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Original article

Transformation of the Lake Bogaily Barrier Beach (Western Crimea) under the Influence of Extreme Storms

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Abstract

Accumulative marine coastal forms of the Azov-Black Sea basin are a key element of coastal abrasion-accumulative geosystems and a valuable commercial resource. Monitoring of the accumulative forms dynamics in the region is a necessary component for successful management of the coastal zone and timely adoption of measures for coastal protection. The purpose of the work is to determine the qualitative and quantitative characteristics of the transformation of the Lake Bogaily Barrier Beach influenced by storms, in particular the extreme storm of November 26–27, 2023. The work uses materials from long-term monitoring observations, satellite images, simulation results of hydrological and lithodynamic processes, literary and archival sources. It was established that in the last 60 years the configuration and topography of the studied accumulative form have changed significantly. Periods were noted when the morphological and dynamic features of the accumulative form did not undergo fundamental changes as well as periods of their significant transformation. In particular, during the storm on November 26–27, 2023, the configuration and topography of the Lake Bogaily Barrier Beach was completely redesigned. The paper reveals characteristic features of the accumulative form dynamics during the storm. The accumulative body was displaced into the water area of the lake. The magnitude of this displacement significantly exceeded that of the retreat of the adjacent bedrock shores. The longitudinal and transverse structure within the barrier beach that existed for several decades has been completely transformed. It is concluded that any extreme storms play a decisive role in the variability of coastal accumulative forms in the region.

Keywords: Black Sea, Crimean Peninsula, coastal geosystem, barrier beach, accumulative form, extreme storm, coastal relief, coastline

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Трансформация пересыпи озера Богайлы (Западный Крым) под воздействием экстремального шторма

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Аннотация

Аккумулятивные морские береговые формы Азово-Черноморского бассейна являются ключевым элементом береговых абразионно-аккумулятивных геосистем и ценным хозяйственным ресурсом. Мониторинг динамики аккумулятивных форм региона является необходимой составляющей успешного управления береговой зоной и своевременного принятия мер по защите берегов. Цель работы – определение качественных и количественных характеристик трансформации пересыпи оз. Богайлы под действием штормов, в частности экстремального шторма 26–27 ноября 2023 г. Использованы материалы многолетних мониторинговых наблюдений, спутниковые снимки, результаты математического моделирования гидрологических процессов, литературные и архивные источники. Установлено, что в последние 60 лет наблюдались значительные изменения конфигурации и рельефа изучаемой аккумулятивной формы. Отмечены периоды, когда морфологические и динамические особенности аккумулятивной формы не претерпевали принципиальных изменений, и периоды ее значительной трансформации. В частности, во время шторма 26–27 ноября 2023 г. конфигурация и рельеф пересыпи оз. Богайлы были значительно изменены. Выявлены характерные черты динамики аккумулятивной формы в ходе шторма. Произошло смещение аккумулятивного тела в акваторию озера, величина этого смещения существенно превысила величину отступания прилегающих коренных берегов. Преобразована существовавшая несколько десятилетий продольная и поперечная структура в пределах пересыпи. Сделан вывод, что экстремальные по тем или иным характеристикам штормы играют определяющую роль в изменчивости береговых аккумулятивных форм региона.

Ключевые слова: Черное море, полуостров Крым, береговая геосистема, пересыпь, аккумулятивные формы, экстремальный шторм, береговой рельеф, береговая линия

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Introduction

Shirshov Institute of Oceanology of RAS and Marine Hydrophysical Institute of RAS have been engaged in research into the dynamics of the Azov–Black Sea coasts for several decades. Particular attention is paid to the investigation of the formation and transformation of coastal accumulative forms, encompassing spits and barrier beaches [1–3].

The combination of anthropogenic and natural factors, particularly storm impacts, has resulted in the transformation of coastal accumulative forms, in some instances leading to their degradation [1]. It is indicated in [4] that transformations of sandy beaches, defined as seasonal, can occur as a result of a single storm event. An improved version of the CROSS P storm deformation model was proposed in [5], incorporating the impact of overflow over the foredune during storm surges. The modelling results demonstrated that during periods of overflow across the foredune, a portion of the transported sediment was transferred to the rear slope. This resulted in a gradual inland migration of the dune belt, accompanied by a decrease in height. The potential for material transport to the rear of the barrier beach and the possibility of its displacement towards the lagoon as a result of an extreme storm are also discussed in [6]. In [7], it was demonstrated that the XBeach model is capable of accurately simulating morphological changes, including those induced by storm activity, such as erosion of dunes and beaches. In [8], the XBeach mathematical model was employed to examine the effects of storm waves on the Lake Bogaily area. The findings revealed that these waves induce significant beach erosion and active reformation of the upper part of the underwater coastal slope. The objective of this study was to obtain quantitative estimates of the water edge retreat rate and bottom topography deformation values for different wave exposure times.

Extreme storm surge tends to have the strongest effect on the redistribution of material in the coastal zone. There are known cases [9] when the volumes of flows transverse to the shoreline reached 200 m^3/m, leading to significant changes in the relief of the accumulative form. However, recent studies [10, 11] have shown that extreme storms can redistribute sediment and, in some cases, stabilise shorelines. The results presented in these studies demonstrate the complex and not always predictable nature of storm effects on accumulative forms.

It is uncommon for extreme storms to occur, and the scientific observations of the transformation of marine coastal accumulative forms in the Azov–Black Sea region as a result of such events are limited in number and nature. No such purposeful observations have been conducted along the coastline of the Crimean Peninsula. Furthermore, there has been an observed increase in the frequency and intensity of storm waves in the Azov–Black Sea basin [12, 13].

In November 2023, the Black Sea was under the influence of a series of deep Mediterranean cyclones. Winds of up to 40 m/s were observed over most of the water area. A storm wave was formed on 26–27 November 2023, exhibiting numerous parameters that surpassed those observed in the region earlier that same year. This allows us to categorise the event as an extreme natural phenomenon [14].

It is relevant to consider the impact of an extreme storm on the Bogaily Lake Barrier Beach in the context of the development of this accumulative form over the past 60 years. The objective of this study is to determine the qualitative and quantitative characteristics of the transformation of the Lake Bogaily Barrier Beach in response to the impact of an extreme storm on 26–27 November 2023.

Materials and methods of research

For the study region (Fig. 1), the first available remote sensing materials are space images from the 1960s–1980s [1]. Satellite images of different years from open sources (Google Earth, Yandex, Bing, etc.) were used to analyse the coastal dynamics. For operational assessment of changes caused by the storm on 26–27 November 2023, data from the Sentinel-2 spacecraft of the European Space Agency were used [2, 3]. To achieve accurate spatial referencing, geometric correction of satellite data was performed. The 9+ GCP (Ground Control Points) polynomial method was used for geometric correction of the images. To improve accuracy, the number of points was significantly increased (more than 20 GCPs were used most often), and they were distributed evenly over the area of the corrected image [15]. Subsequently, for each image, the accuracy of the acquired vector data was evaluated using reference linear objects (street networks and airfield runways) situated in proximity to the coastal area under study. The line of the sea edge and, if possible, the lagoon and cliff edge were digitised based on the multi-temporal images presented in these resources. Taking into account the steep sea slope of the beach, the maximum possible sea level rise at the storm peak of about 0.4 m, as well as the low intensity of surge events, the change in the planned position of the shoreline as a result of sea level fluctuations is significantly lower than the accuracy of measurements. As a result of this work, information on the dynamics of the shoreline and other morphological elements of the studied natural objects in different periods was obtained.

