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Original paper

Transformation of the Western Branch of the Bakalskaya Spit (Northwestern Crimea) as a Result of the Storm on 26–27 November 2023

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Abstract

Accumulative marine coastal forms of the Black Sea are exposed to a number of natural threats, including sea level rise and increased wave action. Monitoring of accumulative forms dynamics in order to timely identify adverse trends in their development is a necessary component for coastal zone management and the development of coastal protection measures. The aim of the work is to determine the qualitative and quantitative characteristics of the transformation of the western branch of the largest accumulative form in the northwestern coast of Crimea – the Bakalskaya Spit – as a result of the storm on 26–27 November 2023. We used cartographic, literary and archival sources as well as remote sensing data, materials of long-term monitoring observations and results of mathematical modeling. In terms of wave parameters and overall power, the 26–27 November 2023 storm was extremely strong but not unique, and in terms of power and other wave parameters it is comparable to the 11 November 2007 storm. It was found that during the extreme storm, the accumulative body shifted to the east. The magnitude of the displacement varies significantly along the length of the spit and exceeds the magnitude of the main shore retreat. The position of zones with different magnitudes of the coastal bar displacement or formation of washouts does not coincide with that in previous storms. Differences in the character and scale of the accumulation body transformation are determined by local in terms of time and space conditions, primarily by the relief of the underwater slope and beach at the time of storm formation. Monitoring of the accumulative body dynamics following the storm recorded self-restoring processes confirming that the lithodynamic system had not been not brought out of the dynamic equilibrium.

Keywords: Black Sea, Crimean Peninsula, Bakalskaya Spit, extreme storm, relief, coastline

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Трансформация западной ветви Бакальской косы (Северо-Западный Крым) в результате шторма 26–27 ноября 2023 года

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Аннотация

Аккумулятивные морские береговые формы Черного моря подвержены ряду природных угроз, в числе которых подъем уровня моря и усиление волнового воздействия. Мониторинг динамики аккумулятивных форм для своевременного выявления неблагоприятных тенденций их развития является необходимой составляющей для управления береговой зоной и разработки мер по защите берегов. Цель работы – определение качественных и количественных характеристик трансформации западной ветви крупнейшей аккумулятивной формы северо-западного побережья Крыма – Бакальской косы – в результате шторма 26–27 ноября 2023 г. Использованы картографические, литературные и архивные источники, данные дистанционного зондирования, материалы многолетних мониторинговых наблюдений, результаты математического моделирования. По волновым параметрам и общей мощности шторм 26–27 ноября 2023 г. является чрезвычайно сильным, но не уникальным, а по мощности и другим параметрам волнения сравним со штормом 11 ноября 2007 г. Установлено, что в ходе шторма произошло смещение аккумулятивного тела на восток. Величина смещения существенно различается на протяженности косы и превышает величину отступания коренного берега. Положение зон с разными величинами смещения берегового вала или образованием промоин не совпадает с положением таких зон в прошлые штормы. Различия в характере и масштабе трансформации аккумулятивного тела определяются локальными во времени и пространстве условиями, прежде всего рельефом подводного склона и пляжа на момент формирования шторма. Мониторинг динамики аккумулятивного тела после шторма зафиксировал процессы самовосстановления, подтверждающие, что литодинамическая система не была выведена из состояния динамического равновесия.

Ключевые слова: Черное море, полуостров Крым, Бакальская коса, экстремальный шторм, рельеф, береговая линия

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Introduction

The Bakalskaya Spit is located in the Karkinitsky Gulf of the Black Sea on the northwestern coast of the Crimean Peninsula. The principal difference between the Bakalskaya Spit and other large accumulative forms of the Black Sea is its location in the depth of the Karkinitsky Gulf, where the action of a number of natural factors is weakened and of some others is intensified. It is a unique natural object determining the hydrodynamic regime of the Karkinitsky Gulf and, at the same time, exposed to hazardous natural phenomena. Transformation of the accumulative body, on the one hand, is a consequence of certain natural impacts (e. g. storms or surges) and, on the other hand, is caused by changes in lithodynamic, hydrodynamic or hydrochemical processes in the bay water area. It is important that the lithodynamic system of the Bakalskaya Spit is little changed anthropogenically, which allows studying the natural transformation of large marine coastal accumulative forms under conditions of sea level rise and increased storm activity [1, 2].

Specialists of Marine Hydrophysical Institute and Southern Branch of Shirshov Institute of Oceanology have been monitoring the Bakalskaya Spit. The scientific material obtained during the expeditions as well as by remote sensing and mathematical modeling methods is reflected in works [3–7]. In the Black Sea, an increasing tendency to frequency and intensity of storm waves was noted [8–11]. Storms, especially extreme ones, lead to the transformation of coastal accumulative forms [12, 13] and in some cases to their degradation [14]. Meanwhile, the impact of extreme storms on accumulative forms is most often considered theoretically [15–17].

In November 2023, the Black Sea was exposed to a series of strong Mediterranean cyclones. Winds of up to 40 m/s were observed over much of the water area [18].

On 26–27 November 2023, a storm surge was formed, the parameters of which reached or exceeded the level of previously observed storms in the region. This allows classifying this storm as an extreme natural phenomenon [19]. As the scientific observations on the transformation of marine coastal accumulative forms of the Black Sea during extreme storms are limited, it seems relevant to consider the impact of the storm on the Bakalskaya Spit. In [20], the impact of this storm on another accumulative form, the Lake Bogaily barrier beach, was considered. It was shown that as a result of the storm, the structure of relief and vegetation cover within the barrier beach that had existed for several decades was completely transformed. The Bogaily barrier beach has undergone a much greater transformation than in the preceding period of 40 years.

It should be noted that the Bakalskaya Spit and the adjacent water area have the status of a landscape and recreational park of regional significance. Nevertheless, sketch projects for the development of a large recreational zone have already been developed by order of local authorities. Unfortunately, these projects ignore completely natural processes taking place on the coast, including dangerous ones. It is expected that the comparison of new data with the results of previous studies will make it possible to assess the changes that occurred during a single storm in comparison with the previous long-term dynamics.

The work aims to determine the qualitative and quantitative characteristics of the transformation of the Bakalskaya Spit western branch as a result of the extreme storm on 26–27 November 2023.

