coasts and the negative aspects of this influence were considered in [5, 6]. It was noted in [7, 8] that on the coast of Georgia, human intervention in natural processes (removal of beach sediments, construction of dams, reservoirs, port facilities in the coastal zone) did not improve the economic condition of the country, and, together with current natural phenomena, provoked an increased trend towards coastal abrasion and disappearance of beaches. It also led to the threat of destruction of the infrastructure located there, which entailed huge material losses (several billion of US dollars).

The anthropogenic impact on the stability of the sea coasts of the Krasnodar Territory and the factors limiting their economic development are given in [9]. Among them, the most noted are reduction of solid runoff, destruction of sand dunes, removal of sand from the beaches, decrease in the volume of biogenic sediments (shells) entering the shores, and others. The negative impact of hydraulic structures on the adjacent areas of the coastal zone in the Ukrainian sector of the Black Sea was considered in [10]. Some aspects of the anthropogenic impact on the coast of Ukraine were given in [11].

The bibliography on the anthropogenic impact on the coastal zone of the Crimea is relatively small. Mostly, the articles cited individual facts of such an impact without a detailed analysis. Perhaps, V.P. Zenkovich was the first to draw attention to the problem of anthropogenic influence on lithodynamics in the Crimea. In an article devoted to the removal of beach material on the Caucasian coast and the negative consequences caused by this removal, he also mentioned the Crimea: "... such developments [of sand] are carried out even in Yalta, on the underwater slope of the Zheltyshevsky (now Primorsky – *the authors*) beach" [12, p. 54].

In response to this publication, a small article was published, which provided the facts of pebble material removal from the coastal zone of Yalta and its consequences [13]. The decrease in the width of the Livadia and Chukurlar beaches over the period of 5–7 years is determined as 22 and 65 cm, respectively, however, these values are less than the typical variability in the calm–storm cycle. Later, the same author noted that as a result of the extraction of 2 million m^3 of sand and gravel from the bottom of Yalta Bay, the width of the Chukurlar beach decreased over 12 years from 17.8 to 14.6 m, and the volume of the pebble beach decreased to 28 % [14]. It is not very clear from the text, whether it decreased by 28 % or to 28 % from the original, rather the former.

In [15], the changes in the material composition of sediments on the beach in Tikhaya Bay (Eastern Crimea, Koktebel region) were analyzed. According to the author, due to the introduction of the sea snail predator into the Black Sea, the number of bottom molluscs sharply decreased. If the share of mollusc shells in the composition of sediments used to be 8 %, in 1974 this value decreased to zero. The destruction of sand dunes was also observed due to the removal of their material for construction purposes, while the width of the beach decreased from 20–25 to 10–17 m (currently its width is 8–13 m – *the authors*). It was concluded (but without specific facts) that "a similar pattern of changes in the material composition and dynamics of sandy beaches was also noted to the west of Karadag in Chalka Bay, in the region of Evpatoriya and in some other places of the Crimea" [15, p. 103].

The values of coastal retreat as a result of functioning of a quarry for the extraction of gravel-sand mixtures in the area of the Saki bay-bar are given in a number of works [16–18]. In a series of works [19–21], which, however, differ little from each other textually and in the facts presented, the change of beaches in the area of Evpatoriya and the village of Privetnoye (Alushta region), data on changes in the width of beaches in Evpatoriya for 1995–1998 were given. The author of these works, not being a specialist in coastal processes, as he himself says, confuses the main and the secondary factors influencing lithodynamics. The main conclusion from his works is as follows: "... over the past half century, the main factor causing reduction of beaches is the anthropogenic factor – removal of sand and pebbles for construction purposes and unauthorized construction of various facilities in the coastal zone, as well as creation of reservoirs that trap sediments" [20, p. 63].

A detailed analysis of the anthropogenic impact on the beaches of the urban-type settlements of Koktebel and Kurortnoe (SCC, Karadag region) was carried out in [22]. The author proves that "artificial removal of sediments from the coastal zone and partial regulation of solid runoff led to a reduction in natural beaches and the need to create artificial beaches" [22, p. 86].

Separate facts of anthropogenic impact on the shores of the Crimean Peninsula are contained in our work [23]. In a brief review of the literature on the issue of anthropogenic impact on the lithodynamics of the Crimean coastal zone, we did not mention works that provide general reasoning without factual material, for example, [24]. Thus, it can be stated that at present there is no work generalizing the data on the technogenic load on the natural lithodynamics of the coastal zone of the Crimean Peninsula.

Materials and methods of research

We used the materials of long-term monitoring observations carried out by Marine Hydrophysical Institute of the Russian Academy of Sciences (echo sounding, georadar surveys, particle size analysis of sediments, tacheometric GPS surveys, measurements of wave currents, etc.). The data of aerial photographs and satellite images of ultra-high resolution, literary and archival sources were analyzed. The response of the coastal zone to the anthropogenic impact was identified as a change in the coastline configuration, appearance of previously non-existing areas of erosion or accumulation, change in the material and particle size distribution of sediments. In this work, we used the classification of types of anthropogenic impact, developed by us with some changes and clarifications [23, 25].

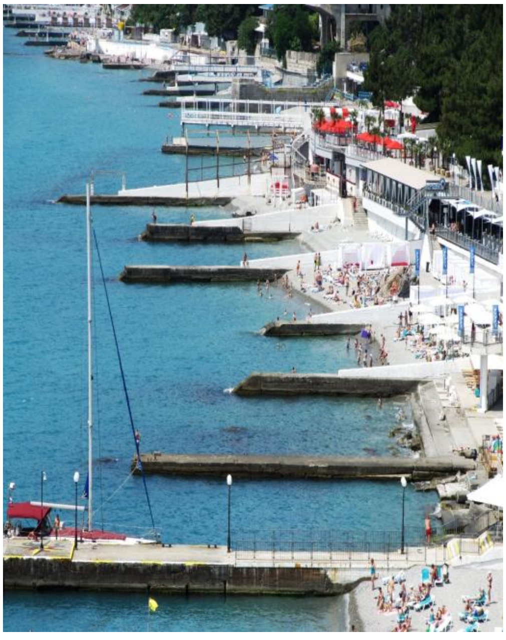
Results and discussion

In descending order of negative consequences on the coastal zone of the Crimean Peninsula, we have identified the following main types of anthropogenic impact: operation of hydraulic structures; permanent construction on the beaches; removal of inert materials from beaches and underwater coastal slope; reduction of solid runoff of rivers; clip closure, dune destruction; artificial opening of embankments; change in the number of molluscs. Let us consider them in more detail.

Operation of hydraulic structures. According to their intended purpose, construction and operation of hydraulic structures should change natural processes. At the same time, positive consequences should prevail over negative ones, and the rationale for the need for these structures is also important. *Design of Marine Coast Protection Works* Rules (SP 277.1325800.2016) introduced in 2017 directly state that coast protection works must ensure only minimal disturbance of natural factors in the physical and environmental aspects in the present and future and must not reduce the aesthetic value of the coast. Not only must the achievement of the goal in the protected area be taken into account, but also the impact of these works on the adjacent sections of the coast. Typical solutions that do not consider specific natural conditions of the coast are unacceptable.

The high degree of anthropogenic pressure on SCC has already been noted above. To date, almost the entire coast, with the exception of hard-to-reach areas, is filled with concrete structures, more than 600 groins have been built. The technogenic load factor $K = l/L$ (where l is the linear dimensions of structures; L is the coast length) on the coast between Cape Sarych and Alushta (about 75 km) is 1.2, which is an extreme value according to the classification given in [26]. Undoubtedly, coast protection works built in the 1970s–1980s of the last century reduced the risk of landslide, expanded the areas of beaches and adjacent territories, but also created problems [27].

Thus, the moving material of artificial beaches almost completely destroys bottom biocenosis; stagnation and pollution occur in the space between the groins; the productive area is partially restored only on concrete surfaces [28]. As a result, the coastal water area of the SCC has lost valuable species of flora and fauna. It is significant that the concrete shore with typical groins for many kilometers worsened the perception of the unique nature of the SCC, especially since a significant part of the structures are either in an emergency or in a pre-emergency state (Fig. 1). Development of any free plot of land and an exorbitant anthropogenic load are already leading to the loss of attractiveness of the SCC as a resort.



F i g . 1 . Anthropogenic coast on the SCC

It is not surprising that vacationers and investors are increasingly paying attention to the coast of Western Crimea, where the anthropogenic load is still not so great (Fig. 2). At the same time, it is important to avoid the mistakes that were made here earlier, in the 1970s–1990s. They were caused by the desire to ennoble the coast with artificial structures using standard solutions that had already been tested in the SCC but did not take into account fundamentally different features of the lithodynamics of the coastal zone of Western Crimea. In fairness, it should be noted that incomplete implementation of design decisions also played a role.

Before human intervention, a feature of the lithodynamics of the coast from Evpatoriya to Sevastopol was an almost uniform alongshore sediment flow directed counterclockwise, which was first noted in [29]. The main source of sediments is abrasion of cliffs and benches. Due to the degree of river control (Belbek, Kacha, Alma), the solid runoff is extremely small. As a result of the construction of transverse beach-retaining structures (groins), the coast has turned out to be divided into a number of separate lithodynamic cells that hardly exchange sediments.

A typical example is the district of the urban-type settlement of Nikolaevka. By the end of the 1970s due to the almost complete cessation of the solid runoff of the river Alma beaches in the northern part of the settlement began to decrease, abrasion of the cliff intensified, threatening the buildings of recreation centers. Vertical walls were built twice, but they were destroyed by storms; later, two groins were built in the area of the nameless cape. They made it possible to build up the beach to the south to a width of 25–35 m (now its width is 10–15 m). However, to the north of the groin (near the complex of recreational facilities), the beach completely disappeared for about 700 m.

At the same time, during the 1980s the construction of slope-stepped embankments was carried out, which also captured the territory of the natural beach. Immediately after the construction, the beaches (whose width was 20 m) began to shrink, by 1999 their width became 2 m. In the absence of a beach, the embankment began to collapse rapidly.

At the beginning of the 21st century, on the southern section, six transverse groins were built in order to protect the sections of embankments that had survived by that time. Implementation of this project caused a significant restructuring of lithodynamics, further degradation of beaches and destruction of coast protection. Without giving all the details of the beach degradation in the settlement of Nikolaevka, which were set out in [30], one should note that now the beaches in many places are a heap of the remains of structures and are closed. Officially, more than 1 km of beaches have been taken out of use. There is a project to restore them, which is worth more than 10 billion rubles. Huge costs of various coast protection measures over the past years largely exceed the costs of low-value buildings on the cliff, which once should have been demolished.

The situation developed similarly in the resort settlement of Peschanoe, located at the mouth of the river Alma. Here the resort zone construction was started in the 1970s without taking into account the state of the main recreational factor – the beach, which by that time had already begun to degrade due to almost

F i g . 2 . Negative effect on lithodynamics of the coastal zone (slightly transformed dunes – orange lines, significantly transformed dunes – purple lines, destroyed dunes – red lines); circles – sand extraction on an industrial scale; black spots denote permanent facilities on the beaches complete cessation of the solid runoff of the river Alma. A beautiful sandy beach, more than 30 m wide, disappeared almost completely by 1982, abrasion of the cliff increased sharply, and a threat to coastal buildings was created.

At first the coast was unsuccessfully protected with vertical walls, and in the 1980s construction of slope-stepped embankments and 15 groins began, which was completed by 1990. After that, the beaches began to shrink, and by 1997 there was no beach in front of the embankment for 200 m.

From the same time, the process of destruction of coast protection works began, which soon became irreversible. The embankment, 1.3 km long, was completely destroyed by 2010. Some of the destroyed structures were subsequently dismantled (for more detail, see [30]). As a result, more than 1 km of the former beach is currently unused (Fig. 3). On most of the remaining beaches (about 2 km), natural sand and pebble beaches are replaced by artificial boulder and gravel beaches.

A typical example of an ill-conceived approach to the recreational development of the coast is the history of construction of a slope-stepped embankment in the village of Beregovoye at the mouth of the river Western Bulganak in 1985–1989, which was caused by the desire to civilize the coast (for more detail, see [30]). Here one can note that before the construction, the width of the pebble-sand beach was from 20 to 25 m. After the construction was completed, the beach began to decrease, by 2006 its maximum width in front of the embankment was 5 m, after which the beach up to 2 m wide appeared and disappeared.

In 2011, the process of deformation of the embankment began, and it was gradually collapsing. In 2021, it was restored according to a new project, as a result of which an artificial beach only 90 m long appeared, backfilled with 60–80 mm crushed stone, under the cover of two groins. On the rest of the embankment (300 m), instead of the beach, a blocky riprap was filled, the discharge of water from the river during floods is provided directly onto the embankment. To the north of

Fig. 3. Part of the embankment in the village of Peschanoe

this structure, the width of the beach decreased from 15–20 m to 10 m, and the rate of cliff abrasion almost doubled.

Negative consequences of a much smaller scale (mainly accumulation and bottom erosion over a length of up to 100 m) were also noted in the system of groins and concrete embankments in the territory of Sevastopol (settlement of Andreevka, Lyubimovka and Uchkuevka microdistricts). The smaller scale can be explained by the peculiarities of the lithodynamics of the region, in particular, by the relatively thin and differently directed in time alongshore sediment flows. On the whole, these projects can be considered successful, they solved the main task - creation of new beach areas with minimal damage in places of receding landslide coasts [31].

Above, we considered hydraulic structures, the main purpose of which is to protect the coast in recreational areas. Another type is constructions for technical purposes only. An example is a water intake structure for a military facility on the northern border of the bay-bar of Lake Kyzyl-Yar, near the town of Saki, built in the early 1980s. On the south side, it is a solid L-shaped reinforced concrete pier extended into the sea and transverse to the shore, and on the northern side it is a straight pier. This structure intercepted the alongshore flow of sediments coming from the south, as a result of which, south of the structure, sediments began to accumulate and the coastline moved out over time for its entire length – 80 m. To the north, downstream erosion began with intensive retreat of the coast; a significant part of the coast located downstream of the sediment flow was affected. As a result, by the end of the 1980s a section of the coast about 3 km long was recognized as emergency; and between 1983–2006 the average coastal retreat over 3 km amounted to 24–33 m.

To protect against the onset of the sea, the sanatoriums located here built coast protection works, including transverse structures (short groins), but the result was the same – build-up of the beach on the protected area and reduction of it on the neighboring ones. *Construction of a Pedestrian Embankment along Morskaya Street in the City of Saki* Project, which is currently being implemented here, initially provided for the construction of two 125 m long groins, although the authors of the article warned of possible consequences. However, at the construction stage of the groin, the bottom erosion and a change in the material composition of the beaches began, which forced the already implemented project to be sent for revision. This resulted in the expenditure of significant financial resources and delayed the implementation of the project by at least two years.

On the embankment of Lake Sasyk-Sivash (between the cities of Evpatoriya and Saki) since the mid-1960s, there is a now abandoned water intake structure to replenish the lake, the waters of which previously served as raw material for a now closed chemical plant. In terms of configuration and geometric dimensions, this structure is similar to the water intake structure described above, however, its construction did not lead to significant negative consequences. Long-term instrumental observations on two opposite sides of the water intake structure and analysis of satellite images show that there is no explicit unidirectional flow here. Depending on the direction of storms, on both sides of the structure, in antiphase, accumulation or erosion is observed with an amplitude of changes in the coastline up to 10 m, which, as a rule, propagate at a distance of up to 50 m from the structure.

When designing port hydraulic structures, as the most expensive, the effect of a whole complex of factors for many years to come is taken into account. According to the master plan for the development of the city of Evpatoriya, adopted in 1948, it was supposed to make a single embankment about 4 km long from the park named after Frunze to the eastern outskirts of Evpatoriya by developing an empty site in the area of Karantinny Cape in the city center.

Instead, a port was built here in 1978. Sandy beaches were concreted, a pier 200 m long was built in the form of a monolithic concrete structure, the tip of which (70 m) was erected on piles. As a result, sediments began to accumulate near the western part of the pier, building up the beach. When the beach reached the end of the concrete part, during southwestern storms, sediments began to go around the continuous part of the pier, creating a shallow on the opposite side. This necessitated dredging, during which, according to the port, up to 150,000 m^3 of sand were removed annually. The beaches to the west of the pier, devoid of reverse flow, began to shrink rapidly. Comparison of aerial photographs from 1941 and 1947 with modern satellite images showed that in a 2.5 km long area, the area of beaches decreased by 52,000 m^2, and the average retreat of the coastline amounted to 20.8 m [32]. Previously, the beaches here were composed of pure yellow sand with a predominant particle size of 0.25 to 0.5 mm [33]. At present, due to the reduction in the vertical thickness of sandy deposits, the content of large pebbles and limestone boulders has sharply increased, especially in the waterfront zone. In some places, clay deposits are exposed after storms.

Interestingly, in the 20th century transverse structures were built in Evpatoriya Bay at different times, while the nature of sediment accumulation unambiguously testified to their two-way alongshore movement with a clockwise direction predominating, which was not taken into account when designing the port [32]. Let us note that its construction was not economically justified both during the Soviet era, and more so now. The main activity of the port, which occupied a valuable seaside area of 6.4 hectares, was extraction of sand in the lake-bay Donuzlav (40 km from the port). For many years, they tried to transfer the Evpatoriya port to Donuzlav. There is currently a plan to convert it into a marina. Here it is appropriate to note that construction of Yalta Cargo Port was not economically justified either. Unfinished and almost not used for its intended purpose, the port has been in a partially destroyed state for 30 years after a severe storm in autumn of 1992.

Returning to Evpatoriya, it can be noted that together with the construction of the port, after the destruction of another embankment by storms (three of them were built in the 20th century), a new one was erected in the central part of the city. To protect the shore, a 1.8 km long shaped wave barrier was erected, while the front of the embankment was set forward 30–50 m from the former water edge. After the construction, the sandy beaches that had existed here before completely disappeared. If earlier the bottom of the western part of the bay was composed of yellow biogenic sand, later, according to the survey data of 2012, it was covered with gray-black silty sand and heavy growth of *Zostera marina*. Currently, the dilapidated embankment is being reconstructed together with an artificial pebble beach. Thus, in Evpatoriya, as a result of the construction of hydraulic structures, the beaches completely disappeared over 3 km and significantly decreased over 2.5 km. Locations of the coast protection works of the Crimea are shown in Fig. 4.

Permanent construction on the beaches (mainly of recreational facilities), despite legal prohibitions in the USSR, Ukraine and the Russian Federation, and its obvious negative impact on the coastal zone has been and remains a common practice. The objects are documented as coast protection works with rest rooms, fishing boxes, rescue stations, reading rooms, etc. A map presenting the location of the largest works is shown in Fig. 5. According to it, most of them are situated on the SCC, but there are enough of them in other resort areas. Let us give some more examples.

On the eastern outskirts of Evpatoriya, in the early 1960s, according to aerial photography, the width of sandy beaches was about 50 m. After the construction of the above-mentioned pier and concrete embankment in Evpatoriya, they began to shrink. Nevertheless, private individuals, whose houses were located behind the front of the beach, gradually erected various buildings on it, approaching the water edge. As a result of the change in the profile and width of the beaches, the wave action on the coast increased with its erosion. Soon this zone and adjacent parts of the coast were declared as being in the state of emergency. Attempts of the city authorities to resettle the houses proved unsuccessful.

F i g . 4 . Coast protection structures

F i g . 5 . Permanent facilities on beaches

The owners of the buildings began to independently strengthen the coast with walls, but the situation deteriorated significantly. The beach disappeared completely for about 1 km, and an unattractive artificial cliff of construction debris up to 2 m high appeared on the shore, presenting a danger to vacationers.

In the beam cut into the cliff to the north of the urban-type settlement of Nikolaevka, in 1989, residential buildings of the *Yakor Cooperative* were erected. By cutting off part of the cliff and fixing the coastline on the beach with concrete, the builders had not taken into account the fact that the coast was receding. As a result of this ill-conceived construction, serious problems arose in the coastal zone for many years. Over time, a cape formed on the site of the embankment, protruding 50 m from the natural configuration of the coast. As a result, the beach to the north disappeared and the cliff accelerated its retreat. Thus, only between 2004–2014 the coastline receded here by 15 m. It is known that wave energy increases on the capes, and this fact aggravates the situation even more. The buildings, which were located earlier in the rear part of the beach, later turned out to be on the water edge. During storms, waves throw stones at the windows of first-line apartments, and the embankment collapses.

In the urban-type settlement of Kacha in 2004–2012 a 400-meter long six-storey apartment complex named *Nash Parus* was built with an official name *Coast protection work with recreational facilities*. Part of it was built on the beach, another part – on the site of a cut cliff. Prior to construction, the average width of the sand and pebble beach was 15–20 m. As early as in the construction period, there was a change in the configuration of the water edge and a decrease in the width of the beach. At present, its width is 2–4 m (sometimes it is completely absent), which is accompanied by a sharp decrease in the volume of beach-forming material and an increase in the content of coarse sediment fractions.

When even moderate intensity storms take place, the beach undergoes wave processing along the entire width, as a result, the wave load on the structure increases. We noted underwashing of the foundation and destruction of the stairways to the sea, abrasion of elements of reinforced concrete structures and exposure of reinforcement. To the south of the apartment complex there is a complex of six-story buildings, the so-called boathouses, with a length of 270 m along the front of the coast. The buildings owned by private individuals are now almost at the water edge (now the width of the beach is 0 to 6 m, it used to be 20–30 m) and threaten people's safety.

In addition to construction on the beaches, a significant danger is construction of buildings on the edges of the cliffs, which is most typical for Sevastopol region: its northern shores are clayey, landslide-prone cliffs. During the Soviet period, only vegetable gardens were allowed here. After the collapse of the USSR, intensive development of these sites began for the construction of dachas and mini-hotels. As a result, about six linear kilometers have now been built up, which has led to the activation of landslides and destruction of buildings. This situation is due to the increased load on landslides by buildings, soaking and weighting of slopes due to irrigation, water leaks and lack of sewerage.

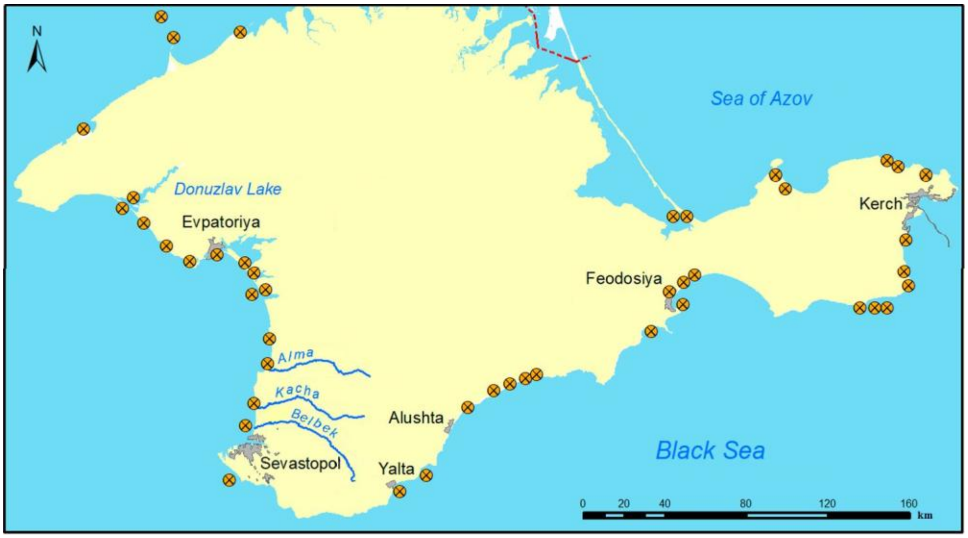
Thus, a huge *Bay of Dreams* hotel, built on the edge in the preserved natural landmark of Laspi Bay on the SCC has forever changed the picturesque landscape. In addition, its construction was carried out on the territory of the development of landslides and tectonic faults. Storms repeatedly eroded the stone filling in front of the hotel's facade, smashed the reinforced concrete wave-breaking wall into separate fragments, and deformed the embankment and boathouses.

Removal of inert materials from beaches and underwater coastal slopes on a small scale has always been carried out for local construction. For a long time, this was not considered something reprehensible. The Evpatoriya City Duma, discussing such removal on the beaches of the eastern outskirts of the city, in a decree of 1887 allowed such activities, imposing a tax on them. Economic growth and urbanization in the 20th century resulted in the need of a large number of inert materials (sand, gravel, pebbles) for the construction industry. In Crimea, the period of their industrial extraction from the coastal zone began in the 1930s; the sand from the Saki bay-bar area was used for the construction of the Dnieper Hydroelectric Station (the sand was of good quality); up to 1000 m^3 of sand was mined per day. Mining here reached its real scale in the post-war period. The sand was not only used for construction in the Crimea, but was also exported by rail and sea to Odessa and other ports. Barriers separating the quarries from the sea narrowed under the influence of storms and arched towards the quarries. At the same time, a reduction of beaches up to 100 m was noted in places adjacent to the quarries. In a survey carried out by a special commission in 1962, it was noted that further mining of sand and gravel should be stopped. Due to the real danger of changing the salinity of the brine in the healing lake and the threat to the famous mud, the quarries were closed, and the sand extraction continued by refilling it from the bottom of the sea. However, the situation continued to deteriorate, after which sand mining was soon completely stopped. Instead of sand dunes, salt lakes and so-called droughts (wetlands) have formed at the site of sand mining, which still exist today.

Even in the middle of the 20th century in Koktebel (Eastern Crimea) there was a sand-gravel-pebble beach 20–30 m wide. It was distinguished by an unusual color due to inclusion of pebbles from the Karadag rocks. Semi-precious stones from the beaches were a welcome souvenir for vacationers. Beach deposits were developed unprofessionally for local construction needs in relatively small volumes. However, in 1954, commercial extraction of sand and gravel mixtures began in the central part of the bay. It was also carried out in neighboring areas near the urban-type settlements of Kurortnoe and Ordzhonikidze, as well as Tikhaya Bay. Large volumes of mixtures were exported, including for the construction of various strategic facilities. The data on actual production volumes are not available, but it is known that it continued until 1967.

As a result, the beaches began to shrink rapidly, and by the mid-1960s their width in the western part of the bay was already 5–10 m, which led to the destruction of the embankment by storm waves [35]. The rapid reduction of the beaches forced the construction of expensive coast protection works, creating artificial beaches with a much worse material composition compared to the natural ones in Koktebel and Kurortnoe. Subsequently, the construction of permanent structures on the beaches in these settlements led to the second wave of beach disappearance. A project for their recovery is currently being developed.

A large area of extraction of sand and gravel mixtures from an underwater slope by suction dredgers in the 1950s–1960s was located in the northern part of Sevastopol, at the mouth of the Belbek and Kacha rivers, as well as in the area of the Uchkuevka beach. In the latter area, the impact of extraction was especially strong, resulting in a landslide of 1.5 km long. Until now, it remains the most active in the region, its catastrophic shifts periodically occur, destroying buildings on the edge of the head fall. In the region of the mouth of the river Kacha, the beach as a whole receded by 20–30 m, which was also affected by the river control. This affected the beaches near the mouth of the river Belbek to a lesser extent, since solid runoff has so far retained up to 80 % of the previously existing volume. Back in the late 1950s V.P. Zenkovich wrote: “Alluvial and beach material is taken in the lower reaches of the Belbek and Kacha rivers, but these removals are replenished during floods and, apparently, do not pose a danger to the stability of the coast” [29, p. 199]. However, in that era, the rivers were not controlled yet. Until the 1970s mining of inert materials was carried out almost everywhere (Fig. 6.), which led to severe consequences in the coastal zone. In this regard, the Decree of the Council of Ministers of the USSR No. 40 of January 17, 1969 “On urgent measures to protect the Black Sea coast from destruction and rational use of the territories of the resorts of the Black Sea coast” was issued, where, among other measures to reduce anthropogenic load on the shores, it was proposed “... to take measures to stop the use of pebbles and sand of the sea coastal strip for the needs of construction”.



F i g . 6 . Proved sites of extraction of inert materials on an industrial scale

In general, this decree was carried out. We know of only one example of illegal sand extraction from the bottom, which was carried out south of Sevastopol and in the area of the Bakalskaya Spit (north-western coast) in 2011–2012. As a result of numerous public protests, sand extraction was banned. After the Crimea was incorporated into the Russian Federation, the same company was issued a license for sand mining at the Bakalskaya Bank until 2019. Now, due to public protests, mining has also been stopped. In 2019, on the cliff of the northern side of Sevastopol, under the guise of creating a recreational zone, the extraction of gravel-pebble mixtures was arranged in two quarries, 165,000 m^3 was mined at a smaller one [36]. By the decision of the city authorities, this work has now been suspended. Currently, there is only one official underwater quarry, in the inner part of Lake Donuzlav, which has a minimal impact on the lithodynamics of the coastal zone of neighboring areas [37]. We are aware of recent attempts to license sand mining in the Crimea at several underwater deposits, but we do not know what decisions have been made. It should be noted that only in the Foros-Alushta section, reserves of 88 million tons have been explored at the bottom, which are classified as off-balance and attract the attention of builders.