In order to undertake an in-depth examination of the relief and associated dynamics, the generation of digital elevation models was essential. In fulfilling this task, materials from aerial surveys carried out using unmanned aerial vehicles (UAVs) were used. A combination of planned and panoramic surveys was conducted in areas with cliffs [16–18]. High-accuracy digital relief models (DRMs) and orthophotomaps were constructed utilising photogrammetric image processing technology. The Agisoft Metashape software was employed to generate high-quality 3D models of objects and orthophoto maps based on digital photographs.

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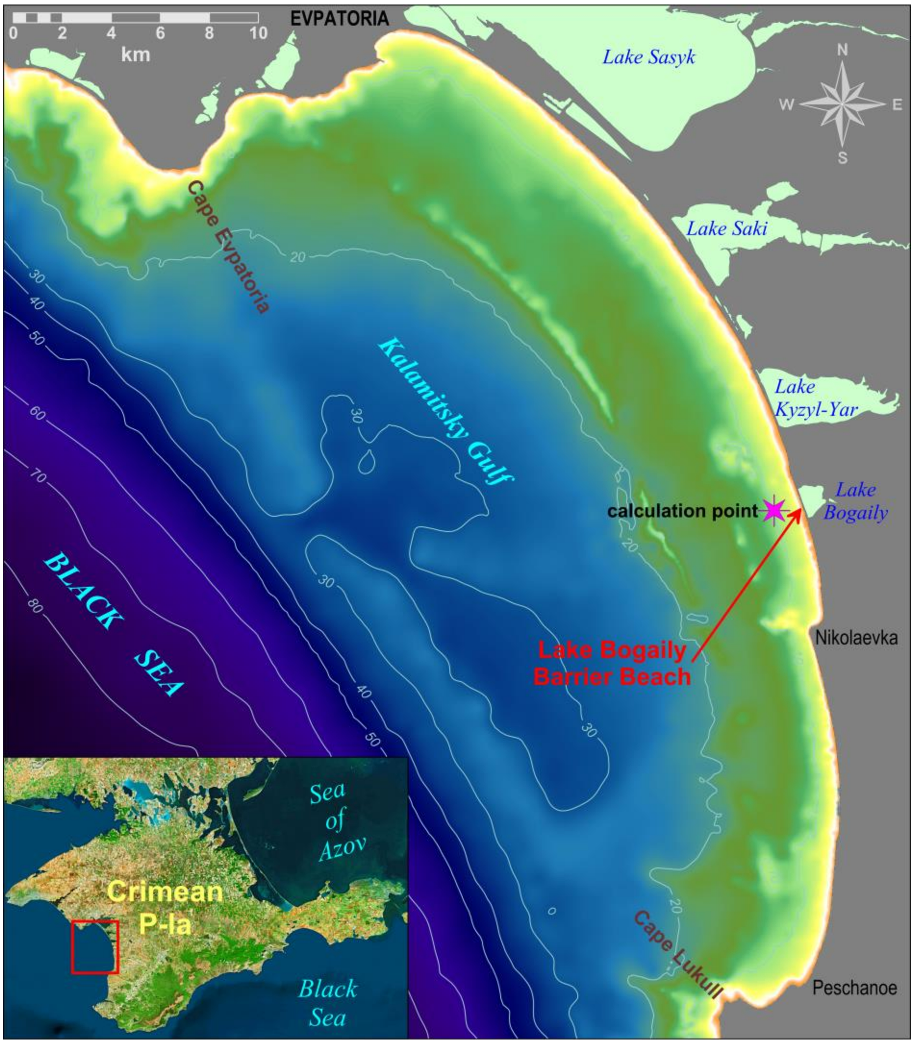
[1] U.S. Department of the Interior U.S. Geological Survey (USGS). Available at: http://earthexplorer.usgs.gov [Accessed: 30 August 2024]

[2] MultiSpectral Instrument (MSI). Available at: https://sentinel.esa.int/web/sentinel/missions/sentinel-2/instrument-payload [Accessed: 30 August 2024]

[3] The operational Copernicus optical high resolution land mission. Available at: http://esamultimedia.esa.int/ docs/S2-Data_Sheet.pdf [Accessed: 30 August 2024]



F i g . 1 . Map-chart of the Kalamitsky Gulf in the Black Sea (data on underwater topography are given using SonarChart™ materials (https://webapp.navionics.com)). The calculation point is the point for which the main wave parameters were calculated

TerraScan Bentley MicroStation module was used to classify photogrammetric point clouds [4)]. The digital images obtained from UAVs were processed to create orthophotos with a resolution of 0.05 m and digital relief models (DRMs) with a grid step of 0.15 × 0.15 m. These materials were employed in the analysis of the topography of the barrier beach.

In addition to remote sensing materials, data of granulometric analysis of beach and bottom sediment samples, morphometric characteristics, geobotanical descriptions obtained during expedition works, as well as archival cartographic materials were used.

The climatic characteristics of wind waves in the Black Sea were calculated using the modern spectral wave model MIKE 21 SW [19] [5)]. A full description of the model, as well as the issues of model verification and tuning are described in [19]. Based on the results of calculations, an array of spatial fields of surface wave parameters was formed with a discreteness of 1 h covering the entire sea area for the period from January 1979 to December 2023.

General characterisation of the Lake Bogaily Barrier Beach

Lake Bogaily is situated in the central region of the Kalamitsky Gulf (Fig. 1), representing an estuary formed at the convergence of the Sukhaya and Bogaily gullies. The lake has a surface area of approximately 0.95 km², with a maximum depth of 20–40 cm near the barrier beach for the majority of the year. The lake barrier beach is 1.4 km in length and 40–70 m in width. The accumulation formation is sustained by sedimentary material derived from the abrasion of the adjacent bank structures on either side. The area is characterised by cliffs reaching heights of up to 8–10 m, comprising clay deposits interlayered with sandstones, gravelites and conglomerates of ancient alluvial origin. The structure of cliffs is described in great detail in [2]. It can be observed that the migration of material typically occurs within a narrow nearshore zone. However, the formation of submarine shafts was not noted. A mixture of fine and medium sand with fine gravel is the predominant composition on the marine underwater slope of the barrier beach, at a depth of 1–1.5 m. Deeper than 2.5 m, siltstones become the predominant composition. In the depth range of 2 to 4 m, no particles larger than 0.25 mm were observed in the samples. It can be concluded that the zone of migration of beach-forming sediment in the area of the Lake Bogaily Barrier Beach is limited to isobaths of 2–2.5 m. Furthermore, it has been observed that fine-grained silty fractions accumulate at greater depths [20].

The barrier beach constitutes part of the Kalamite lithodynamic system of order I [21], which extends between Cape Lukull and Cape Yevpatoria (Fig. 1). The resulting longshore sediment flow is directed northwards as far as Yevpatoria Bay [22]. However, in some areas the direction and intensity of longshore sediment flow is characterised by considerable seasonal and interannual variability [23].

