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Original article

Anthropogenic Impact on the Coastal Zone of Koktebel Bay (Black Sea) over the Last 100 Years

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Abstract

In view of the problem of unsustainable nature management, the paper considers coastal dynamics of a popular Crimean resort. The work aims to provide a post-assessment of changes in the Koktebel Bay coastal zone under the anthropogenic influence. The paper uses materials of surveys, literary and archival sources, data on the digitization of coastlines in space images for 2011–2021. Physical, geographical and lithodynamic characteristics of the bay were given. Anthropogenic impact on the coastal zone and coastline response thereto were considered. It is shown that for the last 100 years, anthropogenic impact on Koktebel Bay has led to a reduction in the width or to disappearance of beaches, changes in their material composition, replacement of the natural landscape by the anthropogenic one and, therefore, its aesthetic attraction has decreased. Three periods were identified in the evolution of the coastal zone. The first one is characterized by a gradual increase in anthropogenic impact on the landscapes of the land and coastal zone. In the second period, the established dynamic balance was disturbed and the balance of sediments became negative. This was due to the regulation of the streamflows and the industrial development of sand, gravel and pebbles in the coastal zone. This led to a sharp decrease in the area of the beaches, up to their complete disappearance in certain areas. The third period is characterized by a dramatic increase in anthropogenic impact, which manifested itself in the active (often illegal) construction of various structures on the beaches and by erection of hydraulic structures in order to protect and restore the beaches. It was shown that to date, man-made coasts occupy about 3 km and here natural processes have transformed into natural-anthropogenic. Natural coastal landscapes have preserved only in the eastern (about 2 km long) and western (about 1.5 km long) parts of the bay with its total length of 7 km. The paper provides information on coastal protection projects: both those fulfilled earlier and those being currently implemented.

Keywords: Black Sea, Crimea, Koktebel Bay, anthropogenic impact, coastline, space images, coastal protection

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Антропогенное воздействие на береговую зону бухты Коктебель (Черное море) за последние 100 лет

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Аннотация
В связи с проблемой нерационального природопользования рассмотрена динамика берегов одного из популярных курортов Крыма. Цель работы – дать ретроспективную оценку изменений береговой зоны бухты Коктебель, подвергающейся антропогенному воздействию. Использованы материалы обследований, литературные и архивные источники, данные оцифровки береговых линий на космических снимках за 2011–2021 гг. Даны физико-географическая и литодинамическая характеристики бухты. Рассмотрено антропогенное воздействие на береговую зону и отклик береговой линии на него. Показано, что за последние 100 лет антропогенное воздействие на бухту Коктебель привело к сокращению ширины или исчезновению пляжей, изменению их вещественного состава, замене естественного ландшафта антропогенным, что снизило его эстетическую привлекательность. Выделено три периода в эволюции береговой зоны. Для первого характерно постепенное нарастание антропогенного воздействия на ландшафты суши и береговой зоны. Во второй период сложившееся динамическое равновесие нарушилось и баланс наносов стал отрицательным. Это было обусловлено зарегулированием стока водотоков и промышленной разработкой песка, гравия и гальки в береговой зоне. Такое воздействие привело к резкому уменьшению площади пляжей, вплоть до полного их исчезновения на отдельных участках. Третий период характеризуется резким увеличением антропогенного воздействия, которое выразилось в активном (часто незаконном) строительстве на пляжах различных сооружений, а также возведением гидротехнических сооружений с целью защиты и восстановления пляжей. Показано, что к настоящему времени техногенные берега занимают около 3 км, здесь природные процессы трансформировались в природно-антропогенные. Природные ландшафты берегов сохранились только в восточной (протяженностью около 2 км) и западной (около 1.5 км) частях бухты при общей ее длине 7 км. Приводятся сведения о проектах защиты берега, выполненных ранее и реализуемых в настоящее время.

Ключевые слова: Черное море, Крым, бухта Коктебель, антропогенное воздействие, береговая линия, космические снимки, берегозащита

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Introduction

The anthropogenic impact on the environment has reached such proportions that it has become one of the main global agenda issues. This impact has not bypassed the coastal zone of seas and oceans. As is known, about 40% of humanity lives in the regions adjacent to it, and the population density is twice as high as the average one [1)].

[1)] Available at: https://www.unep.org/ru/issleduyte-temy/okeany-i-morya/nasha-deyatelnost/rabota-po-regionalnym-moryam/upravlenie [Accessed: 20 May 2024].