Materials and methods of study

Satellite images of different years from open sources (Google Earth, Yandex, Bing, etc.) were used to analyse the coastal relief dynamics. Data from the European Space Agency Sentinel-2 spacecraft imagery were used to provide a rapid assessment of the changes caused by the storm on 26–27 November 2023 [1]. To achieve accurate spatial reference, geometric correction of satellite data was carried out [20]. The sea and lake (lagoon) edge line, coastal bar and cliff's edge were digitised from the images. As a spatial reference of the obtained results, we used a system of virtual reference profiles (RP) drawn through points located at a distance of 200 m from each other. As a result of this work, information on the dynamics of the water's edge and other morphological elements in different time periods was obtained.

The detailed study of the relief and its dynamics required the creation of digital elevation models (DEM). Aerial photographs from unmanned aerial vehicles (UAV) were used [21, 22]. Using the photogrammetric processing technology implemented in Agisoft Metashape software, orthophotos with 0.1 m resolution and DEMs with grid spacing of 0.15 × 0.15 m were constructed.

In addition to remote sensing materials, data from granulometric analysis of beach and bottom sediment samples, morphometric characteristics, archival materials and geobotanical descriptions obtained during expeditions were used.

Calculations of climatic characteristics of wind waves in the Black Sea were carried out using modern spectral wave model MIKE 21 SW [2]. Full description of the model as well as issues of its verification and adjustment are outlined in [23]. Based on the results of calculations, the array of spatial fields of surface wave parameters with a discreteness of 1 h was formed for the entire sea area for the period from January 1979 to December 2023.

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[1] European Space Agency. *Sentinel-2*. 2023. [online] Available at: https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-2-msi/level-1c/product-formatting [Accessed: 12 December 2023].

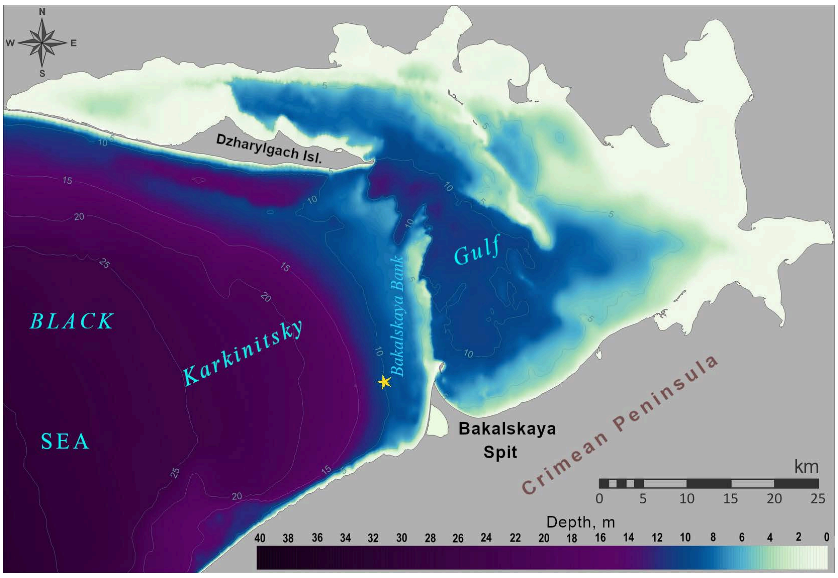
[2] DHI, 2007. *MIKE 21/3 Coupled Model FM: Step-by-Step Training Guide: Coastal Application*. Hørsholm, Denmark: DHI, 190 p.

General characteristics of the Bakalskaya Spit

Morphologically, the Bakalskaya Spit (Fig. 1) is a free double accumulative form up to 8 km long [24]. Both branches are rooted adjacent to active cliffs developed in the Pliocene and Quaternary clay strata. At the junction point of the western branch, the main shore changes its direction sharply from northeastern to eastern. The spit western branch extends almost straight from the point where it is adjacent to the main shore. During the first 4 km, the western branch forms a narrow (60–100 m) barrier beach separating the lagoon (Lake Bakalskoe) from the sea.

The underwater slope in the vicinity of the Bakalskaya Spit is asymmetric, reflecting the development of the spit. The underwater slope to the west of the spit is a shallow water plain descending westwards, with a sharp drop in depth to 7 m on the eastern side close to the shore, followed by a flat gulf bottom. The coastal bar and sediments up to a depth of 2–6 m consist of shell sand with a large admixture of oolites, gravel and pebbles. A layer of grey lake silt emerges on the seabed at depths of up to 2 m against the Lake Bakalskoe barrier beach front.

The geographical position determines the specificity of the hydrodynamic regime of the water area adjacent to the Bakalskaya Spit. The periods with the predominant influence of either waves or currents alternate in the development of



F i g. 1. Schematic map of the Karkinitsky Gulf in the Black Sea (data on underwater topography are given using SonarChart™ materials) (available at https://webapp.navionics.com). The star denotes the point for which the main wave parameters were calculated the accumulative form. The recurrence and velocities of currents from the open sea to the Karkinitsky Gulf and back are comparable, while the wave regimes for the western and eastern sides of the spit are different [25–28]. Northerly and westerly winds are prevailing but the acceleration length is not the same for them. Westerly winds generate a large long open sea wave, while northerly winds generate a low short wave. In terms of power and duration of action, westerly and southwesterly winds exceed considerably easterly and northeasterly winds: average power values to the west of the spit are about 1 kW/m and to the east – 0.5 kW/m [25]. Episodically, storm waves can develop, which are several times more powerful than average storms. For the spit western branch, the most severe storms were observed in 1981 and 1992, north-northwesterly; in 2007, west-northwesterly; in 1981, 2000, 2017, west-southwesterly; and in 1981, 2008, south-southwesterly. The 2007 storm was the most powerful – 60 kW/m. Such extreme events determine the lithodynamic appearance of the spit in many respects. The characteristic trend components of climatic variability of wind waves in the area of the Bakalskaya Spit since 1979 are as follows:

– decrease in the recurrence of west-southwesterly storms;

– significant decrease in the average wave height during north-northwesterly and south-southwesterly storms;

– increase in wave height during west-northwesterly and north-northeasterly storms.