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4) Sentinel Online technical website. Available at: https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-2-msi/level-1c/product-formatting [Accessed: 30 August 2024].

5) DHI Water&Environment. MIKE21/3 Coupled Model FM, 2007. 190 p.

The cliff, and with it the shoreline at Lake Bogaily, is actively retreating. Satellite data show that between 1984 and 2016, the cliff retreated an average of 42 m along the abrasion section north of the barrier beach, and the barrier beach retreated 30–35 m inland. Thus, the rate of retreat of the seashore of the barrier beach is close to the rate of retreat of the adjacent cliffs. The rate of the process in the multiannual regime varies significantly depending on the frequency and strength of storms.

The multiannual regime is dominated by the west-southwest swell [24]. An analysis of the distribution of heights and periods of significant waves over 30 years [25] has shown that the highest wave heights in the adjacent Black Sea area can reach 5.5–6 m with a period of 6.5–7 s during the autumn-winter period. Between April and September, the average monthly height of significant waves does not exceed 4 m and corresponds to the minimum of wind activity. In the area of the Barrier Beach of Lake Bogaly, there are two dominant directions of approach of significant waves (from the northeast and southwest), which determine the reversible nature of the sediment movement along the shore. Mathematical modelling [24] suggests the existence of two sediment flows towards each other with the formation of a convergence zone at the barrier beach in summer [24]. It is likely that the two-way movement of sediment predetermines high shoreline variability in some areas, but increases the stability of the accumulation body as a whole due to the input of sediment from adjacent abrasion areas under all wave conditions.

Prior to the storm of 26–27 November 2023, the cross-sectional profile of the Bogaily Lake Barrier Beach was based on a full profile sand and gravel beach [2]. There were three longitudinal zones within the barrier beach: the beach zone, the ridge zone (dune and vegetation zone) and the estuary zone. The width and other morphometric parameters of these zones changed from time to time, but the general structure of the relief was preserved for decades. Thus, the width of the beach (up to the vegetation strip and the dunes) was 30–40 m. The beach near the shoreline is composed predominantly of gravel, while up the slope it is composed of medium-grained sand. Changes in the topography within the beach during the normal regime were characterised by alternating areas of surface rise and fall or widening and narrowing of the beach due to shoreline migration. Even small storms caused a change in the cross-sectional profile of the beach, most commonly in the nearshore zone. Formation and subsequent destruction of storm rolls and terraces was most commonly observed. In some parts of the barrier beach, formation of washout scarps up to 1 m high was recorded during strong storms accompanied by an increase in longshore currents.

The uplifted part of the barrier beach was originally the crest of a full profile beach (1.8–1.9 m above sea level). As vegetation developed along it, accumulative aeolian forms were formed. In recent decades, until the storm of 26–27 November 2023, a dune ridge up to 0.5 m high (2–2.5 m above sea level), covered with herbaceous vegetation characteristic of coastal aeolian forms, existed along the crest of the barrier beach. Some parts of the dune ridge were separated by depressions – scour holes – where waves overtopped during strong storms. During these periods there was an increase in the width and depth of the scour hole, partial destruction of the aeolian moulds along its sides, and removal of material to the lagoonal shore of the barrier beach and into the lake. In addition to storm damage, the top of the barrier beach has been subject to anthropogenic impacts from vehicle traffic, with significant damage to the relief of the aeolian forms and vegetation.

During the most severe storms, the transfer of gravel and sand material from the seashore to the lakeshore by wave splash has been recorded within the scour holes. This process can be considered as an element of the sediment budget for the shore adjacent to the Lake Bogaily Barrier Beach. In the vicinity of the scour holes on the lake shore of the barrier beach, export cones were formed which determined a peculiar configuration of the lake shore in the form of festoons. No active redistribution of the incoming material along the lake shore was observed, which can be explained by insufficient wave intensity. The near shore depression, except for the cones, was covered with halophytic herbaceous vegetation, which in dry years forms the part of the dried lake bed adjacent to the barrier beach. A berm of vegetation and debris was observed along the lake shore. Until the 1970s, Lake Bogaily was salty and periodically dried up. Subsequently, the discharge water from the poultry farm commenced flowing into the lake, resulting in the lake becoming full year-round. In the southern part, there was a pipeline for the discharge of freshwater and the conveyance of wastewater, which has since been destroyed. Following a reduction in discharge during dry years, the lake dries up completely again in summer.

Dynamics of the shoreline and relief of the Lake Bogaily Barrier Beach

The available archival cartographic materials and satellite images allow us to distinguish several characteristic periods in the development of the accumulative body of the Lake Bogaily Barrier Beach.

In some maps of the nineteenth century, the lake is depicted as a sea bay, with Kichik-Bel Island situated along the line of the modern barrier beach. During this period, it would appear that there was no continuous barrier beach in existence; the lake was connected to the sea by a strait (or straits) of variable width.

The space images of 19 July 1963 and 19 September 1968 reveal the presence of a scour between the lake and the sea in the southern part of the barrier beach, although its precise location varies. It is likely that the cause of this phenomenon is anthropogenic.

The analysis of space images allows us to state with a high degree of confidence that the structure of the over-water body of the barrier beach was completely different to what it became later, at least between the years 1963 and 1968. The images of 19 July 1963 and 19 September 1968 (Fig. 2) demonstrate that the shorelines on the sea and lake sides are straight and almost parallel, and that the barrier beach, with an average width of 80 m, exhibits minimal transverse hydrogenic forms, with the exception of a large scour in the southern part. The longitudinal zones are evident in the structure of the coastal embankments and vegetation along the barrier beach.

An alternative perspective is offered by the image of 21 June 1975. The width of the barrier beach ranges from 60 m in the north to 40 m in the south, which is associated with the elevated water level in the lake. The seaward shoreline remained straight, but the lake shoreline became curved, especially in the southern part.

The longitudinal structure shows a curved shoreline berm crest with no evidence of vegetation, indicating that storm surge has impacted the entire surface of the barrier beach. The most probable cause of these changes is the extreme storms recorded during 1969 [26–28].