Decrease in the solid runoff of rivers and temporary streams due to river control in the 1960s–1970s affected mainly the regions of Western Crimea. In 1964, in the upper reaches of the river Belbek, three reservoirs were built: Klyuchevskoye, Shchastlivoe-I and Shchastlivoe-II, and in 1975 Zagorskoye reservoir was built on the river Kacha. Besides, a whole cascade of storage ponds of a smaller scale was built. Due to the increase in the building area and other economic activities, the erosive washout in the river basins has also decreased. The flow of the river Western Bulganak has stopped completely. Unauthorized sampling of material is carried out directly from the river bed. As a result, the volumes of solid sediments, especially coarse fractions that form beaches, have decreased. To the greatest extent the decrease in solid runoff affected accumulative beaches at the mouths of the Kacha and Alma rivers, as discussed above. Apparently, it had little effect on the beach at the mouth of the Belbek river, since it is the largest river of the Crimea that retained a significant amount of runoff. It should be noted that in 2021, a water intake structure was built 15 km from its mouth. The first six months of its operation showed that it accumulated solid deposits to a large extent. A recommendation was given to discard the obtained material in the mouth zone during its cleaning. It is currently believed that the volume of solid runoff of the Kacha river is 6.72 thousand m^3/year, or 12.1 thousand t/year, and of the Belbek river – 18.0 thousand m^3/year, or 32.4 thousand t/year [38]. This information is also given by the authors of later works, for example [39]. The given data give rise to certain doubts, since observations at the mouth of these rivers have not been carried out for a long time.

The closure of cliffs by various structures leads to a decrease in the inflow of sediments from the wave field into the coastal zone and, as a result, to a reduction in beaches. This factor is most important in Western Crimea. The existence of beaches depends primarily on the sediment reserves on the beach and the possibility of their continuous supply. The main source of sediment replenishment of the coastal zone of the region from the mouth of the river Belbek to Lake Kyzyl-Yar with a length of about 50 km are the products of the cliff destruction as a result of abrasion and landslide processes, namely, layers and lenses of alluvial pebbles and sand of the ancient river network. At different times, part of the cliffs was removed from the balance of sediment supply to the coastal zone as a result of the construction of coast protection works, creation of quarries, and terracing of slopes. The length of active cliffs within the city of Sevastopol from the mouth of the river Belbek to Cape Tubek is about 23 km. At present, according to our calculations, the length of the coast with the cliff closed or withdrawn from inflow into the coastal zone is 4.3 km, or 19 % of the total length. 8.5 km or 32 % of the cliffs are closed between Cape Tubek and Lake Kyzyl-Yar (about 26 km). In general, in Western Crimea, 25 % of the total length of cliffs is not a source of sediment. Our calculations showed that the average specific drift per linear meter per year is on average 1.27 m^3, which means that about 16,000 m^3 per year is removed from the input part of the sediment balance. This indicator is four times less than that given in [40]. Our estimate seems to be more reasonable, since it is based on specific data on the rate of abrasion over a long period and data on the structure of cliffs obtained from boreholes and geomorphological surveys.

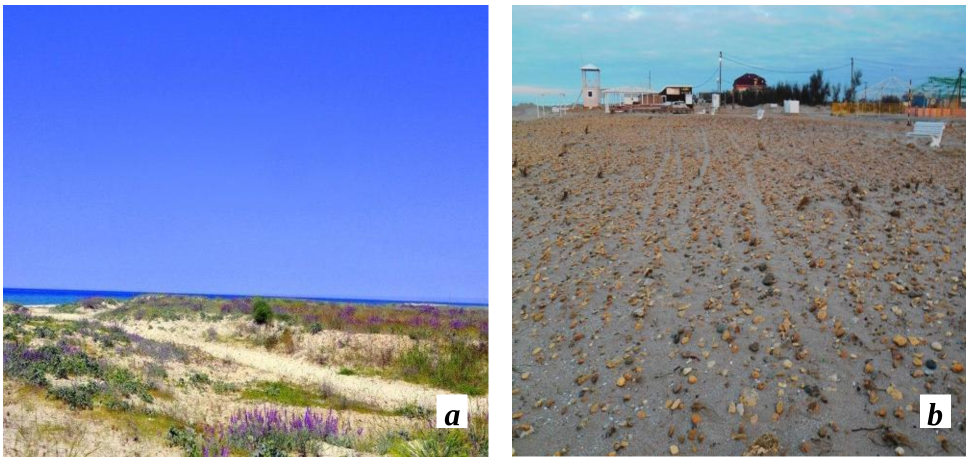
Dune destruction is one of the factors of the negative anthropogenic impact on the coastal zone. It is known that coastal dunes are a natural accumulator of sand, a natural barrier that protects sandy shores from erosion. In addition, sand dunes on the coast are unique ecosystems with a rich diversity of plant communities; in some areas they play a significant role in the balance of sediments. Until recently, coastal dune landscapes occupied fairly large areas of the Crimean coast.

It is enough to look at old photographs of Evpatoriya and Feodosiya to make sure that the coastal parts were occupied by dunes. Their largest range was in Western Crimea.

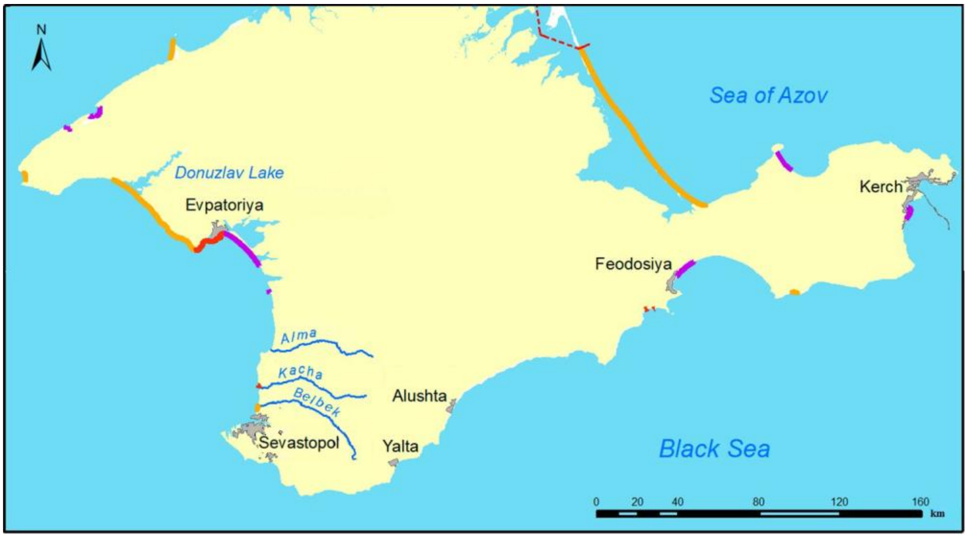
Previously, the dunes were partially destroyed, reconfigured during extreme storms, and then gradually restored. However, in recent decades, human activity has become the most destructive factor. The anthropogenic impact on the dunes is caused by increased coastal urbanization and is expressed in the construction of various recreational facilities, roads, parking lots, unregulated campsites and 'temporary' buildings, planning the natural relief of the beaches. Since beaches in many places are composed, in addition to sand, of fragments of limestone gravel and boulders, sand blowing rather quickly leads to the appearance of ridges of this material on the beach surface (Fig. 7). The material composition of beaches is changing, their recreational properties are sharply deteriorating.

Besides, the dunes are often the site of illegal sand extraction. Destruction of vegetation cover, including by ATVs, which are increasingly used as a recreation element, leads to an increase in the eolian removal of sand from the beach to the sea and to the territory of recreational facilities. Traces of such removals, for example, in the urban-type settlement of Zaozernoe, are visible everywhere. Erection of tall buildings near the dunes prevents the return of sand blown from the coastal zone to the beach, which is another reason for the retreat of the coast.

Prior to the active development of the Black Sea coast of Crimea, the length of its coasts with a dune landscape, according to our estimates, was 94 km. At present, such shores have disappeared completely for about 14 km, and partially for 33 km. Their area continues to decrease (Fig. 8). Due to anthropogenic impact, the dune landscapes of the Crimea are currently under the threat of degradation or extinction. Their natural recovery is either very slow or impossible



F i g . 7 . Dunes before (*a*) and after (*b*) planning of the beach in the vil. of Shtormovoe



F i g . 8 . Location of dunes (slightly transformed dunes – orange lines, considerably transformed dunes – purple lines, destroyed dunes – red lines)

at all, so they need protection and restoration. In December 2021, on the bay-bar of Lake Oyburskoye, where a large dune complex is located, a protected area was created instead of a shrimp farm thanks to the long-term struggle of local residents.

Artificial opening of bay-bars of salt lakes is still limited, although there are plans to use the lakes of Western Crimea for arranging yacht parking; there was also a plan to build a port on Lake Bogayly. The negative impact of bay-bars opening is reduction of the length of beaches and change of sediment dynamics in the adjacent areas. As a result, there is a need to build coast protection works. In the 1950s–1960s, in Western Crimea, bay-bars of Lake Panskoe (Sasyk) in Yarylgach Bay, Lake Donuzlav, Lake Oyburskoye (the bay-bar is currently closed), as well as bay-bars in Kruglaya and Kazachya Bays (Sevastopol) were discovered.

Immediately after digging of the canal in Lake Donuzlav in 1962, to determine changes in the lithodynamic regime, observations were organized over the dynamics of the coastline. After the completion of the canal during 1961–1966 the coastline in the areas adjacent to the canal receded by 25–60 m. In subsequent years, alternating changes in the coastline with its gradual leveling were observed. After two concrete spurs were built, by the 1980s the coast stabilized.

Until 1960s in the southern and western parts of Kruglaya Bay (Sevastopol), there were two sandy bay-bars separating salt lakes. Here, before the Crimean War (1854–1856), there was a mud bath of the military department, according to some sources, it existed in ancient times. As evidenced by aerial photography in 1941, the sandy bay-bar in the southern part was about 400 m long and up to 80 m wide. In the post-war period, the bay-bar was almost completely demolished for construction sand, and the lake turned into a shallow (about 0.5 m) apex part of the bay, overgrown with marine vegetation. Back in the mid-1990s a part of the bay-bar with the beach was preserved here. At the beginning of the 21^{st} century, the beach was destroyed, and apartments were built right on the edge under the guise of fishing boxes. Currently, a filling made of large boulders covered from above with construction debris has been made on the edge to protect the apartments.

Changes in the number of molluscs in the Black Sea have been recorded since the beginning of the 1960s. This fact is usually associated with the invasion of the Black Sea from the Pacific Ocean by the predatory mollusc *Rapana venosa*, which successfully adapted to new conditions and drastically reduced the populations of native molluscs, becoming the predominant species of benthic communities. The invader caused serious damage to oyster and mussel biocenoses, but now, due to undermining of its own food supply, the number of *Rapana venosa* has significantly decreased [41]. However, in some studies on the diet of *Rapana venosa*, it was noted that the oyster is not its preferred food object. In addition, in the northwest of the Black Sea, an outbreak of mortality among oysters began before the mass appearance of *Rapana venosa*, so the question of the influence of the latter on the populations of oysters in the Black Sea is still debatable [42].

In addition, the dynamics of the number of molluscs, obviously, was also affected by anthropogenic pollution of the water area and bottom sediments of the coastal zone by municipal and industrial wastewater. Together, these factors led to a decrease in the number of bottom plant communities that fix the soil, as well as to a decrease in the number of molluscs, the valves of which serve as the source material for the formation of sands. At the deep coasts, this does not actually have any noticeable effect on the sediment volume.

At one time, observations of the process of changing the number of molluscs were not arranged, so there are few publications on this topic. One of them analyzes changes in the taxonomic composition of benthic biocenoses of the Crimean coast [43]. In another, it is noted that compared with the 1940s the mass of zoobenthos decreased by more than eight times [44]. In general, this factor acts as a background factor and is important for the shallow water areas of Western and partly Eastern Crimea.

We have considered the main types of anthropogenic impact on the lithodynamics of the Black Sea coastal zone. In addition to those noted above, one can also indicate unprofessional coast protection in the form of backfilling various materials (up to construction debris) into the waterfront zone, digging trenches parallel to the coast on the beaches or collecting sand in shafts for the winter period, installing concrete slabs on beaches, etc. The degree of technogenic load for various areas of the Black Sea coast of Crimea is shown in the Table. It can be seen that the maximum load is typical for Sevastopol and the SCC.

Anthropogenic load (*K*) for various districts of the Black sea coast of Crimea

Coastal area	*K*	Load degree according to [26]
vil. Portovoe – Evpatoriya	0.02	minimal
Evpatoriya – Sevatopol	0.28	average
Sevastopol	1.18	extreme
Cape Chersonesos – Cape Sarych	0.02	minimal
Cape Sarych – Alushta	1.21	extreme
Alushta – vil. Morskoye	0.60	maximal
vil. Morskoye – Feodosiya	0.05	minimal
Feodosiya – Cape Takil	0.03	minimal

Conclusion

Based on the above, the following conclusions can be drawn. Hydrotechnical construction has the greatest impact on the change in the lithodynamics of the Crimean coastal zone. The construction of transverse hydraulic structures (groins) on the coastal slope in Western Crimea blocked the natural alongshore flow and broke it into separate lithodynamic cells. The consequences manifested themselves in the form of bottom erosion, covering significant parts of the coast.

Despite the previous negative experience, the design and construction of such structures continues. The construction of permanent facilities on beaches leads to at least a reduction in the number of them, and at the most to their complete disappearance, which in the future requires expenses to protect the coast and reduces its recreational properties. The greatest damage is inflicted in the zone immediately adjacent to permanent structures.

The previously carried out selection of inert materials from the beaches and the underwater coastal slope of the Crimean coast required significant material costs for restoration of degraded or vanished beaches.

The decrease in the solid runoff of rivers and temporary watercourses due to their control mainly affected the regions of Western Crimea, while to the greatest extent it affected accumulative beaches at the mouths of the Kacha and Alma rivers.

The closure of cliffs by various structures leads to a decrease in the flow of sediments from the wave field into the coastal zone and, as a result, to a reduction of beaches. This factor is most important in Western Crimea, where 25 % of the total length of the cliffs is not a source of sediments; about 16,000 m^3 per year is removed from the incoming part of the sediment balance.

On the Crimean Peninsula, before the start of its active development, the length of the coast with dune landscape was 94 km. Due to anthropogenic impact, the dunes are under the threat of degradation or extinction, for about half of their length they have already completely disappeared or degraded and their area continues to shrink.

The negative impact of the opening of bay-bars, which is now limited, is to reduce the length of the beaches and change sediment dynamics in the surrounding areas.

Reduction in the number of benthic molluscs, the valves of which serve as the initial material for the formation of sands, acts as a background factor and is important for the shallow water areas of Western and partly Eastern Crimea. Extreme technogenic load is observed in Sevastopol and on the Southern coast, and the minimum load is observed on the eastern and northwestern coasts.

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The Structure of Fields of Oceanological Quantities in the Upwelling Zone at the Herakleian Peninsula (Crimea) in August 2019

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Abstract
Based on the data obtained during an expedition of Marine Hydrophysical Institute in August 2019, the paper considers the morphology of the fields of temperature, salinity, content of total suspended matter and coloured dissolved organic matter in two adjacent areas located along the north-west (area *1*) and south-west (area *2*) coasts of the Herakleian Peninsula. The authors used methods and approaches based on classical oceanographic analysis of the field structure of quantities under study. It is shown that in area *1* with the coastline oriented at an acute angle to the wind arrow, advective processes prevailed, and the structure of the fields of oceanological elements contained no anthropogenic features. In area *2*, the coastline of which is located along the normal to the wind arrow, the surge effect and the rise of water from deep horizons to the sea surface were noted. Here, in the water column, lenses with low salinity, increased content of total suspended and dissolved organic matter were found. These lenses arose under the influence of wastewater distributed in the upwelling ascensional circulation system from a nearby wastewater collector.

Keywords: temperature, salinity, total suspended matter, coloured dissolved organic matter, upwelling, contamination, Herakleian Peninsula, Crimea

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Структура полей океанологических величин в зоне апвеллинга у Гераклейского полуострова (Крым) в августе 2019 года

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Аннотация
На основе данных экспедиции, проведенной Морским гидрофизическим институтом в августе 2019 г., рассмотрены закономерности структуры полей температуры, солености, концентрации общего взвешенного вещества и концентрации окрашенного растворенного органического вещества на двух смежных участках, расположенных вдоль северо-западного (участок *1*) и юго-западного (участок *2*) берегов Гераклейского полуострова. Использованы методы и подходы классической океанографии, основанные на анализе структуры полей рассматриваемых величин. Показано, что на участке *1* с береговой линией, ориентированной под острым углом к вектору ветра, превалировали адвективные процессы, а структура полей океанологических элементов не содержала антропогенных признаков. На участке *2*, береговая линия которого расположена по нормали к вектору ветра, отмечен сгонный эффект и подъем вод из глубинных горизонтов к поверхности моря. Здесь в толще вод обнаружены линзы с пониженной соленостью, повышенным содержанием общего взвешенного и растворенного органического веществ. Эти линзы возникли под влиянием сточных вод, распространявшихся в системе восходящей циркуляции апвеллинга из находящегося рядом коллектора.

Ключевые слова: температура, соленость, общее взвешенное вещество, окрашенное растворенное органическое вещество, апвеллинг, загрязнение, Гераклейский полуостров, Крым

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Introduction

The coastal water area of the Black Sea near the Herakleian Peninsula (Fig. 1) has been studied well enough. Currently, there are some publications [1–8] addressed to water dynamics, modeling, satellite studies of the distribution of pollutants [1)], hydrochemical regime of the region [2)]. Particular interest in this water area is stipulated by the anthropogenic load on the marine environment that has been increased in recent years.

One of the recently published papers [9] analyses the current data on the sources of pollution in the coastal water area under consideration, the volumes of wastewater

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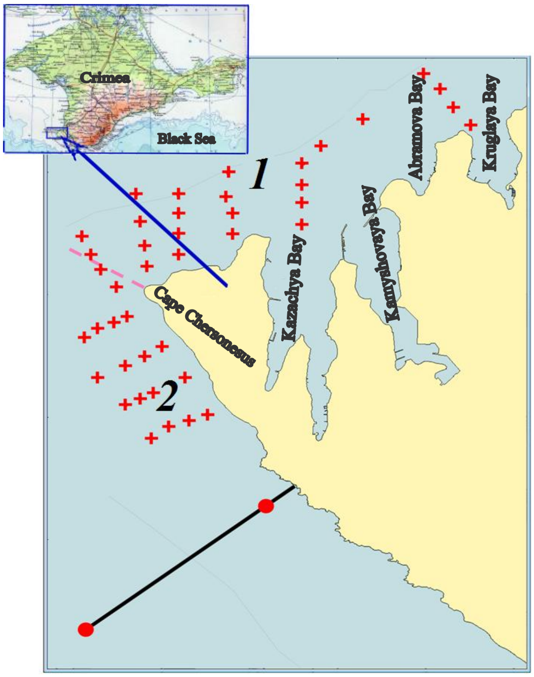
1) URL: http://dvs.net.ru/SWCrimea/stoki_ru.shtml

2) Korshenko, A.N., 2016. *Marine Water Pollution. Annual Report 2015*. Moscow: Nauka, 184 p. (in Russian).



F i g . 1 . Diagram of oceanographic stations of the survey conducted on August 23, 2019 (*1*, *2* – conditionally designated areas of the water area; black line with two red circles – the sewage treatment plant pipeline with two outlets). Inset map – the geographical position of the studied water area

entering it, and the chemical composition of pollutants. Only a few of the above stated publications include the analysis of the fields of oceanographic elements, which are used mainly as a background. From the point of view of oceanology, this coastal water area of the Crimean Peninsula remains insufficiently studied.

The aim of this article is as follows:

– on the basis of the expeditionary data, to identify patterns in the structure of the thermohaline field, as well as the concentration fields of total suspended matter (TSM) and coloured dissolved organic matter (DOM) near the coast of the Herakleian Peninsula;

– to determine the signs of anthropogenic effect on the marine environment in the structure of the fields of the analysed quantities;

– to consider the factors that form the coastal area of contamination.

Materials and methods

The analysis was based on the materials of the expedition organized by Marine Hydrophysical Institute on August 23, 2019, during which synchronous observations of temperature, salinity, TSM and DOM concentrations were carried out in the layer of 0–25 m. The survey was conducted according to the diagram of stations shown in Fig. 1. The depth range in the testing area made from 6 to 150 m. At each station, all four parameters of the environment were synchronously recorded in the *in situ* sounding mode with a depth step of 0.1 m using the *Kondor* Sounding Complex [3)].

[3)] URL: http://ecodevice.com.ru/ecodevice-catalogue/multiturbidimeter-kondor (Accessed: 8.03.2022).

It should be noted that TSM and especially DOM are classified as the most informative indicators of water quality. Currently, DOM is actively used internationally as an indicator of contamination (including bacterial one) of coastal sea and ocean areas [10–12].

At the moment, the maximum permissible concentration of TSM and coloured DOM as a numerical indicator of marine environment contamination has not been determined. Therefore, to assess the significance of the anthropogenic component in the concentration field of these substances, their actual content was compared with the concentration typical for the open waters of the Black Sea off the Crimean coast.

Based on the results of numerous expeditions, we found that in the upper water layer 20–30 m thick off the Crimean coast, the DOM content field was uniform. Its characteristic concentration varies within 1.4–2.1 mg/L, with the salinity making 18.2–18.4 PSU [13].

Parts of the water area subject to anthropogenic effect stand out against the surrounding background in the form of local maxima of the content of this substance. In the Sevastopol coastal area, the concentration of DOM of anthropogenic origin on the sea varies in the range of 2.2–14.8 mg/L. The maximum concentration of this substance was found in the area of the wastewater outlet of Balaklava, located east of the entrance to Balaklava Bay [14].

On the schemes of the horizontal distribution of this quantity, the isoline of the DOM concentration of 2.2 mg/L can be taken as a conventional border separating water with an anthropogenic component and water where the anthropogenic addition is insignificant. By the location of local maxima of DOM concentration, it is possible to determine objects that have an anthropogenic effect on the marine environment [13].

In accordance with [15], in the central part of the Black Sea, the TSM concentration makes 0.2 mg/L. In the Crimean coastal waters, which are not under anthropogenic load due to the influence of the coast and the bottom, it is much higher and makes 0.8 mg/L [16].

Therefore, the concentration of coloured DOM and TSM, 2 mg/L and 0.8 mg/L respectively, is conventional concerning the natural norm for the content of these substances in the Black Sea waters near the Crimean Peninsula.

When we speak about impurities, we use the definition *contamination* adopted from work [17]. Thus, *contamination* means the presence of a substance where it should not be or its concentrations above the background. *Pollution* results or can result in adverse biological consequences for local communities.

The formations found in the structure of the fields of the considered quantities, which did not characterize natural distribution and stood out against the surrounding background, were taken as signs of anthropogenic effect.

Results and discussion

The weather during the survey was determined by the southeastern periphery of the anticyclone with its center over Belarus. The survey was accompanied by the northern, northeastern wind with the average-per-day speed of 6 m/s. The wind speed reached 8–13 m/s at sea during the survey. The sea disturbance made 3-4 points.

For convenience of description and taking into account the peculiarities of the hydrological regime, we conditionally divide the entire water area under consideration into two areas. Area *1* includes waters of the north-west part of the Sevastopol coastal area, from Omega (Kruglaya) Bay to Cape Chersonesus. Area *2* includes waters washing the south-west coast of the Herakleian Peninsula. Area *1* is a relatively shallow (depth less than 30 m) water area, where the fields of the studied quantities were formed under the influence of advective processes. The state of the fields of oceanological quantities of area *2*, which is located above the slope, in an area with predominantly gentle relief and rather sharp increase in depth near the coast, was largely determined by the vertical circulation of water (Fig. 1).

In area *1*, with the coastline oriented at an acute angle to the wind arrow, the wind surge and the corresponding water transport towards the coast prevailed. In area *2*, the coastline of which is located along the normal to the wind arrow, the surge effect and the rise of water from deep horizons to the sea surface were noted. The structure of the water in the respective water areas was characterized by qualitative differences.

A natural boundary was observed between the selected areas in the form of a frontal section in the fields of all four analysed quantities, which was well expressed on the sea (Fig. 2) and indicated by a dotted red line in Fig. 1.

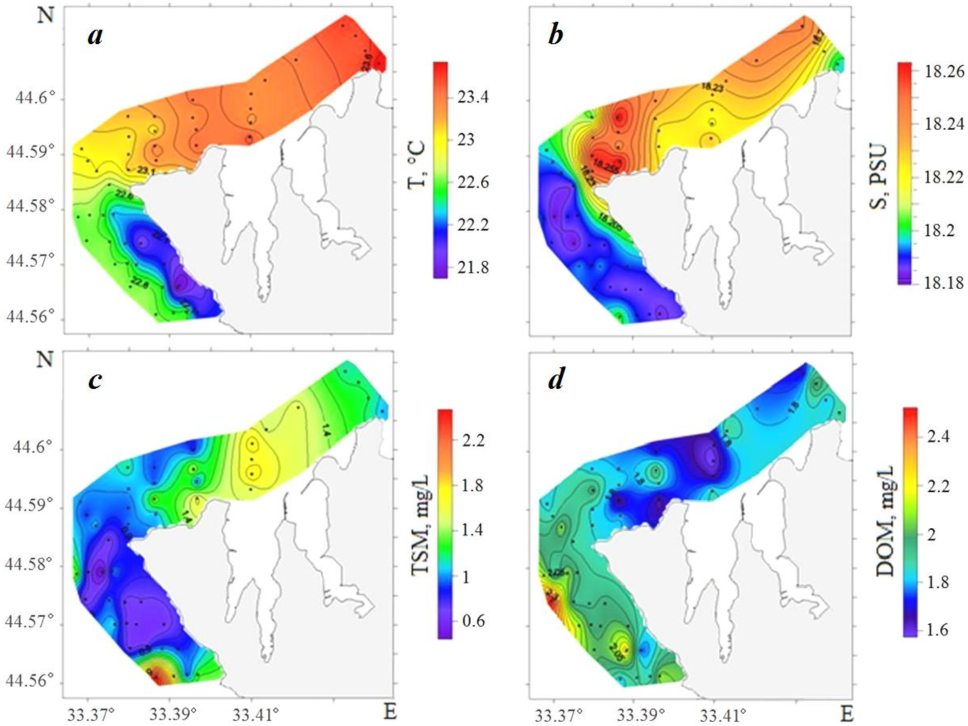
In area *1*, the water column was characterized by uniformity and parameters close to those of the water of the open part of the Sevastopol coastal area. There, water of elevated temperature and salinity with minimum content of TSM (0.6–0.8 mg/L) and DOM (1.6–1.8 mg/L) was transported from the north (Fig. 2).

In area *2*, on the sea, in the temperature field, an upwelling center (minimum 21.6–22.2 °C) is clearly visible, elongated along the south-west coast of the Herakleian Peninsula. In the fields of other elements on the sea surface, the surge effect is not so evident (Fig. 2).

The features of the vertical stratification of the analysed quantities in the subsurface water layer contain more detailed information about upwelling (Fig. 3).

In both areas, a two-layer vertical structure of the temperature field, typical for the summer season, was observed with a monotonically decreasing profile $T(z)$. The upper quasi-homogeneous layer 10–15 m thick was clearly marked. It was underlain by a seasonal thermocline, deeper than which the water temperature slowly decreased with the depth of up to 11–13 °C at 20–25 m horizons. In area *1*, the thermocline was located in the 13–20 m layer, and its surface was almost horizontal. In area *2*, influenced by upwelling, the thermocline was raised near the coast and was located at a shallower depth, among the horizons of 8–15 m (Fig. 3, *a*).

The salinity in the upper water layer in area *1*, equal to 18.1–18.3 PSU, was higher by 0.1–0.2 PSU compared to area *2*. That is, in the ascending circulation system, less saline water was exposed to the surface of area *2* (Fig. 3, *b*).