The wave regime determines the cardinal difference in the relief structure and dynamics of the western and eastern branches of the spit. In the multi-year regime, the dominant role of the eastward-directed wave can be observed. The accumulative body of the Bakalskaya Spit (including the underwater part – the Bakalskaya Bank) shifted eastward during its development, which is reflected in the transverse profile of the spit (Fig. 1): the western slope is gentle, while the eastern slope is steep [29]. For the above-water part of the spit, this process is manifested by washout of its western branch and accumulation on the eastern shore. The sediment budget depends on the products of coastal abrasion and shell directly from the underwater slope. Although the main volume of sediments enters the lithodynamic system from the west, the western branch shifts eastwards (the shore retreats) in the form of a coastal bar 1.2–1.6 m high and 20–50 m wide. In waves with a significant longshore component, the movement of sediment here occurs in a distal direction; in cross-shore waves, the previous sediments are washed out, transporting material to the inner part of the spit. The eastern branch advances into the sea area (accumulation is observed) as new generations of coastal bars 0.5–1.2 m high and 5–10 m wide are formed.

Thus, the current development of the Bakalskaya Spit is determined by changes in the number, direction and intensity of storms, fluctuations in the volume of sediment input and anthropogenic sediment extraction [1, 7, 24].

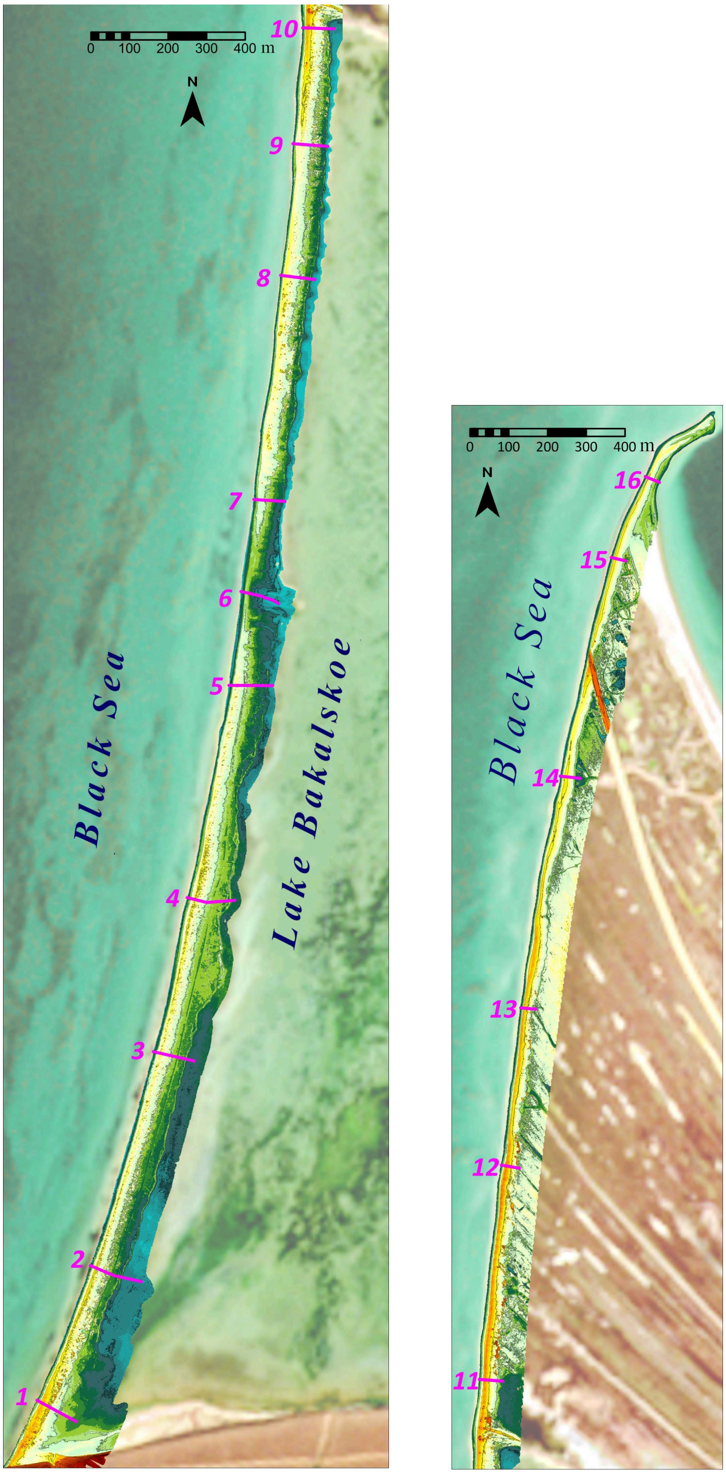
Structure of the western branch

The relief of the above-water part of the western branch of the Bakalskaya Spit is based on a full profile sand-shell beach (Fig. 2). Within the western branch, the following main zones can be distinguished, traced in one form or another along almost the entire length of the spit:

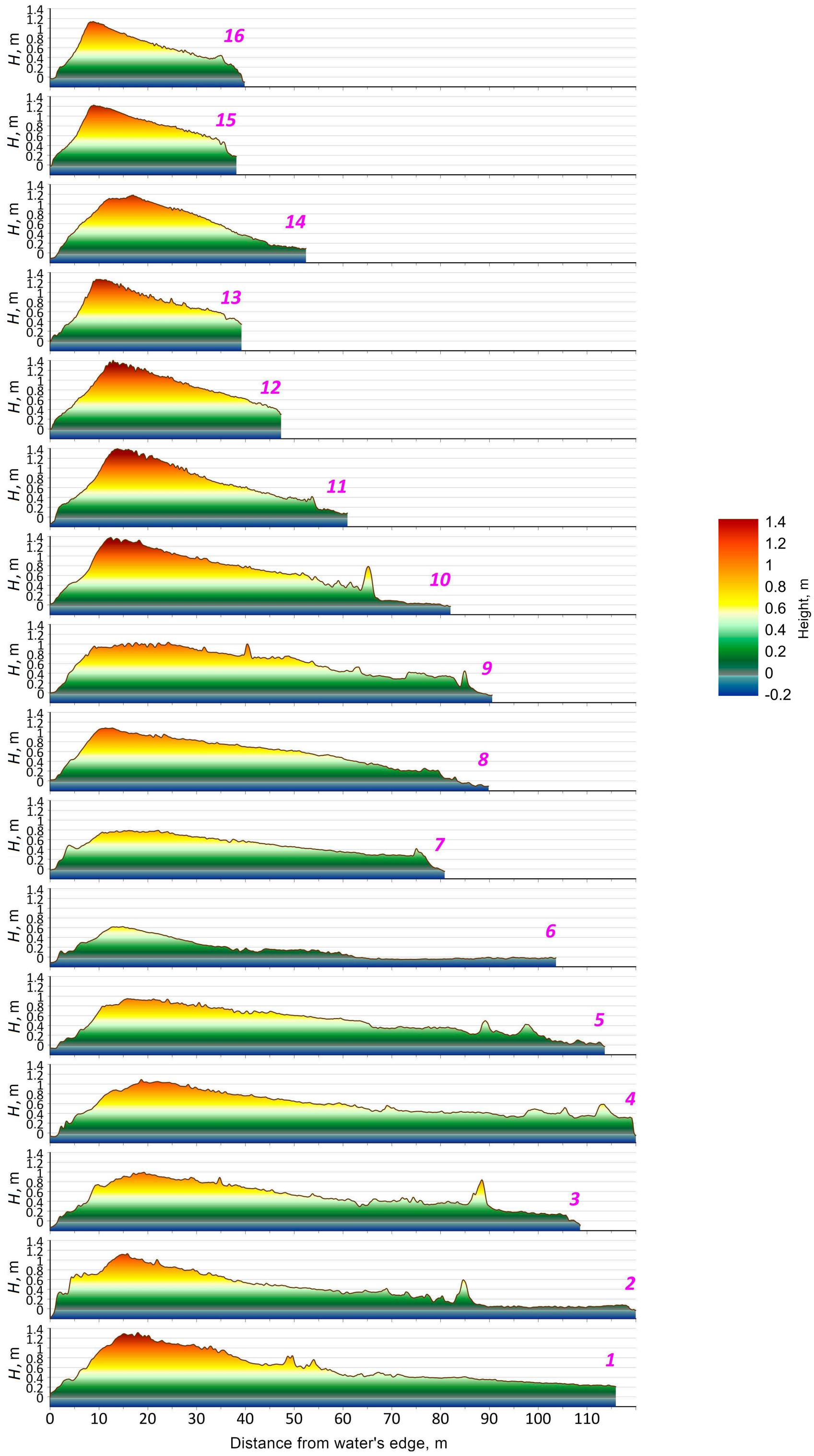
1. Active beach zone. It is characterised by the most variable relief, exposed to the action of waves throughout most of its development. The width is rarely more than 10 m (Figs. 2, 3) and the slope towards the sea is characteristic. Within the beach, a storm bank (less often several) is usually formed, and sometimes culp formation is observed. When the longshore currents intensify and are accompanied by material export, a beach scarp is formed (Fig. 3, *c*). Dense matting of algal remnants is occasionally formed at the root part of the spit along the edge (Fig. 3, *a*). As the shore retreats near the water's edge, sediments of the inner part of the spit are exposed, i.e. bars (shell, sand, pebbles, often lithified) or inter-bar depressions (silt with a mixture of shell, with a framework of vegetation remnants). The latter are more resistant to washout and contribute to the formation of capes (Fig. 3, *c*). The greatest variability of the plan position of the coastline, formation and destruction of storm banks and terraces are observed near the distal part of the coastline (Fig. 3, *e*), where fluctuations in the volume of sediments moving in different directions are most significant.

2. Ridge zone. The most elevated part of the coastal bar (from 0.6 m at the Lake Bakalskoe barrier beach to 1.4 m at the root and northern parts), it is located 10–15 m from the sea's edge (Fig. 2). The main features of the relief of this zone are formed during the strongest storms, when wave overtopping of the ridge of the coastal bar is observed along its entire length and is accompanied by the transfer of material to the rear side. During moderate storms, the wave splash crosses the ridge only through depressions in it, where seawater flowing into the inner part of the spit is concentrated and runoff troughs are formed. Between storms, runoff troughs are transformed into erosion cuts under the action of precipitation. Within the ridge zone, a more or less developed vegetation cover is present, which is destroyed during strong storms. Aeolian forms with associated vegetation have formed in places on the most elevated parts of the western branch central part.

3. Rear zone (lagoon for the Lake Bakalskoe barrier beach). Transition zone where migration of Lake Bakalskoe material transported by waves from the sea slope or surface runoff from the ridge zone is completed. The relief is represented by the surface sloping away from the sea, dissected by runoff troughs. The transition to the surface of the inner part of the spit has a pronounced bend, the transition to the bottom of the lagoon is smoother and is distinguished only by the composition of sediments. Areas of splash flow discharge are characterised by tongue-shaped protrusions (Fig. 3, *f*), frequency and configuration of which differ significantly along the length of the spit. The zone is usually characterised by developed vegetation cover.



F i g . 2 . The relief of the Bakalskaya Spit western branch (*a*), transverse profiles (*b*): *left* – barrier beach of Bakalskoe Lake, *right* – main part of the spit. The numerals indicate the numbers of the profiles



Continued Fig. 2.

F i g . 3 . The western branch of the Bakalskaya Spit: *a* – the root part; *b* – the barrier beach of Bakalskoe Lake; *c* – a cape formed at the sea water's edge as a result of the exposure of vegetation remnants of the inner part of the spit; *d* – the beach in the central part of the spit; *e* – the distal part of the spit; *f* – the overflow cone on the shore of Bakalskoe Lake