The Black Sea is no exception. For thousands of years, its coastline has changed under the influence of natural factors, but remained a stable self-regulating system. However, constant anthropogenic impact on the coastal zone has brought it out of this state since the mid-20th century. The coastline has begun to retreat intensively over a considerable distance destroying some coastal objects and posing a threat to others. The reduction and disappearance of beaches, deterioration of their material composition have reduced the recreational attractiveness of the resort. In a number of regions, landscapes have changed from natural to man-made.

Researchers from different countries recognize the dominant role of the anthropogenic factor in changing the natural environment of the Black Sea coastal zone over the past 100 years [1–6]. The same can be said about the coastal zone of the Crimean Peninsula [7–10]. We classified the types of anthropogenic impact on the coastal zone of the Black Sea coast of Crimea in [10, 11]. In [12], changes in the coastal zone over the past 100 years were studied using the example of the resort of Yevpatoriya and it is shown that these changes were caused mainly by ill-considered actions in the past. Unfortunately, even now, when developing business projects, previously acquired experience is often ignored, which leads to negative consequences. In this sense, the stages of the development of the coastal zone in Koktebel Bay, which is a well-known resort area, are typical.

Koktebel became a popular summer holiday resting place at the end of the 19th century. As early as the 1890s, famous writers, artists and scientists visited the estate of Eduard Junge, the owner of the surrounding lands, which he sold for summer cottages. Despite such fame of Koktebel Bay, there are very few literary sources devoted to its nature. In our opinion, this is due to the proximity of the bay to the Kara Dag massif, which was given primary importance due to the uniqueness of its nature. Among the oldest ones, we can note publications [2), 3)] containing the information concerning the width and material composition of the Koktebel beaches.

The first scientific survey of the bottom of the bay by divers was carried out in 1939 under the leadership of Academician R. A. Orbeli, founder of the Russian underwater archeology [4)]. In the western part, the remains of an ancient underwater breakwall were discovered. Some of its masonry was removed and used in the construction of the pier and in 1933–1934 its remains were blown up. Presence of the ancient breakwall, absence of ancient Black Sea terraces on the shore, as well as shallow waters and configuration of the bay made it possible for V. P. Zenkovich to conclude that the shore of the bay was ingressive, experiencing modern submergence [4)]. This monograph published in 1954 and classified until 1992 contains only one and a half pages devoted to Koktebel Bay. The work mainly describes its eastern wing – Toprakh-Kaya Cape. The monograph dedicated to Kara Dag contains some information about the bay [13]. Work [14] examines the issues of morphology

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[2)] Elpatievsky, S.Ya., 1913. [*Crimean Notes*]. Moscow, 149 p. (in Russian).

[3)] Voloshinov, I.M., 1929. [*Crimean Guide. Crimean Society of Naturalists and Nature Lovers*]. Simferepol: Krymskoe Gosudarstvennoe Idatelstvo, 614 p. (in Russian).

[4)] Zenkovich, V.P., 1954. [*Morphology and Dynamics of the Black Sea Coasts Within the Borders of the USSR. Part III. Section II (Southern Crimea, Kerch and Taman Peninsulas)*]. Moscow, 234 p. (in Russian).

and dynamics of the eastern coasts of Crimea. Some peculiar conclusions on the reasons for the reduction of beaches in Koktebel are given in [15]. The modern granulometric composition of sediments in Koktebel Bay based on the results of a survey by MHI in 2021 is considered in [16].

In our opinion, the most information about Koktebel Bay is contained in the monograph by A.A. Klyukin devoted mainly to the South-Eastern Crimea exogeodynamics [17]. However, the information is scattered across several chapters and does not provide a comprehensive picture of the natural conditions and coastal dynamics.

This work aims to provide post-assessment of changes in the Koktebel Bay coastal zone over the past 100 years under the anthropogenic impact.