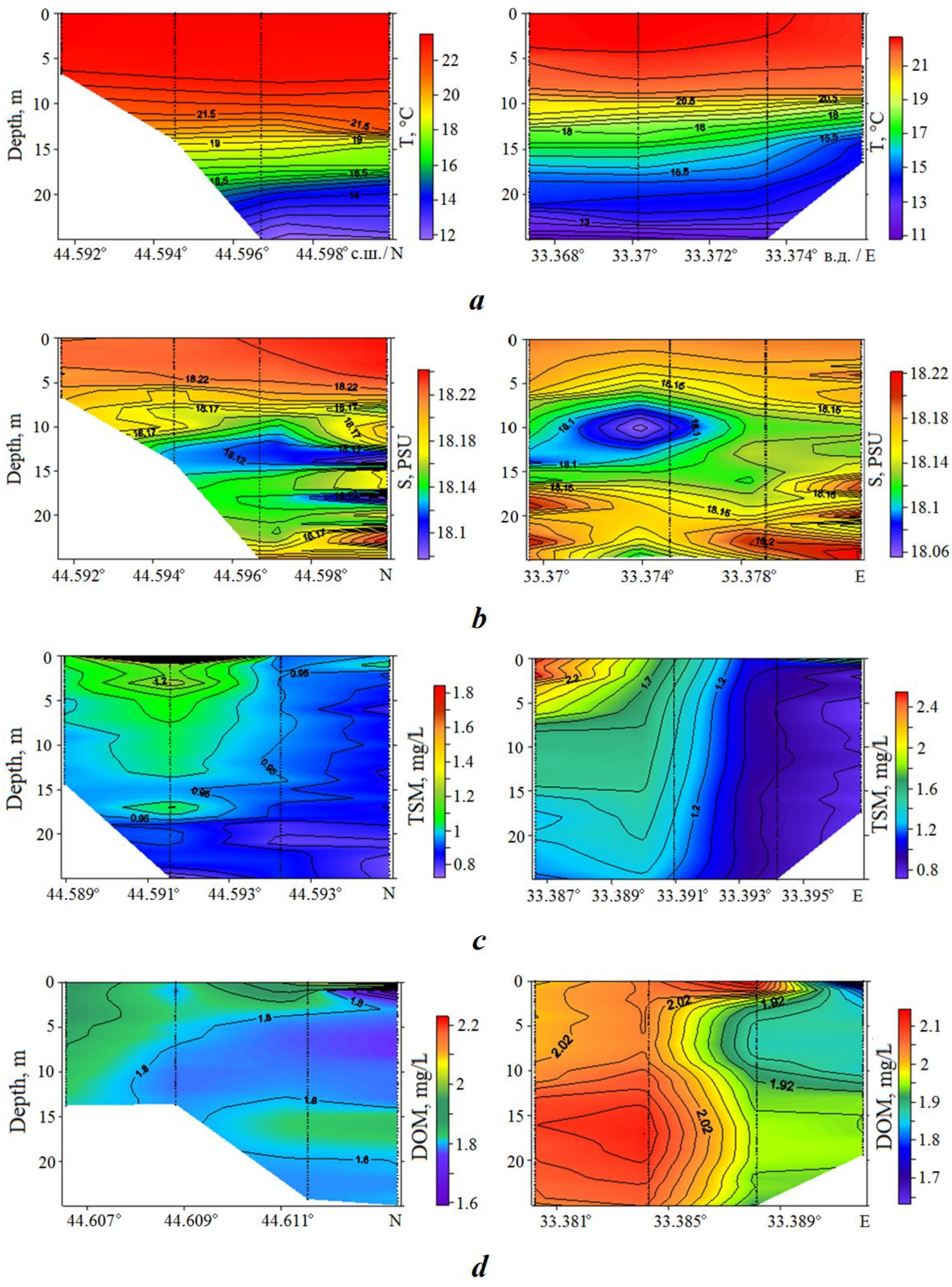


F i g . 2 . Distribution of *a* – temperature, °C; *b* – salinity, PSU; *c* – TSM concentration, mg/L; *d* – coloured DOM concentration, mg/L in the upper water layer in August 2019 according to the MHI expedition data

In contrast to the structure of the temperature field, the salinity field was relatively uniform along the vertical. From the surface to the lower sounding horizon, the salinity throughout the considered area varied within 0.2–0.3 PSU and was characterized by nonmonotonous vertical stratification. Distribution $S(z)$ is a nonmonotonous function of depth with an intermediate minimum located in the 5–20 m layer (Fig. 3, *b*).

An important element of the stratification of the haline field is the presence of structural heterogeneities in the subsurface water with their salinity reduced by 0.05–0.17 PSU relative to the surrounding background. These formations were most apparent in area *2*, where they were identified as separate lenses with a vertical and horizontal scale of about 10 m and 200–400 m (Fig. 3, *b*).

The structure of the TSM concentration field in the analysed areas also differed significantly. On the sea, in shallow area *1*, the TSM concentration varied in the range of 1.1–2.0 mg/L. The field of this quantity was characterized by homogeneity. On the surface of the predominant part of the water area in area *2*, the TSM content was minimal (0.4–1.1 mg/L), except for its extreme south area.



F i g . 3 . Vertical distribution of *a* – temperature, °C; *b* – salinity, PSU; *c* – concentration of TSV, mg/L; *d* – concentration of coloured DOM, mg/L in Section 1 (left) and in Section 2 (right) in August 2019 according to the MHI expedition data

Here, against the background of a low-gradient TSM field, a lens with its vertical scale of 5–7 m and maximum concentration of 2.4–2.5 mg/L within the entire considered water area was clearly distinguished, which was three times higher than the natural norm (Fig. 3, *c*).

In the vertical structure of the TSM concentration field, as well as in the structure of the haline field, inhomogeneities in the form of lenses with an increased content of this substance relative to the surrounding background, were revealed in the water column. Moreover, such structural formations were more often observed in area *2*, where they were more evident (Fig. 3, *c*).

The concentration field of coloured DOM also had noticeable structural differences. On the surface of the predominant part of the water area in area *2*, the content of this substance was close to the norm and made 2.0–2.1 mg/L. In the south-west part of this area, a lens with the maximum DOM concentration (up to 2.4 mg/L) was observed, which was traced throughout the entire water column from the surface to the lower sounding horizon. In most of the water area in area *1*, the concentration of DOM on the sea was minimal, 1.6–1.8 mg/L (see Fig. 2).

In the vertical structure of the concentration field of coloured DOM, as well as in the structure of the haline field and the TSM concentration field, individual lenses with an increased content of this substance were noted in the water column. Similar structural formations were more often observed in area *2*, where they were more apparent, and the concentration of DOM in their cores reached 2.5–2.7 mg/L exceeding the natural norm by 1.2–1.4 times (Fig. 3, *d*).

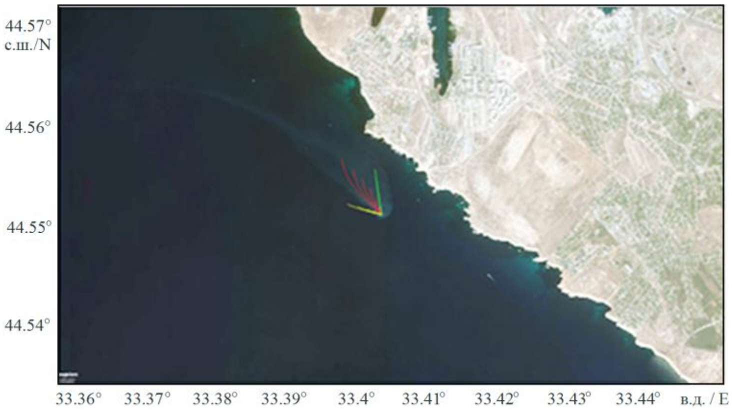
The above information indicates that the fields of salinity, TSM and DOM concentrations in area *2* had a component that was not present in area *1*. In area *2*, in the upwelling ascensional circulation system, water came to the sea surface from deep horizons, which had low salinity and high concentration of TSM and DOM exceeding the natural norm. That water was evidently of anthropogenic origin.

Based on the analysis of a series of hydrochemical surveys, numerical modeling methods and satellite hydrophysics [3–9], the main source of pollution of the considered water area has been established – wastewater collector of the *Yuzhnye* treatment facilities. The traces of the spread of wastewater from this source can be clearly visible on satellite images (Fig. 4).

Conclusion

Based on the data of the expedition conducted in the area of the Herakleian Peninsula in August 2019, the structure of the fields of temperature, salinity, TSM content and coloured dissolved organic matter (DOM) was analysed.

Two areas of the region under study are conventionally marked, namely: the water area located along the north-west (area *1*) coast and the water area near the south-west (area *2*) coast of the Herakleian Peninsula, where the fields of the analysed values were formed under the influence of various factors having their own properties.



F i g . 4 . Traces of the spread of wastewater from the collector of the *Yuzhnye* treatment facilities in the satellite image of the water area near the Heraclean Peninsula (*Google Earth* image)

In area *1* with the coastline oriented at an acute angle to the wind arrow, advective processes prevailed, and the structure of the fields of oceanological elements contained no anthropogenic features. In area *2*, the coastline of which is located along the normal to the wind arrow, the surge effect and the rise of water from deep horizons to the sea surface were noted. In the water column, lenses with low salinity, increased content of TSM and DOM were found, higher than the natural norm.

It is shown that the main source of pollution of the water area under consideration is associated with the wastewater collector of the *Yuzhnye* treatment facilities.

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All the authors have read and approved the final manuscript.

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Redox Conditions and Characteristics of Bottom Sediments in the Bays of the Sevastopol Region

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Abstract

The paper aims at assessing redox conditions in the bottom sediments of Kamyshovaya Bay in comparison with those in other bays of the Sevastopol region, and at studying the geochemical characteristics of bottom sediments and the chemical composition of pore waters. The data obtained during expedition research onboard the R/V *Victoria* in July 2021 were analyzed. Using the polarographic method of analysis with the use of a glass Au-Hg microelectrode, experimental data were obtained on the vertical distribution of oxygen, hydrogen sulfide, oxidized and reduced forms of iron in the pore waters of Kamyshovaya Bay in summer. Geochemical characteristics of bottom sediments were determined, such as particle size distribution and organic carbon content. The peculiarities of their spatial and vertical distribution were considered. The particle size distribution of sediments in the bay varies. In the upper part of the bay, sediments are represented by shell gravel and sand, and in the central and southern parts, aleurite and pelite silts prevail. The content of organic carbon in the surface layer of Kamyshovaya Bay bottom sediments ranges from 0.3 to 2.2 % dry mass, with an average value of 1.2 % dry mass, which is lower than in other bays of the Sevastopol region. It was found that the main characteristics of pore waters were determined by processes involving dissolved forms of iron (Fe (II, III), FeS) and hydrogen sulfide. In the upper layer of sediments, suboxic conditions were noted, which indicates the development of oxygen deficiency and formation of ecological risk zones for the bay ecosystem.

Keywords: bottom sediments, pore waters, oxygen, polarographic analysis, particle size distribution, organic carbon, Black Sea, Kamyshovaya Bay

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Окислительно-восстановительные условия и характеристики донных отложений бухт Севастопольского региона

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Аннотация
Цель работы – оценить окислительно-восстановительные условия в донных отложениях Камышовой бухты в сравнении с другими бухтами Севастопольского региона, изучить геохимические характеристики донных отложений и химического состава поровых вод. Проанализированы данные, полученные в ходе экспедиционных исследований на НИС «Виктория» в июле 2021 г. С помощью полярографического метода анализа с использованием стеклянного Au-Hg-микроэлектрода получены натурные данные вертикального распределения кислорода, сероводорода, окисленных и восстановленных форм железа в поровых водах Камышовой бухты в летний сезон. Определены геохимические характеристики донных отложений: гранулометрический состав, содержание органического углерода. Рассмотрены особенности их пространственного и вертикального распределения. Гранулометрический состав осадков в бухте разнообразен. В верховье бухты отложения представлены ракушечным гравием и песком, а в центральной и южной частях преобладают алевритовые и пелитовые илы. Содержание органического углерода в поверхностном слое донных отложений Камышовой бухты изменяется от 0.3 до 2.2 % сухой массы при среднем значении 1.2 % сухой массы, что ниже, чем в других бухтах Севастопольского региона. Установлено, что основные характеристики поровых вод определялись процессами с участием растворенных форм железа (Fe (II, III), FeS) и сероводорода. В верхнем слое отложений отмечены субкислородные условия, что указывает на развитие дефицита кислорода и формирование зон экологического риска экосистемы бухты.

Ключевые слова: донные отложения, поровые воды, кислород, полярография, гранулометрический состав, органический углерод, Черное море, Камышовая бухта.

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Introduction

Bottom sediments are a thermodynamically non-equilibrium system with a certain energy reserve, generally determined by the content of the organic matter (OM) and the processes of its transformation [1]. In the *water-bottom* interface, significant gradients of substance concentration are observed with the formation of the flows of substances, which depend on the conditions and characteristics of

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[1] Volkov, I.I., 1979. *Ocean Chemistry. Vol. 2: Geochemistry of Bottom Sediments.* Moscow: Nauka, 536 p. (in Russian).

both the bottom water layer and the bottom sediments themselves. To the greatest extent, this applies to oxygen and hydrogen sulfide, which are the determining substances in the study of the formation of environmental redox conditions, as well as the components that determine the possibility and conditions for the existence of benthic organisms [1]. It should be noted that hydrogen sulfide is a catalytic poison resulting in respiratory depression and death of benthic organisms [2].

It is known that dissolved oxygen from the surface layer of water enters the bottom layer of water and bottom sediments due to the processes of advection and diffusion. If the rate of its consumption in the oxidation process exceeds the rate of its intake, oxygen deficiency goes poorly. [3]. Nevertheless, the course and intensity of biogeochemical processes associated with the involvement of oxygen primarily depend on the geochemical characteristics of bottom sediments (organic carbon content and particle size distribution of sediments) [4]. The consumption of oxygen for the respiration of microorganisms, as well as its involvement in biogeochemical processes with OM and other reduced compounds, results in the predominance of the process of OM anaerobic oxidation.

Consequently, the reduced forms of nitrogen, metals, and sulfur appear in the upper layer of bottom sediments, and anoxia areas are formed [5]. Thus, the chemical composition of pore waters reflects the biogeochemical processes occurring in bottom sediments [6].

The increase in the number of coastal ecosystems, in the bottom sediments and near-bottom water layer of which oxygen deficiency is observed, is primarily associated with an increase in the OM flow due to anthropogenic activity [7].

Kamyshovaya Bay is a typical example of a marine coastal ecosystem subject to anthropogenic impact. On its shores, the Sevastopol Sea Fishing Port, an oil terminal, two permanent and one emergency sewage outlets, storm drains, a cement plant, a boiler station, and multi-storey buildings are located [8, 9]. The breakwater at the entrance to the bay hinders water exchange with the open part of the sea and contributes to the accumulation of pollutants, including organic carbon, in bottom sediments.

For many years, researchers of the Institute of Biology of the Southern Seas of the Russian Academy of Sciences (IBSS, Sevastopol) have been studying the ecosystem of Kamyshovaya Bay. In [9, 10], the main hydrological characteristics of waters and geochemical characteristics of sediments were studied, and the content of chloroform-extractable substances (CES) and hydrocarbons in the surface layer of bottom sediments of the bay was estimated. It was established that the natural humidity in the bottom sediments of Kamyshovaya Bay varied from 28 to 52 %, its value was close to that of Sevastopol Bay. Oxidized conditions (Eh from +276 mV) in the sands of the mouth of the bay gave way to reduced conditions (Eh up to −59 mV) in the silts of the central part, while pH varied from 7.3 to 8.3. Nevertheless, most of the surface layer of bottom sediments is characterized by oxidized conditions. Pollution of bottom sediments with CEV and oil products was observed in the central part of the bay, while the values of their concentrations here were substantially lower than in other bays of the Sevastopol region [9, 10].

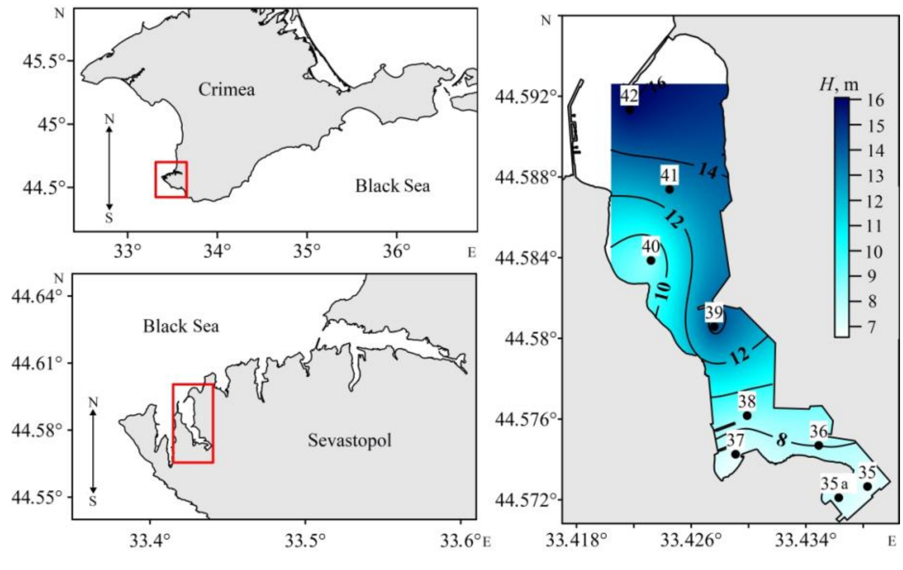
Since 2014, the cargo turnover of the fishing port of Kamyshovaya Bay has decreased, as well as the number of ships entering the port. By 2017, the cargo turnover dropped to 300 thousand tons from 2.5 million tons [10]. Nevertheless, the level of pollution of bottom sediments remains, although in some areas it has been slightly reduced [11]. At the same time, no studies on the features of the spatial and vertical distribution of organic carbon (C_{org}) in the bottom sediments of Kamyshovaya Bay, as well as the vertical distribution of oxygen, hydrogen sulfide and other key components of pore waters, have been previously conducted. Similar studies were carried out for such bays of the Sevastopol Region as Balaklava Bay [12], Sevastopol Bay [4, 13], Omega [13], and coastal regions of the Crimean shelf [14, 15].

This work aims at the assessment of the redox conditions in the bottom sediments of Kamyshovaya Bay and other bays of the Sevastopol Region, studies of the geochemical characteristics of bottom sediments and chemical composition of pore waters.

Materials and methods

Bottom sediment samples to study the physicochemical characteristics of sediments and chemical composition of pore waters were taken in July 2021. A total of nine samples of the surface layer of bottom sediments and two cores were taken (Fig. 1).

Sample taking and preparation of bottom sediments were carried out in accordance with regulatory documents (GOST 17.1.5.01-80; ISO 5667-19:2004). Samples of the upper layer of sediments (0–5 cm) were taken using a Petersen grab. Bottom sediment cores for studying the vertical structure of the sediment



F i g . 1 . Map of bottom sediment sampling stations were taken using Plexiglas tubes, hermetically sealed from above and below. This method of sampling made it possible to preserve the fine structure of the surface layer of bottom sediments and the bottom water layer.

To obtain the chemical profile of pore waters, the polarographic method of analysis was used with a glass Au–Hg microelectrode [4, 16, 17]. A silver chloride electrode saturated with silver chloride was used as a reference electrode, and a platinum electrode was used as an auxiliary one. Profiling of bottom sediment cores was carried out with a vertical resolution of 1 to 10 mm. The main advantage of the method is the ability to analyze the composition of the pore waters of bottom sediments under conditions as close to natural ones as possible, without disrupting the sample and additional sample preparation, with high sensitivity (in particular, O_2 – 5 μM, H_2S – 3 μM). The method error makes 10 %. Using this method, it is possible to study the dynamic processes occurring in the upper layer of sediments, where great varieties of reactions take place, including the mineralization of OM [4, 16, 17]. In the laboratory, to analyze the physicochemical characteristics, the cores were separated into layers 1–2 cm thick using a manual extruder and an acrylic ring.

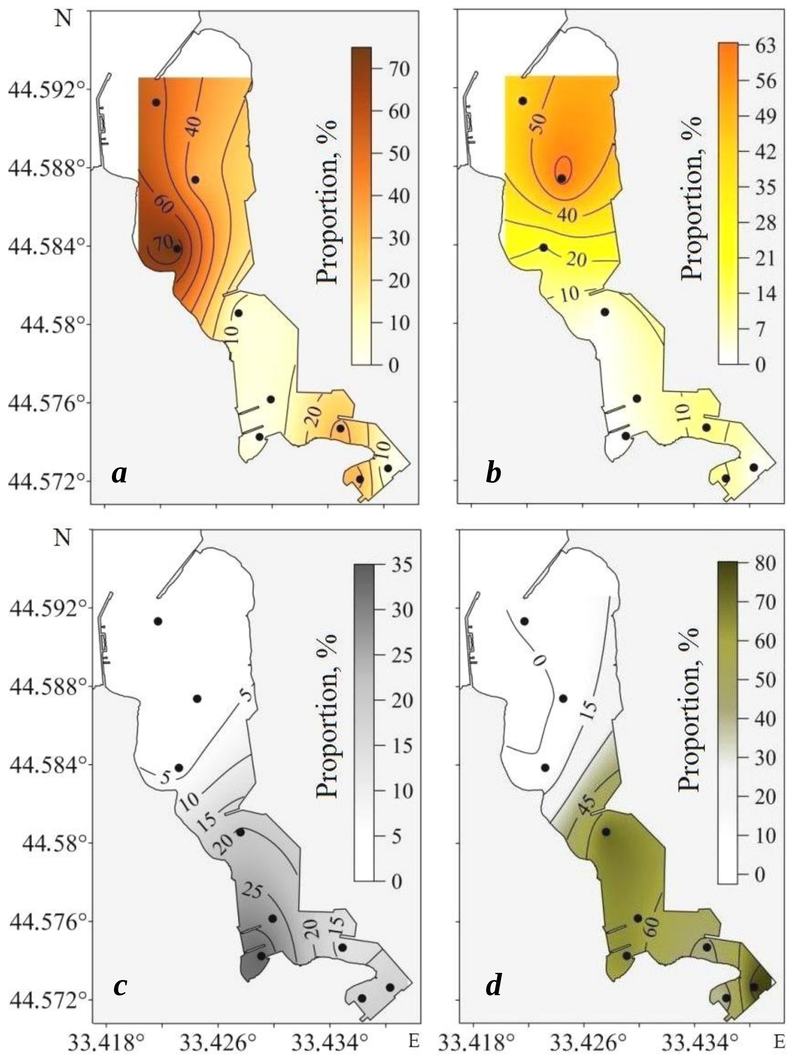
The particle size distribution of bottom sediments was determined by the mass content of particles of various sizes expressed as a percentage, in relation to the mass of the soil dry analysis. In this case, a combined method of decantation and dispersion was used. The aleurite and pelite fraction (≤ 0.05 mm) was separated by wet sieving followed by gravimetric determination of the dry mass. Coarse fractions (> 0.05 mm) were separated by dry screening using standard sieves (GOST 12536-2014).

The content of C_{org} was determined by the coulometric analysis using *AN-7529* express analyzer according to the method adapted for sea bottom sediments [18].

Results and discussion

The particle size distribution of sediments in the bay is diverse (Fig. 2, Table 1). It is established that the average size of sediment particles in Kamyshovaya Bay (1.5 mm) is higher than the average particle size in Sevastopol (0.23 mm), Kazachya (0.45 mm) [19], and Balaklava (0.46 mm) [20] Bays.

In the head of the bay (stations 40–42), sediments are represented by shell gravel and detritus, as well as sand (Fig. 2, *a*, *b*). In this part of the bay, the maximum concentration of coarse-dispersed gravel and pebble material (34–76 %) and the minimum concentration of fine-dispersed pelite-aleuritic silts (1–2 %) are observed. Toward the apex, the proportion of coarse-grained shell material decreases, while the proportion of fine-grained pelite silts increases. In the bay central part (stations 37–39), sediments consist mainly of aleuritic and pelitic silts (Fig. 2, *c*, *d*), and the proportion of the clay fraction in this area makes on average 94 %. Sediments in the southern part of the bay are characterized by the presence of shell detritus (up to 33%), as well as the maximum content of pelite material (81 %) in the apex station (station 35a).



F i g . 2 . Distribution of gravel (*a*), sand (*b*), aleurite and pelite (*c*), pelite and aleurite (*d*) fractions in bottom sediments

The increased proportion of finely dispersed material in the central part and especially in the southern shallow part of the bay is primarily determined by the peculiarities of the morphometry of the bay and a large number of moorings and piers acting as wave shadows resulting in the accumulation of material, as well as by the features of hydrodynamics and weak water exchange. Thus, all the rain and municipal wastewater material accumulates here.

This was reflected in the distribution of organic carbon in the surface layer of bottom sediments of Kamyshovaya Bay (Fig. 3, *a*; Table 1), which varied from 0.3–0.4 % dry wt. at the stations near the bay outlet up to 2–2.2 % dry wt.

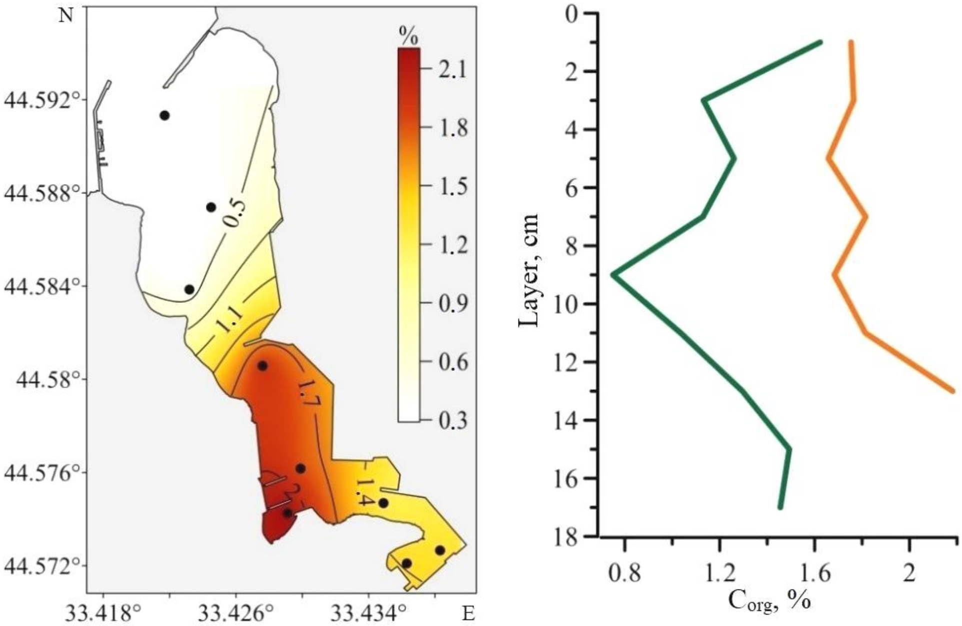
T a b l e 1 . Particle size distribution of bottom sediments and organic carbon content

Station number	Fractions, %				C_{org}, %
	Gravel (10–1 mm)	Sand (< 1–0.1 mm)	Aleurite-pelitic (< 0.1–0.05 mm)	Pelite-aleuritic (< 0.05–0.001 mm)	
42	53.4	44.2	1.3	1.1	0.3
41	33.8	63.6	1.2	1.4	0.3
40	75.8	19.3	3.1	1.8	0.4
39	5.1	2.3	20.7	71.9	1.9
38	5.0	5.1	27.0	63.0	1.3
37	0	1.1	33.7	65.2	2.2
36	33.0	12.1	12.9	42.0	1.2
35	32.8	11.0	17.0	39.2	1.8
35a	0	1.3	18.1	80.6	1.4

at the stations in the central bay with a gradual decrease in its apex. The average C_{org} content in the bottom sediments of Kamyshovaya Bay (1.2 % dry wt.) was lower compared to other bays of the Sevastopol Region: Omega (1.4 % dry wt.), Balaklava (1.97 % dry wt.) [20], Kazachya (2.7 % dry wt.) [21], Sevastopol (3.7 % dry wt.) and Streletskaya (4.3 % dry wt.) Bays [21]. This can indicate the absence of a permanent source of OM in the bay. The maximum values of the organic carbon content were observed in the places of accumulation of finely dispersed material (Fig. 2; 3, *a*). As for the samples of the sediments surface layer, a high positive correlation (0.91) between the concentrations of C_{org} and the content of pelite-aleuritic material was observed.

Except for the spatial variability of the content of organic carbon in the surface layer of bottom sediments, its vertical profile was also studied for stations 35a and 39 (Fig. 3, *b*, Table 2). It was established that for the central bay (station 39), the C_{org} value in the 0–10 cm layer remained practically unchanged (within 0.1 %), while in the 12–14 cm layer it increased, reaching the maximum – 2.2 % dry wt. This nature of the vertical C_{org} can indicate that the level of the man-caused impact on the bottom sediments of Kamyshovaya Bay has not changed in recent years.

For the apex of the southern part of the bay (station 35a), the C_{org} concentration in the 0–10 cm layer decreased from 1.6 % to 0.7 % dry wt., and then increased to 1.5 % dry wt. in the 16–18 cm layer. Elevated C_{org} concentrations in the upper layers of the apex point to the presence of OM sources in this area, probably of anthropogenic origin.



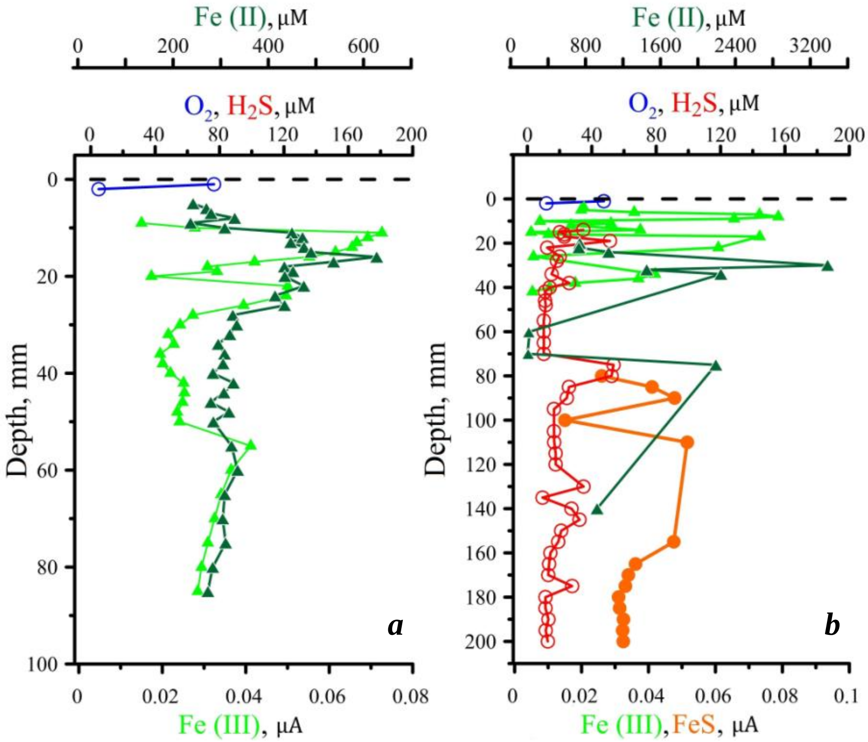
a ***b***

F i g . 3 . Peculiarities of spatial (*a*) and vertical (*b*) distribution of C_{org} in bottom sediments of the bay (green line – St. 35a, orange line – St. 39)

T a b l e 2 . Vertical distribution of organic carbon in bottom sediments

Station number	C_{org}, %, in sediment layer, cm								
	0–2	2–4	4–6	6–8	8–10	10–12	12–14	14–16	16–18
35	1.62	1.13	1.26	1.13	0.75	1.04	1.30	1.49	1.46
39	1.75	1.76	1.66	1.82	1.68	1.81	2.18	–	–

Analysis of the pore waters of bottom sediments showed the development of oxygen deficiency in the upper layer of sediments at station 39 (67 % sat., 163 μM). A similar situation is observed in Sevastopol (122 μM) [13] and Kazachya (126 μM) Bays. As a comparison, the oxygen concentration in the upper layer of sediments in the coastal areas of the Crimean Peninsula shelf varied on average from 200 to 300 μM [4, 15]. Oxygen at station 39 penetrated the sediment to a depth of 2 mm (Fig. 4, *a*). In general, the insignificant depth of oxygen penetration into the sediment can be explained by the finely dispersed nature of the sediments in Kamyshovaya Bay.