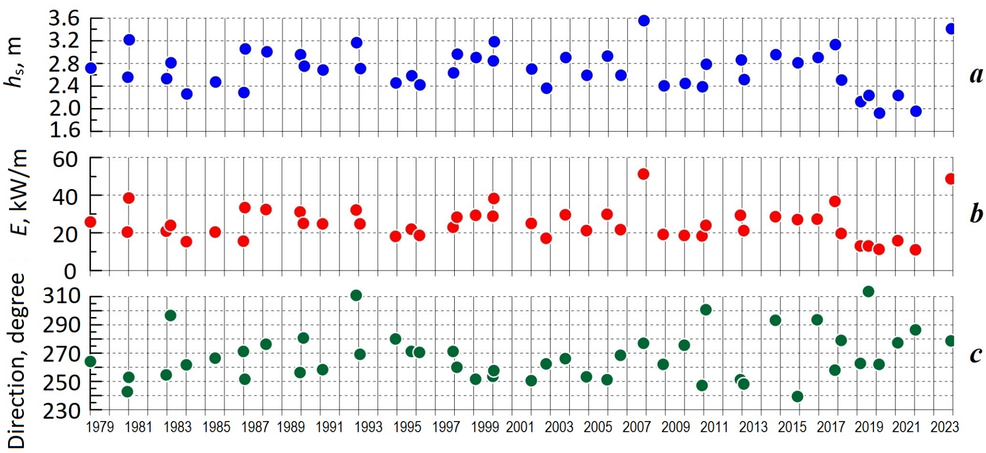
4. Shore of Lake Bakalskoe along the barrier beach. This zone is developed under the influence of the sea. The overtopping of waves over the barrier beach ridge is accompanied by the transport of material from the sea slope and the washout of the runoff troughs, resulting in the formation of numerous alluvial fans on the lakeshore (Fig. 3, *f*), which create a kind of culp configuration. The development of the shores of Lake Bakalskoe is significantly influenced by lake level fluctuations caused by seasonal changes in the amount of precipitation or seawater input during strong storms. Complete drying of the lake was not observed. The lakeshore, with the exception of active fans, is covered with near-water halophytic herbaceous vegetation, which in dry years develops part of the drying area. During the seasonal development of algae accompanied by a drop in the lake water level, a solid cover 15–30 cm thick is formed of dead vegetation remnants in shallow waters and the drying area. This cover further reduces wave action on the lakeshores. During periods of high standing water, a bank of vegetation

and debris is formed along the lake shoreline under the action of waves. Along the barrier beach, during heavy storms at sea, this bank is usually destroyed by the splash currents and a new one begins to form. No active longshore redistribution of material can be observed along most of the lake shoreline, which can be explained by the low intensity of the corresponding wave direction or the absence of sediments.

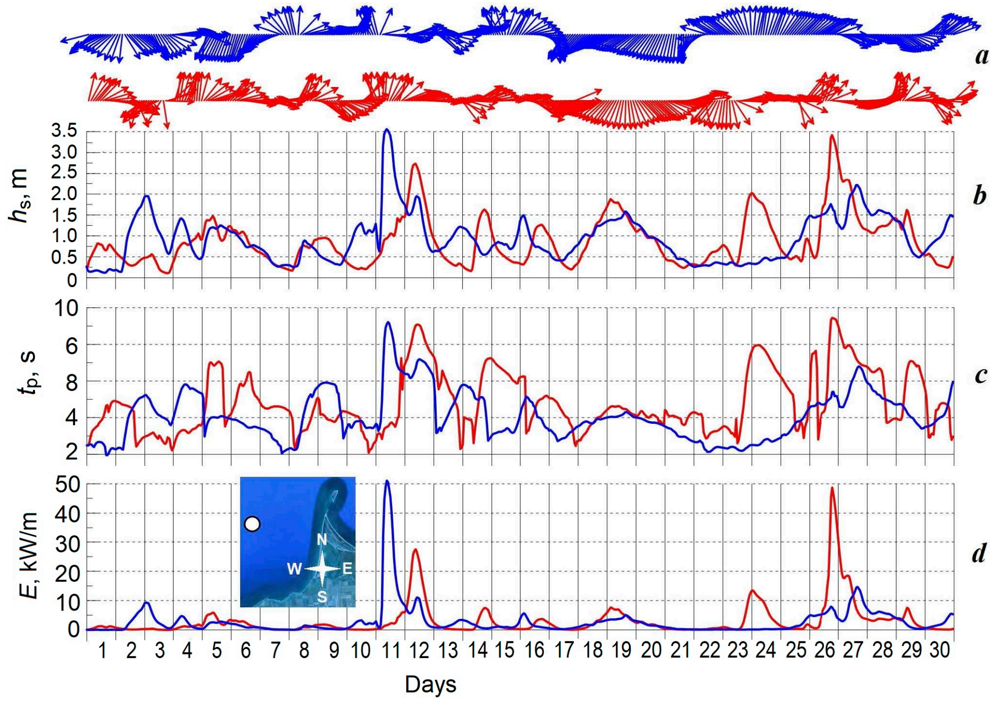
Characteristics of the storm on 26–27 November 2023

To analyse the nature of storm impact on the shore, the main wave parameters (significant wave heights, peak periods of the spectrum, average propagation directions) were calculated. The calculation point was located 5200 m from the shore at an isobath of 10 m (Fig. 1). In addition, the wave power was calculated, which is a representative characteristic since it depends on two integral wave parameters, namely wave height and wave energy period. Simplifying a little, we can say that the energy period is the period of a monochromatic wave with a power equivalent to the power of given irregular waves. Wave power is expressed in kilowatts per metre of wave front.

Fig. 4 shows maximum wave heights and power of particular storms west of the Bakalskaya Spit over the last 45 years. Storms were analysed that developed waves with significant heights exceeding the 2.5 m level. If this threshold was not met in a particular year, the characteristics of just the largest storm were chosen for that year. As can be seen in Fig. 4, over the last 45 years, the 26–27 November 2023 storm is comparable in energy and wave height to the 11 November 2007 storm.



F i g . 4 . Parameters of the largest storms west of the Bakalskaya Spit: *a* – maximum significant wave heights; *b* – maximum wave power; *c* – general directions of storms



F i g . 5 . The main parameters of wind waves for the water area west of the Bakalskaya Spit in November 2007 (blue) and 2023 (red): *a* – propagation directions; *b* – significant wave heights; *c* – peak and mean wave periods; *d* – wave power

Fig. 5 presents a series of significant wave heights, periods, power and wave directions for the water area west of the Bakalskaya Spit in November 2023. In addition, the figure provides graphs of the same parameters for November 2007 to compare. It can be seen that both in November 2007 and November 2023 the western branch of the Bakalskaya Spit was under the influence of significant waves, including a storm with a power of over 25 kW/m on 12 November 2023. At the time of the greatest development of the storm on 26 November 2023 at an isobath of 10 m, the wave parameters were as follows: significant wave height – 3.4 m, period – 7 s, length – 75 m. The wave surge height during the storm was 0.15–0.55 m. It should be noted that the November 2007 storm is slightly higher in power than the similar storm of 2023. Most likely, these two cases characterise the degree of possible maximum wind wave development for the water area under consideration.