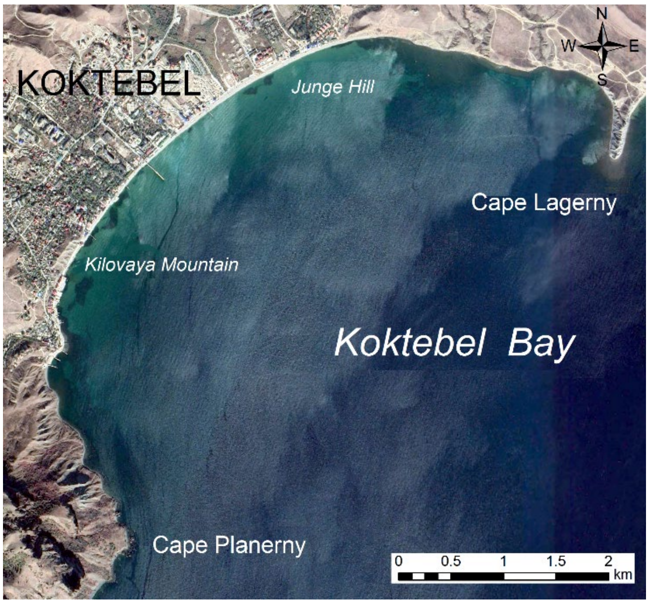
Materials and methods

We analyzed the materials of the Koktebel Bay surveys in 2009 and 2021 carried out by Marine Hydrophysical Institute of Russian Academy of Sciences (MHI). The work used the data on the digitizing of coastlines in space images of the Google Earth service for 2011–2021. At the same time, to compare the coastlines, they were additionally referenced by clearly visible landmarks on the coast of the urban-type settlement of Koktebel due to insufficient reference accuracy for our purposes. Since there were no such landmarks outside the settlement, the images were referenced to coastal roads, which are fairly stable elements of the landscape. In addition, literary and archival sources were used, mainly departmental reports of liquidated organizations (Division of Landslide Protection, Yalta Team of KrymMorGeologiya Association, Institute of Mineral Resources of the Ministry of Geology of the Ukrainian SSR). An electronic archive of photographic images of the Crimean Peninsula coasts created at MHI was also used.

Physical, geographical and lithodynamic characteristics of Koktebel Bay

Koktebel Bay (here and below the official names of geographical objects are given) is located between Cape Planerny (formerly called Malchin) in the west and Cape Lagerny (formerly called Toprakh-Kaya) in the east (Fig. 1). The resort village (urban-type settlement) of Koktebel is located on the shore of the bay. The length of the bay coastline is about 7 km. The distance along the line connecting the above mentioned capes is about 4 km, with the largest perpendicular to this line being 2 km long. Thus, the bay forms an almost perfect semicircle.

In its southern part, the coastline is most indented and forms a series of small bays with boulder heaps on the edge and near the shore. The landslide of boulder heaps in the water stretches for 1.5 km, and they are also noted in the eastern part near Cape Lagerny. The coast in the western part is mountainous and abrasive, with small bays. In the eastern part, it is abrasive, with landslide and loose rocks. The central part of the coast can be classified as accumulative and man-made according to the prevailing modern exogenous processes [11].



F i g . 1 . Sketch-map of Koktebel Bay

The southern edge of the bay consists of cliffs of the Magnitny Ridge, which is part of the Kara Dag massif. The strong volcanic rocks of this part of the bay are replaced to the north, first by a long valley, on the shore of which there was previously a pier and now three groins, and then by a protrusion of an abrasive shore up to 30 m high composed of loose clay shales and marls (Kilovaya Mountain). Previously, the coast here was bordered by a wide pebble and sand beach. The open arc of the bay apex, 2 km long, borders an alluvial lowland, now almost completely developed. From the north, the slopes of Biyuk-Yanyshar Hill (up to 200 m high) approach the bay forming an active cliff about 10 m high near the shore. The cliff is composed of brown Quaternary and gray Jurassic clays. At the foot of the hill, in the western part adjacent to the Koktebel beaches, small (up to 3 m wide) boulder and block beaches are located, which gradually wedge out completely to the east. Cape Lagerny, which closes Koktebel Bay from the east, is an elongated narrow peninsula (more than half a kilometer long) made of gray Jurassic clays (Fig. 2). A narrow (2–3 m) platform lies at the foot of the cape cliffs. It is made up of exposed rock, in some places covered by small accumulations of rubble. This platform slopes down to the water gently and forms a wide bench. In front of the cape and on both sides of it, at a distance of up to 200 m from the water edge, blocks and plates of sandstone and clay shale washed out of the cape clay layer are scattered.

Koktebel Bay is shallow, with the 5 m isobath running on average at a distance of 200–300 m from the water edge and with depths of 10–15 m at the outer boundary of the bay. The western part of the bay is deeper, the shallowness of the bottom increases in its eastern part. Here, the 1 m isobath is located 100–120 m from the shore.

