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Features of the morphology and dynamics of the shallow-island part of the Dolgaya Spit (the Sea of Azov)

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Abstract

The relief of large coastal accumulative bodies, including cuspate spits, is an important subject in scientific and applied research. A characteristic feature of similar accumulative bodies is a shallow underwater part. The aim of this work is to study the shallow-island part structure of the Dolgaya Spit (the Sea of Azov) and to identify the natural mechanism that determines both the variability of accumulative body over short time intervals and the high stability of the geosystem as a whole. Digital elevation models (DEM) for the studied area were built on the basis of remote sensing data (Sentinel-2). It is established that the length of the shallow-island part is about 20 km. There are shelly shoals and islands with a complex configuration and relief. Sea level, the wind-wave regimes and the sediment load are the main factors that determine the dynamic equilibrium of the shallow-island part of the Dolgaya Spit and its relief. The Dolgaya Spit has distinctive features of a free accumulative body influenced by longshore sediment flow. The configuration of its surface part is characteristic of many cuspate spits formed by two sediment streams. But the shallow-island part develops under the influence of alternating transverse movements of water masses and waves from opposite sectors. The coexistence of signs of the near-shore bar and cuspate spit provides grounds for classifying the Dolgaya Spit not as a cuspate accumulative body (in particular as Azov-type spit) but as a separate type developing under joint action of transverse and longshore sediment flows.

Keywords: *submarine relief, spit, coastal dynamics, remote sensing, Sea of Azov*

Rezumat. Caracteristici ale morfologiei și dinamicii insulei superficiale a Spitului Dolgaya (Marea Azov)

Relieful depunerilor sedimentare marine, ca de exemplu bancurile de nisip submerse, este un subiect important pentru cercetarea științifică și cu caracter aplicativ. O trăsătură de bază a acestor depunri sedimentare este dată de existența unor adâncimi mai mici. Lucrarea de față își propune să analizeze structura de mică adâncime generată de spitul Dolgaya (Marea Azov) și să identifice mecanismele naturale care determină atât variabilitatea acumulărilor pe o perioadă scurtă de timp și stabilitatea mare a gesosistemului ca întreg. Modelele digitale de elevație pentru zona de studiu au fost realizate cu ajutorul teledetecției (Sentinel-2). S-a stabilit că lungimea banculuisubmers este de aproape 20 km. Există și bancuri de cochilii și insule cu o configurație și relief complex. Nivelul mării, regimul vânturilor și al valurilor, precum și încărcătura de sedimente sunt principalii factori care determină atât echilibrul dinamic al insulei superficiale a Spitului Dolgaya și al reliefului acesteia. Spitul Dolgaya are caracteristicile distinctive ale unui corp e acumulare influențat de transportul sedimentor în lungul țărmului. Configurația părții exondate este marcată de prezența bancurilor de nisip formate de doi curenți de nisip. Totuși, partea mai puțin adâncă se dezvoltă sub influența mișcărilor transversale alternante ale maselor de apă și valurlor din sectoare diferite. Datorită prezenței aluviunilor în apropierea țărmurilor, precum și a bancului submers, putem considera că Spitul Dolgya nu este o corp de acumulare (de tipul spiturilor Azov), ci mai degrabă este un tip separat, care se dezvoltă sub acțiunea conjugată a depunerilor de sedimente atât transversal, cât și în lungul țărmului.

Cuvinte-cheie: *relief submers, spit, dinamica țărmului, tele-detecție, Marea Azov*

Introduction

The relief of large marine accumulative bodies is an important subject of study in scientific and applied research. High variability is common to most natural geosystems, in particular to coastal accumulative ones. Alteration of one or more components of geosystems usually results in a transformation of the accumulative body, but not in the degradation of the whole geosystem. However, if natural changes in external conditions exceed a certain limit, or are enhanced by anthropogenic influences, irreversible destruction of the geosystem can occur. The study of the landform morphology and dynamics of marine coastal accumulative bodies makes it possible to identify the mechanisms of their formation and evolution and to assess composition and significance of acting factors.