Transformation of the western branch during the storm on 26–27 November 2023

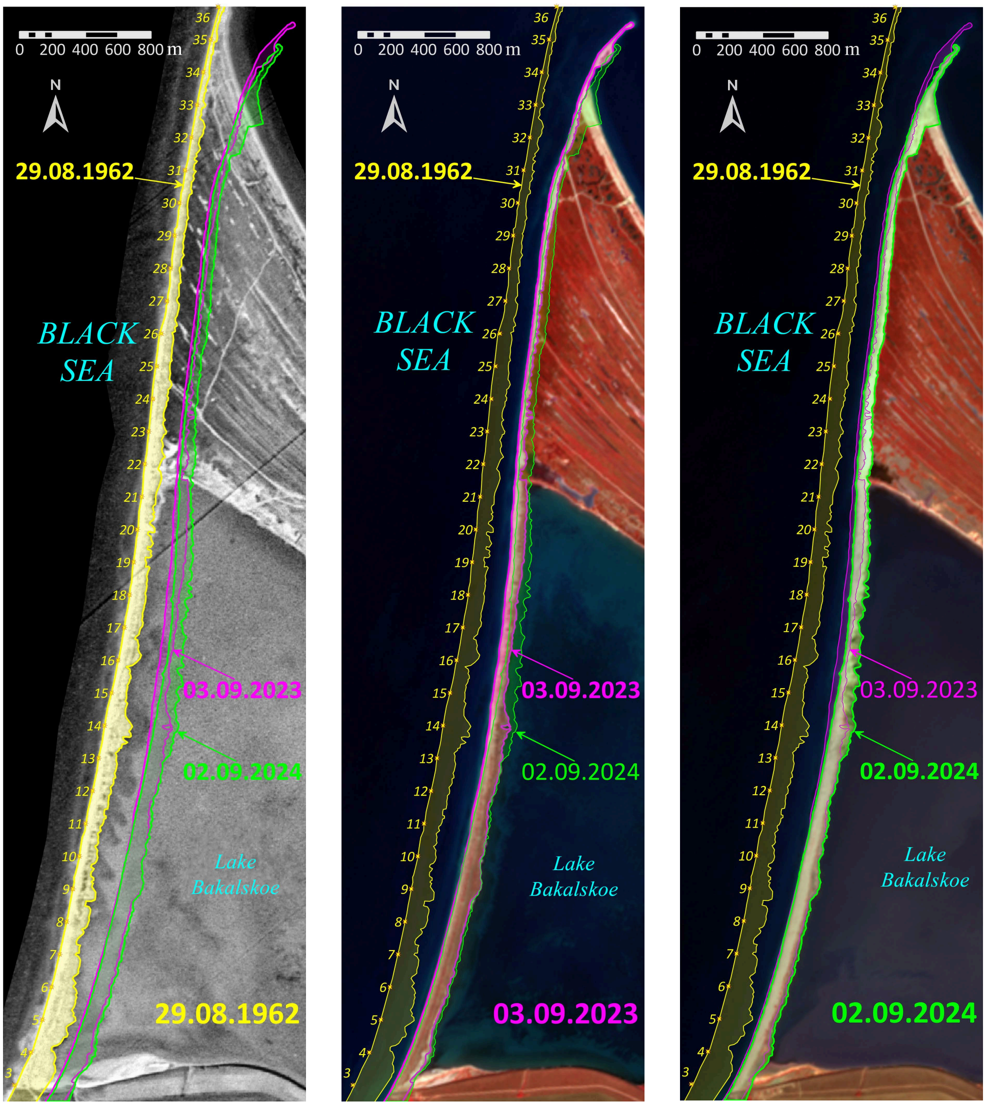
As shown in [18, 30], the storm of 26–27 November 2023 is extreme for the Western Crimea on the scale of several decades in terms of wave parameters and overall power. A somewhat different picture is observed in the area of the Bakalskaya Spit located in the Karkinitsky Gulf. According to the scale and nature of changes in the shore configuration and coastal bar relief of the western branch of the Bakalskaya Spit, it can be concluded that the storm in question was extremely strong but not unique. This storm is comparable to the storm of 11 November 2007 in terms of power and other wave parameters (Fig. 5).

During the 2007 and 2023 storms, wave action with overtopping of the beach ridge was observed along the entire length of the coastal bar on the spit western branch. The bar surface was levelled and existing vegetation was either destroyed or buried under a layer of sand. The coastal bar width increased considerably, with clearly visible tongues of sand streams, which were pushing on the inner part of the spit (Fig. 6). Numerous washouts were formed in the Lake Bakalskoe barrier beach, with pronounced traces of sediment movement from the seashore to the lakeshore (Fig. 6).