F i g . 2 . View of Koktebel Bay from Biyuk-Yanyshar Hill

Further, the depth quickly increases, the distance between the 5 and 10 m isobaths is no more than 150 m. The source of beach material replenishment was previously the discharge of several watercourses flowing into the bay. In the central part, the mouth of the Yantiq River (the length and catchment area are about 10 km and 50 km^2, respectively) with the eponymous erosion gully and some temporary watercourses nearby.

Koktebel Bay is located to the east of the Southern Coast of Crimea (SCC), the border of which is considered to be Cape Planerny. The climate here, unlike the SCC subtropical Mediterranean climate, is coastal, moderately warm. The average annual air temperature is about 12°C, the average annual precipitation is about 400 mm. According to the data from the nearest hydrometeorological station Feodosia, the most frequent winds here are strong (10 m/s and more) ones from the northwest, northeast, south, southwest and west. The most frequent waves are those from the eastern, southeastern and southern directions. In total, waves from these directions account for 96% of all cases per year. Storms from the southern and eastern directions are most dangerous in terms of waves.

The beaches of Koktebel Bay are fed by the products of abrasion, erosion of landslides and rockslides, as well as biogenic material from the underwater coastal slope. Currently, the capes and wings of the bay are mainly subject to abrasive erosion. At the same time, it is mainly the eastern wing of the bay that is abraded (at the base of the cliffs and on the bench), while currently almost no abrasion is observed in the bay itself. Up to 90% of abrasion products arrive during the cold period, with the most active storms. In stormy years, which usually recur every 5–6 years, the volume of sediments exceeds the average value several times [17]. Sediments migrate along the coast from the capes to the bay and along the bay in both directions depending on the sea wave regime. When the proportion of relatively rare southern storms increases in the wave regime, sediments migrate from the southwestern and western parts to the northeastern and eastern parts of the bay, which is the main process in sediment dynamics.

The main source of beach material replenishment is stipulated by the erosion of landslide and rockslide tongues, where small ones are washed away during the storm season and relatively large ones – over the course of several years. Thus, the largest landslide from Cape Lagerny was completely washed away in eight years [17]. In 1913, the tongue of a large landslide located on the slope of the Kok-Kaya Ridge (western wing of the bay) protruded into the water area by more than 10 m and was washed away. In the spring of 1958, 6 m of the sliding tongue were cut off at the northeastern outskirts of Koktebel [15]. In 1980–1983, 5 thousand m^3 of loam were washed away from the sliding tongue extended into the water area near Cape Planerny [4]. At the same time, the drift products contain only 25% of the wave field sediments as they quickly become soaked and washed away. The drift increases in wet years and decreases in dry ones. The largest amount of sediments enters the coastal zone when wet years precede stormy years or coincide with them [17].

Anthropogenic impact and coastal dynamics

At the beginning of the 20th century, the shores of Koktebel Bay were a sparsely populated area. Old photographs show no significant construction (Fig. 3).

Works [2), 3)] noted a beach with an incomplete profile and a width of up to 30 m along the coast. The bay bottom was sandy and shallow, the coastal shoal went tens of meters from the shore. The beach was predominantly composed of sand – a product of alluvial deposits carried away by watercourses. There was also a large amount of rounded pebbles from the solid rocks of the Kara Dag massif. On the back side of the beach, a clear ledge was observed everywhere, along which alluvial clays were washed away, so that the shore was not accumulative even at the top of the bay. In the western part of the bay shore, there were small sections of the beach cluttered with stones, with rocks of volcanic origin above them. It was noted that quite significant landslides sometimes occured in this area, traces of which were visible in the structure of the coastal slope [4)].

Fig. 3. View of the western part of Koktebel Bay, photo 1914

The first significant intervention in the nature of the bay occurred in the 1920s. In 1925, a pier about 200 m long was built in its western part for loading trass (volcanic rock used to make a special type of cement) from a quarry developed nearby. The rock was extracted using blasting methods. When the material was delivered to the coast of the bay for crushing, rocks not related to trass were dumped into the water and accumulated in the coastal zone [5)]. The first embankment was built in the 1930s. During the Great Patriotic War, the German troops built up the coast with various anti-landing structures, including concrete ones, using local materials. They were dismantled after the war.