Geosystems of accumulative bodies, known as cuspate spits, are peculiar and complex (Rosen, 1975, Zenkovich, 1959). Cuspate spits are one of a family of shoreline reorientation features that includes cusplike structures, giant cusps, looped spits, and cuspate forelands (Rosen, 1982). These accumulative bodies are formed in stretches of coastline where two sediment streams meet. Examples include: Point Pelee peninsula (Lake Erie); cuspate foreland at northeast end of Graham Island (Pacific coast of Canada); cuspate spits of St. Lawrence Island (USA); Cape Dungeness (southern coast of Britain); Cape Kolka (the Baltic Sea); Cape Henlopen (Atlantic coast of the USA); the Bakalskaya Spit (the Black Sea). Some of these accumulative bodies were distinguished into a special type and received the name of Azov-type spits. These include the Belosarayskaya Spit and the Obitochnaya Spit (the Sea of Azov) (Zenkovich, 1967, Fisher, 1955, Kosyan, Krylenko, 2019, Price, Wilson, 1956). Many active hydrological and other factors determine the complex lithodynamic regime of cuspate spits, and, as a result, high variability in time and space. At the same time, cuspate spit geosystems often show high stability, persisting over long periods of time. Most of these accumulative bodies are specially protected areas. This once again points to the complexity and uniqueness of these natural sites.

The object of the present study is the geosystem of an accumulative body of the Sea of Azov – the Dolgaya Spit (Fig. 1). The aim of our research is to discover features of the structure of the shallow-island part of the Dolgaya Spit and to identify the natural mechanism that determines both the variability of the accumulative body over short time intervals and the high stability of the geosystem as a whole. Based on the obtained up-to-date information on the structure and dynamics of the shallow-island part of the Dolgaya Spit, supplemented by historical and literary data, analysis of the regularities of the structure and evolution of this natural site has been carried out.

Fig. 1: Geographical location of the Dolgaya Spit

Characteristics of the development of the accumulative geosystem of the Dolgaya Spit

The Sea of Azov is one of the smallest on the planet and is situated in Western part of Europe. The length of the shores of the Azov Sea in 2018 amounted to 3430 km, its area – to 40 570 km^2 (Krylenko, Krylenko, Aleynikov, 2019). A feature of the modern dynamics of the shores of the Sea of Azov is predominance of erosion processes. Not only indigenous shores are subject to erosion, but also accumulative bodies such as spits, sandbars of lagoons and estuaries (Kosyan, Krylenko, 2019). The Yeysk Peninsula is washed by the waters of the Sea of Azov and the Taganrog Bay. Sand-shell accumulative bodies such as the Yeysk spit, the Dolgaya Spit and the Kamyshevatsk Spit adjoin the peninsula (Zenkovich, 1958) (Fig. 1).

Fluctuations in the level of the Sea of Azov during the Holocene repeatedly led to transformation of the accumulative bodies at the NW end of the Yeysk Peninsula. Before the Phanagoria regression (≈ 3,000 years ago), the sea level was close to that of present days. During that period, there was probably an accumulative body, close in lithodynamic regime and structure to the present-day Dolgaya Spit (Artyukhin, 1987). During the Phanagorian regression, the sea level lowered, on average, by 5 m in comparison with that of the present day (Matishov and Polshin, 2019). Due to the decrease in the sea level the influence of runoff currents in the Taganrog Bay increased. The accumulative body of the Paleo-Dolgaya Spit was

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almost completely eroded (except for the accumulative terrace along the original coast). The washed out material was redeposited in the direction of the resulting direction of the sediment flow (to the SW), determined by prevailing SW waves and runoff currents of the Don at that time. During subsequent transgression, the influence of W and SW disturbances increased. From this point on, the resulting direction of the sediment flow was directed to NW. Approximately 2,500 years ago, two small curved spits arose at the projections of the original shore, growing towards each other. About 1-1,200 years ago, these spits joined each other and later developed together, forming the accumulative body of the Dolgaya Spit as a cuspate spit.