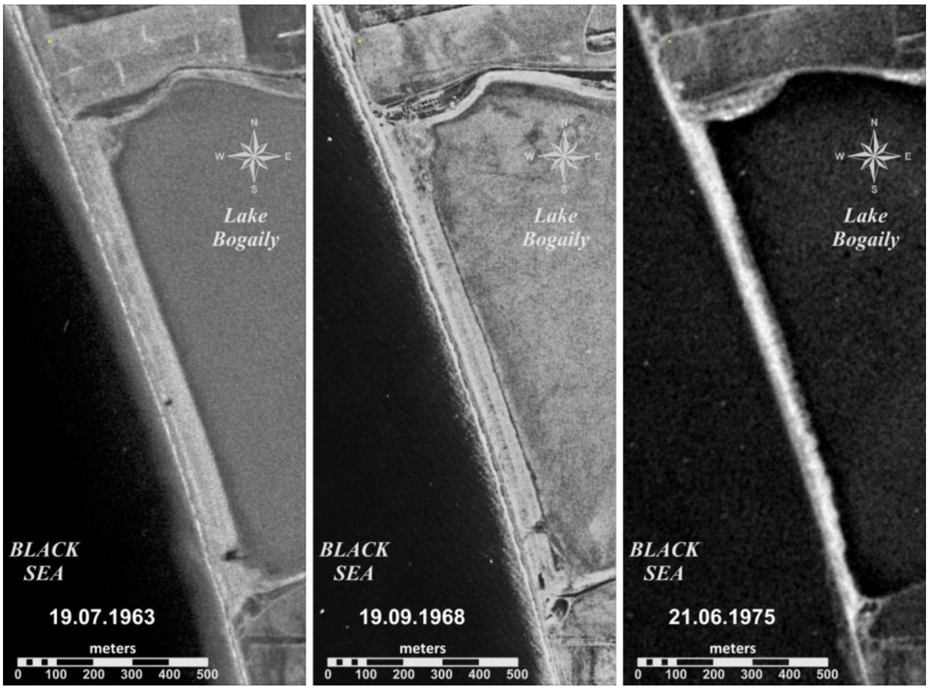
The image dated 31 July 1984 (Fig. 3) illustrates the restoration of the barrier beach structure in the form of a beach strip, a dune ridge with developed lagoonal slope vegetation, and a drying strip with emergent vegetation along the lakeshore. The width of the barrier beach varies from 40 m in the southern part to 60 m in the northern part. The seaward edge line is almost straight, with a few gentle bends in the southern part of the lake edge line. Trails traversing the dune and vegetative bands are discernible, yet there is no indication of substantial transverse scouring or evidence of drift cone formation along the lakeshore.

Unfortunately, detailed images of the period 1984–2005 could not be located. As a result, it is challenging to determine the extent to which the extreme storm of 15 November 1992 impacted the Barrier Beach of Lake Bogaily.

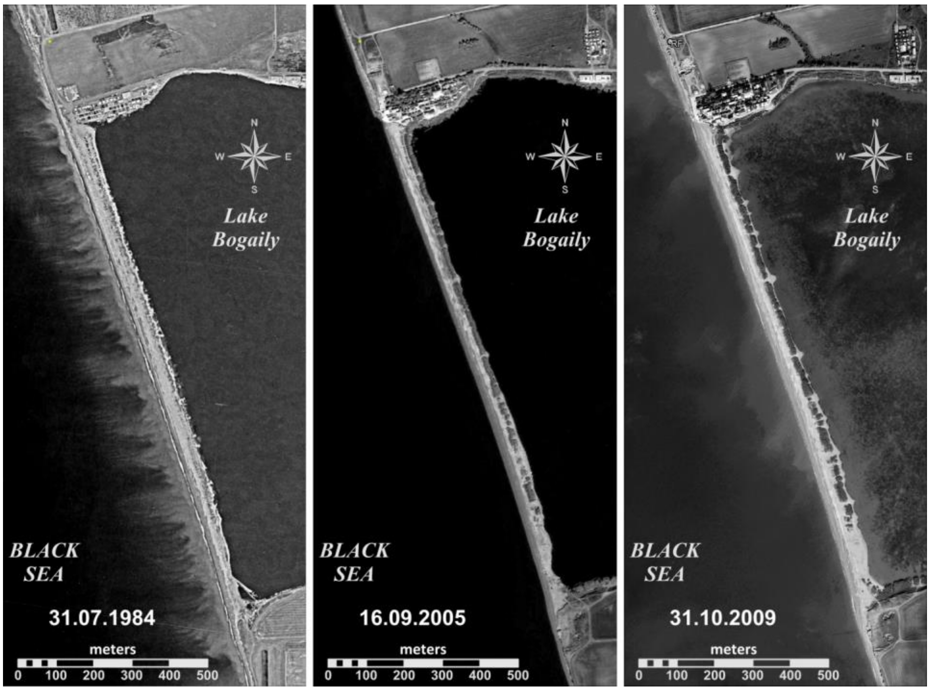
The configuration of the barrier beach (Fig. 3) in the 2005 image is very similar to that observed in 1975, showing a levelled sea-front line and a curved lake-front line. The width of the barrier beach at two-thirds of the northern extent is approximately 50 m, subsequently increasing to 60 m. Thereafter, at approximately 100 m from the southern boundary, there is a notable narrowing to 30 m. In the longitudinal structure, the strip of beach, dunes and adjacent vegetation is clearly discernible. The width of these zones along the barrier beach varies in a gradual manner without exhibiting abrupt changes. The 08 May 2005 image also displays transverse scour holes that separate the vegetation strip. The largest of these holes on the lagoonal shore correspond to export cones. The general configuration of the sea and estuarine banks in the image dated 31 October 2009 (Fig. 3) has remained largely unchanged in comparison with the image dated 08 May 2005. However, the export cones are now much more visible and are present at the majority of scour holes. It can thus be concluded that the extreme storm of November 2007 did not have a significant impact on the morphological structure of the Lake Bogaily Barrier Beach. Rather, its impact was limited to the expansion of scour holes and export cones. As illustrated in Fig. 4, the aforementioned structure was largely preserved until the November 2023 storm.

One should note significant variations in the mean annual rate of sea level retreat. Fig. 5 shows that in 1963–1984 the shore retreated insignificantly – from 5 m in the central part of the barrier beach to 15 m in the areas adjacent to the bedrock shore. The rate of shore retreat was considerably more pronounced between 1984 and 2005 (Fig. 5). The retreat is 25–30 m along the barrier beach and to the north of it, and 20 m along the cliff to the south of the barrier beach. It is important to note the impact of the cross structure (reinforced concrete boathouse) at the junction of the northern part of the barrier beach with the cliff. The filling of the inlet corner to the north and the downward scour to the south of the structure are clearly visible. The impact of this structure can be observed in subsequent periods, even in instances where it has undergone partial destruction. It is noteworthy that there were instances when the position of the inlet corner and the downstream scour zone were reversed.

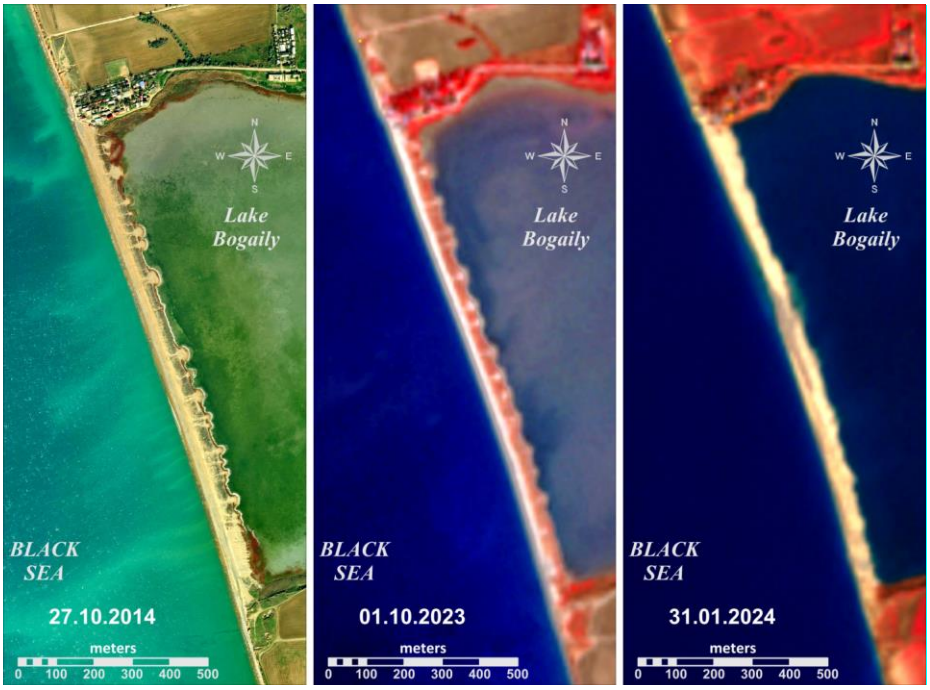
In view of the distribution and composition of sediment on the submarine slope along the Lake Bogaily Barrier Beach and adjacent abrasion-prone bedrock