Until the mid-20th century, there were isolated small ponds in the gullies and valleys adjacent to Koktebel. In the second half of the century, most of the watercourses flowing into the bay were regulated, and about seventy reservoirs were formed, which sharply reduced the liquid and solid runoff. This was also facilitated by plowing, terracing and afforestation of the slopes adjacent to the bay. Here is a typical example: previously, an alluvial cone protruded into the water area from the mouth of the Yantiq River, the underwater continuation of which was traced on the bottom as evidenced by topographic maps of that time. Currently, this cone appears only after significant floods.

According to some data, before the regulation of the flow, the volume of removals from erosion forms had been comparable to the volume of abrasion products and erosion from coastal slopes, and it became half as much after the regulation, so less wave field sediments entered the coastal zone of the sea [17].

In the late 1950s, a new embankment with a breakwater wall was built in Koktebel, part of which was extended onto the beach. This design of the hydraulic structure subsequently played a negative role. At that time, there was still a sandy, gravel and pebble beach 20–30 m wide. It was distinguished by an unusual color due to the inclusion of pebbles from the Kara Dag rocks. It should be noted that the beach deposits were then and previously developed in an improvised manner for local construction needs, but in relatively small quantities. Beginning in 1954, industrial extraction of sand and gravel mixtures took place in the central part of the bay and on the beach. It was also carried out in neighboring areas: near the urban-type settlement of Kurortnoye, the urban-type settlement of Ordzhonikidze, in Tikhaya Bay (to the east of Cape Lagerny) and in the area of Feodosia.

The actual volumes of extraction, which continued until 1967, are unknown (according to estimates given in [14], they amounted to 1.5 million tons). As a result, the beaches began to shrink rapidly and their width in the western part of the bay was 5–10 m by the mid-1960s, and the water edge came right up to the cliff (Fig. 4).

The beach no longer provided any damping of the wave energy of even small storms. The beaches in the eastern part of the bay also became smaller. At Junge Hill, there was no beach at all and one could pass to the other side there with the help of footbridges in the water.

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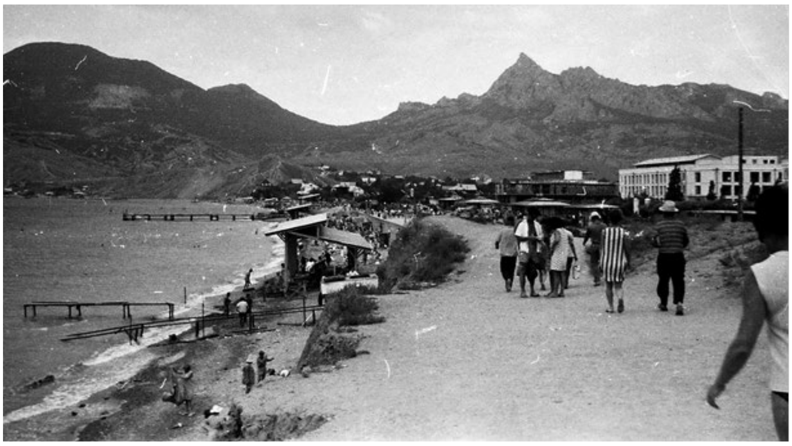
5) Rumanova, D.A., 1941. [*Report on Route Surveys of Coloured Stone Deposits and Experimental Mining of them on Mount Karadag and its Vicinity*]. Simferopol: Azchergeolupravlenie Krym. Geolbyuro, 66 p. (in Russian).



F i g . 4 . A beach in Koktebel. Photo 1965

As a result of the use of beach material for economic and construction purposes lasted for more than 10 years, an emergency situation took place on the coast of the bay. Thus, in some places, the foundation of the retaining breakwater wall was washed away. Article [15] stated that the reduction of the beaches was caused by tectonic subsidence of the Koktebel Bay land. The velocity was determined as 2 m/year based on the fact that the beaches between 1963–1967 decreased by an average of 8 m. This statement contradicts clearly existing ideas about the velocity of the Earth crust vertical movements in this area, which is approximately three orders of magnitude less.

A strong storm in January 1967 washed away the remains of the beach, collapsed the retaining walls and destroyed the embankment (Fig. 5). The coast was washed away over a stretch of more than 2 km. The Koktebel beach practically ceased its existence and the buildings located behind the embankment were under threat of destruction.