The image of the present position of the Dolgaya Spit appeared on maps of the Sea of Azov in the 14th century (Fig. 2). Characteristically, all maps, even the oldest ones, show the Dolgaya Spit as a chain of islands. A detailed map of the Taganrog Bay by Peter Bergman (1702) shows the contours of underwater and above-water accumulative bodies of the Dolgaya Spit (Fig. 3) with measured depths. In (Budischev, 1808) there is information about the Dolgaya Spit and its submarine shoal: "The spit extends from the Obryv Cape to the NW – at first as an external sandy spit 11.64 km long, then it is continued for 8.45 km by a chain of small islands. The spit and the islands are surrounded by a narrow shoal, no more than 2.4 km wide and 26.4 km long, with a tongue bent to the north. Elevations and depressions are marked along the longitudinal axis of the shoal. The Sailing Directions of the Sea of Azov (Sukhomlin, 1854) contains the following information about the Dolgaya Spit: "The Doldaya Spit is 0.5 m wide and stretches from the Obryv Cape to the NW for 15.74 km. Together with occasionally formed islands the underwater extension of the Dolgaya Spit, stretching 9.3 km to the NW of the surface part, forms a long shoal 2.8 km wide". The sailing directions are supplemented by a map of the Sea of Azov by E.P. Manganari (Papacoma, 2020), a remarkably accurate representation of the coastal configuration and the submarine relief (Fig. 4).

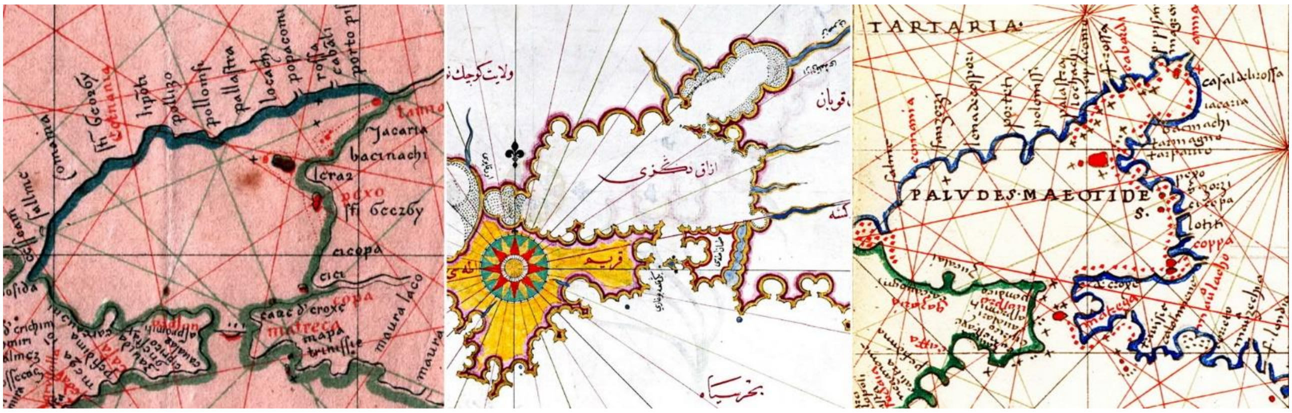

Fig. 2: The Dolgaya Spit on ancient maps: the portolan by Petro Vesconte (1318) on the left; a map in the atlas by Piri Reis (1525) in the centre, and the portolan by Battista Agnese (1540) on the right (Papacoma, 2020)