F i g . 2 . Development of the Lake Bogaily Barrier Beach in 1963–1975

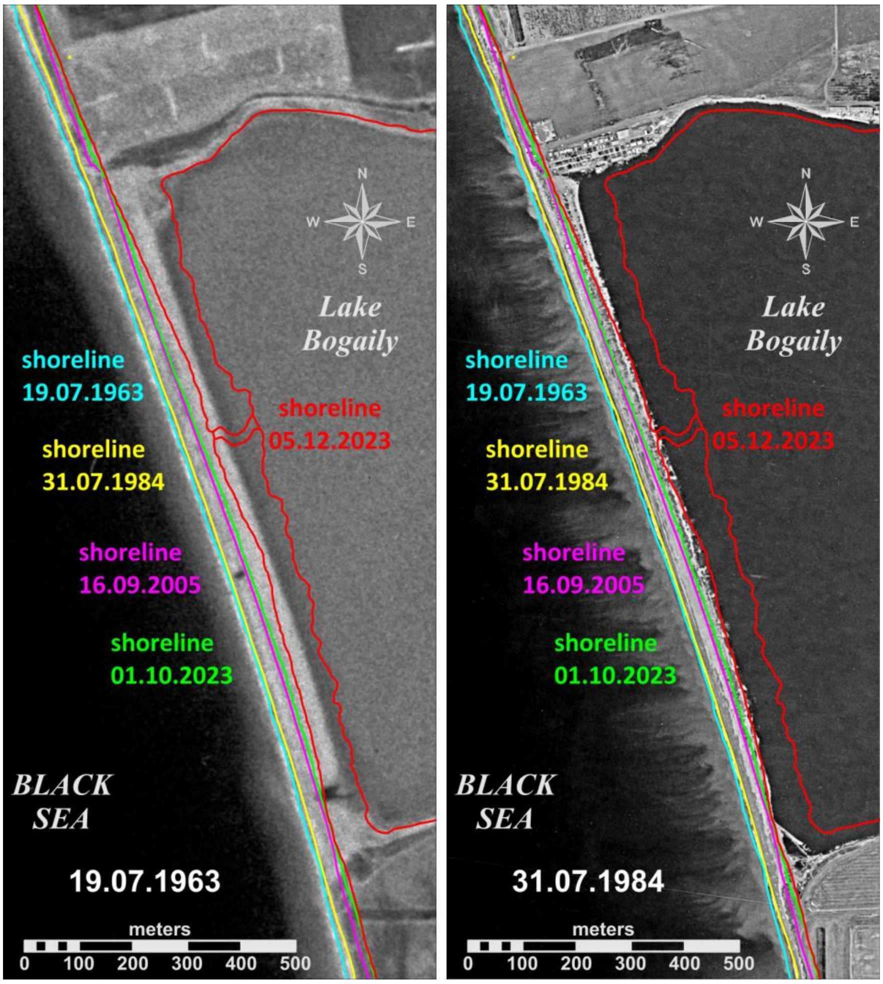


F i g . 3 . Development of the Lake Bogaily Barrier Beach in 1984–2009



F i g . 4 . Development of the Lake Bogaily Barrier Beach in 2014–2024

shores [20], as well as analyses of remote sensing data, it can be concluded that the actual capacity of the longshore sediment flux is relatively small. It is worth noting here that from the 1960s onwards the sediment flow in the system has been decreasing, due to river regulation, the blocking of cliffs by bank protection structures, the construction of transverse structures and other factors. The southern boundary of the lithodynamic system, which encompasses the overflow of Lake Bogaily, can currently be identified as an unnamed cape situated in the southern region of the Nikolaevka settlement. This is characterised by a system of two groins. In contrast, the northern boundary is represented by the transverse structure of the water intake at Lake Kyzyl-Yar. The absence of substantial sedimentary deposits within the lithodynamic system, mobilised by storms of varying directions and with a notable longshore component, contributes to the absence of significant fluctuations in the volume of material arriving at the barrier beach. This determines the relative flatness of the seaward edge of the barrier beach and uniformity of the transverse profile along its entire length. The absence of bends in the shoreline and underwater slope favours uniform distribution of wave energy and increases the overall stability of the overwater part of the accumulative form. This is probably the reason why the position and configuration of scour holes and associated drift cones on the lagoonal shore have been stable for several decades. In recent decades, significant wave damage to vegetation along the sea slope of the dunes and on the sides of stationary scour holes has rarely been observed.



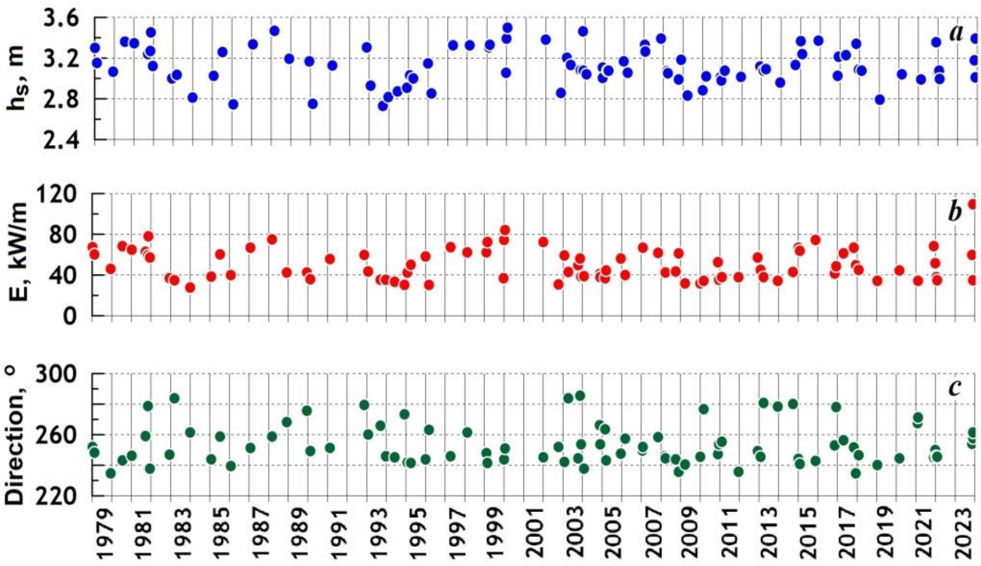
F i g . 5 . Development of the Lake Bogaily Barrier Beach in 1963–2023