F i g . 5 . Consequences of the storm dated 13 January 1967. Photo 1967

In 1967, the Yalta Department of the GIPROKommunStroy Institute developed a project for emergency coastal protection measures, which envisaged partial restoration of the beaches by backfilling the water edge zone with imported material. The material was backfilled on the western wing of the bay in the amount of 150 thousand m^3 in approximately equal proportions of limestone rubble from the quarry of Mount Agarmysh (near the town of Stary Krym) and granite from the Donbass deposits. Taking into account the content of clay impurities, the actual volume was about 90 thousand m^3. Over 12 years, the rubble turned into pebbles. Its roundness was from 2.4 to 3.4 points on a four-point scale [6)].

As a result of the backfilling carried out in the coast sections where the width of the beach had been 2–4 m in 1966, by 1969 it had increased to 30–35 m, but the recreational properties of the previously existing beach were lost. The project envisaged the delivery of 360 thousand m^3 of beach-forming material more, but this stage of the project was not implemented.

Over a period of 13 years (1968–1981), the artificial beach material shifted almost entirely toward the center of the bay exposing the shore in the area of the municipal beach and the beach of the Koktebel Art Center. The width of the beaches in the western wing of the bay decreased significantly and the coastal zone experienced a significant increase in depth. Exposure and erosion of the bedrock were observed. The risk of destruction of the embankment in the western section of the bay arose again. To remedy the situation, several proposals were considered and an option was adopted that included the construction of coastal protection structures in six sections of the bay and the creation of a reserve backfill zone to replenish the beach in a specially designated area in the western wing of the bay. The expediency of such a solution was confirmed by the experience of 1967.

According to the 1984–1990 project of the Yalta Department of the UkrYuzhGIPROKommunStroy Institute, embankments with a stepped slope structure designed to dampen residual wave energy were built and an artificial beach was created. In addition, reserve filling of crushed stone in the amount of 144 thousand m^3 was carried out in the westernmost section of the coast. The width of the beach area along the entire length of the bay was restored. In 1988, the western section of the bay represented an artificial pebble beach leaning against the foot of the coastal slope; the width of the above-water part of the beach here reached 43 m (Fig. 6).

The implemented scheme of coastal protection structures performed its functions until the beginning of the 21st century, until capital construction began on the reserve filling area, accompanied by the degradation of the beaches. Thus, if the width of the beach on the western wing of the bay in 2002 was 22 m, then by 2004 it had decreased to 4–9 m. Let us give several examples of unauthorized construction.

In 2005, in the area northeast of the rescue station, where there was an artificial pebble beach and a prefabricated stepped slope structure made of flight slabs, part of the stepped slope structure was dismantled without permission and

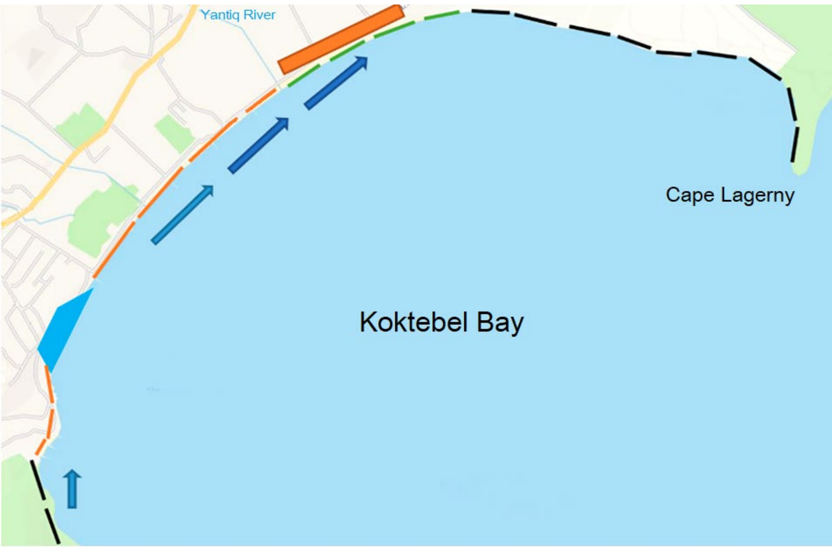
[6)] Romanyuk, O.S., 1988. [*Report on Topic "Drawing up an Inventory of the Overwater Part of the Crimean Coastline at a Scale of 1:200,000". KKGRE, IMR*]. Simferopol, 497 p. (in Russian).