F i g . 4 . Vertical profiles of pore waters of Kamyshovaya Bay at Stations 39 (*a*) and 35a (*b*) in July 2021

The main component of pore waters was iron (Fig. 4, *a*). The concentration of Fe (II) increased with depth, reaching its maximum (628 μM) in the 16 mm layer, and then decreasing. The maximum content of Fe (III) was observed in the 11 mm layer, with the features of the vertical distribution similar to those of Fe (II). No hydrogen sulfide was recorded at this station. Thus, suboxygen conditions were observed in the surface layer of bottom sediments. The main biogeochemical processes proceeded with the participation of iron (Fe (II, III)).

In the bottom sediments surface layer in the apex part (station 35a), the oxygen content decreased to 48 μM (20 % sat.). The chemistry of pore waters was determined by processes including dissolved forms of iron (Fe (II, III)) and hydrogen sulfide (Fig. 4b). The pore water predominant component was hydrogen sulfide. In general, its distribution was uniform, with the maxima in the 19 and 75 mm layers (with the values of 51 and 53 μM, respectively). The peak of hydrogen sulfide in the upper part of the core can indicate a 'fresh' source of the organic matter. At the same time, the content of hydrogen sulfide in the pore waters of this area was lower compared to its content in other bays of the Sevastopol Region. Thus, in Balaklava Bay, the maximum concentrations of hydrogen sulfide reached 73 μM [12], in Omega – 213 μM, in Kazachya – 941 μM, in Yuzhnaya – 1,538 μM [13]. As a comparison, on the western coast of the Crimean Peninsula, the concentration of hydrogen sulfide in bottom sediments reached 276–435 μM [15]. At the same time, the pore waters of bottom sediments in the apex part of Kamyshovaya Bay were characterized by a high content of Fe (II) with a maximum concentration of 3,384 μM in the sediments upper layer (0–30 mm). The obtained values are significantly higher than in Balaklava (861 μM) and Kazachya (2,005 μM) Bays, and are close to the value obtained at the station in the Yalta Region (4,500 μM) [15], but lower than in Yuzhnaya Bay (8,292 μM). Based on the vertical profile of the pore waters components, it can be concluded that suboxygen conditions are still observed in the upper part of the sediment (0–10 mm), but anaerobic conditions predominate below.

Conclusions

New field data on the chemical composition of pore water (vertical distribution of oxygen, hydrogen sulfide, oxidized and reduced forms of iron) and geochemical characteristics of bottom sediments (particle size distribution, organic carbon content) for Kamyshovaya Bay are obtained and analyzed.

It is established that the chemistry of pore waters is determined by processes involving dissolved forms of iron (Fe (II, III)) and hydrogen sulfide. Suboxygen conditions are observed in the upper layer of sediments, which indicates the formation of zones of ecological risk in the ecosystem of the bay.

In the head of the bay, sediments are represented by shell gravel and sand, and in the central and southern parts by aleurite and pelite silts. The content of organic carbon in the surface layer of the bottom sediments of Kamyshovaya Bay varies from 0.3 to 2.2 % dry wt., which is lower than in other bays of the Sevastopol Region.

The analysis of the obtained results suggests the absence of significant permanent sources of OM. Nevertheless, despite the previously observed general decrease in the man-caused impact on the ecosystem of the bay in recent years, the content of OM increases. Apparently, the increase in the content of OM against the background of a decreasing man-caused impact is explained by the influence of such natural factors as the influx of terrigenous material with storm drains, the morphology of the apex of the bay, its weak water exchange with other parts of the water area and with the open sea.

The continuation of such trends can lead to a change of the currently observed suboxygen conditions in bottom sediments by anaerobic ones. The risk of suffocation phenomena will increase resulting in the appearance of lifeless spaces in the water area.

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Assessment of the Ability of Suspended Matter in the Sea of Azov to Concentrate Heavy Metals

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Abstract
With a large specific surface area, suspended matter can concentrate heavy metals to high levels. Falling down by gravity, suspended particles can deposit pollutants into the bottom sediments thus participating in the self-purification of sea water. The purpose of this work is to assess the ability of suspended matter in the Sea of Azov to concentrate Pb, Zn, Cu, Cd, and Hg. For the purpose of the study, two areas of the Sea of Azov were identified (Taganrog Bay and the central part of the sea) given their morphometric and hydrological features. Mass concentrations of Pb, Zn, Cu, Cd were determined by the electrothermal atomic absorption method; measurements of the mass concentration of Hg were carried out by the method of flameless atomic absorption spectrometry. The content of each metal in suspended matter was calculated in relation to that in water based on the accumulation factors. The obtained accumulation factors indicate a high ability of suspended matter to concentrate mercury, copper and zinc. The concentration of cadmium in the suspended matter was insignificant. This is because in surface waters cadmium migrates mainly in a dissolved state, with the suspended forms normally not exceeding 20–30 %. The content of lead in the suspended matter did not exceed 12.4 % in the central part of the sea and 15.8 % in Taganrog Bay, both of its total content. It is shown that when the values of the factors of heavy metal accumulation by suspended matter exceed 105, almost the entire volume of the studied heavy metals is in the suspended matter. These data indicate the high significance of the suspended matter concentrating ability for self-purification of water from heavy metals

Keywords: Sea of Azov, suspended matter, mercury, lead, cadmium, copper, zinc, accumulation factor

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Оценка способности взвесей Азовского моря концентрировать тяжелые металлы

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Аннотация
Обладая большой удельной поверхностью, взвешенное вещество может концентрировать тяжелые металлы до высоких уровней. Опускаясь в результате гравитации, взвешенные частицы могут депонировать загрязнения в толщу донных отложений, таким образом участвуя в самоочищении морской воды. Цель работы заключалась в оценке способности взвесей Азовского моря концентрировать Pb, Zn, Cu, Cd и Hg. Для исследования были выделены два района Азовского моря – Таганрогский залив и центральная часть моря, что связано с их морфометрическими и гидрологическими особенностями. Массовые концентрации Pb, Zn, Cu, Cd определялись электротермическим атомно-абсорбционным методом; измерения массовой концентрации Hg проводились методом беспламенной атомно-абсорбционной спектрометрии. Содержание каждого металла во взвеси по отношению к его содержанию в воде было рассчитано на основе коэффициентов накопления. Полученные коэффициенты накопления свидетельствуют о высокой способности взвесей концентрировать ртуть, медь и цинк. Концентрирование кадмия на взвесях было незначительным, это связано с тем, что в поверхностных водах кадмий мигрирует в основном в растворенном состоянии, взвешенные формы, как правило, не превышают 20–30 % от его валового содержания. Содержание свинца во взвешенном веществе не превышало 12.4 % в центральной части моря и 15.8 % в Таганрогском заливе от общего его содержания. Показано, что при значениях коэффициентов накопления тяжелых металлов , бо́ль 10^5, практически весь объем исследуемых тяжелых металлов находится на взвеси. Эти данные свидетельствуют о высокой значимости фактора концентрирующей способности взвесей в самоочищении вод от тяжелых металлов.

Ключевые слова: Азовское море, взвешенное вещество, ртуть, свинец, кадмий, медь, цинк, коэффициент накопления

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Introduction

A characteristic feature of the biospheric cycles of mass exchange is their discontinuity, which manifests itself in the imbalance of masses at the so-called input and output of the cycle. The removal of an excess part of the migrating masses from the migration cycle with their accumulation in any component of the natural environment (in sediments, soil, a large body of water, etc.) or with their redeployment to another migration flow maintains the steady state of open non-equilibrium natural systems and the direction of their development [1)].

When studying the biogeochemical features of the behavior of heavy metals in marine ecosystems, two approaches are employed. The first one is based on the determination of the concentration of metals in various components of ecosystems. The second one involves the assessment of metal flows caused by the physical movement of matter and biogeochemical processes that change this matter. In real practice, these are interrelated characteristics, since the system concentration changes only when the incoming flow is not equal to the outgoing one. Any change in the concentration of the metal results in the occurrence of a corresponding flow. It should be noted that the converse is not always true, i.e., it is quite common when very intense flows of metals in the system are not accompanied by a change in concentration. This occurs when the incoming flow is equal to the outgoing one. Ideally, to study the behavior of metals in marine ecosystems, it is necessary to create and use models that combine concentration and flow characteristics [2)].

Unlike most organic pollutants subject to gradual destruction, heavy metals are just redistributed among various components of ecosystems. The main biogeochemical mechanism of self-purification of sea water from heavy metals is its sedimentation by suspended matter [1, 2]. With a large specific surface area, suspended matter can concentrate heavy metals to high levels. Moving downwards due to gravity, suspended particles can deposit pollutants into the bottom sediments, thus participating in the self-purification of sea water [1)].

Dissolved forms of metals entering the coastal area with river runoff, slope wash or aerially, are assimilated by phytoplankton and sorbed on various suspended particles. During the destruction of plankton, some elements go back into solution. The metals remaining in the solid either settle down or pass through the food chain into zooplankton. The metals absorbed by zooplankton also partially go back into solution and partially settle down as a part of organomineral aggregates. At the very bottom and in the upper layer of bottom sediments, a complex of biogeochemical processes takes place with both the mobilization of some metals into pore and bottom water and the reverse binding of metals into sulfides and hydroxides formed. The transformation and destruction of organic matter represent the engine of growth for the transformation of metals at the bottom and in sediments.

[1)] Dobrovolsky, V.V., 1999. Range of Masses of Dispersed Chemical Elements Migrating in the Soil-Vegetation System in Zonal Phytocenoses of the World Land. In: GEOKHI RAS, 1999. *Proceedings of the Second Russian School Geochemical Ecology and Biogeochemical Zoning of the Biosphere, Moscow, 25-28 January 1999*. Moscow: GEOKHI RAS, pp. 32–33 (in Russian). Polikarpov, G.G. and Egorov, V.N., 1986. [*Marine Dynamic Radiochemoecology*]. Moscow: Energoatomizdat, 176 p. (in Russian).

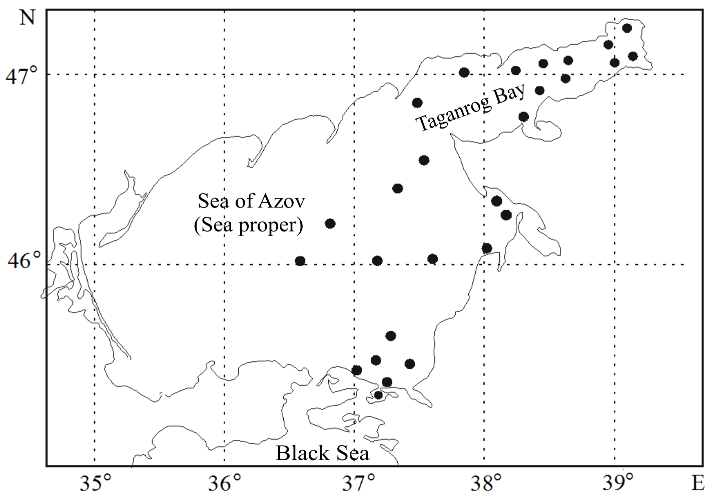
[2)] Shul'kin, V.M., 2007. [*Heavy Metals in River and Coastal Marine Ecosystems. Dissertation of the Doctor of Geographical Sciences*]. Vladivostok: Pacific Institute of Geography DO RAS, 289 p. (in Russian).

As judged by rather low content of most dissolved metals in sea and, moreover, in ocean water compared to river water, the general trend in the behavior of most heavy metals represents their removal and binding as a part of the settling material and further in bottom sediments. Metals, initially entering the sea with terrigenous suspended solid material, mainly continue their migration as its part, although at high concentration of mobile forms of metals in terrigenous suspended solid material, their desorption into water is possible with increased salinity in estuaries [3].

A great number of works have been devoted to the study of the content of heavy metals in water and bottom sediments of the Sea of Azov in different years [2, 4–8]. The results of the study by A.V. Mikhailenko (2018) on establishing patterns of spatial distribution of heavy metal concentrations in water and in the suspended matter of the Sea of Azov, are advantageous [5]. Since suspended matter can concentrate heavy metals to high levels due to its large specific surface, the assessment of the accumulation of Pb, Zn, Cu, Cd and Hg in suspended solid material is considered to be a relevant study. The aim of this study is to assess the ability of suspended solid material to concentrate mercury, copper, cadmium, zinc and lead in the spring-and-summer and autumn-and-winter periods in the central part of the Sea of Azov and in Taganrog Bay. It continues the series of studies established by [9].

Materials and methods

The work used data on the concentration of Pb, Zn, Cu, Cd, Hg in the water and in the suspended matter of the Sea of Azov in 2015, provided by *Azovmorinformtsentr* Federal State Budgetary Institution in cooperation with the Department of Ecology and Nature Management of MGRI. For analysis, water samples were taken using *PE-1220* sampling system according to GOST R 51592-2000 in the surface (0–5 m) layer at 27 points (Fig.) in spring (March and April), summer (June and July), autumn (September and October) and winter (December). Unfiltered samples (total form) were used to determine metals.



Sampling points

Chemical analysis of water samples concerning lead content was carried out in accordance with the method stipulated by Federal Environmental Regulatory Documents PND F 14.1:2:4.140-98, the limit of detection made 0.0002 mg/L; cadmium – PND F 14.1:2:4.140-98, the limit of detection – 0.00001 mg/L; copper – PND F 14.1:2:4.140-98, the limit of detection – 0.0001 mg/L; zinc – M-MVI-539-03, the limit of detection – 0.001 mg/L; mercury – PND F 14.1:2:4.260-2010, the limit of detection – 0.01 mg/L. The concentrations of the above stated heavy metals were measured using *KVANT-Z-ETA* atomic absorption spectrometer.

In the work, two areas were identified in the Sea of Azov – Taganrog Bay and the open water area of the Sea of Azov (the sea proper), which was associated with their morphometric and hydrological features.

Table 1 shows the threshold limit values of the heavy metals under consideration in the sea water.

Literature data [5] were also used to determine the concentration of heavy metals in the suspended matter of the Sea of Azov.

The accumulation factors of heavy metals by suspended matter (K_{sm}) were calculated using the following equation

$$K_{sm} = \frac{1000 \cdot C_{sm}}{C_w},$$

where C_{sm} – concentration of heavy metal in suspended matter, μg/g, based on dry weight; C_w – concentration of heavy metal in water, μg/L [1].

The accumulation factors were calculated based on the results of observations with an accuracy of three significant figures, which corresponded to an error with the value not more than 0.1 %.

The content of heavy metal in suspended solid material (P_{ssm}) in relation to its content in the marine environment was calculated by the following formula [1]

$$P_{ssm} = \frac{m_{sp} \cdot K_{sm} \cdot 100}{m_{sp} \cdot K_{sm} + 1} \ (\%), \quad (1)$$

where m_{sp} – specific mass of suspended solid material in water, g/m^3.

T a b l e 1 . Threshold limit values of heavy metals in water (TLV$_w$)[3)]

Parameter	Metal				
	Pb	Zn	Cu	Cd	Hg
Class of hazard	3	3	3	2	1
TLV$_w$, μg/L	10.0	50.0	5.0	10.0	0.1

[3)] 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. URL: http://publication.pravo.gov.ru/Document/View/0001201701160006 (Accessed: 25.02.2022).

Results and discussion

Table 2 shows that in the observed period of time (2015), the concentrations of Hg, Pb, Zn and Cu in many samples exceeded the TLV. Attention is drawn to the average values of copper concentration in water, which exceeded the TLV in all seasons in the sea proper and in Taganrog Bay, as well as high concentrations of zinc in Taganrog Bay. High concentrations of copper were also observed in the suspended matter (Table 3).

Suspended matter is a complex polydisperse multicomponent system. The material composition of the suspended solid material in the Sea of Azov is characterized by considerable diversity. According to the genetic trait, mineral components of terrigenous and chemogenic origin, as well as organic residues at various stages of mineralization, are distinguished in the suspended material. As it is shown by Yu.P. Khrustalev (1981) studies, during the year the terrigenous component of suspended solid material prevails [4)]. The terrigenous type of suspended matter is characterized by the predominance of products of coastal abrasion and river runoff (more than 70 %) in its composition

T a b l e 2 . Content of heavy metals in water of the Sea of Azov in 2015 (total form), µg/L

Area	Hg	Cu	Cd	Zn	Pb
spring and summer					
Sea proper (15)	0.003–0.283 0.045	4.0–23.8 10.10	0.1–1.4 0.41	7.3–34.0 31.60	3.9–34.0 12.18
Taganrog Bay (12)	0.002–0.042 0.034	9.2–20.5 14.1	0.2–1.7 0.89	8.0–127.0 57.2	1.0–13.0 4.46
autumn and winter					
Sea proper (15)	0.004–0.460 0.069	27.0–27.3 8.7	0.2–1.7 0.82	7.1–74.1 35.1	5.4–11.0 7.9
Taganrog Bay (12)	0.008–0.130 0.061	1.6–27.7 8.8	0.01–6.6 1.44	9.7–120.0 34.2	3.4–17.0 7.45

Note: in brackets – number of samples; above the line – concentration range; under the line – average value.

[4)] Khrustalev, Yu.P., Ganicheva, L.Z. and Volkova, E.N., 1981. Geochemistry of Suspended Sediment of the Sea of Azov. In: Yu. P. Khrustalev, 1981. *Geographical Aspects of Hydrological and Hydrochemical Study of the Azov Basin*. Leningrad: GO USSR, pp. 76–87 (in Russian).

T a b l e 3 . Content of heavy metals in the suspended matter of the Sea of Azov in 2015, μg/L [5, p. 103]

Area	Hg	Cu	Cd	Zn	Pb
spring and summer					
Sea proper	0.001–0.234 0.043	1.0–19.0 9.6	0.03–0.09 0.035	3.6–50.7 29.2	2.94–3.10 1.1
Taganrog Bay	0.005–0.027 0.013	0.3–31.1 11.2	0.01–0.14 0.06	4.3–83.4 31.5	0.72 –1.58 1.32
autumn and winter					
Sea proper	0.001–0.09 0.020	0.3–31.1 7.5	0.02–0.6 0.14	3.1–80.1 31.6	0.21–2.77 0.98
Taganrog Bay	0.003–0.314 0.055	0.4–29.3 7.7	0.03– 0.7 0.05	3.3–79.4 27.0	0.27–1.48 1.18

Note: above the line – concentration range; under the line – average value.

and is represented mainly by pelitic fractions. The content of aleuritic particles increases (up to 50 %) in the delta-front areas of the rivers during the flood period and during intense waves in the coastal area [10, p. 52].

In the Sea of Azov, there is an area of constantly high content of suspended matter (Taganrog Bay) and an area of its lower concentrations (the sea proper). It should be noted that under conditions of wind activity, the content of suspended matter can increase by a factor of 2–6. In this case, such changes in concentration depend on the nature of the soil in the area of waves. Bottom sediments of muddy bottom are mobilized most intensively into the water layer [11].

In the vertical distribution of suspended particles, a clear increase in their number from the surface horizon of the water layer to the bottom one was established. According to the averaged data, the concentration of suspended solid material in the bottom layer makes 111.0–165.8 mg/L. The amount of suspended solid material in the bottom layer is determined by the level of sedimentation processes, the nature of the soil and its predisposition to the spreading of sediments. The maximum values of suspended solid material concentrations are noted in the bottom horizon above clayey silts (218–229 mg/L), and the minimum values are noted above sandy and shelly soils (83.5–87.4 mg/L)[5].

[5] Mirzoyan, Z.A., 1984. [*Suspended Sediment in the Sea of Azov and Its Role in Feeding Plankton and Benthic Animals. Dissertation of the Candidate of Biological Sciences*]. Rostov-on-Don : AzNIIRKH, 168 p. (in Russian).

Table 4. Factors of heavy metal accumulation by suspended matter (K_{sm}) and content of heavy metals in suspensions (P_{ssm}), %, in relation to their content in the aquatic environment

Area	Hg	Cu	Cd	Zn	Pb
spring and summer					
Sea proper	1.132 / 95.6	1.011 / 95.0	0.005 / 8.3	0.640 / 92.4	0.005 / 9.1
Taganrog Bay	0.016 / 38.2	0.099 / 79.4	0.002 / 6.7	0.031 / 55.1	0.011 / 29.6
autumn and winter					
Sea proper	0.021 / 29.0	0.329 / 86.2	0.011 / 17.1	0.475 / 90.0	0.007 / 12.4
Taganrog Bay	0.235 / 90.2	0.179 / 87.5	0.001 / 3.5	0.096 / 78.9	0.005 / 15.8

Note: above the line – $K_{sm} \cdot 10^6$; under the line – P_{ssm}

Table 4 shows the results of the calculation of the accumulation factor of heavy metals by suspended solid material and the content of heavy metal in suspensions in relation to its content in the marine environment.

The obtained accumulation coefficients indicate a high ability of suspensions to concentrate mercury, copper and zinc in the spring-and-summer and autumn-and-winter periods both in Taganrog Bay and in the sea proper. The calculated content of heavy metals in suspended solid material ranged from 29 to 95.6 % of their total content in the marine environment.

Similar results are presented in the studies by A.P. Stetsyuk and V.N. Egorov (2018), in which the dependencies of mercury concentration by suspended matter of the Crimean shelf of the Black Sea were determined. In [12, p. 3], the coefficients of the ability of suspensions to concentrate mercury were in the range of $0.023 \cdot 10^6$–$7.067 \cdot 10^6$, and the mercury content on suspensions reached 98 % of the total mercury content in the marine environment.

The content of cadmium in suspended solid material was insignificant and made 3.5–6.7 % for Taganrog Bay and 8.3–17.1 % for the sea proper. This may be resulted from the fact that cadmium migrates in surface water mainly in the dissolved state; suspended forms, as a rule, do not exceed 20–30 % [6)].

[6)] Perelman, A.I. and Kasimov, N.S., 2000. *Landscape Geochemistry*. Moscow: MGU, 565 p. (in Russian).

Lead is characterized by a low degree of solubility, which determines its entry into the river runoff of the Don and the Kuban mainly in suspended state. The accumulation factors of the lead by suspended solid material, and, consequently, its content in suspended solid material, were expected to be higher. Nevertheless, our results show that the lead content in suspended matter does not exceed 12.4 % in the sea proper and 15.8 % in Taganrog Bay of its total content in the marine environment. This situation can be explained by the fact that the value of the accumulation factor by suspended solid material depends on the concentration of heavy metal in water, as at low values of C_w, the accumulation factor increases, and with an increase in C_w, it decreases. The concentration of lead in the central part of the sea and in Taganrog Bay during the study period was high, often exceeding the TLV by 2–3 times. This fact can confirm the effect of saturation of suspended solid material with lead. Similar dependences were obtained in the study of the sorption capacity of the bottom sediments of the Sea of Azov concerning lead. The materials shown in the work of Academician G.G. Matishov (2017) demonstrated that the increased intensity of sedimentary self-purification of water at low concentration of lead in water was provided by high (at $K_l > n \cdot 10^4$ units) concentrating ability of bottom sediments. With an increase in the degree of water pollution with lead to MPC (10 μg/L), the K_l value decreased by more than two orders of value and, accordingly, the contribution of sedimentation processes to water self-purification decreased [2].

In general, the results presented in this work show that the accumulation factor can be interpreted as an important indicator of the intensity of biogeochemical cycles of marine environment pollutants.

Conclusions

The obtained accumulation factors indicate a high ability of suspensions to concentrate mercury, copper and zinc in the spring-and-summer and autumn-and-winter periods both in Taganrog Bay and in the sea proper. The conducted studies show that with the values of the accumulation factors $K_{sm} > 10^5$, almost all the content of the studied heavy metals is located in suspended solid material. These data confirm the high importance of the factor of the concentrating ability of suspensions in the self-purification of water from heavy metals.

The content of cadmium in suspended solid material was insignificant, up to 6.7 % in the Taganrog Bay and up to 17.1 % in the sea proper, which can be explained by the weak complexing ability of cadmium compared to other metals.

High concentrations of lead in the water of the Sea of Azov can determine the low accumulation factors of this metal in suspended solid material. This can confirm the fact of saturation of suspended solid material with lead. Thus, the significance of the concentrating ability of suspended solid material depends on the concentration of heavy metals in water. At low values, it prevails over other biogeochemical mechanisms of water self-purification and decreases with increasing concentration.

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New and Rare Fish Species off the Northern Shore of the Black Sea and Anthropogenic Factors Affecting their Penetration and Naturalization (Review)

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Abstract

Currently, according to various sources, the ichthyofauna of the Black Sea includes up to 260 species and subspecies of fish. From 1999 to 2014, twenty-five new representatives of ichthyofauna were discovered in the Black Sea, which is about 10 % of the total number. Over the last twenty years alone, the number of benthic organisms that are the main food of bottom and near-bottom fish has increased by 29 species, which is almost half of all benthic animals newly discovered over a hundred years of observations. A whole range of various factors is responsible for the penetration of Mediterranean species with subsequent naturalization in the Black Sea. These include not only a dramatic change in climate, but also a change in the natural coast landscape associated with economic activities. Goods exchange between countries has been increasing lately, most of the goods are transported by sea, which in turn intensifies shipping, and this increases the risk of invaders with ship ballast water. Meanwhile, due to economic activities in the coastal zone, new habitat conditions and other ecological systems are forming attracting representatives of alien species. The paper analyzes the literature data on new and rare species of ichthyofauna in the Black Sea over the past 20 years. At the moment, according to generalized data, there are 30 new and rare species and subspecies of fish at the northern shores of the Black Sea alone. Since 2014, *Seriola dumerili, Lithognathus mormyrus, Dentex dentex, Gobius couchi, Lagocephalus sceleratus, Acanthurus monroviae* have been found in different parts of the northern part of the sea. The paper also considers possible consequences of construction of the *Istanbul* shipping canal (a back-up route for the Bosphorus Strait), which is planned to link the Marmara and Black Seas. After the implementation of this project, the risk of invasion of new alien species into the Azov-Black Sea basin will increase.

Keywords: Black Sea, anthropogenic factor, new species, ichthyofauna, invasive species

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Новые и редкие виды рыб у северного побережья Черного моря и антропогенные факторы, влияющие на их проникновение и натурализацию (обзор)

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Аннотация
В настоящее время ихтиофауна Черного моря насчитывает, по разным источникам, около 260 видов и подвидов рыб. В акватории Черного моря за период 1999–2014 гг. было обнаружено 25 новых представителей ихтиофауны, это примерно 10 % от общего числа. При этом только за последние двадцать лет число бентосных организмов, являющихся основным кормом донных и придонных рыб, увеличилось на 29 видов, что составляет почти половину от всех новых обнаруженных бентосных животных за сто лет наблюдений. Проникновению средиземноморских видов с последующей натурализацией в Черном море способствует целый комплекс различных факторов: это не только резкое изменение климата, но и изменение природного ландшафта побережья, связанное с хозяйственной деятельностью человека. В последнее время возрастает товарообмен между странами, основная часть товаров доставляется при помощи морского транспорта, что в свою очередь повышает интенсивность судоходства и увеличивает риск проникновения вселенцев с балластными водами судов. В то же время из-за хозяйственной деятельности в прибрежной зоне формируются новые условия обитания, иные экологические системы, привлекающие представителей чужеродных видов. В настоящей работе проанализированы литературные данные о новых и редких видах ихтиофауны в Черном море за последние 20 лет. На данный момент только у северных берегов Черного моря по обобщенным данным насчитывается 30 новых и редких видов и подвидов рыб. С 2014 г. в разных районах северной части моря обнаружены *Seriola dumerili*, *Lithognathus mormyrus*, *Dentex dentex*, *Gobius couchi*, *Lagocephalus sceleratus*, *Acanthurus monroviae* и др. Рассмотрены возможные последствия строительства судоходного канала «Стамбул» (дублера пролива Босфор), который, как планируется, свяжет Мраморное и Черное моря. После реализации этого проекта возрастет опасность проникновения новых чужеродных видов в Азово-Черноморский бассейн.

Ключевые слова: Черное море, антропогенный фактор, новые виды, ихтиофауна, инвазивные виды

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Introduction

When describing new invasive species and analyzing the reasons for the appearance of a particular species in a biocenosis, researchers, as a rule, refer to the climatic changes of recent years caused by an increase in water and atmosphere temperatures, a decrease in river floods, etc. Undoubtedly, these factors significantly affect biodiversity of the seas. However, anthropogenic factors have the most significant impact on the change of biota.