Characteristics of the 26–27 November 2023 storm

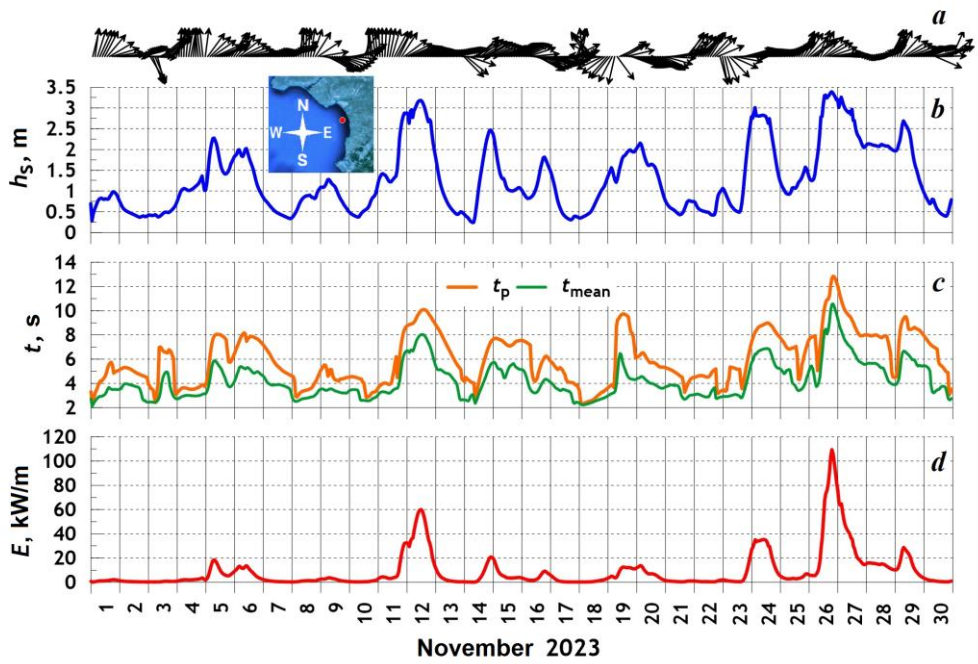
To analyse the nature of storm impact on the shore, the main wave parameters (significant wave heights, spectrum peak periods, average propagation directions) were calculated. The calculation point was located 4500 m from the shore at an isobath of 10 m (see Fig. 1). In addition, wave power was calculated, which is a representative characteristic because it depends on two integral wave parameters, namely wave height and wave energy period. In essence, the power period is the period of a monochromatic wave with a power equivalent to the power of a given irregular swell. The power of a wave is expressed in kilowatts per metre of wave front.

Fig. 6 shows the maximum wave heights and power in individual storms over the past 45 years in the area of the Lake Bogaily Barrier Beach. The selection was limited to storms with significant wave heights exceeding 2.5 m. It is acknowledged that the selection of an appropriate threshold level is always a matter for debate. In this instance, the objective is to identify the most intense storms that occurred in a specific year from a multitude of storms. As can be seen from Fig. 6, the 2023 storm is the most powerful in terms of energy over the past 45 years, with wave heights slightly inferior to those recorded, for example, in 1981, 1988, 1999 and 2003.

Fig. 7 shows a series of significant wave heights, periods, strengths and directions at the Lake Bogaily Barrier Beach for November 2023. It shows that the Lake Bogaily Barrier Beach was under the influence of developed wave action for almost the entire month. Three storms with power greater than 30 kW/m were observed, including an extreme storm on 26–27 November. As shown in Fig. 6, *b*, this storm is the strongest in terms of power (109 kW/m) for the Lake Bogaily Barrier Beach in the last 45 years. Previously, the strongest storm was the storm of 2000 (82 kW/m). At the time of the largest storm development on 26 November 2023 at the isobath of 10 m near the Barrier Beach of Lake Bogaily, the wave parameters were as follows: significant wave height – 3.4 m, period – 12.8 s, length – 160 m. The surge height during the storm was 0.21–0.54 m.



F i g . 6 . Parameters of the largest storms near the Lake Bogaily Barrier Beach: *a* – maximum significant wave heights; *b* – maximum wave power; *c* – general directions of storms

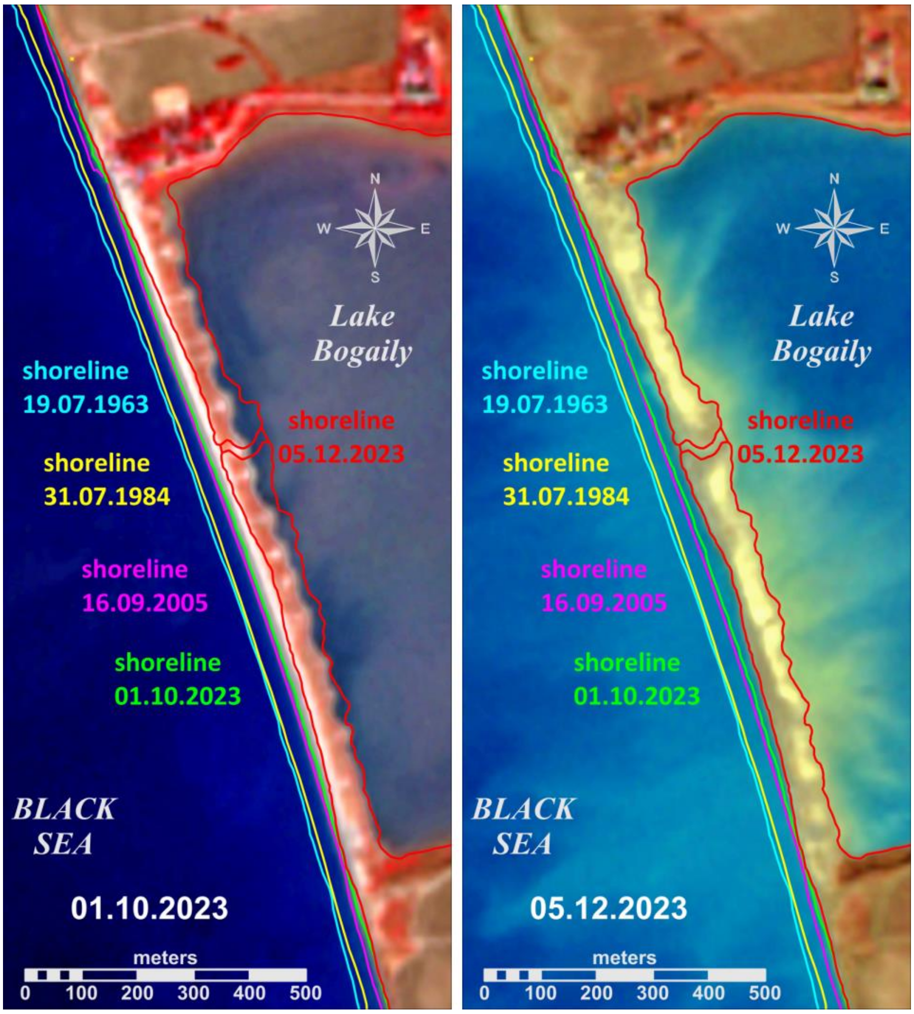


F i g . 7 . The main parameters of wind waves near the Lake Bogaily Barrier Beach: *a* – propagation directions; *b* – significant wave heights; *c* – peak and mean wave periods; *d* – wave power