F i g . 6 . An artificial beach in the western part of Koktebel Bay. Photo 1988

a vertical wall was erected. Here, part of the embankment was expanded by means of a stepped slope structure – a vertical reinforced concrete wall was erected along the abutment of the flight slabs, the sinus was filled with soil, a concrete covering was installed and later concrete tiles were laid on top of the concrete. The vertical wall installed instead of the existing slope structure contributed to the degradation of the beach, which subsequently led to its erosion and destruction. In the central part, to the west of the Voloshin House Museum, two platforms protruding into the sea were built illegally. Such transverse structures represent an obstacle to the existing flow of sediments and cause the accumulation of beach material in front of the structure and erosion behind the structure (in the direction of the flow). By 2009, this process had already been quite pronounced. Since the sediment flow is directed toward the center of the bay, the width of the above-water part of the beach northeast of the above mentioned platforms (in the area of the Voloshin House Museum) has decreased by 6–8 m in two years since the start of construction of the sites (2006); at the same time, beach material accumulated to the southwest. The structures built in the waterfront zone and extended into the sea prevented the natural movement of material and they were subjected to the intense wave action, as a result of which some of them were destroyed (Fig. 7).

When the Autonomous Republic of Crimea was a Ukrainian region, applications were repeatedly sent to administrative bodies indicating the inadmissibility of construction on the reserve filling area and the inevitability of the destruction of the constructed structures, but no effective measures were taken (Fig. 8).

Altogether, the general nature of the lithodynamic processes occurring in the bay remained unchanged throughout the 1990s and 2000s: the beach remained fairly stable in the central part of the bay; seasonal changes in the width of the above-water part of the beach were within 5 m with a beach width of up to 45 m; steady degradation of the beach was observed in the southwestern part (the reserve filling area).



F i g . 7 . Lithodynamics diagram. Black dashed line – areas of abrasion, orange one – coast retreat, green one – a relatively stable coast. Orange rectangle – place of sand extraction, blue trapezoid – place of reserve filling. Arrows – average long-term direction of sediment movement

F i g . 8 . Reserve filling area. Photo 2021

In the last decade, it has become possible to analyze changes in the coastline using satellite images. To determine the change in beach width between 2009 and 2021, we use satellite images from this time and the results of surveys conducted in September 2009 and November 2021. A total of 15 images with a resolution of 0.6 m per pixel were used for the analysis.

The width of the beach to the west of the reserve filling area has hardly changed. Over the past period, it has fluctuated within 1–3 m, i.e. at the threshold of the method accuracy. It was difficult to determine the seaward boundary due to the boulders in the watershed zone. The reserve filling area is a pile of remains of reinforced concrete structures built at different times. The natural and later artificial beaches that existed here disappeared without a trace. By 2017, the buildings at the foot of Kilovaya Mountain had been almost completely destroyed by the sea. To the west of the Koktebel embankment, the width of the beaches was 9–13 m in 2009; in 2021, it remained unchanged. In fact, the beach has shrunk on the embankment from 9–18 m to 2 m (in the area of the illegally constructed platform), and in the eastern part of the embankment – to 8–12 m. At the same time, the interannual variability of the beach width in this section of the coast was about 5–6 m.

An analysis of the change in the beach area reduced to its length showed that for the period 2009–2021, on average, the width of the beaches along the embankment decreased by 4.8 m. In 2021, the width of the beach near the Voloshin monument was 10 m. To the east of the embankment, according to satellite images for 2008–2020, the configuration and width of the beach remained almost unchanged; in 2021, the beach was 15–20 m wide.

Further east, to Junge Hill and further east, the width of the above-water part of the beach ranged from 33 to 42 m according to a 2009 survey and satellite images. During this time, the width of the beach changed insignificantly (1–2 m). By 2021, the configuration of the coastline and the width of the beaches had hardly changed.

Further east, right up to the beginning of the cliff, the beach has gradually decreases. Its width and configuration of the coastline remained almost unchanged over the period 2009–2021 according to satellite images and survey materials from November 2021. In the area of the beginning of the cliff, the beach width in 2021 was 12 m, which corresponds to the 2021image. Further east, over a distance of 1 km, the abrasion coast in 2011–2021 retreated at an average rate of 0.7 m/year (Fig. 9). The rate of retreat of the coastline of the western part of Cape Lagerny during the same period was two times less – about 0.3 m/year.

Summarizing the results of the analysis of satellite images for 2011–2021 in comparison with the survey data of 2009 and 2021, it can be said that there were no changes along the greater length of the coastline of the urban-type settlement of Koktebel. At the same time, the beach completely disappeared in the reserve filling area and it decreased by 6–8 m in the area of the embankment.