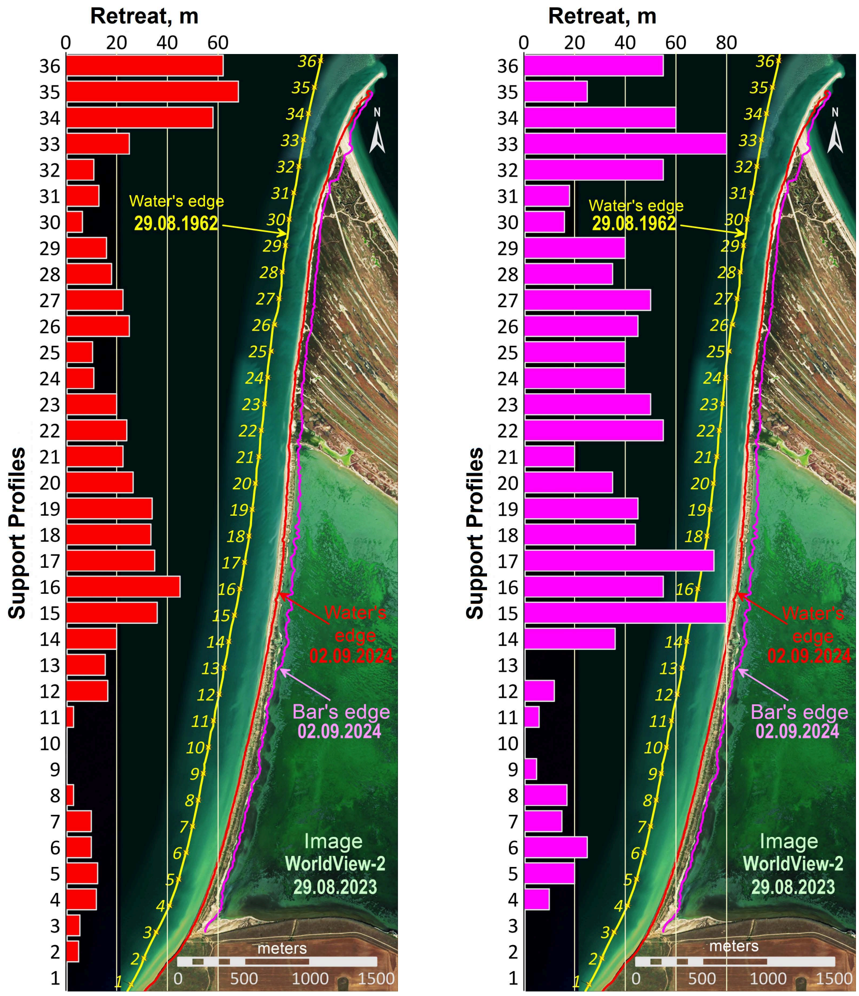
Figs. 7 and 8, *a* demonstrate the western branch sea's edge retreat values from 03.09.2023 (pre-storm) to 02.09.2024 (post-storm and restoration of bar integrity). It can be seen that the amount of retreat varies considerably along the entire spit. In the section of the main shore south of the spit, the retreat is either absent (RP *1*) or does not exceed 5 m (RP *2* – RP *3*). At the root part of the spit, the edge retreat is relatively small (10–12 m), and at the RP *8* – RP *11* section it does not exceed 5 m. In the northern part of the Lake Bakalskoe barrier beach (RP *12* – RP *22*), the retreat values increase significantly, averaging 28 m and reaching 45 m at RP *16*. In the section where the western branch is a bar extending over the inner part of the spit (RP *23* – RP *33*), the retreat is slightly less, averaging 16.2 m. Within the distal end (RP *34* – RP *36*), the western shore retreated approximately 60 m.

F i g . 6 . Transformation of the western branch of the Bakalskaya Spit during the storm: *left* – a washout in the barrier beach of Bakalskoe Lake; *right* – movement of sand from the seashore to the inner part of the spit

Figs. 7 and 8, *b* show the western branch sea's edge displacement values from 03.09.2023 (pre-storm) to 02.09.2024 (post-storm and restoration of bar integrity). It can be seen that the amount of displacement varies considerably along the entire spit. The edge retreat is small (10 m on average) at the root part of the spit (RP *3* – RP *13*), while it is either absent or does not exceed 5 m on profiles *10* and *13*. In the northern part of the Lake Bakalskoe barrier beach (RP *12* – RP *22*), the displacement values increase significantly, averaging 49.5 m



F i g . 7 . The transformation scheme of the western branch of the Bakalskaya Spit since 1962 and during the storm on 26–27 November 2023 and reaching 80 m at RP *15*. In the section where the western branch is a bar extending over the inner part of the spit, the displacement remains high between RP *23* and RP *29* (43 m on average) and decreases sharply to 16–18 m between RP *30* and RP *31*. It is possible that the decline at this section is due to the presence of a high crushed shell limestone roadbed extending at an acute angle to the edge. To the north of the road, the bar displacement increases sharply, reaching 80 m at RP *33*. A strong (up to 60 m) displacement to the east of the distal end was noted (RP *34* – RP *36*). During the storm, the distal length was reduced by 380 m and subsequently restored by 220 m.



F i g . 8 . Retreat of the sea water's edge (*left*) and the rear part of the beach bar (*right*) of the western branch of the Bakalskaya Spit during the storm on November 26–27, 2023. The numbers indicate the numbers of the support profiles, the distance between the profiles is 200 m

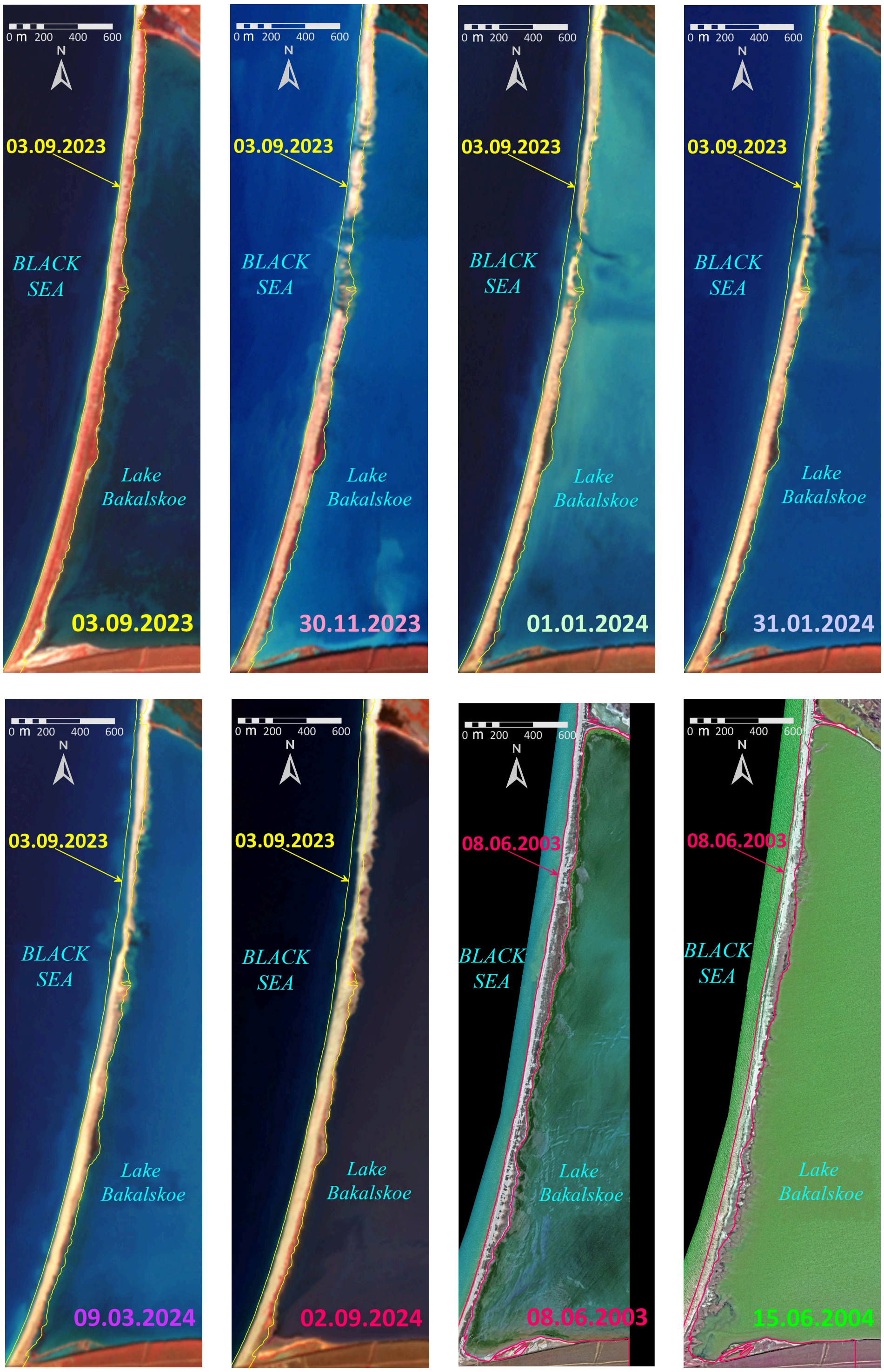
It should be noted that for the entire length of the western branch no evidence of longshore sediment movement during storms is observed, all changes being caused by cross-shore water movements. This is probably due to the long wave lengths. The front of the waves approaching from the open sea, when in contact with the seabed, turned parallel to the shoreline at a considerable distance from the shore and approached it almost at normal.