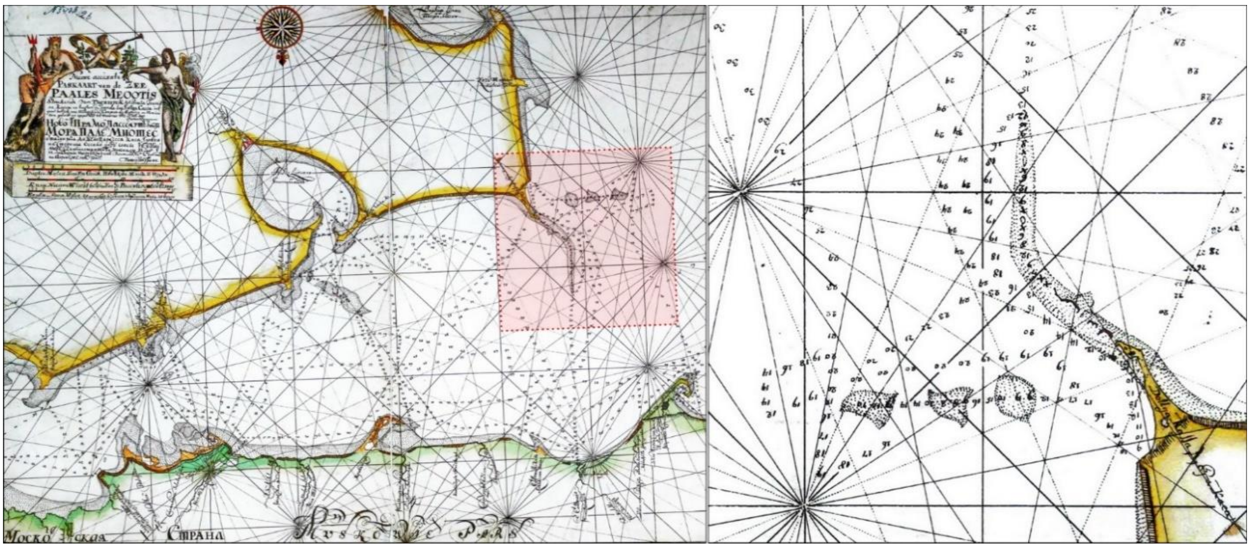

Fig. 3: Map of the Taganrog Bay by Peter Bergman 1702 (south on top). On the right: fragment with an image of the Dolgaya Spit (north on top) (Papacoma, 2020)

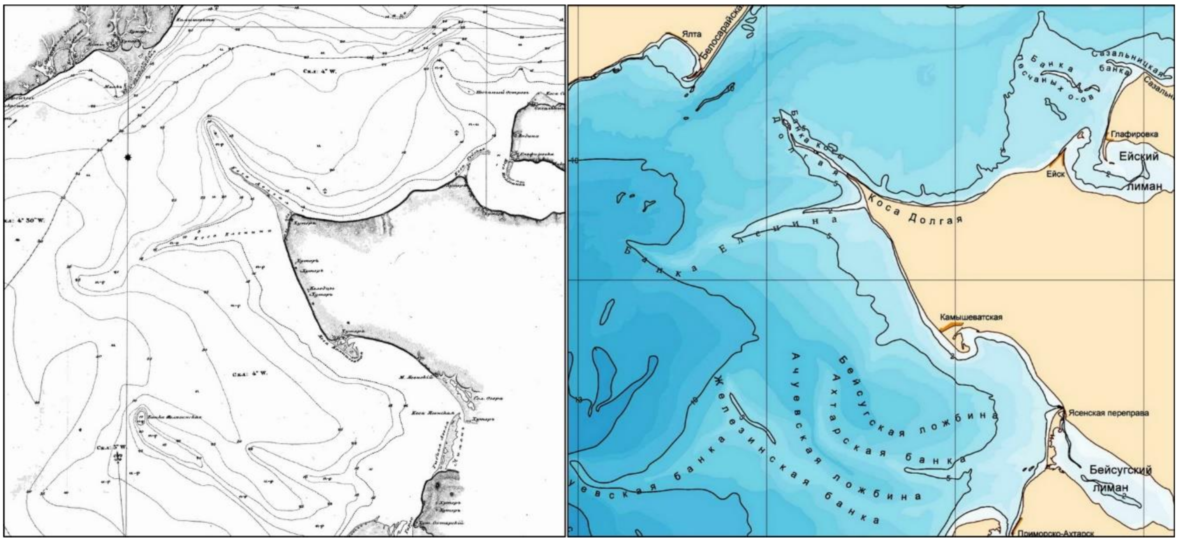

Fig. 4: Area of the Dolgaya Spit on a fragment of the map of the Sea of Azov by E.P. Manganari (1833) – on the left (Papacoma, 2020). Modern bathymetric map – on the right (Matishov et al., 2006)

Analysis of historical maps shows that the Dolgaya Spit's geosystem has been highly stable over the centuries. This accumulative body retains its structure: it consists of an above-water part (in a form of a cuspate spit), islands and shoals. During the development of the accumulative body of the Dolgaya Spit, the length of the above-water part of the spit periodically increased along the axis of the underwater shoal. At other times, on the contrary, the above-water part eroded or fragmented into a chain of more or less extended islands. As far as available maps show, the chain of the islands has never been connected into a single accumulative body. Over the last 150 years, the maximum length of the surface part (14 km) was observed in the 1940s and 1950s (Mamykina, and Khrustalev, 1980; Khrustalev, Scherbakov, 1974, Matishov, 2020). The comparison of maps from 1702 and 1833 with modern maps shows that the longitudinal axis of the underwater part and islands of the Dolgaya Spit geosystem is gradually shifting to the SW.