During this period, the beach material of the central part of the bay was replenished due to the erosion of the bottom in the western section in the area of Kilovaya Mountain. This material moved in the eastern direction and as a result, the water line in the area of Voloshin house was relatively stable, while the depth

F i g . 9 . Satellite image of the eastern part of Koktebel Bay in the area of the observation deck (September 2011). Red line – coastline in August 2021. Black lines – roads in August 2021

in the collapse zone in the area of Kilovaya Mountain increased significantly. It can be said that after the artificially created deficit of beach-forming sediments and the subsequent creation of artificial beaches in the coastal zone, a new state of dynamic balance was established, in which the volume of sediments on natural beaches in the long-term regime remains more or less constant and changes in either direction are temporary.

Conclusion

Thus, the anthropogenic impact on Koktebel Bay over the last 100 years has led to a reduction or disappearance of beaches, change in their material composition and replacement of the natural landscape with an anthropogenic one, which has reduced its aesthetic attraction.

Three periods can be distinguished in the evolution of the coastal zone of Koktebel Bay. In the first (starting from the 1920s), anthropogenic impact on the landscapes of the land and coastal zone increased gradually. In the incoming part of the sediment balance, solid runoff of watercourses and coastal abrasion prevailed, and sediment accumulation prevailed in the outgoing part. Some increase in solid runoff associated with anthropogenic impact on landscapes and the development of accelerated erosion was compensated by periodic removal of small volumes of sediment from the beaches for local construction needs.

During the second period (from the middle of the 20th century), the established dynamic balance was disrupted and the sediment balance became negative. This was stipulated by the regulation of the runoff and industrial extraction of sand, gravel and pebbles in the coastal zone. This impact led to a sharp decrease in the width of the beaches, up to their complete disappearance in some areas.

The third period (from the last quarter of the 20th century to the present) is characterized by a sharp increase in anthropogenic impact, which was expressed in the active (often illegal) construction of various structures on the beaches to protect and restore the beaches by erecting hydraulic structures. In the incoming part of the sediment balance, such a component as artificial beach filling appeared, which partially compensates for the sediment deficit. A new dynamic balance has been established in the coastal zone over the past 10 years. By now, man-made shores occupy about 3 km, where natural processes have transformed into natural-anthropogenic ones. Natural coastal landscapes have been preserved only in the eastern (about 2 km) and western (about 1.5 km) parts of Koktebel Bay. The engineering load coefficient (the ratio of the total length of engineering structures to the length of the coast) for Koktebel Bay is currently 0.4.

It should be noted that artificial beaches remained the only way to preserve the coast of Koktebel Bay. However, they also have some disadvantages. Thus, the operation of artificial beaches must be accompanied by long-term additional costs for backfilling the material. Concrete structures reduce the aesthetic attraction of the coast and worsen water exchange in the water area (for example, three groins in the western part of the bay). The ability of water to self-purify in the bay is limited, especially in summer, which significantly worsens the quality of sea water and sanitary and epidemiological situation. Coarse debris of artificial beaches is less comfortable for recreation. Abrasion of crushed stone is accompanied by additional flow of suspended matter into the water area, decrease in water transparency and change in the composition of bottom sediments, which also affects the benthos negatively.

Therefore, when developing a new project for the reconstruction of the embankment and restoration of the beaches of Koktebel Bay with a total length of 1850 m, these provisions were taken into account. Thus, the original project provided for the construction of a system of groins. As a result of numerous discussions, including ones with the participation of employees of MHI, this project was rejected and another version was adopted. It provides for the construction of one groin 70 m long and backfilling of the beach with a width of 35 to 45 m. The groin located in the western part of the bay should limit the movement of beach material in the western direction and at the same time should not distort the natural landscape of Koktebel Bay significantly. Taking into account the movement of beach material, the criterion for assessing the need to replenish the beach area will be the width of the beach in the groin area. The beach material recommended by the project is gravel with a fraction of no more than 40 mm. Reconstruction of the embankment began in 2023 and is expected to be completed at the end of 2024.

In conclusion, we want to note that the number of vacationers to Koktebel Bay and consequently the economy of the region will depend on the ecological state of the coastal zone of the sea and its provision with comfortable beach resources, landscape diversity and coast attractiveness. Under the conditions of land private ownership, the state must regulate issues related to the strengthening of the coast, protection of the coastal zone and coast of resort and recreational regions. It is necessary to use modern effective methods and technologies to protect the coast that do not violate the landscape appearance of the territory and the ecological state of coastal waters.

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