Transformation of the western branch after the storm of 26–27 November 2023

During the storm, the Lake Bakalskoe barrier beach underwent the greatest changes. In its northern part, two groups of continuous washouts with lengths of 550 and 150 m along the barrier beach were formed (image from 30.11.2023 in Fig. 9). During the storm, the flow of both water and sediments was directed towards the lake. Excess water in the lake led to flooding of the low-lying areas of the inner part of the spit. After the end of the storm and the lowering of sea level, the water began to backflow through the washouts, accompanied by the transport of sand to the seashore. After the levels normalised, the cross-water movement stopped and conditions were created for the barrier beach integrity to be restored. During the month following the storm, the northern group of washouts disappeared completely (image from 01.01.2024 in Fig. 9), while the largest scour holes remained in the southern group, and they were significantly shallower. After another month, only one washout was observed within the barrier beach (image from 31.01.2024 in Fig. 9), which also disappeared during the following two months (image from 09.03.2024 in Fig. 9).

The restoration of the barrier beach was accompanied by changes in the position of both sea and lagoon's edges. Furthermore, most of the changes in the configuration of the lagoon shoreline were associated with fluctuations in lake level. On the seashore, the changes in configuration were associated with the redistribution of sediment both longitudinally and transversely. In contrast to the Lake Bogaily barrier beach [20], where the seaward movement of the sea's edge was observed during the post-storm period, on the western branch of the Bakalskaya Spit, the shore retreat continued after the end of the storm. The washouts were closed by sediments from adjacent shoreline areas. As a result, the highest values of shore retreat following the storm were observed in the northern part of the Lake Bakalskoe barrier beach, where washouts had been formed during the storm.

It should be noted that the areas of washout formation and shore retreat during storms are not stationary. Fig. 9 (images from 08.06.2003 and 15.06.2004) shows that after a series of October 2003 storms with a power of 25 and 34.2 kW/m, washout formation and shore retreat occurred in the southern part of the Lake Bakalskoe barrier beach. Such irregularity is most likely caused by fluctuations in the volume and location of sediment stores on the underwater slope adjacent to the Bakalskaya Spit from the west. The presence of sediment stores is indicated by underwater bars along the spit western branch (see Fig. 2). The irregular nature of storm passage and the mosaic distribution of sediment accumulations cause significant variations in the volume of material entering the near-edge zone. Analysis of space images shows that "plumes" of sediments are periodically formed along the spit western branch, gradually shifting along the shore from the foot



F i g . 9. Transformation of the barrier beach of Lake Bakalskoe after the storm on 26–27 November 2023. For comparison, illustrations of the transformation of the barrier beach in 2003–2004 are given of the spit to the distal, which causes significant changes in the relief of the underwater slope, configuration of the shoreline, beach width and profile. It is this feature that contributes to changing the position of washouts formed during storms.

Another consequence of the storm was the destruction of vegetation within the entire coastal bar. By autumn 2024, the vegetation within the coastal bar had not yet been restored, which is clearly visible when comparing the images from 03.09.2023 and 02.09.2024 (Fig. 9).

Conclusion

In terms of wave parameters and overall power, the 26–27 November 2023 storm is extreme for Western Crimea on the scale of several decades. However, in the area of the Bakalskaya Spit located in the Karkinitsky Gulf, the storm in question is extremely strong but not unique, and it is comparable to the storm of 11 November 2007 in terms of power and other wave parameters. A similar conclusion can be drawn from the scale and nature of changes in the shore configuration and coastal bar relief of the western branch of the Bakalskaya Spit. Most likely, these two storms determine the limits of possible maximum wind wave development for the water area under consideration, and the differences in the nature and scale of the accumulation body transformation are determined by local conditions in time and space, primarily the relief of the underwater slope and beach at the time of storm formation.

The relief of the above-water part of the western branch of the Bakalskaya Spit is based on a full profile beach, within which the main zones are distinguished, which can be traced almost along the entire length of the spit. During the 26–27 November 2023 storm, wave action with overtopping of the beach ridge was observed along the entire length of the coastal bar of the spit western branch. All zones underwent significant transformation. The coastal bar width increased significantly due to its displacement to the inner part of the spit by a distance that exceeded the retreat of the sea's edge. The bar surface was leveled and vegetation was either destroyed or buried under a layer of sand. Numerous washouts were formed on the Lake Bakalskoe barrier beach, which transported sediments from the seashore to the lakeshore.

In general, the effects of the 26–27 November 2023 storm on the western branch of the Bakalskaya Spit are large-scale but not critical. As can be seen from the dynamics of the barrier beach following the storm, self-restoring processes can be traced, confirming that the lithodynamic system was not brought out of the dynamic equilibrium.

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