From the side of the Taganrog Bay and the open Sea of Azov, the Dolgaya Spit adjoins a abrasion shore composed of loess-like loams. The cliffs are 5-10 m high (Fig. 5) and the shore is eroding and receding at an average rate of 1-1.5 m per year (Kosyan and Krylenko. 2019).

Fig. 5: Abrasive shores at the root of the Dolgaya Spit: on the left – the Taganrog Bay (NE); on the right – the open Sea of Azov (SW)

The modern accumulative body of the Dolgaya Spit was formed mainly due to material of biogenic origin (shell) coming from the seabed. Abrasion products played some role in the initial stage of spit

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formation, but now the role of the biogenic source is much greater. The sediment of the Dolgaya Spit is dominated by shells: the sediment of the distal part and the shoal contain over 80% of the *Cerastoderma glaucum* clam shells, while that of the islands contains 90-95%. (Bespalova, 2007; Matishov, 2020).

Until the middle of the 20th century, the Dolgaya Spit was unaffected by human activity and developed exclusively under the influence of natural factors, after which the spit and underwater shoal were subjected to intensive shell mining. Y.V. Artyukhin estimates that a total of up to 4 million m3 of material was extracted from the accumulative body of the Dolgaya Spit (Artyukhin et al., 2015). From this point on, erosion processes at the tip of the Dolgaya Spit started to occur (Artyukhin, 1987), while the near-root part of the spit was generally stable (Fig. 6). In the 1990s, gullies formed in the spit (Bespalova, 2007) and it divided into a main part adjacent to the original shore and a shallow island part (Fig. 6). In subsequent years, the shallow island part of the Dolgaya Spit was mostly a chain of long (2 km or more) narrow islands extending along the axis of the bank. The overall length and relative position of the islands were constantly changing.

On 24 September 2014, a SW storm lasting more than a day, accompanied by a surge, destroyed the distal of the main part of the spit and all the islands. Since then, the Dolgaya Spit geosystem has been represented by a relatively stable near-shore part and an extremely dynamic submarine shoal, along the axis of which islands have started to form again since 2016 (Krylenko, Krylenko, 2017).