Realignment of the barrier beach topography during the storm of 26–27 November 2023

It is clear that the storm of 26–27 November 2023 is an extreme storm in terms of the scale and nature of the changes to the configuration and relief of the Lake Bogaily Barrier Beach on a scale of several decades. Direct wave action with overtopping of the beach crest was observed along the entire length of the barrier beach. The transfer of material from the seaward to the lagoon side of the barrier beach shifted the seaward edge line to the east (Fig. 8). The seaward retreat of the seaward side of the barrier beach near the abutment to the cliffs of the rocky shore was 5–10 m, which is close to the amount of storm induced cliff retreat. In the central part of the barrier beach, the retreat increases to 20 m, and in the area of the formed rill and slightly to the north, the retreat exceeds 30 m, even with subsequent coastal levelling. The magnitude of the retreat can be estimated by comparing it with a 60-year (1963–2023) retreat of 40–45 m (Figs. 5, 8).

It should be noted that there is no evidence of longshore sediment movement during the storm, with all changes being caused by cross-shore water movement. This is probably a consequence of the long length of the waves approaching



F i g . 8 . Development of the Lake Bogaily Barrier Beach since 1963 and during the storm in November 2023. *Left* – the barrier beach before the storm, *right* – that after the storm

from the open sea, the front of which turned parallel to the coastline on contact with the seabed at a considerable distance from the shore. It is possible that the same circumstance caused a significant rise in sea level during the storm.

The storm surge covered even the highest parts of the barrier beach and destroyed pre-existing landforms. The storm surge completely destroyed the characteristic longitudinal structure that had existed for several decades, including bands of dunes and vegetation (Fig. 9). In essence, the former orderly longitudinal and transversal structure that had been formed and maintained over decades was transformed into a full profile beach with steep marine and gentle lagoonal slopes.

F i g . 9 . View of the Lake Bogaily Barrier Beach from the south side (2021)

A similar process was observed both before and during the storm of 26–27 November 2023 on a number of accumulation forms in the Black Sea, in particular on the Solyonoye Lake Barrier Beach and in the southern part of the Anapa Barrier Beach. As noted above, a similar large-scale transformation of the relief of the Lake Bogaily Barrier Beach may have occurred in the late 1960s and early 1970s.

As a result of the extreme storm, the system of transverse scour holes with export cones in the inner (lake) part of the barrier beach has completely disappeared. During normal heavy storms, these scour holes acted as a safety valve, allowing some of the wave surge to pass into the lake and helping to attenuate the wave energy. It is likely that the presence of such stationary scour holes on the sandy barrier beach is a sign of its maturity and the prolonged absence of extreme storm events.

The formation of a lake outflow channel occurred in the central part of the barrier beach where the lake outflow was concentrated in one of the pre-existing stationary scour holes. In the southern part of the barrier beach, where the cross-sectional height and width were minimal prior to the storm and where rills had been observed in the past, water flow was impeded by concrete structures. In the central part of the barrier beach, several depressions formed after the storm on what had previously been an almost straight line at the seaward edge. By the end of January 2024, the depression formed during the storm was completely washed out, but the depression in the body of the barrier beach remained. At the same time, there was a tendency for the seaward line to flatten out. Given the continued high water level in the lake and the complete destruction of the vegetation along the lagoon shore of the barrier beach, partial levelling of the lake shore line by wave action is expected, although the general configuration is likely to be maintained. As can be seen from the dynamics of the barrier beach after the storm, self-recovery processes are evident.

Conclusion

The analysis of the long-term dynamics of the Lake Bogaily Barrier Beach confirms the assumption of the leading role of strong storms in the development of marine coastal accumulation forms. In particular, during and as a result of the extreme storm of 26–27 November 2023, the following was observed:

1. The configuration and relief of the Barrier Beach at Lake Bogaily was completely changed, the accumulation was displaced into the lake water area, and the magnitude of this displacement significantly exceeded the retreat of the adjacent bedrock shores.

2. The seaward edge line, which had previously been almost straight, formed several concavities in the central part of the barrier beach after the storm.

3. The retreat of the barrier beach near the abutment to the cliffs of the bedrock shore was 5–10 m, in the central part of the barrier – up to 20 m, in the area of the formed rill and slightly to the north – more than 30 m, even taking into account the subsequent levelling of the shore.

4. The previously existing system of transverse scour holes with export cones in the inner (lake) part of the barrier beach completely disappeared.

5. The impact of the storm surge completely destroyed the characteristic longitudinal structure that had existed for several decades, including strips of dunes and vegetation.

6. By the end of January 2024, the rill formed during the storm was completely washed out and a levelling of the seaward edge line was observed.

As a result, the storm has completely altered the decades-old relief and vegetation structure within the barrier beach. The Bogaily Lake Barrier Beach has undergone much greater change than in the previous 40-year period. It is clear that extreme storms play a critical role in the development of both the Bogaily Lake Barrier Beach and similar coastal accumulation forms in the region.

REFERENCES

1. Kosyan, R.D., Krylenko, V.V. and Krylenko, M.V., 2021. *Geosystem of the Anapa Bay-Bar*. Moscow: Nauchny Mir, 262 p. (in Russian).
2. Krylenko, V.V., Goryachkin, Yu.N., Kosyan, R.D., Krylenko, M.V. and Kharitonova, L.V., 2021. Similarities and Differences of Small Bay-Bars of the North-Eastern Part of the Black Sea. *Ecological Safety of Coastal and Shelf Zones of Sea*, (1), pp. 63–83. https://doi.org/10.22449/2413-5577-2021-1-63-83 (in Russian).
3. Goryachkin, Yu.N., Kosyan, R.D. and Krylenko, V.V., 2018. A Comprehensive Assessment of the Crimea West Coast. *Ecological Safety of Coastal and Shelf Zones of Sea*, (3), pp. 41–55. https://doi.org/10.22449/2413-5577-2018-3-41-55 (in Russian).