Not only drastic climate change contributes to the penetration of Mediterranean species into the Black Sea – the migration process with the subsequent naturalization of new species is also facilitated by the change in the natural landscape of the shore caused by human economic activity. In addition, organisms invading with ship ballast water do not die in a new environment. What is more, they create stable, reproductive populations forming new habitat conditions, other ecological systems that attract representatives of alien species.

A good example of the interrelation between the anthropogenic factor and the emergence of new species in places of active anthropogenic activity is the situation that existed from 1997 to 2007 in the coastal zone along the northeastern shore of Turkey. There, during that period, global changes in the landscape structure of the bottom occurred due to the construction of a highway, breakwaters, fishing ports, harbors, etc. along the shore.

Thus, for the first time, a new geological environment emerged along the southeastern coast of the Black Sea representing a large protected area with sandy bottom, which, according to various sources, covers 400–500 km of coastline and up to 10 m of depth [1, 2]. As a comparison, the length of the Black Sea coast of the Krasnodar Krai from the Kerch Strait to Adler, taking into account the indented coastline, also makes about 400 km. All over the Black Sea, this is rather large area.

A large number of marine invertebrates, such as bivalve mollusks, copepods, and small polychaetes, inhabit the newly formed conditions. The latter are the most attractive food source for both local fish species and invasive fish. Thus, striped seabream *Lithognathus mormyrus* (Linnaeus, 1758) can set the pattern.

Having penetrated from the Mediterranean Sea in the late 1990s – early 2000s, it found favorable habitats off the Black Sea shore of Turkey [1]. Probably, it was from there that it started spreading along the coastline to the north of the Black Sea, where it formed a stable reproductive population [3–6].

Many changes have taken place in recent years along the Russian shore of the Black Sea, including the construction of the Kerch over bridge, sand extraction at Cape Fiolent and the Bakalskaya Spit in the Crimea, etc. As a rule, any changes in the landscape result in the appearance of new invasive species. The main groups among alien species are represented by polychaetes, crustaceans, mollusks, i.e. the groups of benthic animals that predominate in the fauna of the Black Sea. It is known that over a century of research in the Black Sea basin, 61 alien species of benthos representatives were recorded. Over the last twenty years alone, their number has increased by 29 species, which is almost half (48 %) of all benthic animals newly discovered over a hundred years of observations [7].

Moreover, according to literature sources, by 2014, 25 new species and subspecies of fish had been discovered in the Black Sea, which made approximately 10 % of all known species of the local ichthyofauna [8]. At the same time, the maximum number of species found was registered in the family of Gobies (Gobiidae) and Seabreams (Sparidae) [5]. It should be noted that representatives of these species prefer the coastal zone, where such an anthropogenic factor as bottom structure change conditioned upon economic activities, mainly prevails.

The aim of our study is to analyze data on the emergence of new fish species in the northern part of the Black Sea over the past twenty years of observations and to identify the interconnection between anthropogenic factors and causes of the immigration and adaptation of new invaders in the Black Sea basin.

Results and discussion

Currently, according to various sources, the Black Sea ichthyofauna numbers from 184 [1)] to 263 [2)] species and subspecies of fish including incidental ones known from single finds [9].

The Black Sea ecosystem at this stage is still far from its stable state and therefore is very sensitive to external influences. Poor species diversity of the representatives of the ichthyofauna determines the low resistance to the penetration of alien species.

The development of the Black Sea by the Mediterranean fauna is a rather young process, which is a consequence of its relatively recent unification with the Mediterranean Sea from the point of view of the geology. A sustainable community of species has not yet developed in this basin. The ichthyofauna here has been constantly formed, including the present time.

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1) Vasil'eva, E.D., 2007. *Fish of the Black Sea. Key to Marine, Brackish-Water, Euryhaline, and Anadromous Species with Color Illustrations Collected by S.V. Bogorodsky.* Moscow: VNIRO Publ., 238 p. (in Russian).

2) Boltachev, A.R. and Karpova, E.P., 2017. *Marine Fishes of the Crimean Peninsula.* Simferopol: Biznes-Inform, 376 p. (in Russian).

A significant part of modern representatives of the Black Sea fish species are Mediterranean invaders entering the Black Sea through the Bosphorus Strait. Only a small number of inhabitants of the ichthyofauna are purely local, Ponto-Caspian fish species.

Goods exchange between different countries has been increasing with the industrial development of such countries. One of the cost-effective ways of delivering goods is water transport. This, in turn, increases the risk of invaders both with ballast water and on foul ship bottoms.

The number of biota species of the Azov-Black Sea basin is growing continuously. The instability of the Black Sea ecosystem makes it extremely important to observe the processes occurring in the populations of marine fauna. In particular, it is necessary to control the emergence of invasive species, as well as to analyze the dynamics of their numbers.

In either case, any human economic activity in the coastal zone affects the biodiversity not only of a certain section of the coastline where changes have occurred, but of the entire Azov-Black Sea basin.

When analyzing the collected data, we were mainly interested in the cases of finds of new ichthyofauna species in the northern part of the Black Sea, namely, off the Caucasian and Crimean shores, as these are the most accessible areas for further research. However, to get the whole picture, the cases of finds in the northwestern part of the sea are also included in the Table. The species composition of new and rare fish species described in the literature over the past twenty years is given in the Table.

Some fish species were found earlier in the northern part of the Black Sea (more than twenty years ago). For example, this is gilthead seabream, or gilthead bream, *Sparus aurata* (Linnaeus, 1758), which was recorded off the Caucasian shore in 1937 [18, p. 278]. Round sardinella, or black sprat, *Sardinella aurita* (Valenciennes, 1847) was recorded off the Crimean shore in 1981 and in 1988 [12]. It is interesting to note that the number of finds of these species increased after 1999. Thinlip grey mullet *Liza ramada* (Risso, 1810) was registered off the Crimean shore in 1930, then it was not found for many years, and only in the autumn period of 2006 and 2012 it was observed by spearfishers near Balaklava Bay [8, 14]. European barracuda *Sphyraena sphyraena* (Linnaeus, 1758) was found in 2007 near Streletskaya Bay (Crimea) [14]. Previously, it was recorded near Odessa, in Balaklava Bay in 1905 and near Sevastopol in 1950 [14, 18].

As described earlier, Gobies (Gobiidae) remain the most widespread in the Black Sea in terms of the number of new species (see Figure). It is difficult to estimate the percentage of species biomass at this stage.

It follows from the Table that the majority (~ 80 %) of alien fish species found in the northern part of the Black Sea during the study period inhabits bottom and near-bottom areas. Schooling pelagic species make seasonal migrations and normally appear in the Black Sea periodically.

New and rare fish species registered off the northern shore of the Black Sea since 1998

English name	Latin name	Year of detection		Groups	Feeds	Source
		Crimea	Caucasus			
I. Herrings (Clupeidae)						
1. Round sardinella	*Sardinella aurita* Valenciennes, 1847	1981 1998	NA	*P.*	–	[8–12], work [3)]
II. Cods (Gadidae)						
2. Blue whiting	*Micromesistius poutassou* (Risso, 1827)	1999	NA	*P.*–*Nb.*	–	[8, 10, 13], work [2)]
III. Mullets (Mugildae)						
3. Thicklip grey mullet	*Chelon labrosus* (Risso, 1827)	1999	?	*P.*	+	[9, 10], works [1–3)]
4. Thinlip grey mullet	*Liza ramada* (Risso, 1810)	1930 2006	?	*P.*	+	[8, 10, 14], works [1, 3)]
IV. Pipefishes (Syngnathidae)						
5. Greater pipefish	*Syngnathus acus* (Linnaeus, 1758)	2006	NA	*Nb.*	+	[8, 14], work [2)]
V. Carangids (Carangidae)						
6. Greater amberjack	*Seriola dumerili* (Risso 1810)	–	2018	*P.*	–	[15], work [1)]
VI. Flying Gurnards (Dactylopteridae)						
7. Flying gurnard	*Dactylopterus volitans* (Linnaeus, 1758)	2013	NA	*Nb.*	+	[8], works [1, 2)]

[3)] Movchan, Yu.V., 2011. *Fish of Ukraine*. Kyiv: Zoloty Vorota, 444 p. (in Ukrainian).

Continued

English name	Latin name	Year of detection		Groups	Feeds	Source
		Crimea	Caucasus			
VII. Scorpionfishes (Scorpaenidae)						
8. Korean rockfish	*Sebastes schlegelii* Hilgendorf, 1880	2013	2019	*Nb.*	–	[16]
VIII. Seabreams (Sparidae)						
9. Salema	*Sarpa salpa* (Linnaeus, 1758)	1999	2007	*Nb.*	+	[8, 10, 17], work [2)]
10. Gilthead bream / Gilthead seabream	*Sparus aurata* (Linnaeus, 1758)	1999	1937	*Nb.*	+	[8, 10, 18], work [2)]
11. White seabream	*Diplodus sargus* (Linnaeus, 1758)	2008	NA	*Nb.*	+	[19], works [1, 2)]
12. Striped seabream	*Lithognathus, mormyrus* (Linnaeus, 1758)	2013	2016	*Nb.*	+	[3–6, 9], work [1)]
13. Common dentex	*Dentex dentex* (Linnaeus, 1758)	2014	NA	*Nb.*	+	[9, 20], works [1, 2)]
IX. Butterflyfishes (Chaetodontidae)						
14. Pennant coralfish	*Heniochus acuminatus* (Linnaeus, 1758)	2003	NA	*P.–Nb.*	+	[8, 21], work [2)]
X. Blennies (Blenniidae)						
15. Incognito blenny	*Parablennius incognitus* (Bath, 1968)	2002	2001	*B.*	+	[8, 11, 14, 22], work [2)]
XI. Clingfishes (Gobiesocidae)						
16. Small-headed clingfish	*Apletodon dentatus bacescui* (Murgoci, 1940)	2013	NA	*B.*	+	[11, 23, 24], work [2)]

Continued

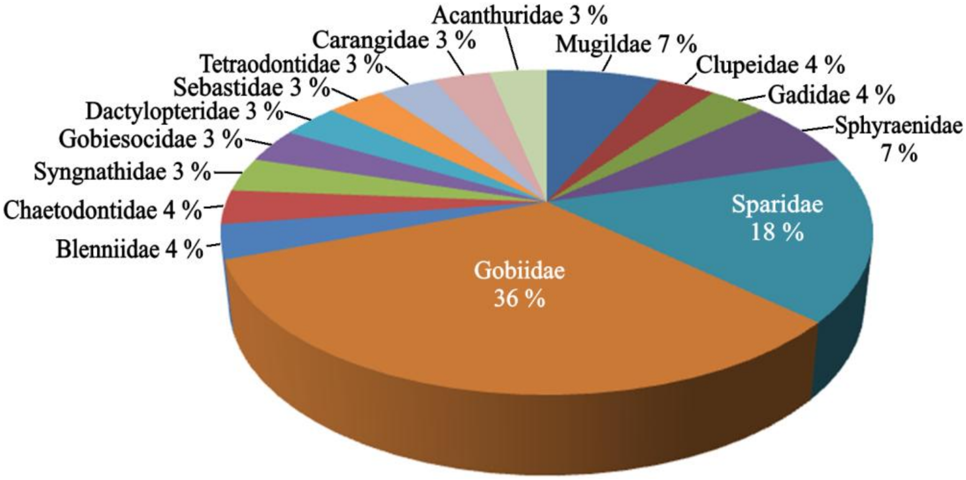
English name	Latin name	Year of detection		Groups	Feeds	Source
		Crimea	Caucasus			
XII. Gobies (Gobiidae)						
17. Red-mouthed goby	*Gobius cruentatus* Gmelin, 1789	2002	2004	*B.*	+	[8, 9, 14, 19, 25, 26], works [2, 3)]
18. Bath's goby	*Pomatoschistus bathi* Miller, 1982	2003	NA	*B.*	+	[8, 9, 26–28], works [2, 3)]
19. Chameleon goby	*Tridentiger trigonocephalus* (Gill, 1859)	2006	NA	*B.*	+	[8, 26, 29, 30], works [1, 2)]
20. Yellow-headed goby	*Gobius xanthocephalus* Heymer & Zander, 1992	2007	2003	*B.*	+	[8, 12, 14, 26, 27, 31], works [1–3)]
21. Large-headed goby	*Millerigobius macrocephalus* (Kolombatovic, 1891)	2009	NA	*B.*	+	[10, 26], works [2, 3)]
22. Steinitz's goby	*Gammogobius steinitzi* (Bath, 1971)	2011	NA	*B.*	+	[8, 26, 31, 32], works [2, 4)]
23. Chestnut goby	*Chromogobius quadrivittatus* (Steindachner, 1863)	2012	1939	*B.*	+	[8, 26, 33, 34], works [2, 4)]
24. Kolombatovic's goby	*Chromogobius zebratus* (Kolombatović, 1891)	2013	NA	*B.*	+	[8, 26, 31, 35], work [2)]
25. Zebra goby	*Zebrus zebrus* (Risso, 1827)	2013	NA	*B.*	+	[8, 26], work [2)]
26. Couch's goby	*Gobius couchi* Miller & El-Tawil, 1974	2016	NA	*B.*	+	[36], work [4)]

[4)] Parin, N.V. and Evseenko, S.A., 2014. *Fishes of Russian Seas: Annotated Catalogue.* Moscow: Tovarishchestvo nauchnykh izdaniy KMK, 217 p. Vol. 53 (in Russian).

English name	Latin name	Year of detection		Groups	Feeds	Source
		Crimea	Caucasus			
XIII. Sea pikes (*Sphyraenidae*)						
27. Red barracuda	*Sphyraena pinguis* Günther, 1874	1999	NA	*P.*	–	[8, 37], work [2)]
28. European barracuda	*Sphyraena sphyraena* (Linnaeus, 1758)	1950 2007	NA	*P.*	–	[14], works [1, 2)]
XIV. Blowfishes (*Tetraodontidae*)						
29. Silver-cheeked toadfish	*Lagocephalus sceleratus* (Gmelin, 1789)	2014	NA	*Nb.*	+	[38, 39], work [2)]
XV. Surgeonfishes (*Acanthuridae*)						
30. Monrovia doctorfish	*Acanthurus monroviae* Steindachner, 1876	2018	NA	*Nb.*	+	[40]

Note: *P.* – pelagic, *Nb.* – near bottom, *B.* – bottom, +/– presence/absence of benthic organisms in the diet; NA – no data available; ? – data are not specified.

Gobies (Gobiidae), Blennies (Blenniidae), Groupers (Serranidae), etc. belong to the so-called local fish species that do not migrate over long distances. Most of the representatives of these species spend the warm period of the year in the coastal zone of the sea, making minor feeding and spawning migrations, and in winter they go to the depths. Seabreams (Sparidae), or Stumpnoses, prefer mainly areas of the continental shelf, sometimes going beyond its edge. Obviously, some of these species gradually migrated from the Mediterranean, Aegean and Marmara seas, others penetrated with ship ballast water, were released by aquarists and then found favorable living conditions in the Black Sea waters.



The percentage of new fish families found in the northern part of the Black Sea since 1999

Probably, some species, such as pennant coralfish *Heniochus acuminatus* (Linnaeus, 1758), Monrovia doctorfish *Acanthurus monroviae* (Steindachner, 1876), red barracuda *Sphyraena pinguis* (Günther, 1874), accidentally migrated to the Black Sea, and in the present climatic environment they are unlikely to be able to find suitable conditions for survival.

We dare assume that, perhaps, in the near future, a new invader will appear in the waters of the Black Sea – Red Sea goatfish *Parupeneus forsskali* (Fourmanoir & Guézé, 1976). The assumption is based on the facts of the rapid spread of this species in the Mediterranean Sea. Until the 2000s, this species was common in the Red Sea and the Gulf of Aden. As a result of migration through the Suez Canal (the so-called Lessepsian migration), *P. forsskali* entered the Mediterranean Sea. In December 2012, the first record was described – *Parupeneus forsskali* (Fourmanoir & Guézé, 1976) in the eastern Mediterranean Sea north of Beirut (Lebanon) [41]. In 2013, the first record of *P. forsskali* off the shore of Israel was described [42]. Off the shore of Cyprus, the first record of this species took place in August 2014 [43]. Not far from the shore of Syria, the first find was recorded in 2016 [44]. Currently, this species has become massive off the southern shore of Turkey. According to the observations of Turkish fishermen, in the region of Kemer (Turkey) in 2021, the catches of Red Sea goatfish exceeded the catches of local Mullidae species. Currently, *P. forsskali* has been recorded off the shore of Bodrum (Turkey) in the Aegean Sea.

In 2014, A.R. Boltachev et al. described 25 new representatives of the ichthyofauna in the Black Sea, of which 21 species were found in the coastal zone of Crimea [8].

Thus, at the moment, according to the generalized data, there are 30 new and rare species and subspecies of fish belonging to 15 families near the northern shores of the Black Sea (see Table).

It is worth noting that in 2014 the striped seabream *L. mormyrus* (Linnaeus, 1758) was assigned to the group of sporadically occurring species [8]. Now it has naturalized and breeds in the northern part of the Black Sea [4, 5]. At the same time, toothed grouper *E. caninus* (Valenciennes, 1834), caught in April 2013 in the coastal zone of Crimea near Cape Aya, was included in the group of incidentally found species (single finds) [8]. Later it turned out that the species was Korean rockfish *Sebastes schlegelii* (Hilgendorf, 1880), the finds of which have become more frequent off not only the Crimean shore, but also the Caucasian one, "which with a high degree of probability indicates the successful immigration of the species" [16, p. 34].

Such species as curled picarel *Centracanthus cirrus* (Rafinesque, 1810), Mediterranean rainbow wrasse *Coris julis* (Linnaeus, 1758), slender sharksucker *Echeneis naucrates* (Linnaeus, 1758) and some others, previously noted off the coasts of Turkey, Bulgaria, and Romania are [1)] among the periodically occurring species in the Black Sea [8]. However, these fish have not yet been found off the northern shore of the Black Sea.

Conclusion

Thus, if we compare the data available from recent studies of the Black Sea biota, it becomes obvious that over the past twenty years, the number of alien species of zoobenthos, i.e. the main feeds of near-bottom and bottom fish, has increased by almost half, and over the same years, the number of new representatives of ichthyofauna has increased by about 10 %. Of course, the processes of immigration of zoobenthos and fish representatives can proceed in parallel, but, undoubtedly, they are interconnected. It is interesting to note that it was at that time or, more precisely, in the late 1990s – early 2000s, that significant changes took place in the coastal landscape of the southeastern shore of the Black Sea, which, apparently, created favourable conditions for the habitat and distribution for some new invasive species. Of course, all these migration processes also occur in connection with climate change. However, anthropogenic factors accelerate natural changes in the Black Sea biota. At the same time, it should be taken into account that some species may turn out to be invasive, and this will possibly affect native species in the future.

The main ways of penetration of alien species into the water area of the Azov-Black Sea basin can be carried out in two main ways. They are as follows:

a) introduction – intentional or accidental anthropogenic immigration of species into habitats that are unnatural for them. This method includes the penetration of organisms with ballast water, on the hulls of ships;

b) natural way – migration through the Bosphorus Strait.

Debates in the media are opened from time to time concerning environmentally dubious projects in the area of the Azov and Black Seas. This is stipulated by both economic and political considerations.

One of the above stated projects is the Turkish *Istanbul*. This is the construction of a canal, which, according to the plan, will run parallel to the Bosphorus, 20–30 km west and southwest of the city of Istanbul. The implementation of the project can further provide passage from the Marmara to the Black Sea for about 185 ships every single day. The construction started in 2021, and it is planned to be completed in 6–7 years. The declared length of the canal is about 45 km with its minimum width of 275 m and depth of 20–25 m [5)].

Once the shipping canal is put into operation, the risk of alien species immigration will increase significantly. In this case, both ways of immigration stated above will take place, which will affect the increase in the number of new invasive species in the Black Sea without a doubt.

Presumably, the implementation of these plans will significantly change the biocenoses of the Black and Azov Seas, which are currently already in an unstable state. Possible reduction in commercial fish stocks due to food competition with invasive species or the influence of other factors (new diseases, extermination of fish roe by other species) is of strategic importance for the state.

It is possible to predict which representatives of the ichthyofauna will penetrate into the Black Sea, but when they naturalize in this basin, it is difficult to predict the influence of invasive species on the entire biocenosis as a whole.

Before the implementation of such global projects as *Istanbul*, it is advisable to conduct detailed international environmental assessment with the participation of scientists from all countries of the Black Sea basin. In addition, it is necessary to develop a publicly accessible interactive map for continuous monitoring of both prospecting and ongoing construction works in the coastal zone of the sea. Such open data will help scientists predict environmental risks in the implementation of any construction projects. Such a geographic information system could combine disaggregated data of construction and environmental assessments and would also help in more accurate calculation of possible damage to aquatic biological resources.

The task of introducing new preventive measures and developing technical devices on ships to prevent the entry of alien species into ballast water remains urgent. International Maritime Organization (IMO) adopted Ballast Water Management Convention [6)], which has already been in force since September 8, 2017. However, these requirements are often not met. Employees of the SSC of RAS have repeatedly recorded cases of violation of discharge of both ballast and black water from transport ships. Thus, we recommend installing buoy stations or using existing beacons to monitor water quality in certain areas. This will make it possible to track, which ship was in the area with pollution increase. Strengthening of control over the implementation of the convention is the most important task.

[5)] Turkey started implementing the project of the Istanbul Canal bypassing the Bosphorus, June 26, 2021. Available at: https://tass.ru/ekonomika/11760907 (Accessed: 4 March 2022).

[6)] Available at: https://www.ballast-water-treatment.com/en/ballast-water-management-regulation/imo-bwm-convention (Accessed: 3 March 2022).

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Nikolay A. Zherdev – conclusion formulation

Daniil A. Bukhmin – review of literature sources on the research problem

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The Status of Plankton Algocenosis in the North-East Part of the Black Sea (2011–2020)

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Abstract
The paper presents the research results of taxonomic composition and quantitative development of phytoplankton in the Abkhazian sector of the Black Sea in spring-and-autumn periods 2011–2020. Water was sampled onboard the R/V *Deneb* of SSC RAS on several horizons in the upper layer of the sea, up to 50 m. One hundred and nine (109) species of phytoplankton of 10 classes were found, among them 18 potentially toxic and harmful and 2 new for the eastern coast of the Black Sea species of planktonic algae. The average values of abundance and biomass in the water area were 40.26 thousand cells/L (from 8.8 thousand cells/L in autumn to 90 thousand cells/L in spring) and 74 mg/m^3 (from 64 mg/m^3 in autumn to 78 mg/m^3 in summer). The highest values (79 thousand cells/L and 113 mg/m^3) were observed on the sea surface (0–2 m), which was 1.5–18 times higher than on other studied horizons (10–50 m). The maximum abundance of plankton cells (476 thousand cells/L) was observed in the upper sea horizon in May 2013. This was associated with intense development of primnesian algae (*Emiliania huxleyi*), which formed 95 % of the total abundance and 53 % of the biomass during that period. The basis of the phytoplankton abundance and biomass generally was formed by diatomic (30 % and 31 %, respectively) and dinophytic algae (30 % and 60 %, respectively). In spring and autumn, the role of cryptophytic algae increased (up to 20 % of the total abundance).

Keywords: phytoplankton, taxonomic composition, abundance, biomass, Abkhazian sector, Black Sea

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Состояние сообщества фитопланктона в северо-восточной части Черного моря (2011–2020 гг.)

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Аннотация
Представлены результаты исследования таксономического состава и количественного развития фитопланктона в районе Абхазии (Черное море) в весенне-осенний периоды 2011–2020 гг. Пробы воды отбирали с борта НИС «Денеб» ЮНЦ РАН на нескольких горизонтах, расположенных в верхнем слое моря, до 50 м. Обнаружено 109 видов фитопланктона из 10 классов, среди них 18 потенциально токсичных и вредоносных и два новых для восточного побережья Черного моря вида планктонных водорослей. Средние по акватории значения численности и биомассы составили 40.26 тыс. кл./л (от 8.8 тыс. кл./л осенью до 90 тыс. кл./л весной) и 74 мг/м^3 (от 64 мг/м^3 осенью до 78 мг/м^3 летом). Наиболее высокие значения (79 тыс. кл./л и 113 мг/м^3) отмечены в поверхностном слое моря (0–2 м), что в 1.5–18 раз выше, чем в других исследуемых слоях (10–50 м). Максимальное количество планктонных клеток (476 тыс. кл./л) наблюдали в верхнем слое моря в мае 2013 г., что было связано с интенсивным развитием примнезиевых водорослей (*Emiliania huxleyi*), которые в этот период формировали 95 % общей численности и 53 % биомассы. В целом основу численности и биомассы фитопланктона формировали диатомовые (30 и 31 % соответственно) и динофитовые водоросли (30 и 60 % соответственно). Весной и осенью повышалась роль криптофитовых водорослей (до 20 % общей численности).

Ключевые слова: фитопланктон, таксономический состав, численность, биомасса, район Абхазии, Черное море

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Marine scientific research in the waters of the Republic of Abkhazia was carried out until the mid-1980s and were completely stopped in 1991 in connection with the collapse of the USSR and the military conflict between Abkhazia and Georgia. In June 2010, in the territorial waters of the Republic of Abkhazia, the staff of SSC RAS resumed complex ecosystem studies and made a baseline assessment of the current ecological state of the Abkhazian waters. In the composition of phytoplankton, 91 taxa (rank below the genus) of microalgae from 8 divisions were identified. Dinophytic and diatomic algae were the most diversified ones in terms of species – 49 and 17 species, respectively. The largest abundance of species was found in such genera as *Chaetoceros, Protoperidinium, Prorocentrum, Gynmodinium, Dinophysis, Ceratium*. The main contribution to the formation of the abundance of phytoplankton was made by small-celled green and dinophytic algae [1, 2]. The maximum values of abundance and biomass were noted in the near-surface layer of the sea (663.7 thousand cells/L and 1.7 g/m^3). The biomass of phytoplankton was formed mainly due to the development of two groups of phytoplankton: dinophytic and diatomic algae, which is typical for the summer period of development of the Black Sea algocenosis [2]. In March 2011 and for the last part of May 2013, the bloom of coccolithophorids ($2 \cdot 10^6$ – $4.4 \cdot 10^6$ cells/L) was noted in the Abkhazian sector of the Black Sea [3, 4].

For the period from June to September in 2016–2017, 55 following taxa were found in the phytoplankton of the Sukhumi Bay: Bacillariophyta (21), Dinophyta (28), as well as Cyanophyta, Cryptophyta, Euglenophyta, Chrysophyta. The average values of phytoplankton abundance for the period of study made 234.0 ± 67.9 thousand cells/L, biomass – 471.0 ± 141.2 mg/m^3. The maximum abundance (582 thousand cells/L) was observed in July, the maximum biomass (658–1120 mg/m^3) – in August. In summer (June–July), the value of the coccolithophorid *Emiliania huxleyi* increased (80–96 % of the total phytoplankton abundance). Diatomic algae dominated in late summer – early autumn (82–94 % of the total phytoplankton abundance). The abundance of *Dactyliosolen fragilissimu, Pseudosolenia calcar-avis, Pseudonitzschia pseudodelicatissima, Talassiosira* sp., *Skeletonema costatum* was observed in August, and in September – that one of *Cylindrotheca closterium*. The proportion of dinoflagellates in the total phytoplankton biomass in June–July varied from 65 to 48 % (300–130 mg/m^3). *Prorocentrum micans, Scrippsiella trochoidea, Dinophysis rotundata,* the species of genera *Protoperidinium, Gyrodinium, Glenodinium, Gymnodinium* were in the mass. Among the dinophytic algae, such a rare for the Black Sea species as *Peridinium quinquecorne* was registered. During the study, 2–8 % of the total abundance of phytoplankton was formed by euglena algae (genera *Eutreptia, Euglena*) and cyanobacteriae (*Oscillatoria, Lyngbya*). The presence of these species indicates higher levels of nutrients, pollution and desalination of the marine area [5]. As a part of the phytoplankton of the estuarine sections of the rivers of the coast of Abkhazia, 84 taxa were identified with a rank below the genus, among them diatoms – 44, green – 17, euglena – 10, others – 13 [6].

Thus, the phytoplankton studies carried out earlier in the Abkhazian sector were episodic and did not reflect the features of seasonal changes in the abundance of planktonic algae over a long period. Therefore, the purpose of our work is to trace the main changes in the taxonomic structure, abundance and biomass of planktonic algocenoses in the main growing season (spring-autumn) in 2011–2020.

Characteristics of the study area

Hydrophysical conditions in the Abkhazian sector were studied in 2011–2013 [3, 4]. The analysis of long-term data obtained in the study area showed that the average monthly water temperature on the sea surface during the year varies from 8.7 ºC in February to 25.7 ºC in August. The annual range of average monthly salinity values in the coastal areas of the sea is not so large: the average values were recorded in June–July (16.63–16.68 ‰); the highest salinity values were observed from August to January (17.35–17.74 ‰); from February to May, the salinity values decreased (from 17.07 to 16.08 ‰) with an increase in the volume of territorial runoff.

Materials and methods

The studies were carried out in the open part of the Black Sea, in the Abkhazian sector, during the voyages of the R/V *Deneb* of SSC RAS in different seasons of 2011–2020. The study of the vertical structure of phytoplankton was carried out at the horizons of 0, 5, 10, 25, and 50 m or at 3–5 horizons: surface; ½ water layer up to the thermocline; at the beginning, directly in the layer and at the end of the thermocline. Totally, 247 samples were taken and processed. Phytoplankton samples were collected during daylight hours in 1–1.5 L bottles and fixed with Lugol's solution. In order to preserve the coccolithophorids, the duplicate samples were fixed with formalin to a final concentration of 1–2 %. The sedimentation method was used to concentrate the samples [1, 2]. Phytoplankton organisms were counted quantitatively using MICMED-2 and MICMED-5 microscopes in chambers with the volume of 0.05 and 0.1 mL using objectives of 10×/0.30 and 40×/0.65 at least three times. To determine rare and large forms of phytoplankton, a part of the concentrate (1/5–1/10) was examined. The minimum size of considered cells makes 3–5 μm. Guidelines [7, 8] were used for species identification. The raw biomass of algae was estimated by the volumetric method, based on the size and shape of the cells according to the most similar geometric similarity, assuming the specific gravity of algae equal to one, using the original and literature data on cell volume measurements for each species [9].

To assess the similarity of the taxonomic composition [3] of the microalgae communities in the studied water areas of the Black Sea, the Sørensen–Czekanowski (Dice) coefficient (Cs) was applied [10]:

$$Cs = (2C / (A+B)) \cdot 100\ \%,$$

where A, B – total abundance of species recorded in compared samples; C – abundance of forms common to two compared samples.

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Results and discussion

Taxonomic composition

In the period from 2011 to 2020, 109 species of algae were found in the phytoplankton of the studied Abkhazian sector, as well as several taxonomic forms, which were not identified to the species level and belonged to the following classes: Bacillariophyceae (diatomic), Dinophyceae (dinophytic), Prymnesiophyceae (primnesian), Cyanophyceae (blue-green), Dictyochophyceae (dictyochales) and Ebriaphyceae (ebridian), Cryptophyceae (cryptophytic), Euglenophyceae (euglena), Prasinophyceae (prasinophytic) and Chlorophyceae (green) (Appendix, Table A.1). Dinophytic (71 species) and diatomic (27 species) algae were distinguished by the greatest species diversity. Other classes numbered from one to three species. Previous studies (spring-autumn periods of 2005–2011) showed that the taxonomic composition of phytoplankton in the open northeastern part of the Black Sea (NEBS) – from the Kerch Strait to Abkhazia – included significant number of dinophytic species (78), while the diversity of diatomic algae (37) was significantly inferior to them [11]. The similarity coefficient (*Cs*) of taxonomic composition in the Abkhazian sector and in the Russian open NEBS made 86 %. The largest abundance of species (62–71) in the Abkhazian sector was found in the spring-and-summer seasons (May–July) 2011–2013, which was due to the high diversity of warm-water species of dinophytic algae forming the part of algocenosis (43–58). At other times, the total number of phytoplankton species was somewhat lower (42–50).

The mesohalobiotic representatives of blue-green (genera *Oscillatoria, Planktolyngbya, Anabaena, Aphanizomenon*) and euglena algae (*Eutreptia lanowii, Euglena viridis* and *Euglena* sp.), typical for desalinated and eutrophic water areas, were not widespread and preferred the upper layers of the sea (0–15 m). Few representatives of dictyochales (*Dictyocha speculum, Octactis octonaria*) and ebridian (*Hermesinum adriaticum*) were usually found in the lower studied layers (30–50 m). In the study area, 14 potentially toxic and harmful species of planktonic dinophytic algae of the genera *Ceratium, Prorocentrum, Dinophysis, Lingulodinium, Polykrikos, Protoceratium, Protoperidinium;* 2 species of the diatomic of the genus *Pseudonitzschia*; 2 species of the blue-green genera *Planktolyngbya, Aphanizomenon* were detected, which, due to their small abundance, could not have any significant negative impact on marine flora and fauna (Appendix, Table A.1).

In September 2014, in the study sector of the sea, a species of dinophytic algae − *Oxyphysis oxytoxoides* Kofoid – new for the eastern part of the Black Sea, was found in a small amount (on average 23 cells/L). In her review article on the dinophyte algae of the Black Sea, L. M. Terenko indicates it as an exotic species, known only in the waters of the Bulgarian coast, where, however, it often results in the bloom of water [12, 13]. In May 2013, another species new to the study sector of the sea was discovered (with an average abundance of 8 cells/L) – *Spatulodinium pseudonoctiluca* (Pouchet) J.Cachon & M.Cachon.

Quantitative values of development and their vertical distribution

The average values of abundance and biomass for the entire study period were 40.26 thousand cells/L and 74 mg/m^3, respectively. The abundance values were close to the long-term averages (54 thousand cells/L) recorded in the open NEBS in the 0–50 m layer in the spring-and-autumn periods of 2007–2011; and biomass values were significantly (four times) inferior to them (280 mg/m^3) [11]. The highest values of abundance and biomass in the Abkhazian sector (79 thousand cells/L and 113 mg/m^3) were noted on the sea surface (0–2 m). In the 10–20 m layer, these values were 1.4–2.3 times lower (35 thousand cells/L and 81 mg/m^3), while in the 25–30 m layer (19 thousand cells/L and 48 mg/m^3) − 2.3–4 times lower (Fig. 1 and 2). In the lower studied layer of the sea (40–50 m), the values of phytoplankton abundance (4.5 thousand cells/L and 28 mg/m^3), respectively, were 4–18 times lower than the surface values.

The maximum abundance of planktonic cells (476 thousand cells/L) was observed in the upper layer of the sea in May 2013. High abundance values (51 and 104 thousand cells/L) on the sea surface were also noted in the summer periods of 2011 and 2012. All abundance peaks were stipulated by the intensive development of primnesian algae (*Emiliania huxleyi*), which during this period formed up to 95 % of the total abundance and 53% of the phytoplankton biomass [4)]. According to the IO RAS researchers, this species was the reason for the bloom of water on the sea surface in the Abkhazian sector in the spring of 2011 and 2013 [3, 4]. In other seasons, the abundance values on the sea surface did not exceed 26 thousand cells/L. Two peaks of cell density were noted in the 10–20 m layer (87 and 112 thousand cells/L) in July 2012 and in May 2013. One abundance peak (68 thousand cells/L) was found in the 25–30 m layer in May 2013.

High biomass values (120–216 mg/m^3) on the sea surface were noted in May, July 2011–2013, October 2011 and September 2014; at other times, these values in the upper layer of the sea varied in the range of 45–92 mg/m^3. The maximum biomass values (140 mg/m^3) in the 10–20 m layer were observed in July 2012; during the rest of the study period, they amounted to 32–93 mg/m^3. In the 25–30 m layer, biomass values varied from 33 mg/m^3 (July 2011) to 72 mg/m^3 (April 2012).

Seasonal dynamics of dominant classes and species of algae

In general, the highest total values of phytoplankton abundance in the studied water column (surface – 50 m) were recorded in the spring time (90 thousand cells/L). In summer, the total number decreased by more than two times (39 thousand cells/L), in autumn it was minimal (8.8 thousand cells/L) and was an order of magnitude inferior to the spring values. At the same time, the biomass values of the entire community of planktonic microalgae in the studied layer of the sea changed little depending on the season: 66 mg/m^3 in spring and 64 mg/m^3 in autumn, while some increase in biomass was observed in summer (78 mg/m^3).

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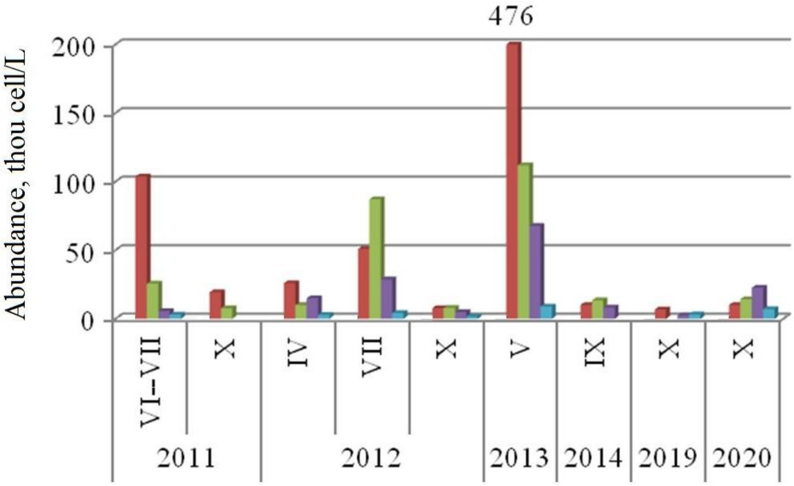

Fig. 1. Vertical distribution of the total phytoplankton abundance in layers 0–2 m (red), 10–20 m (green); 25–30 m (purple), 40–50 m (blue) in the Abkhazian sector of the Black Sea in different seasons of 2011–2020

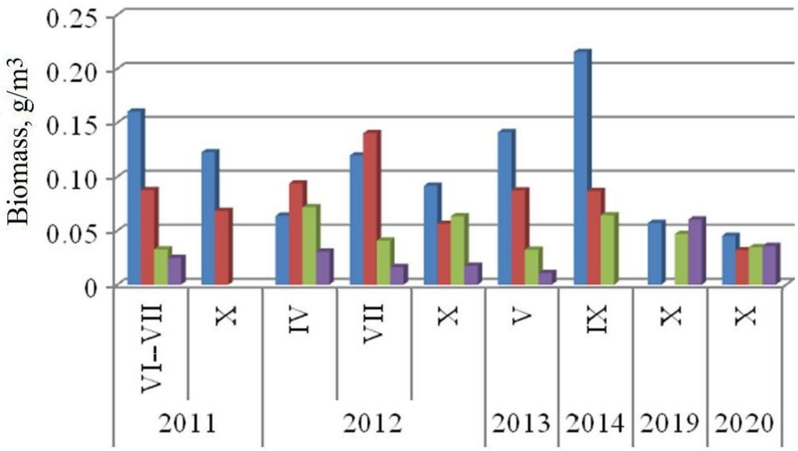

Fig. 2. Vertical distribution of the total phytoplankton biomass in layers 0–2 m (blue), 10–20 m (red), 25–30 m (green), 40–50 m (purple) in the Abkhazian sector of the Black Sea in different seasons of 2011–2020

As detailed above, primnesian algae were one of the dominant components of plankton: they formed from 36–68 % of the abundance in July 2011 and 2012, 35–45 % in October 2019 and 2020, up to 95 % of the abundance in May 2013.

Cryptophytic algae were significantly dominant in abundance (from 4 to 20 %) in 2011, 2012 and 2014, with their maximum proportion (17–20 %) observed in April 2012 and September 2014.

On average, the diatomic algae formed 30 % (from 1 to 55 %) of the total abundance and 31 % (from 5 to 77 %) of the biomass during the study period. Their maximum proportion in abundance values (55 %) was observed in April 2012; in biomass values (58–77 %) – in the autumn period of 2014 and 2019. In a significant number among them there were medium-sized species of algae of the genera *Chaetoceros*, *Pseudonitzschia,* as well as *Dactyliosolen fragilissimus*, *Nitzschia tenuirostris, Thalassionema nitzschioides*, etc. (Appendix, Table A.2). As a rule, the large-celled species *Pseudosolenia calcar-avis* was dominant in diatomic biomass. Occasionally, the role of *Proboscia alata, Chaetoceros affinis*, *Ch. curvisetus* and *Thalassionema nitzschioides* increased.

Dinophytic algae also formed on average 30 % of the total abundance (from 3 to 59 %), while they accounted for the main component of the phytoplankton biomass, namely, 60 % on average (from 22 to 84 %). A high proportion (50–59 %) of dinophytic algae in abundance values was noted in the autumn period of 2012 and 2014. Their role increased in the spring-and-summer periods of 2011 and 2012 and in the autumn periods of 2014 and 2020 in terms of biomass (76–84 %). Small species of algae of the genera *Prorocentrum, Gymnodinium, Gyrodinium,* as well as *Heterocapsa rotundata, Katodinium glaucum, Torodinium robustrum*, were dominant in abundance. The large-celled representatives of the genera *Ceratium, Protoperidinium, Dinophysis,* as well as *Polykrikos cofoidi, Gyrodinium spirale, Protoceratium reticulatum, Diplopsalis lenticula* and some others, were dominant in biomass.

It should be noted that if in the upper layers (0–20 m) high abundance of primnesian algae was observed, then in the deeper layers of the sea (30–50 m) the dinophytic algae dominated, probably due to their possible transition to heterotrophic and mixotrophic types of nutrition.

In the open NEBS, in the spring-and-autumn periods of 2007–2011, the diatomic (40 %), primnesian (34 %) and dinophytic (23 %) algae also were dominant in phytoplankton abundance. The greatest contribution to the phytoplankton biomass was made by diatomic (55 %) and dinophytic (42 %) algae. The leading species in abundance among diatomic algae were *Nitzschia tenuirostris, Thalassionema nitzschioides, Proboscia alata, Pseudosolenia calcar-avis, Skeletonema costatum*, species of the genera *Chaetoceros* and *Pseudo-nitzschia;* among dinophytic ones – *Prorocentrum cordatum, Scrippsiella trochoidea*, representatives of the genera *Gymnodinium* and *Gyrodinium* [11]. The main component of the biomass was formed by numerous medium and large-celled species of diatomic algae, such as *Proboscia alata, Pseudosolenia calcar-avis*, and dinophytic algae of the genera *Ceratium, Protoperidinium, Scrippsiella* and *Prorocentrum.* In the warm period of the year (June–July), in the temperature range from 20 to 24 °C, an increase in the proportion of *Emiliania huxleyi* (up to 67 % of the phytoplankton abundance) was also observed. The species preferred the upper (up to 20 m) layer of the sea.

Conclusions

In the spring-and-autumn periods of 2011–2020, 109 species of phytoplankton from 10 classes were found in the Abkhazian sector, among them 18 potentially toxic and harmful, and 2 species of planktonic algae new for the eastern part of the Black Sea. The species diversity was somewhat inferior to the species diversity noted in the Russian sector of the open NEBS in 2005–2011 (136 species). However, the similarity coefficient of taxonomic composition (the Sørensen–Czekanowski (Dice) coefficient, *Cs*) in the compared sectors was quite high and made 86 %.

The average abundance values concerning the water area made 40.26 thousand cells/L and were close to the long-term average values (54 thousand cells/L) noted in the open NEBS in the 0–50 m layer in the spring-and-autumn periods of 2007–2011. The average values of biomass (74 mg/m^3) were significantly (four times) inferior to the long-term average values (280 mg/m^3).

In the dynamics throughout the season, the peak of phytoplankton abundance (90 thousand cells/L) in the studied layer of the sea (with the surface of 50 m) was recorded in the spring time; in summer and autumn, these values decreased by 2–10 times. Biomass values changed little depending on the season: 66 mg/m^3 in spring, 64 mg/m^3 in autumn, and 78 mg/m^3 in summer.

The highest values (79 thousand cells/L and 113 mg/m^3) were noted in the surface layer of the sea (0–2 m), which is 1.5–18 times higher than in other studied layers (10–50 m). The maximum number of planktonic cells (476 thousand cells/L) was observed in the upper layer of the sea in May 2013, which was associated with the intensive development of primnesian algae (*Emiliania huxleyi*), which were dominant in abundance (95 %) and biomass (53 %) during that period. An increase in the proportion of primnesian algae in the warm season is generally recorded throughout the open NEBS water area.

The maximum value of biomass (216 mg/m^3) on the sea surface was noted in September 2014. 77 % of it was formed by a large-celled species of diatomic algae, *Pseudosolenia calcar-avis,* which is one of the dominant taxa of the Black Sea phytoplankton.

During the study, diatomic and dinophytic algae in the Abkhazian sector, as well as in the Russian open NEBS, constituted a significant part of phytoplankton abundance (totalling to 60 %) and biomass (91 %). In April 2012 and in September 2014, cryptophytic algae made up a significant part of the abundance (17–20 %).

Thus, the results of the study supplement significantly the previously published works covering phytoplankton in the Abkhazian sector of the Black Sea. New data on the seasonal dynamics of species diversity, quantitative development and horizontal distribution of planktonic algae in the studied sector of the sea are presented.

Table A.1. Taxonomic composition of phytoplankton in the Abkhazian sector of the Black Sea in 2011–2020

Algae taxa	Year and month of the study								
	2011		2012			2013	2014	2019	2020
	VI–VII	X	IV	VII	X	V	IX	X	X
BACILLARIOPHYCEAE:									
Cerataulina pelagica (Cleve) Hendey	+	–	–	–	–	+	–	+	–
Chaetoceros anastomosans Grun	–	–	+	–	–	–	–	–	–
Chaetoceros affinis Lauder	+	+	+	+	+	–	–	+	+
Chaetoceros compressus Lauder	+	+	+	–	+	–	–	+	+
Chaetoceros curvisetus Cleve	+	–	+	+	–	–	–	–	+
Chaetoceros diversus Cleve	–	–	–	–	–	–	–	–	+
Chaetoceros insignis Proshkina-Lavrenko	–	–	+	–	–	–	–	–	–
Chaetoceros peruvianus Brightwell	–	–	–	–	–	–	–	+	–
Chaetoceros scabrosus Proshkina-Lavrenko	+	–	–	–	–	–	–	+	+
Chaetoceros tortissimus Gran	–	–	–	–	–	–	–	+	–
Chaetoceros spp.	–	–	+	–	–	–	–	+	+
Cocconeis scutellum Ehrenberg	–	–	–	–	–	+	–	–	–
Coscinodiscus granii Gough	–	–	–	–	+	–	–	–	–
Coscinodiscus sp.	+	–	+	+	–	+	–	–	–
Cyclotella sp.	–	–	+	–	–	–	–	–	–
Dactyliosolen fragilissimus (Bergon) Hasle	–	+	–	+	–	–	–	+	+

Continued

Algae taxa	Year and month of the study								
	2011		2012			2013	2014	2019	2020
	VI–VII	X	IV	VII	X	V	IX	X	X
Ditylum brightwellii (T.West) Grunow	–	–	+	–	–	–	–	–	–
Grammatophora marina (Lyngbye) Kützing	–	–	–	–	–	+	–	–	–
Gyrosigma sp.	–	–	–	–	–	–	–	+	–
Hemiaulus hauckii Grunow ex Van Heurck	–	–	–	–	+	–	–	+	–
Nitzschia longissima (Brébisson) Ralfs in Pritchard	–	–	–	–	–	–	–	+	–
Nitzschia tenuirostris Mer.	+	+	+	+	+	+	–	+	+
Odontella mobiliensis (Bailey) Grunow	–	+	–	–	–	–	–		–
Planktoniella sol (Wallich) Schutt	+	–	–	+	–	+	–	+	–
Pleurosigma elongatum Smith	+	+	+	+	+	+	–	+	+
Pseudo-nitzschia pseudodelicatissima (Hasle) Hasle (complex)**	+	+	+	+	+	+	+	+	+
Pseudo-nitzschia seriata (Cleve) H.Peragallo (complex)**	–	–	–	–	–	–	–	+	–
Pseudonitzschia sp.	+	–	+	–	–	+	–		–
Proboscia alata (Brightwell) Sundström	–	–	+	+	–	–	–	+	+
Pseudosolenia calcar-avis (Schultze) Sundstrom	+	+	+	+	+	+	+	+	+
Skeletonema costatum (Greville) Cleve	+	–	–	–	+	–	–	–	–
Thalassionema nitzschioides (Grunow) Mereschkowsky	+	+	+	+	+	+	+	+	+
Thalassiosira sp.	–	–	+	–	–	+	–	+	–
DINOPHYCEAE:									
Akashiwo sanguinea (Hirasaka) Hansen et Moestrup**	+	–	+	+	+	+	+	–	–
Alexandrium sp.**	+	+	–	–	–	+	+	–	–

Continued

Algae taxa	Year and month of the study								
	2011		2012			2013	2014	2019	2020
	VI–VII	X	IV	VII	X	V	IX	X	X
Amphidinium amphidinoides (Geitler) Schiller	–	–	–	–	–	+	–	–	–
Amphidinium crassum Lohmann	–	–	–	–	–	+	–	+	–
Amphidinium longum Lohmann	–	–	–	+	–	–	–	–	–
Amphidinium sphenoides Wulff	–	–	–	–	–	–	–	+	+
Amphidinium sp.	+	+	–	–	–	+	+	–	–
Ceratium furca (Ehrenberg) Claparède & Lachmann	+	+	+	+	+	+	+	+	+
Ceratium fusus (Ehrenberg) Dujardin**	+	+	+	+	+	+	+	+	+
Ceratium tripos (O.F.Müller) Nitzsch**	+	+	+	+	+	+	+	–	+
Cochlodinium archimedes (Pouchet) Lemmermann	–	–	–	–	–	–	–	–	+
Cochlodinium citron Kofoid & Swezy	+	+	+	+	–	+	–	+	+
Cochlodinium sp.	+	–	–	–	–	+	–	–	–
Dinophysis acuminata Clap.et Lachm.**	+	–	+	+	+	+	–	+	–
Dinophysis acuta Ehrenberg**	+	+	–	+	+	+	+	+	+
Dinophysis caudata Saville-Kent**	+	+	+	+	+	+	+	+	+
Dinophysis fortii Pavillard	+	–	–	–	–	+	–	–	–
Dinophysis hastata Stein	–	–	–	–	–	–	+	–	–
Dinophysis odiosa (Pavillard) Tai & Skogsberg	+	–	–	–	–	+	–	–	–
Dinophysis rotundata Claparède & Lachmann	+	+	+	+	+	+	+	+	+
Dinophysis pulchella (Lebour) Balech	–	–	–	+	–	–	–	–	–
Dinophysis sacculus Stein	+	+	–	–	–	+	+	–	–

Continued

Algae taxa	Year and month of the study								
	2011		2012			2013	2014	2019	2020
	VI–VII	X	IV	VII	X	V	IX	X	X
Dinophysis sp.	+	+	–	–	+	+	–	–	–
Diplopsalis lenticula Bergh	+	+	+	+	+	+	+	+	–
Diplopsalis sp.	+	–	–	–	–	–	–	–	–
Dissodinium pseudolunula Swift ex Elbrächter & Drebes	–	–	+	–	–	–	–	–	–
Ensiculifera carinata Matsuoka, Kobayashi & Gains	+	–	+	+	+	+	+	–	–
Glenodinium sp.	+	–	+	+	+	+		–	–
Gymnodinium agile Kofoid et Swezy, 1921	–	+	–	–	–	+	–	–	–
Gymnodinium agiliforme J.Schiller, 1928	–	+	–	+	+	+	+	–	–
Gymnodinium blax Harris.	+	–	–	+	–	+	+	–	+
Gymnodinium nana Schiller	+	+	–	+	+	–	–	–	–
Gymnodinium simplex (Lohm.) Kofoid et Swezy	+	+	+	+	+	+	+	–	–
Gymnodinium wulffii Schill.	+	+	+	+	+	+	+	–	+
Gymnodinium sp.	+	+	+	+	+	+	+	+	+
Gyrodinium flagellare Schiller	–	–	–	–	–	+	–	–	+
*Gyrodinium fusiforme*Kofoid & Swezy	+	+	+	+	+	+	+	–	–
Gyrodinium spirale (Bergh) Kofoid et Swezy	+	+	+	+	+	+	+	+	+
Gyrodinium sp.	+	+	–	+	+	+	–	+	–
Gonyaulax digitalis (Pouchet) Kofoid	+	+	–	+	+	+	–	+	–
Gonyaulax polygramma Stein	–	–	–	–	–	–	–	+	–
Gonyaulax spinifera (Clap.et Lachm.) Diesing	+	–	+	+	+	+	+	+	–

Continued

Algae taxa	Year and month of the study								
	2011		2012			2013	2014	2019	2020
	VI–VII	X	IV	VII	X	V	IX	X	X
Gonyaulax verior Sournia	+	–	–	+	–	+	–	–	–
Gonyaulax sp.	+	–	–	–	–	+	–	+	+
Heterocapsa rotundata (Lohmann) G.Hansen	–	–	–	+	+	+	+	–	+
Heterocapsa sp.	–	–	–	–	–	+	–	–	–
Heterocapsa triquetra (Ehrenberg) Stein	+	–	+	+	–	+	+	–	–
Katodinium glaucum (Lebour) Loeblich	+	+	+	+	–	+	+	–	+
Lessardia elongata Saldarriaga & Taylor	+	–	–	–	–	–	–	–	+
Lingulodinium polyedrum (Stein) Dodge**	+	–	–	+	–	+	–	+	–
Mesoporos perforatus (Gran) Lillick	–	–	–	–	–	+	+	–	–
Oblea rotunda (Lebour) Balech ex Sournia	+	+	+	+	+	+	–	–	–
Oxyphysis oxytoxoides Kofoid*	–	–	–	–	–	–	+	–	–
Oxytoxum variabile Schill.	–	–	–	+	–	+	+	–	–
Pronoctiluca pelagica Fabre-Domergue	–	+	–	+	+	+	+	–	+
Prorocentrum compressum (Bailey) Abé ex Dodge	+	+	+	+	+	+	+	+	+
Prorocentrum cordatum (Ostenfeld) Dodge**	+	+	+	+	+	+	+	+	+
Prorocentrum micans Ehrenberg**	+	+	+	+	+	+	+	+	+
Prorocentrum minimum (Pavillard) Schiller	–	+	–	–	–	+	–	–	+
Prorocentrum sp.	–	–	–	–	–		–	+	+
Protoperidinium bipes (Paulsen) Balech (=*Peridinium minusculum* Pav.)	+	–	–	+	–	+	–	–	+

Continued

Algae taxa	Year and month of the study								
	2011		2012			2013	2014	2019	2020
	VI–VII	X	IV	VII	X	V	IX	X	X
Protoperidinium brevipes (Paulsen) Balech	–	–	–	+	–	+	–	–	+
Protoperidinium conicum (Gran) Balech	+	+	–	–	–	–	–	+	+
Protoperidinium crassipes (Kofoid) Balech**	+	+	+	+	+	+	+	–	–
Protoperidinium depressum (Bailey) Balech	+	–	+	+	–	+	+	–	–
Protoperidinium divergens (Ehrenberg) Balech	+	+	+	+	+	+	+	+	+
Protoperidinium globulus (Stein) Balech	–	–	–	+	–	–	–	–	–
Protoperidinium granii (Ostenfeld) Balech	+	–	+	–	–	+	–	–	–
Protoperidinium knipowitschii (Usachev) Balech	–	+	–	+	+	+	–	–	–
Protoperidinium oblongum (Auriv.) Parke et Dodge	+	–	–	+	+	+	+	+	–
Protoperidinium pallidum (Ostenfeld) Balech	–	+	–	–	–	+	–	+	+
Protoperidinium pellucidum Bergh	+	–	+	+	–	+	+	–	+
Protoperidinium sinaicum (Matzenauer) Balech	–	–	–	–	–	–	–	–	+
Protoperidinium steinii (Jørgensen) Balech	+	+	–	+	+	+	+	+	+
Protoperidinium thorianum (Paulsen) Balech	–	–	–	–	–	+	–	–	–
Protoperidinium spp.	+	+	+	+	+	+	+	+	+
Polykrikos kofoidii Chatton**	+	+	+	+	+	+	–	–	+
Protoceratium reticulatum (Clap.et Lachm.) Butschli**	+	+	–	+	+	+	+	+	+
Protoceratium areolatum Kofoid**	–	–	–	–	+	+	–	–	–
Pyrocystis lunula (Schütt) Schütt (= *Gymnodinium lunula* Schütt)	–	–	–	–	–	+	–	–	–

Continued

Algae taxa	Year and month of the study								
	2011		2012			2013	2014	2019	2020
	VI–VII	X	IV	VII	X	V	IX	X	X
Scrippsiella trochoidea (Stein) Balech ex Loeblich	+	+	+	+	+	+	+	–	+
Spatulodinium pseudonoctiluca (Pouchet) J.Cachon & M.Cachon*	–	–	–	–	–	+	–	–	–
Torodinium robustum Kofoid & Swezy	+	+	+	+	+	+	+	+	+
Spora dinophyta	–	–	–	–	–	+	+	–	+
PRYMNESIOPHYCEAE:									
Emiliania huxleyi (Lohmann) Hay et Mohler	+	–	–	+	–	+	–	+	+
Isochrysis sp.	–	–	–	–	–	–	–	–	+
DICTYOCHOPHYCEAE:									
Dictyocha speculum Ehrenberg	+	+	+	+	+	+	+	+	+
Octactis octonaria (Ehrenberg) Hovasse	–	–	+	–	+	–	–	+	+
EBRIAPHYCEAE:									
Hermesinum adriaticum Zacharias	–	–	–	–	–	–	–	–	+
CYANOPHYCEAE:									
Anabaena sp.	+	–	–	+	–	–	–	–	–
Aphanizomenon elenkinii Kisselev**	+	–	–	–	–	–	–	–	–
Oscillatoria sp.	–	+	–	–	–	–	–	–	–
Planktolyngbya limnetica (Lemmermann) Komárková-Legnerová & Cronberg**	+	+	+	+	+	+	–	–	+

End of table

Algae taxa	Year and month of the study								
	2011		2012			2013	2014	2019	2020
	VI–VII	X	IV	VII	X	V	IX	X	X
CRYPTOPHYCEAE:									
Plagioselmis prolonga Butcher ex Novarino	+	+	+	+	+	+	+	+	–
EUGLENOPHYCEAE:									
Euglena sp.	+	–	–	+	–	+	+	–	+
Euglena viridis (O.F.Müller) Ehrenberg	–	–	–	–	–	–	–	+	–
Eutreptia lanowii Steuer	+	–	–	+	–	–	–	–	–
PRASINOPHYCEAE:									
Pterosperma undulatum Ostenfeld	+	+	–	–	–	–	–	+	–
CHLOROPHYCEAE:									
Scenedesmus sp.	–	–	–	–	–	+	–	–	–

* New for the eastern part of the Black Sea species.