4. Korzinin, D.V., 2021. Special Aspects of Deformation of Coastal Profile During a Full Storm Cycle. *Journal of Oceanological Research*, 49(2), pp. 45–56. https://doi.org/10.29006/1564-2291.JOR-2021.49(2).3 (in Russian).
5. Leont'yev, I.O., Ryabchuk, D.V. and Sergeev, A.Y., 2015. Modeling of Storm-Induced Deformations of a Sandy Coast (Based on the Example of the Eastern Gulf of Finland). *Oceanology*, 55(1), pp. 131–141. https://doi.org/10.1134/S000143701406006X
6. Leont'yev, I.O. and Akivis, T.M., 2020. Modeling of Coastal Dynamics of the Anapa Bay-Bar. *Oceanology*, 60(2), pp. 279–285. https://doi.org/10.1134/S000143702002006X
7. Bugajny, N., Furmańczyk, K., Dudzińska-Nowak, J. and Paplińska-Swerpel, B., 2013. Modelling Morphological Changes of Beach and Dune Induced by Storm on the Southern Baltic Coast Using XBeach (Case Study: Dziwnow Spit). *Journal of Coastal Research*, 65(sp1), pp. 672–677. https://doi.org/10.2112/SI65-114.1
8. Gurov, K.I., Udovik, V.F. and Fomin, V.V., 2019. Modeling of the Coastal Zone Relief and Granulometric Composition Changes of Sediments in the Region of the Bogaily Lake Bay-Bar (the Western Crimea) during Storm. *Physical Oceanography*, 26(2), pp. 170–180. https://doi.org/10.22449/1573-160X-2019-2-170-180
9. Scott, T., Masselink, G., O'Hare, T., Saulter, A., Poate, T., Russell, P., Davidson, M. and Conley, D., 2016. The Extreme 2013/2014 Winter Storms: Beach Recovery Along the Southwest Coast of England. *Marine Geology*, 382, pp. 224–241. http://dx.doi.org/10.1016/j.margeo.2016.10.011
10. Harley, M.D., Masselink, G., Ruiz de Alegría-Arzaburu, A., Valiente, N.G. and Scott, T., 2022. Single Extreme Storm Sequence Can Offset Decades of Shoreline Retreat Projected to Result from Sea-Level Rise. *Communications Earth and Environment*, 3, 112. https://doi.org/10.1038/s43247-022-00437-2
11. Kim, T.-K., Lim, C., Lee, J.-L., 2021. Vulnerability Analysis of Episodic Beach Erosion by Applying Storm Wave Scenarios to a Shoreline Response Model. *Frontiers in Marine Science*, 8, 759067. https://doi.org/10.3389/fmars.2021.759067
12. Belokopytov, V.N., Fomin, V.V. and Ingerov, A.V., 2017. On Multidisciplinary Investigations of Dangerous Natural Phenomena in the Azov-Black Sea Basin. *Physical Oceanography*, (3), pp. 28–44. https://doi.org/10.22449/1573-160X-2017-3-28-44
13. Divinsky, B.V., Kubryakov, A.A. and Kosyan, R.D., 2020. Interannual Variability of the Wind-Wave Regime Parameters in the Black Sea. *Physical Oceanography*, 27(4), pp. 337–351. https://doi.org/10.22449/1573-160X-2020-4-337-351
14. Bogdanovich, A.Yu., Lipka, O.N., Krylenko, M.V., Andreeva, A.P. and Dobrolyubova, K.O., 2021. Climate Threats in the North-West Caucasus Black Sea Coast: Modern Trends. *Fundamental and Applied Climatology*, 7(4), pp. 44–70, https://doi.org/10.21513/2410-8758-2021-4-44-70 (in Russian).
15. Krylenko, M., Krylenko, V. and Kosyan, R., 2015. Accumulative Coast Dynamics Estimation by Satellite Camera Records. In: D. G. Hadjimitsis, K. Themistocleous, S. Michaelides, G. Papadavid, eds., 2015. *Proceedings of SPIE, Third International Conference on Remote Sensing and Geoinformation of the Environment*. Paphos, Cyprus. Vol. 9535, 95351K. https://doi.org/10.1117/12.2192495
16. Boyko, E., Krylenko, V. and Krylenko, M., 2015. LIDAR and Airphoto Technology in the Study of the Black Sea Accumulative Coasts. In: D. G. Hadjimitsis, K. Themistocleous, S. Michaelides, G. Papadavid, eds., 2015. *Proceedings of SPIE, Third International Conference on Remote Sensing and Geoinformation of the Environment*. Paphos, Cyprus. Vol. 9535, 95351Q. https://doi.org/10.1117/12.2192577

17. Krylenko, V.V. and Rudnev, V.I., 2018. Technique of Photographic Aerial Survey of the Bakalskaya Spit. *Ecological Safety of Coastal and Shelf Zones of Sea*, (4), pp. 59–64. https://doi.org/10.22449/2413-5577-2018-4-59-64 (in Russian).
18. Krylenko, M. and Krylenko, V., 2020. Features of Performing High-Precision Survey of the Abrasion Coast Relief by UAV. *Bulletin of Science and Practice*, 6(2), 10–19. https://doi.org/10.33619/2414-2948/51/01 (in Russian).
19. Divinsky, B. and Kosyan, R., 2017. Spatiotemporal Variability of the Black Sea Wave Climate in the Last 37 Years. *Continental Shelf Research*, 136, pp. 1–19. https://dx.doi.org/10.1016/j.csr.2017.01.008
20. Gurov, K.I., 2018. Results of Sediment Granulometric Composition Monitoring in Coastal Zone of the Kalamitsky Bay. *Ecological Safety of Coastal and Shelf Zones of Sea*, (3), pp. 56–63. https://doi.org/10.22449/2413-5577-2018-3-56-63 (in Russian).
21. Shuisky, Yu.D., 2005. Basical Peculiarities of Morphology and Dynamic of the Western Crimea Peninsula Coast. In: MHI, 2005. *Ekologicheskaya Bezopasnost' Pribrezhnykh i Shel'fovykh Zon i Kompleksnoe Ispol'zovanie Resursov Shel'fa* [Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources]. Sevastopol: ECOSI-Gidrofizika. Iss. 13, pp. 62–72 (in Russian).
22. Goryachkin, Yu.N. and Dolotov, V.V., 2019. *Sea Coasts of Crimea*. Sevastopol: Colorit, 256 p. (in Russian).
23. Udovik, V.F. and Goryachkin, Yu.N., 2013. [Interannual Variability of the Alongshore Sediment Flow in the Coastal Zone of the Western Crimea]. In: MHI, 2013. *Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources*. Sevastopol: ECOSI-Gidrofizika. Iss. 27, pp. 363–368 (in Russian).
24. Kharitonova, L.V. and Fomin, V.V., 2017. Spatial Structure of Sediment Flow in the Coastal Zone of the Western Crimea on according Numerical Simulation. *Ecological Safety of Coastal and Shelf Zones of Sea*, 1, pp. 48–58 (in Russian).
25. Kharitonova, L.V. and Fomin, V.V., 2012. Statistical Characteristics of Wind Waves in the Coastal Zone of the Western Crimea according to Retrospective Calculations for 1979–2010. In: MHI, 2012. *Ekologicheskaya Bezopasnost' Pribrezhnykh i Shel'fovykh Zon i Kompleksnoe Ispol'zovanie Resursov Shel'fa* [Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources]. Sevastopol: ECOSI-Gidrofizika. Iss. 26, pp. 24–33 (in Russian).
26. Gippius, F.N. and Arkhipkin, V.S., 2017. Interannual Variability of Storm Waves in the Black Sea According to Numerical Modeling Results. *Vestnik Moskovskogo Universiteta. Seria 5, Geografia*, (1), pp. 38–47 (in Russian).
27. Zhuk, V.O. and Yergina, E.I., 2018. Space-Time Variability of Climate of Winter Seasons in Crimea. *Scientific Notes of V.I. Vernadsky Crimean Federal University. Geography. Geology*, 4(1), pp. 104–121 (in Russian).
28. Krinko, E.F. and Semenov, V.S., 2021. The Consequences of the 1969 Pitsunda Storm and Measures to Overcome Them. *Science in the South of Russia*, 17(2), pp. 90–97. https://doi.org/10.7868/S25000640210210 (in Russian).

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