** Potentially toxic or harmful species.

Note: Species names are given according to global classification Algaebase (Available at: https://www.algaebase.org/search/species) and WORMS (Available at: https://www.marinespecies.org/aphia.php?p=search).

Table A.2. Dominant taxa of phytoplankton in the Abkhazian sector of the Black Sea in different seasons of 2011–2020

Year and month of the study		Dominant in abundance	Dominant in biomass
2011	VI–VII	Cryptophytes, 6 %: *Plagioselmis prolonga* Prymnesiales, 36 %: *Emiliania huxleyi* Diatoms, 39 %: *Chaetoceros affinis, Thalassionema nitzschioides* Dinophytes, 17 %: *Gyrodinium fusiforme*, species of genus *Gymnodinium, Prorocentrum cordatum, Scrippsiella trochoidea*	Diatoms, 22 %: *Chaetoceros affinis, Pseudosolenia calcar-avis* Dinophytes, 76 %: *Ceratium tripos, C. furca, Diplopsalis lenticula, Ensiculifera carinata, Protoperidinium divergens, P. crassipes, P. steinii, Scrippsiella trochoidea*
	X	Cryptophytes, 9 %: *Plagioselmis prolonga* Diatoms, 47 %: *Chaetoceros affinis, Ch. compressum, Dactyliosolen fragilissimus, Pseudonitzschia pseudodelicatissima, Thalassionema nitzschioides, Pseudosolenia calcar-avis* Dinophytes, 42 %: species of genus *Gymnodinium, Prorocentrum cordatum, P. micans, Katodinium glaucum, Torodinium robustrum*	Diatoms, 34 %: *Pseudosolenia calcar-avis* Dinophytes, 65 %: species of genus *Ceratium, Dinophysis caudata, D. rotundata, Prorocentrum micans, Protoperidinium divergens, P. crassipes, P. steinii, Protoceratium reticulatum*
2012	IV	Cryptophytes, 17 %: *Plagioselmis prolonga* Diatoms, 55 %: *Chaetoceros affinis, C. insignis, C. curvisetus, Chaetoceros* sp., *Nitzschia tenuirostris, Pseudonitzschia pseudodelicatissima* and *Proboscia alata* Dinophytes, 26 %: *Prorocentrum cordatum, Katodinium glaucum, Scrippsiella trochoidea*, species of genera *Gymnodinium* and *Gyrodinium*	Diatoms, 22 %: *Pseudosolenia calcar-avis* and *Proboscia alata*, species of genera *Chaetoceros* and *Coscinodiscus* Dinophytes, 77 %: *Ceratium tripos, C. fusus, C. furca, Diplopsalis lenticula, Protoperidinium crassipes* and *P. depressum*

Continued

Year and month of the study		Dominant in abundance	Dominant in biomass
2012	VII	Prymnesiales, 68 %: *Emiliania huxleyi* Diatoms, 5 %: *Pseudonitzschia pseudodelicatissima, Pseudosolenia calcar-avis* and *Nitzschia tenuirostris* Dinophytes, 21%: *Gymnodinium simplex, G. nana, G. blax, Gymnodinium* sp., *Gyrodinium fusiforme, Katodinium glaucum, Prorocentrum cordatum, Lessardia elongata, Amphidinium longum*	Diatoms, 12 %: *Pseudosolenia calcar-avis.* Dinophytes, 83 %: *Ceratium furca, C. tripos, Diplopsalis lenticula, Dinophysis caudata, D. rotundata, Lingulodinium polyedrum, Protoperidinium divergens, P. crassipes, Polykrikos kofoidii*
	X	Cryptophytes, 4 %: *Plagioselmis prolonga* Diatoms, 45 %: *Pseudosolenia calcar-avis, Chaetoceros affinis, Thalassionema nitzschioides, Chaetoceros compressum, Skeletonema costatum, Hemiaulax hauckii* Dinophytes, 50 %: *Prorocentrum cordatum,* genus *Gymnodinium, Gyrodinium fusiforme Scrippsiella trochoidea, Torodinium robustum*	Diatoms, 42 %: *Pseudosolenia calcar-avis* Dinophytes, 57 %: *Ceratium furca, C. tripos, Dinophysis rotundata, Akashiwo sanguinea, Protoperidinium divergens, P. crassipes*
2013	V	Prymnesiales, 95 %: *Emiliania huxleyi* Diatoms, 1 %: *Pseudonitzschia pseudodelicatissima* Dinophytes, 3 %: species of genus *Gymnodinium, Gyrodinium, Prorocentrum, Scrippsiella trochoidea, Torodinium robustum*	Prymnesiales, 53 %: *Emiliania huxleyi* Diatoms, 5 %: *Pseudosolenia calcar-avis* Dinophytes, 41 %: *Ceratium furca, C. tripos, P. micans, Protoperidinium crassipes, Dinophysis acuta, D. rotundata, Spatulodinium pseudonoctiluca, Polykrikos kofoidii*

End of table

Year and month of the study		Dominant in abundance	Dominant in biomass
2014	IX	Cryptophytes, 20 %: *Plagioselmis prolonga* Diatoms, 20 %: *Pseudosolenia calcar-avis* and *Thalassionema nitzschioides* Dinophytes, 59 %: *Gyrodinium fusiforme, Katodinium glaucum, Akashiwo sanguinea,* genus *Gymnodinium*	Diatoms, 77 %: *Pseudosolenia calcar-avis* Dinophytes, 22 %: *Ceratium tripos, C. fusus, C. furca, Dinophysis rotundata, Protoperidinium depressum*
2019	X	Prymnesiales, 35 %: *Emiliania huxleyi* Diatoms, 44 %: *Proboscia alata, Chaetoceros affinis, Ch. scabrosus, Ch. tortissimus, Pseudo-nitzschia seriata, Ps. pseudodelicatissima,* and *Pseudosolenia calcar-avis* Dinophytes, 17%: *Prorocentrum cordatum* and *P. micans,* species of genera *Gymnodinium, Gyrodinium*	Diatoms, 58%: *Proboscia alata,* genus *Chaetoceros, Pseudosolenia calcar-avis* Dinophytes, 41 %: *Ceratium furca, C. fusus, Diplopsalis lenticula, Prorocentrum micans, Protoceratium reticulatum,* representatives of genera *Dinophysis, Gyrodinium* and *Protoperidinium*
2020	X	Prymnesiales, 45 %: *Emiliania huxleyi* and *Isochrysis* sp. Diatoms, 17 %: *Thalassionema nitzschioides, Chaetoceros affinis, Nitzschia tenuirostris* Dinophytes, 36 %: *Prorocentrum cordatum, P. micans, Heterocapsa rotundata, Katodinium glaucum, Torodinium robustrum*	Diatoms, 9 %: *Chaetoceros affinis, Ch. curvisetus, Thalassionema nitzschioides* and *Pseudosolenia calcar-avis* Dinophytes, 84 %: *Dinophysis rotundata, Polykrikos cofoidi, Gyrodinium spirale, Protoceratium reticulatum, Protoperidinium divergens, Ceratium tripos, C. fusus, C. furca* and *Prorocentrum micans*

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Meiobenthos of Sevastopol Bay (Black Sea): Current State and Long-Term Changes

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Abstract
The paper presents data (density, taxonomic composition) on the meiobenthos population of Sevastopol Bay (the Black Sea) in 2018 as compared with the results of previous studies. The data were obtained using standard hydrobiological methods. Eleven large taxa were identified as part of the bay's multicellular meiobenthos: Nematoda, Harpacticoida, Ostracoda, Kinorhyncha, Halacaridae categorized as eumeobenthos, and small specimens of Polychaeta, Oligochaeta, Turbellaria, Nemertea, Amphipoda, Cumacea categorized as pseudomeiobenthos. Nematodes dominated, averaging from 37.7 to 88.5 % of the total number of meiobenthos. The meiobenthos density varied from 8 to 248 ind./10 cm^2 while the meiobenthos distribution across the bay was uneven. Artilleriyskaya Bay and an area in the centre of Sevastopol Bay were marked by consistently low values of the meiobenthos density. At other sites, meiobenthos characteristics varied widely. The paper considers in greater detail Yuzhnaya Bay and the top of Sevastopol Bay, where the largest changes in the studied parameters have occurred over the past 25 years. In 2018, the highest indices of taxonomic diversity and the density of meiobenthos organisms were noted here. Uneven distribution of meiobenthos in very extended Sevastopol Bay is associated both with different particle size distribution of bottom sediments and with the influence of numerous various sources of pollution. This unevenness persists for a long time with a significant difference among the values of various years; changes in different parts of the bay occur rather synchronously.

Keywords: meiobenthos, long-term changes, Sevastopol Bay, Black Sea

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Мейобентос Севастопольской бухты (Черное море): современное состояние и многолетние изменения

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Аннотация
Приведены данные о плотности и таксономическом составе мейобентосного населения б. Севастопольской (Черное море) в 2018 г., которые сравнены с результатами предыдущих исследований. Данные получены стандартными гидробиологическими методами. В составе многоклеточного мейобентоса бухты определены 11 крупных таксонов: Nematoda, Harpacticoida, Ostracoda, Kinorhyncha, Halacaridae, которые отнесены к эвмейобентосу, и мелкие экземпляры Polychaeta, Oligochaeta, Turbellaria, Nemertea, Amphipoda, Cumacea псевдомейобентоса. Доминировали нематоды, составляя в среднем от 37.7 до 88.5 % общей численности мейобентоса. Численность мейобентоса изменялась от 8 до 248 экз./10 см^2, при этом наблюдалась неравномерность распределения мейобентоса по бухте. Стабильно низкими показателями численности характеризуются б. Артиллерийская и участок в центре б. Севастопольской. На других участках наблюдали широкую вариабельность характеристик мейобентоса. Более подробно рассмотрены вершина б. Севастопольской и б. Южная, где за 25 лет произошли наибольшие изменения по изучаемым параметрам. В 2018 г. здесь отмечены самые высокие показатели таксономического разнообразия и плотности поселения организмов мейобентоса. Неравномерность распределения мейобентоса в очень протяженной б. Севастопольской связана как с разным гранулометрическим составом донных отложений, так и с влиянием многочисленных разнообразных источников загрязнения. Эта неравномерность сохраняется в течение длительного времени при достоверной разнице между показателями разных лет, изменения в различных частях бухты происходят довольно синхронно.

Ключевые слова: мейобентос, многолетние изменения, Севастопольская бухта, Черное море

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Introduction

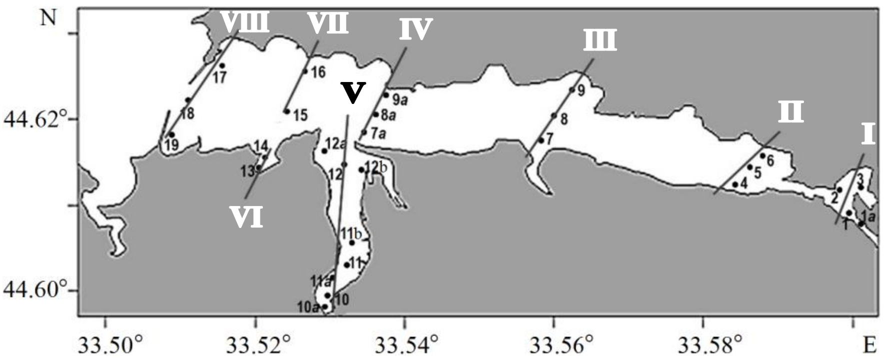
The study of the meiobenthos of the Sevastopol coastal water has a significant history. Thus, the first information concerning nematodes was given in the works of I. N. Filipyev in 1918. Faunistic studies of various taxonomic groups of this benthos aggregation have been carried out during the 20th century [1] and continue nowadays [2, 3]. The focus area of A. O. Kovalevsky IBSS Department of Marine Sanitary Hydrobiology is the study of the dependence of the meiobenthic organisms' distribution on the level of pollution of bottom sediments. Related work has begun more than 30 years ago and is carried out with the frequency of integrated sanitary and biological surveys once every three years. Sevastopol Bay is elongated in the latitudinal direction with its length of 7 km. At the top, the Chyornaya River enters the bay, which is its paleochannel.

Its mouth, narrowed by moles, is opened to the west. The coastline is crenelated and forms many smaller bays, which differ from each other in their depth, types of bottom sediments and water exchange nature. Along the shores and in the water area of the bay, there are various industrial facilities, which, like coastal residential construction, represent the sources of heterogeneous pollution [4]. The pollution nature and level of the bay have repeatedly changed over a quarter of the century, which was caused by socio-economic reasons [5, 6].

In connection with the new data collected during long-term monitoring, the aim of this work is to characterize the current state of Sevastopol Bay meiobenthos as compared with the results of previous studies [7, 8]. The most closed areas with limited water exchange, classified as moderately and heavily polluted, are considered in more detail [9, 10].

Materials and methods

In 2018, meiobenthos of Sevastopol Bay bottom sediments was studied at 27 permanent sampling stations (Fig. 1) during the so-called biological summer season [11] (in July–August), as well as during the surveys of 1994–2006. The material was sampled in three replications with a tube 3.4 cm in diameter, from the bottom lifted on board the vessel using a Petersen grab with sampling area of 0.038 m^2. Samples of bottom sediments were washed through a sieve with a mesh diameter of 1 mm in order to separate macrobenthic organisms. The filtrate was collected with *76PA-50* silk bolting cloth (mesh size – 0.082 μm), the sediments were fixed with 96 % ethanol. Samples were microscoped using



F i g . 1 . Grid of meiobenthos sampling stations during complex sanitary and biological surveys. Roman numerals stand for transects a Bogorov chamber to determine the density of representatives of the meiobenthos main taxonomic groups with recalculation of the density of organisms per 10 cm^2.

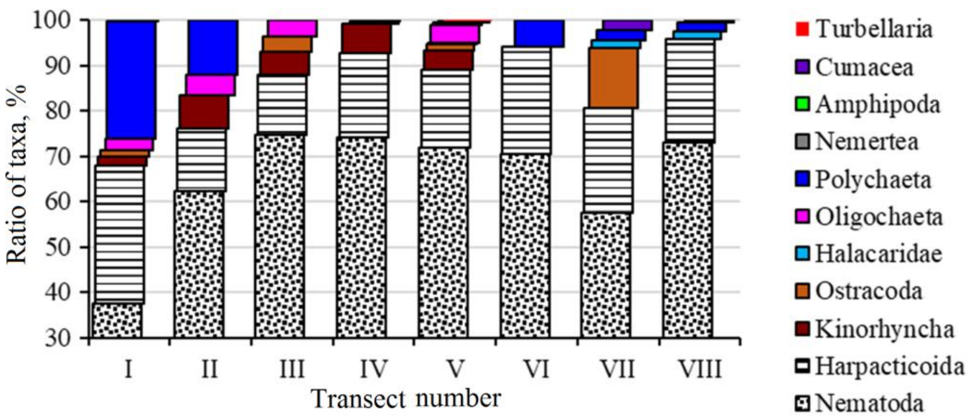
Results and discussion

The samples taken showed the representatives of such taxa as Nematoda, Harpacticoida, Ostracoda, Kinorhyncha, Halacaridae categorized as eumeobenthos, and small specimens of Polychaeta, Oligochaeta, Turbellaria, Nemertea, Amphipoda, Cumacea, categorized as pseudomeiobenthos. A total of 11 large taxa were identified (Fig. 2).

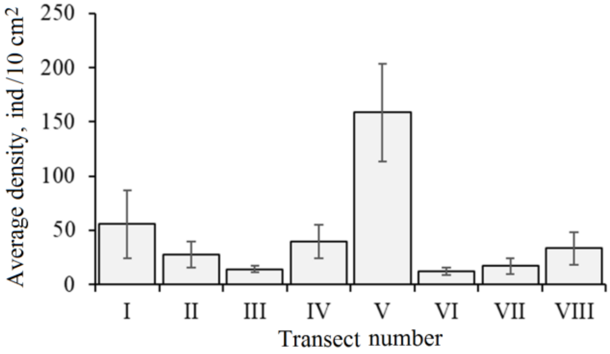
Fig. 2 shows that Nematoda dominated, averaging from 34.9 to 85.7 % of the total number of meiobenthos. Harpacticoida are also presented at all the stations, ranging from 14.6 to 25.1 %. The remaining groups were not found at all the stations, and their proportion made less than 10 %, except for Kinorhyncha at the mouth of the bay (16.6 %) and Polychaeta at the top (25.7 %), as well as at the mouth (15.2 %). The meiobenthos density varied from 8 to 248 ind./10 cm^2 (Fig. 3). The minimum values were noted in transects III and VI (Artilleriyskaya Bay), the maximum ones – in transect V (Yuzhnaya Bay).

The areas of the bay where bottom sediments have been classified as polluted for a long time are considered in detail [7, 8, 10]. These are the areas of the Inkerman boat basin and the adjacent water area (transects I and II), as well as Yuzhnaya Bay (transect V).

The meiobenthos of Sevastopol Bay top at stations 1–6 is represented by eight large taxa dominated by eumeiobenthos, which, in turn, is dominated by Nematoda (from 20.0 to 100.0 %) (Fig. 4). Harpacticoida accounted for up to 41.4% of the total density. At station 3, Ostracoda made a significant contribution to the density. Pseudomeiobenthos is represented by worms with the predominance of Polychaeta, whose contribution to the total density was significant in the estuarine area (the place of the Chyornaya River inflow, station 1). At the very mouth (station 1a), the number of meiobenthos is insignificant. The total



F i g . 2 . Representation and ratio of meiobenthos taxa in Sevastopol Bay in 2018

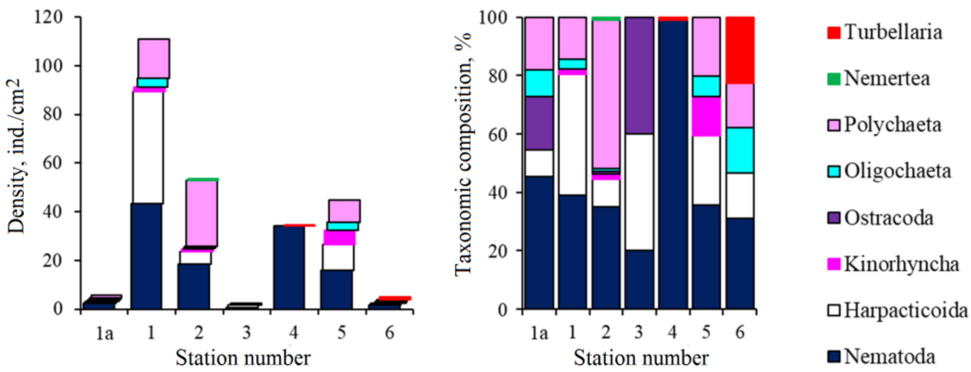


F i g . 3 . The average density of meiobenthos of Sevastopol Bay in 2018

abundance varied within 4.4–128.2 ind./10 cm^2 with the maximum values at station 1; the maximum taxonomic diversity was also noted there.

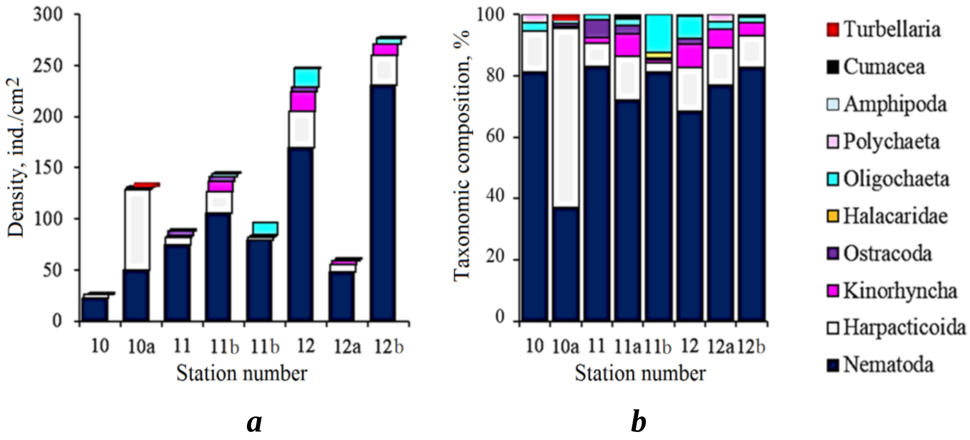
Yuzhnaya Bay meiobenthos (stations 10–12) is represented by nine large taxa with the significant predominance of eumeiobenthos (Fig. 5). It, in turn, was dominated by Nematoda (37.1–83.0 %). Harpacticoida accounted for 3.1 to 58.4 % of the total density. Pseudomeiobenthos is represented mainly by juvenile specimens of worms with the predominance of Oligochaeta. Malacostracans (Cumacea) were recorded at two stations. The total density of meiobenthos varied within 32.3–321.6 ind./10 cm^2 with a tendency to increase towards the exit from the bay.

Due to the small sample size, nonparametric statistical methods were used to compare the data on the density of meiobenthic population and its taxonomic diversity obtained at stations I, II, V in 2018 with similar indices of past surveys.



a *b*

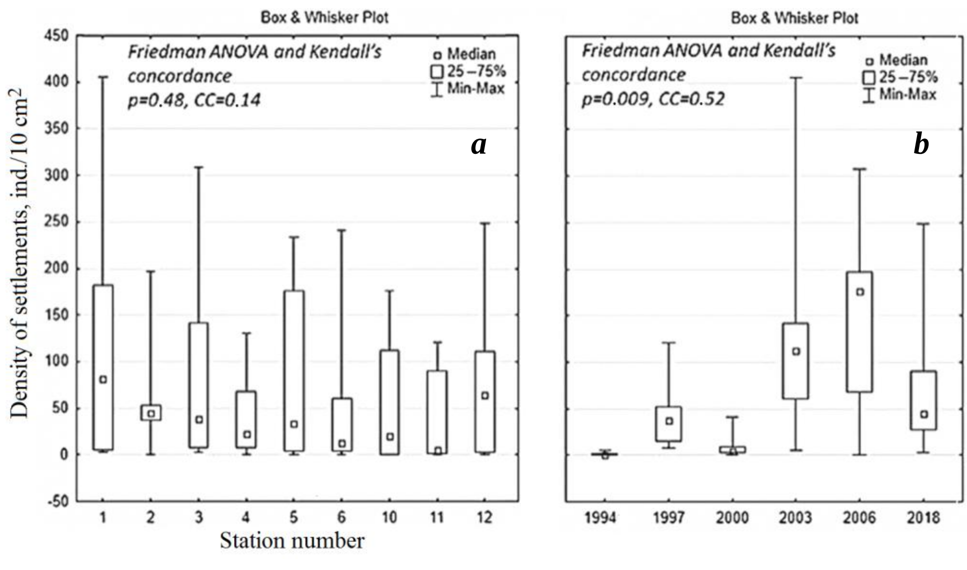
F i g . 4 . Density (*a*) and taxonomic composition (*b*) of meiobenthos at the top third of Sevastopol Bay, 2018



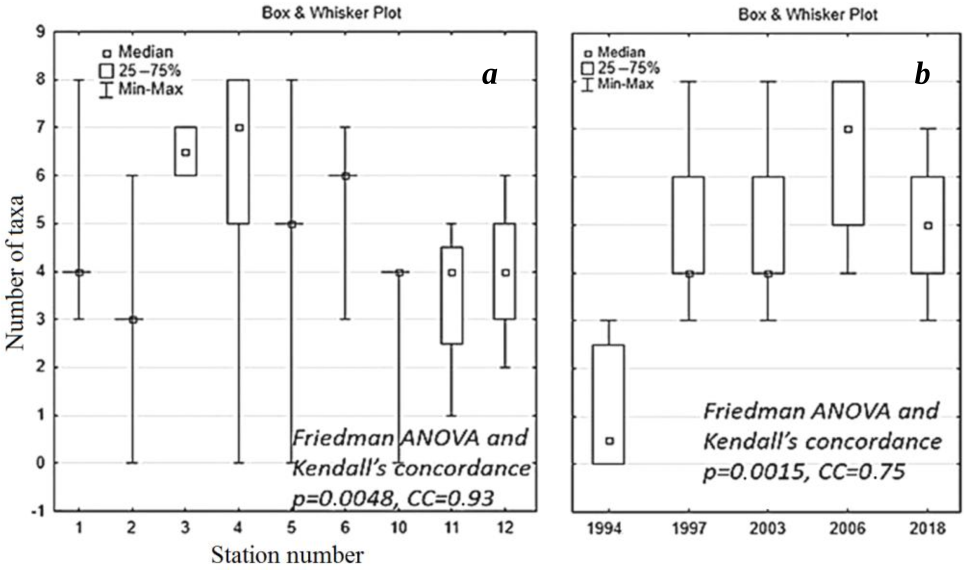
F i g . 5 . Density (*a*) and taxonomic composition (*b*) of meiobenthos of Yuzhnaya Bay, 2018

Friedman ANOVA and Kendall's coefficient of concordance were used to test the validity of the hypothesis about the spatial and interannual variability of the meiobenthos density of settlements and taxonomic diversity. Differences were considered statistically significant at a significance level of 0.05. Data processing was carried out using *Microsoft Excel* and *Statistica 12* software packages.

Analysis of variance showed the absence of statistically significant differences in the change in the density of the meiobenthos settlement at the stations of transects I, II, V (p = 0.48, concordance coefficient (*CC* = 0.14)) (Fig. 6, *a*).



F i g . 6 . Changes in the density of meiobenthos settlements at stations of transects I, II, V in 1994–2018: *a* – by stations; *b* – by years



F i g . 7 . Changes in the number of meiobenthic taxa at stations of transects I, II, V in 1994–2018: *a* – by stations; *b* – by years

Time analysis showed the reliability of differences in the density of maiobenthos in transects I, II, V in different years (Fig. 6, *b*). Thus, higher values were observed in 2003 and 2006, minimum ones – in 1994 and 2000. It was noted earlier that at the beginning of the 21st century there had been an increase in the density and biomass of meiobenthos both in the eastern part of the Black Sea and in the estuarine zone of the Danube [12, 13].

Analysis of data on the taxonomic diversity of Sevastopol Bay meiobenthos shows a significant difference both among the stations (Fig. 7, *a*) and among individual years of studies (Fig. 7, *b*).

Conclusion

The presented results reflecting the current state of Sevastopol Bay meiobenthos, have shown that the previously noted so-called depressed areas are preserved in the bottom sediments of the water area – these are Artilleriyskaya Bay and central part of Sevastopol Bay. Yuzhnaya Bay, on the contrary, in 2018 had the highest indices of taxonomic diversity and density of meiobenthic organisms' settlements. High density and diversity are also noted at the top of Sevastopol Bay.

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Contribution of the authors:

Elena V. Guseva – analysis of composition and abundance of meiobenthos, preparation of graphic materials, literature data analysis, analysis of the results and their interpretation, article composition

Sergey V. Alyomov – research problem statement, analysis and discussion of the results, manuscript editing

All the authors have read and approved the final manuscript.

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Criterion-Statistical Assessment of the Sustainability of Black Sea Local Coastal Eco-Socio-Economic Systems of the Krasnodar Krai

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Abstract

The marine coastal zone is characterized by extremely intense natural processes. It is also an area of particularly intense economic expansion. This makes it necessary to consider the coastal zone as a single eco-socio-economic system, which takes into account the variability of the spatial scale of the impact and stability of the existing processes – from local to district and further to regional and global levels. This requires comprehensive monitoring of the sustainability not only of regions but also of lower-level territories. However, at present, there are no unified methods for determining the sustainability of such coastal territorial systems. The paper proposes a criterion-statistical approach to assess the sustainability of local coastal eco-socio-economic systems in the form of a complex system of indicators by three factors of sustainability: natural-ecological, economic and social ones. As a result, it becomes possible to obtain quantitative estimates for individual factors and those in the form of a comprehensive integral index of the sustainability of the local coastal eco-socio-economic system. The application of the approach allows assessing the sustainability of local coastal systems and performing an appropriate spatial analysis, with the identification of stable (key) and unstable local coastal systems as territorial units of the local level of governance. This approach is universal and is approved in 18 local Black Sea coastal municipalities of the Krasnodar Krai. In the future, the approach will be used for implementation of the *Coastal eco-socio-economic systems of the Krasnodar Krai* GIS, which will allow for spatial territorial planning and forecasting of sustainable development of coastal eco-socio-economic systems at all levels of governance (regional, district and local).

Keywords: coastal eco-socio-economic system, local spatial level, sustainability, criterion-statistical approach, indicator system, Black sea, Krasnodar Krai

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Критериально-статистическая оценка устойчивости локальных береговых эко-социо-экономических систем Черноморского побережья Краснодарского края

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Аннотация

Береговая зона моря характеризуется крайне интенсивными природными процессами. Кроме того, она является областью особенно высокой экономической экспансии. Это приводит к необходимости рассматривать морскую береговую зону как единую береговую эко-социо-экономическую систему, учитывающую пространственные масштабы воздействия и степень устойчивости происходящих процессов: от локального к районному и далее к региональному и глобальному уровням. При этом необходим комплексный мониторинг устойчивости не только регионов, но и территорий более низких иерархических уровней. Однако в настоящее время не существует унифицированных методов определения устойчивости низкоуровневых береговых территориальных систем. В работе предлагается критериально-статистический подход к оценке устойчивости локальных береговых эко-социо-экономических систем в виде совокупности индикаторов по трем факторам устойчивости: природно-экологическому, экономическому и социальному. В результате становится возможным получить количественные оценки устойчивости по отдельным факторам и в виде комплексного интегрального индекса устойчивости локальной береговой эко-социо-экономической системы. Применение данного подхода позволяет оценить стабильность локальных береговых систем и выполнить соответствующий пространственный анализ с выявлением устойчивых (узловых) и неустойчивых локальных береговых систем как территориальных единиц локального уровня управления. Данный подход является универсальным и апробирован на 18 локальных приморских муниципальных образованиях районов Черноморского побережья Краснодарского края. В дальнейшем подход будет использован при реализации ГИС-оболочки «Береговые эко-социо-экономические системы Краснодарского края», что позволит осуществлять пространственное территориальное планирование и прогнозировать устойчивое развитие береговых эко-социо-экономических систем на всех уровнях управления (региональный, районный и локальный).

Ключевые слова: береговая эко-социо-экономическая система, локальный пространственный уровень, устойчивость, критериально-статистический подход, система индикаторов, Черное море, Краснодарский край

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Introduction

Considering various types of economic activities in the seas and oceans, it should be noted that actually all of them are closely linked to the coastal zone. Being a natural border area of three environments, it is characterized by a dramatically intense interaction of natural processes and expansion of the economic activity. This is generally accompanied by an increasing anthropogenic impact on the natural environment. It leads to the necessity to see the coastal zone as a unified eco-socio-economic system given the variability of spatial scales of impact on the natural environment and sustainability of the existing processes: from the local to the district level and further to the regional and global levels. At the same time, talking about sustainability of territorial systems, the factors and parameters of sustainability of global and regional scale are generally considered and less often those of the district spatial level, whereas very little attention is paid to local territorial systems. Though the management of territories as eco-socio-economic systems depends not only on economic and social factors but also on natural ones as well as ecosystem patterns [1–4].

Thus, it is necessary to perform comprehensive monitoring of the sustainability of territorial objects, including the eco-socio-economic analysis of development factors not only for the regions as a whole, but also for the territories of lower hierarchical levels. When applied to a local spatial level, this approach will significantly improve the reliability and validity of comprehensive development forecasts and reflect the feasibility of strategic objectives for development of territories of high spatial scale (districts and regions) in general [5–11].

The paper considers the criterion-statistical approach to the sustainability assessment of local coastal eco-socio-economic systems, which is calculated through a set of indicators of various sustainability factors. A local coastal municipality together with inland waters is considered as a local coastal system. Examples of such coastal systems are the Black Sea coastal municipalities of Krasnodar Krai settlements. This approach allows for a comparative assessment of sustainability of local coastal systems, both as a whole and by various components, and identification of the most significant factors affecting the sustainability of a territorial coastal entity.

Key approaches to the assessment of the sustainability of coastal eco-socio-economic systems

The sustainability of a system is understood as ability of the latter to ensure normal functioning of resource use processes under the existing set of natural, environmental, social-economic and other factors [1]. At present, there are various approaches to the assessment of the sustainability of eco-socio-economic systems, including those focused on coastal territorial entities. However, most of the research addresses the levels of countries and regions, while at the local level, except for cities, mechanisms of balanced development of territories are poorly considered [10, 12, 13]. A number of works are specialized in territorial entities of a certain type [1)], including coastal areas [1, 13–18]. In addition, some works contain to a certain extent a comprehensive approach to the assessment of the sustainability of the territory and consider environmental and economic, economic and managerial and other relationships. But these studies are mostly regional in nature [19–24].

The systems of assessment of the sustainability of territories at the district and local spatial levels have been studied less extensively, mainly due to lack of available statistical data. Methods for assessing the socio-economic development of territories of district municipal entities of the Russian Federation (RF) are the most widespread and developed. The calculation of sustainability is based on integral and partial criteria, reflecting the state (mainly socio-economic) of municipal entities; similar aspects are devoted to the works of foreign authors [25–29]. When building the systems of indicators that allow assessing the sustainability of territorial entities, the statistical approach based on official data of statistical agencies is mainly used. This approach makes it possible to build a mathematical model and establish the relationship between the indicators of various factors under consideration by applying methods of analysis of variance and regression statistics of dual regression equation. Such models are often linked to a specific region [2)] or constituent entity of the Russian Federation [30–36]. In foreign methodologies, a significant part is played by expert systems based on the integral opinion of invited experts as well [12, 15, 26, 27, 29, 37–40].

However, such systems are mostly of a general nature. The result is that the final estimates are less informative and unspecific as well as highly dependent on the experts' subjectivity extent in relation to the territorial entity in question. The wide application of the first group of statistical methods is quite understandable for the regional level, for which a range of statistical products of the global, federal and regional levels is available. But for lower territorial levels (especially for local municipalities) the number of such indicators drops dramatically. In addition, natural parameters gain greater importance, e. g. geomorphological

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[1)] BSC, 2013. *Guideline on Integrated Coastal Zone Management in the Black Sea.* Turkey: The Commission on the Protection of the Black Sea against Pollution, 2013. Available at: http://blacksea-commission.org/Downloads/Black_Sea_ICZM_Guideline/Black_Sea_ICZM_Guideline.pdf [Accessed: 11 March 2022].

[2)] Bobylyov, S.N., Zubarevich, N.V. and Solovyova, S.V., 2011. [*Sustainable Development: Methodology and Methods of Measurement*]. Moscow: Ekonomika, 358 p. (in Russian).

indicators of coastal stability, which are not available in statistical digests at all. The variability of such parameters generally cannot be considered using rigorous statistical methods. In this case, it is necessary to use expert-criterion approaches, which allow a quantitative assessment of an element of coastal system stability based on an expert opinion but using an unambiguous system of criteria and classification attributes [1, 15, 38–40]. On the whole, it is evident that the two discussed methods need to be combined into a single criterion-statistical approach to assessment of sustainability of an eco-socio-economic coastal system at the local spatial level.

Factor elements of the criterion-statistical approach to assessment of the sustainability of local coastal eco-socio-economic systems

One of the main convenient methods for assessment of the sustainability of coastal eco-socio-economic systems is the indicator method. It is based on identification of the main factors determining the sustainability of a coastal territorial system and the development of a system of indicators describing these factors. This approach makes it possible both to assess the current sustainability of a coastal system and to analyze the development trends of this territorial system as a whole and by individual factors and to take into account their interrelation. In contrast to coastal eco-socio-economic systems at the regional and district management levels, the local spatial level is characterized by the absence of explicit geopolitical, geo-economic, and other long-term sustainability factors. In this regard, it is possible to consider three factors as components [1]: natural-environmental, economic, and social. Each of these factors is determined by a set of indicators, the values of which are calculated on the basis of statistical or expert-criterion approaches. The methods for calculating the indicators are given in [1] and are based on the following principles.

1. The indicators are presented in dimensionless form by calculating the transition from the absolute values of the indicators.

2. The indicators take values from −1 to +1 (maximum negative and maximum positive degree of impact of the considered parameter on the system, respectively), which will allow smoothing strongly prevailing indicators during the assessment of the sustainability factor.

3. Indicators derived by applying the expert-criterion approach are minimally characterized by a subjective expert opinion and are based on clear parametric and spatial indicators.

4. When calculating a single sustainability factor and integral indicator, indicators are considered without using weight functions [1, 12, 13, 17]. Their introduction will lead to ambiguity in assessing the importance of each indicator due to the artificial prevalence or underestimation of any eco-socio-economic direction.

5. Within a single sustainability factor, indicators do not depend (no cross impact) on each other.

On the basis of these principles, sets of 8 indicators have been created for each considered factor of the coastal eco-socio-economic system sustainability. Methodologies for calculating statistical indicators are given in [1], and the primary sources of expert-criterion indicators [1)] are [14, 15, 37–41].

The comprehensive integral index of the local coastal eco-socio-economic system sustainability is calculated as the average of all indicators and allows the development of an assessment scale of sustainability classes. At the same time, the calculation of integral indicators as a set of individual indicators does not use any weight functions, thus avoiding ambiguity while assessing the importance of each indicator [1, 17].

Indicator calculation algorithms for assessing the sustainability of local coastal eco-socio-economic systems

Indicators of natural-environmental sustainability

Indicator of geomorphological sustainability of coasts

The indicator values are calculated using the method of expert-criterion assessment based on the expert assessment of the local coastal eco-socio-economic system typification by five gradations: from rocky and fjord coasts with very little abrasion (1 point) to fine-sand beaches, including sandy sediments, salt marshes, deltas, etc. (5 points), according to the formula

$$I_G = \frac{\sum_{i=1}^{5}\left(T_i \cdot \frac{p_i}{100}\right) - 1}{2} + 1, \qquad (1)$$

where T_i is an assessment of the gradation of the i-th type of coast, an integer within 1...5; p_i is the percentage of the i-th type of coast length of the total coast length, %.

Coast retreat indicator

The indicator is calculated by the formula (1) using the criterion assessment method based on the assessment (according to remote sensing data) of accumulation or retreat of coasts of the local coastal eco-socio-economic system typified by five gradations: from coast accumulation over 2 m/year (1 point) to coast retreat over 2 m/year (5 points).

Coast instability (abrasion) indicator

The indicator values are calculated using the criterion assessment method based on the ratio of the length of falling abrasion coasts of the local coastal eco-socio-economic system to the total length of its coastline, according to the formula

$$I_{AS} = 1 - 2\frac{L_{Us}}{L_C}, \qquad (2)$$

where L_{Us} is the length of abrasion coasts, km; L_C is the total length of the studied section of coast, km.

Fortified coastline indicator

The indicator is calculated using the criterion assessment method based on the ratio of the length of the fortified coastline of the local coastal eco-economic system to the total length of its coastline, according to the formula

$$I_{FC} = 2\frac{L_{FC}}{L_C} - 1, \tag{3}$$

where L_{FC} is the length of the coast with a positive score for the parameter in question, km.

Indicator of uncontaminated parts of coastline

The indicator values are calculated using the formula (3) according to the criterion assessment method and based on the ratio of the length of uncontaminated parts of the coastline of the local coastal eco-socio-economic system to the total length of its coastline.

Natural hazard intensity indicator

The indicator is calculated using the criterion assessment method and includes the following set of parameters:

1) frequency of storms with wind speeds exceeding 15 m/s, by five gradations from < 5 % (1 point) to > 12 % (5 points);

2) height of waves of 3% exceedance probability, by five gradations from < 1 m (1 point) to > 4 m (5 points);

3) tidal heights, by five gradations from < 0.3 m (1 point) to > 2 m (5 points).

The calculation formula is as follows

$$I_{GS} = \frac{1}{2} + \frac{\sum_{i=1}^{5}(W_i \cdot p_i) + \sum_{i=1}^{5}(Wa_i \cdot p_i) + \sum_{i=1}^{5}(Ti_i \cdot p_i)}{6}, \tag{4}$$

where the assessment of the gradation of the i-th coastal type is determined by the following parameters: W_i – by the 1st parameter, an integer within 1...5; W_{ai} – by the 2nd parameter, an integer within 1...5; T_{ii} – by the 3d parameter, an integer within 1...5.

The value for each characteristic is calculated based on the percentage ratio of the types of coastline of the local eco-socio-economic system to the respective assessment to the total length of its coastline.

Protected areas (PA) indicator

The indicator values are calculated based on the deviation degree of the PA area present in a local coastal municipality from the total PA area present on the RF territory (as a territory of a higher spatial level), with the normalization per area unit, according to the formula

$$I_{PA} = \begin{cases} \dfrac{PA_L/S_L}{PA_F/S_F} - 1 & \text{if } \dfrac{PA_L/S_L}{PA_F/S_F} \le 2, \\ 1 & \text{if } \dfrac{PA_L/S_L}{PA_F/S_F} > 2, \end{cases} \tag{5}$$

where PA_L is the value of the parameter for a municipality; PA_F is the value of the parameter for the RF as a whole; S_L is the value of the normalizing index for a municipality; S_F is the value of the normalizing index for the RF as a whole.

Indicator of solid municipal waste removal

The indicator is calculated using the formula (5) based on the degree of deviation of the value of solid waste removal from sources located in the local coastal municipality from the total value of solid waste removal from sources located in the RF (as a territory of a higher spatial level), normalized per unit of population.

Indicators of the economic sustainability

Indicator of the recreational attractiveness of the coastal system

The indicator values are calculated using the formula (1) according to the method of expert-criterion assessment based on the expert assessment of the local coastal eco-socio-economic system typification by five gradations: from a very high degree of recreational attractiveness (1 point) to its absence (5 points).

Indicator of anthropogenic hazards intensity

The indicator values are calculated using the formula (1) according to the method of expert-criterion assessment and based on the expert assessment of the local coastal eco-socio-economic system type by five gradations: from the actual absence of anthropogenic hazards for the coastal territory (1 point) to an absolutely anthropogenic coastal territory (5 points).

Transport infrastructure development indicator

The indicator values are calculated using the formula (5) based on the degree of deviation of the length of hard-surface roads on the territory of a local coastal municipality from the length of hard-surface roads located in the territory of the RF (as a territory of a higher spatial level), normalized per area unit.

Budget revenue indicator

The indicator is calculated by the formula (5) based on the deviation degree of the local budget revenues of a local coastal municipality from the total local budget revenues of all local municipalities located on the territory of the RF (as a territory of a higher spatial level), normalized per unit of population.

Investment indicator

The indicator values are calculated using the formula (5) based on the deviation degree of the investment value in fixed capital of the local coastal municipality from the total investment value in fixed capital for all local municipalities located on the territory of the RF (as a territory of a higher spatial level), normalized per unit of population.

Tourism potential indicator

The indicator values are calculated based on two parameters (the number of rooms in collective accommodation facilities (e. g. hotels, hostels, apartments; parameter 1) and the number of collective accommodation facilities (parameter 2)) according to the formula

$$I_{TP} = \frac{1}{2}\left(\frac{P1_L/S_L}{P1_F/S_F} + \frac{P2_L/S_L}{P2_F/S_F} \right) - 1, \tag{6}$$

where $P1_L$ is the value of parameter 1 for the municipality; $P1_F$ is the value of parameter 1 for the RF; $P2_L$ is the value of parameter 2 for the studied coastal municipality; $P2_F$ is the value of parameter 2 for the RF.

The calculation uses the method for calculating the deviation of the value of each parameter of the local coastal municipality from the total value of the parameter for all local municipalities located on the territory of the RF (as a territory of a higher spatial level), normalized per unit of population.

Indicator of subsidies from the RF budgets

The indicator values are calculated based on the degree of deviation of subsidy amount to the budget of the local coastal municipality from the federal budget of the RF from the total subsidy amount to the budgets of all local municipalities of the RF from the federal budget, normalized per budget amount unit, according to the formula

$$I_{PA} = \begin{cases} 1 - \dfrac{PA_L/S_L}{PA_F/S_F} & \text{if } \dfrac{PA_L/S_L}{PA_F/S_F} \le 2, \\ -1 & \text{if } \dfrac{PA_L/S_L}{PA_F/S_F} > 2. \end{cases}$$

Indicator of port cargo turnover

The indicator values are calculated based on the degree of deviation of the cargo turnover of ports located on the territory of a local coastal municipality from the maximum cargo turnover of ports located on the territory of one municipality of the RF, according to the formula

$$I_{HT} = 2\frac{H_L}{H_{\max} - 1},$$

where H_L is the cargo turnover amount of ports located on the territory of a municipality, million tons; H_{max} is the maximum cargo turnover amount of ports located on the territory of one RF municipality, million tons.

Indicators of social sustainability factor

Indicator of socio-economic importance

The indicator values are calculated using the method of expert-criterion assessment, based on the presence of certain types of facilities on the territory of the local coastal municipality. The calculation includes the following set of parameters:

– settlements, by five gradations: from their absence (1 point) to the presence of a metropolis (5 points);

– cultural heritage sites, by two gradations: their absence (1 point) and presence (5 points);

– roads, by five gradations: from their absence (1 point) to federal highways (5 points);

– railway network, by two gradations: their absence (1 point) and presence (5 points);

– type of land use, by five gradations: from the impossibility of economic land use due to the terrain nature (1 point) to the presence of large anthropogenic objects, e. g. enterprises, port complexes, etc. (5 points);

– protected areas (PA), by five grades: from their absence (1 point) to a UNESCO natural monument (5 points).

The calculation formula is as follows

$$I_{SEI} = \frac{S_S + S_{CH} + S_{HW} + S_{RW} + S_{LU} + S_{PA}}{12} - \frac{3}{2},$$

where S_S – assessment based on the settlement type, an integer within 1...5; S_{CH} – assessment based on the cultural heritage type, an integer within 1...5; S_{HW} – assessment based on the road type rating, an integer within 1...5; S_{RW} – assessment based on the railway type, an integer within 1...5; S_{LU} – assessment based on the land use type, an integer within 1...5; S_{PA} – assessment based on protected area type, units.

In case there are several objects of different gradations when considering a single parameter, the one highest value counts.

Indicator of measures taken to improve the sustainability of the coastal system

The indicator values are calculated using the method of expert-criterion assessment and based on the expert assessment of the quantity and quality of measures implemented on the territory of the local coastal municipality to increase the sustainability and preservation of the coastal system, by five gradations: from a high degree of concern and number of measures (1 point) to absence of measures and concern about implementation thereof (5 points). The indicator value is calculated for the municipality as a whole.

Indicator of the natural landscape disturbance level and the need for landscape restoration and maintenance

The indicator values are calculated for coastal areas of the local coastal municipality using the method of expert-criterion assessment. The calculation includes the following set of parameters:

1) the natural coastal landscape disturbance level due to anthropogenic activities, by five gradations: from the absence of any disturbance (1 point) to complete anthropogenic transformation of the landscape (5 points);

2) the degree of need (possibility and importance) for restoration of the natural coastal landscape, by five grades: from no need (possibility and

importance) for landscape restoration (1 point) to an obligation of landscape restoration, including through creation of PAs and cessation of economic activities (5 points).

The calculation formula is as follows

$$I_{CL} = \frac{\sum_{i=1}^{5}(V_i \cdot p_i) + \sum_{i=1}^{5}(R_i \cdot p_i)}{4} + \frac{1}{2},$$

where V_i is the gradation assessment of the i-th coast type by the 1st parameter, an integer within 1...5; R_i is the gradation assessment of the *i*-th coast type by the 2nd parameter, an integer within 1...5.

Indicator of the presence of an area development plan

The indicator is calculated using the method of expert-criterion assessment based on the expert assessment, which considers how much the territorial development plan of a local coastal municipality takes into account the peculiarities of the coastal system, its sustainable development and conservation of coastal landscapes by five gradations: from the availability of a separate section in the territorial development plan related to sustainable development of the coastal system and a road map for implementing this section of the plan (1 point) to the absence of the plan itself (5 points). The indicator value is calculated for the municipality as a whole.

Indicator of housing conditions

The indicator values are calculated according to the formula (5) based on the degree of deviation of the area of commissioned residential houses located on the territory of the local coastal municipality from the total area of those located on the territory of the RF (as the territory of a higher spatial level), normalized per unit of population.

Indicator of social infrastructure facility availability for the population

The indicator is calculated by the formula (6) using two parameters:

1) the number of comprehensive education organizations (parameter 1);

2) the number of healthcare organizations (parameter 2).

The calculation uses the method of calculating the deviation of the value of each parameter of a local coastal municipality from the total value of the parameter for all local municipalities located on the territory of the RF (as the territory of a higher spatial level), with normalization per unit of population.

Indicator of population growth

The indicator is calculated using the following formula

$$I_{PG} = \begin{cases} \dfrac{B_L}{B_F} - \dfrac{Mor_L}{Mor_F} & \text{if } \left(\dfrac{B_L}{B_F} - \dfrac{Mor_L}{Mor_F}\right) \le 1, \\ 1 & \text{if } \left(\dfrac{B_L}{B_F} - \dfrac{Mor_L}{Mor_F}\right) > 1, \end{cases}$$

where B_L is the fertility rate for the municipality, ‰; B_F is the fertility rate for the RF, ‰; Mor_L is the mortality rate for the municipality, ‰; Mor_F is the mortality rate for the RF, ‰.

The calculation uses the methodology of calculating the deviation of the values of each parameter for a local coastal municipality from the value of the parameter for the RF (as a territory of a higher spatial level) as a whole.

Indicator of the population migration balance value

The indicator values are calculated according to the formula as an average of the values obtained:

1) by the deviation degree of the migration gain/outflow value for the local coastal municipality from the parameter value for the RF (as the territory of a higher spatial level);

2) by the deviation degree of migration gain/outflow values for the local coastal municipality from its extreme values for the whole set of local municipalities of the Krasnodar Krai.

$$I_M = \begin{cases} \dfrac{M_L - M_{L\min}}{M_{L\max} - M_{L\min}} & \text{if} \quad \dfrac{M_L/H_L}{M_F/H_F} > 2, \\ \dfrac{M_L - M_{L\min}}{M_{L\max} - M_{L\min}} - 1 & \text{if} \quad \dfrac{M_L/H_L}{M_F/H_F} < 0, \\ \dfrac{1}{2} \cdot \left(\dfrac{M_L/H_L}{M_F/H_F} + \dfrac{M_L - M_{L\min}}{M_{L\max} - M_{L\min}} \right) - \dfrac{1}{2} & \text{if} \quad 0 \le \dfrac{M_L/H_L}{M_F/H_F} \le 2, \end{cases}$$

where M_L – migration gain/outflow for the municipality, people; M_F – migration gain/outflow for the Russian Federation, people; $M_{L\min}$ – minimum value of migration gain/outflow for the entire population of municipalities in the region, people; $M_{L\max}$ – maximum value of migration gain/outflow for the entire population of municipalities in the region, people.

Criterion-statistical assessment of the sustainability of the Black Sea local coastal eco-socio-economic systems

The resulting system of criterion-statistical assessment of the sustainability of local coastal eco-socio-economic systems is approved for local municipalities, which are part of the district municipalities of the Krasnodar Krai located at the Black Sea. A total of 18 local coastal systems were thus considered, including:

– eight local municipalities in the Temryuksky District (Temryuk urban settlement and rural settlements: Golubitskaya, Akhtanizovskaya, Fontalovskaya, Zaporozhskaya, Sennoy, Taman, Novotaman);

– the resort city of Anapa;

– the city of Novorossiysk;

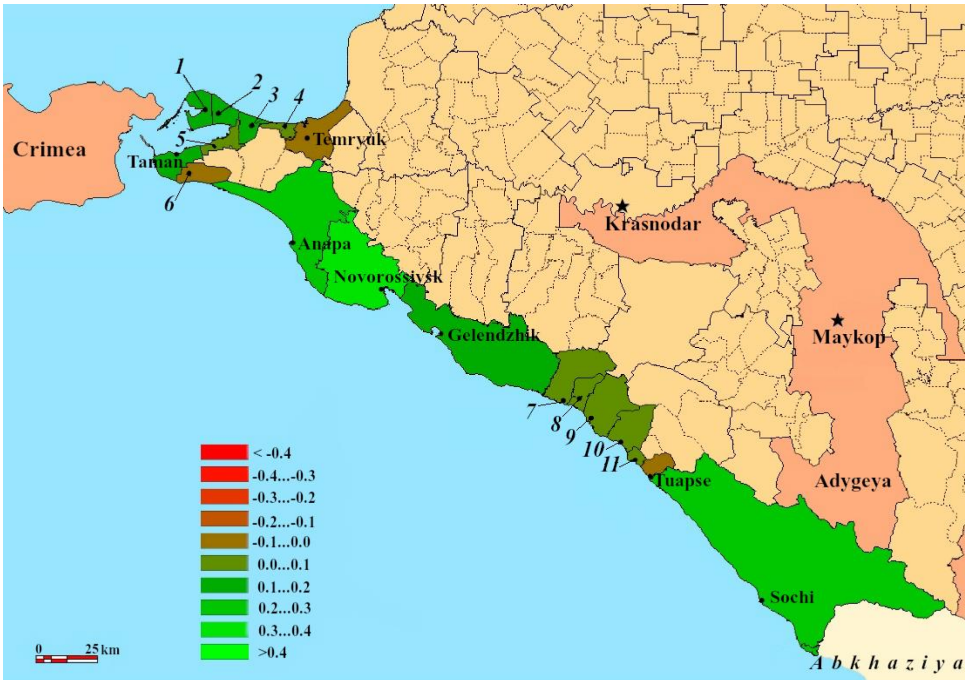
– the resort city of Gelendzhik;

– six local municipalities of the Tuapse District (urban settlements: Dzhubga, Novomikhaylovskoe, Tuapse; rural settlements: Tenginka, Nebug, Shepsi);

– the resort city of Sochi.

As baseline data, the authors used statistical information from open sources and administrations of coastal municipalities of district and local management levels for 2019 as well as data from satellite remote sensing and field research conducted as part of the above projects. The scale for assessment of the sustainability of coastal eco-socio-economic systems by factor and comprehensive index consists of 10 gradations: from −0.4 and below (critical unsustainability) to 0.4 and above (significant sustainability, favourable situation).

Based on the totality of all factors and the comprehensive index of sustainability in 2019, of all local coastal eco-socio-economic systems of the Black Sea coast of the Krasnodar Krai the most sustainable is the city of Novorossiysk (the value of the comprehensive index of sustainability is 0.34), which is associated with fairly high values of all indices (see table, figure). Next are the resort cities of Anapa and Sochi with index values of 0.24 and 0.22, respectively.



Comprehensive integral index of the stability of local Black Sea coastal eco-socio-economic systems of the Krasnodar Krai, 2019 (*1* – Zaporozhskaya; *2* – Fontalovskaya; *3* – Akhtanizovskaya; *4* – Golubitskaya; *5* – Sennoy; *6* – Tamansky; *7* – Dzhubga; *8* – Tenginka; *9* – Novomikhaylovskoe; *10* – Nebug; *11* – Shepsi)

Factors and comprehensive integral index of the sustainability estimation for the Black Sea local coastal eco-socio-economic systems (local municipalities) of the Krasnodar Krai

Local municipality	Natural-ecological factor	Economic factor	Social factor	Integral sustain-ability index
Temryuk US	0.04	–0.03	–0.11	–0.03
Golubitskaya RS	–0.16	0.11	0.12	0.02
Ahktanizovskaya RS	–0.17	0.30	0.17	0.10
Fontalovskaya RS	–0.01	0.11	0.23	0.11
Zaporozhskaya RS	0.11	0.20	0.11	0.14
Sennoy RS	–0.19	0.20	0.11	0.04
Taman RS	–0.05	0.36	0.06	0.12
Novotaman RS	–0.12	–0.07	0.07	–0.04
Anapa Resort City	–0.06	0.18	0.61	0.24
Novorossiysk City	0.24	0.52	0.27	0.34
Gelendzhik Resort City	0.03	0.28	0.11	0.14
Dzhubga MS	0.00	0.06	0.06	0.04
Tenginka RS	–0.07	0.11	–0.02	0.01
Novomikhaylovskoe US	0.05	0.16	0.04	0.09
Nebug RS	0.03	0.13	0.06	0.07
Tuapse US	0.28	0.26	–0.27	0.09
Shepsi RS	–0.16	0.06	0.01	–0.03
Sochi Resort CIty	0.14	0.18	0.36	0.22

Note: US – urban settlement; RS – rural settlement.

Conclusion

As a result of the performed work, the authors present a criterion-statistical approach to integrated assessment of the sustainability of local coastal eco-socio-economic systems based on the indicator approach. Use of aggregate indicators for three sustainability factors (natural-environmental, economic, social) makes it possible to obtain quantitative assessments of the sustainability by individual factors and a comprehensive integral index of sustainability of a local coastal eco-socio-economic system. The considered approach allows performing:

– comprehensive analysis of the sustainability of a local coastal eco-socio-economic system with the identification of sustainability and unsustainability factors;

– assessment of the sustainability of local coastal systems and an appropriate spatial analysis with the identification of stable (key) and unstable local coastal systems as territorial units of the local level of governance.

The criterion-statistical approach to assessing the sustainability of coastal systems is approved in 18 local coastal municipalities of the districts of the Black Sea coast of the Krasnodar Krai. As a result, it is shown that the most sustainable of the local coastal systems is the city of Novorossiysk with the value of the complex sustainability index of 0.34, which is associated with failrly high index values for all sustainability factors. The local coastal systems of Temryuk (Temryuk urban settlement and Novotaman rural settlement) and Tuapse (Shepsi rural settlement) districts are the least sustainable, with the main negative contribution to the sustainability assessment for these coastal systems being the natural and environmental factor. In general, the local coastal systems of the Black Sea coast of the Krasnodar Krai have positive values of the comprehensive sustainability index, with the main contribution being made by the high tourism potential, transport infrastructure development level, stable socio-demographic situation and high degree of natural and environmental sustainability. This approach is universal and can be used in other coastal regions of the RF to assess the sustainability of local coastal eco-socio-economic systems. In the future, when implementing the *Coastal eco-socio-economic systems of Krasnodar Krai* GIS, this approach will enable spatial territory planning and forecasting of sustainable development of coastal eco-socio-economic systems at all governance levels (regional, district, and local) taking into account medium- and long-term natural, ecological and socio-economic dynamics of variability to improve the efficiency of environmental management decisions in the marine coastal zone.

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