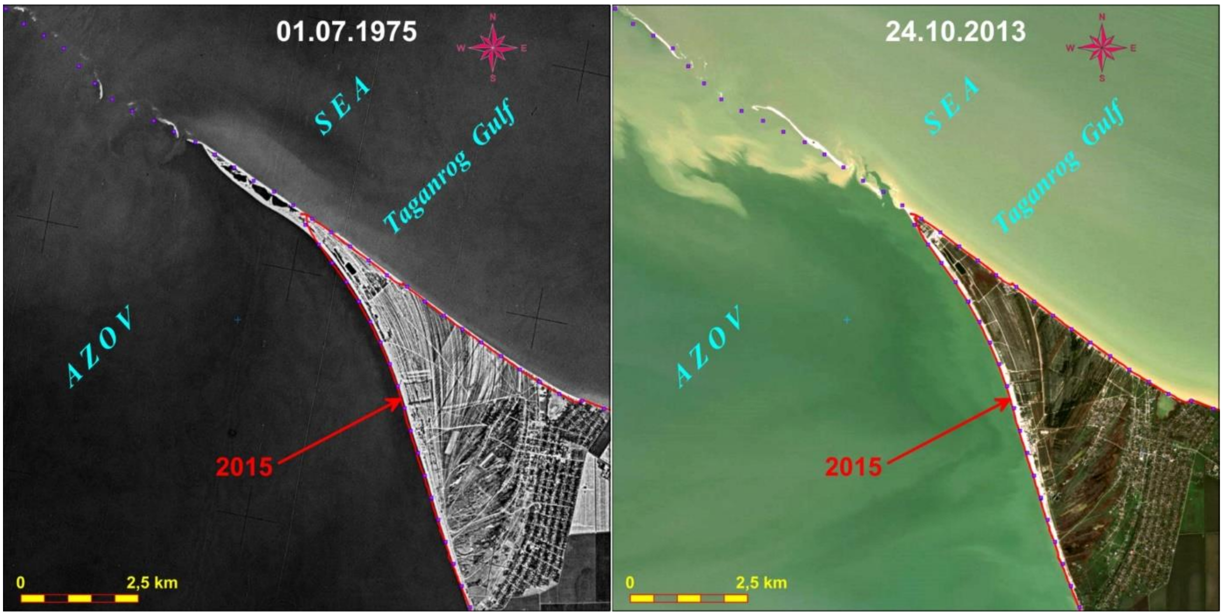

Fig. 6: Variability of the Dolgaya Spit: on the left – 1975, on the right – 2013. The red line marks the shoreline contour in 2015, following the erosion of the distal part and islands by the storm on 24.09.2014

Methodology

A characteristic feature of the Dolgaya Spit geosystem, like that of many other accumulative coastal bodies, is an extensive shallow underwater part. It is usually the most dynamic and variable part of the accumulative body, and the most difficult to study, as there are many methods for studying the surface relief, while the set of methods for studying the underwater relief is much smaller.

For a long time, underwater survey methods involved only direct measurements. Traditional bathymetric survey of water areas requires large material and time costs. In shallow areas, where both high detail of the terrain and its greatest variability are observed, bathymetric survey from the shipboard is often difficult or impossible. When studying underwater relief in the coastal zone, field measurements are usually conducted only along a small number of transverse and longitudal profiles. This is usually insufficient for identifying microforms of relief and studying its dynamics (Krylenko and Krylenko, 2018).

With the development of aviation and space industry, remote sensing methods dominated the study of underwater relief. The appearance of remote sensing satellites equipped with high-and medium-resolution spectrometers to detect radiation in a large number of spectral channels opened up new opportunities for the study of underwater relief in the depth range of 0-25 m. To date, a number of scientific studies and developed algorithms for calculating water depths using remotely sensed data are available (Chybicki, 2017, Hedley et al, 2005, Krylenko et al., 2019, Lyzenga, Malinas, Tanis, 2006). In this work, two algorithms were used to generate depth maps: Stumpf (2003) and Lyzenga (2006).

The waters of the Sea of Azov are characterized by increased turbidity associated with storms, biological processes, river runoff. According to the classification provided by the EOMAP Satellite Derived Bathymetry web service, the Sea of Azov belongs to turbid waters, with potentially possible depth for calculations of 5-10 m. There is no up-to-date information on the parameters of the water masses and bottom sediment for the entire study area. According to comparative testing (Zimin et al., 2018), both methods gave satisfactory results when generating depth maps from remotely sensed data for the Baltic, White and Black Seas with similar conditions (Chybicki, 2017, Traganos et al., 2018).

Sentinel-2, processing level 2A (Sentinel Online, 2020) images were used as input data. At the first stage, visual analysis of the available images was made. The criteria for selection were that the following conditions were met: no clouds over the study area, no strong waves, no surface film, minimal area of high turbidity zones. Unfortunately, there are extremely few images suitable for processing. The following images were used to map the underwater terrain: S2B_20180921_082959_109_37TCM; S2B_20180921_082959_117_37TDM; S2B_2019-10-16_121728_37TCM and S2B_2019-10-16_121728_37TDM

Pre-processing of images included correction of sun glare and creation of a mask of the water surface.

Hedley (2005) algorithm was used for the correction of sun glare. To eliminate sun glare, the algorithm uses the correlation between the visible (RED) and near infrared channel NIR.

The water surface mask was calculated using the formula of normalized difference water index: NDWI = (GREEN - NIR)/(GREEN + NIR). The resulting raster values are divided into two classes: water and land. The processed smoothed raster was converted into a polygonal vector object class.

Digital elevation models (DEM) were constructed for the study area with water depths up to 7 m (Fig. 7). Software implementation of depth mapping was performed using certified software ScanEx Image Processor. We used Blue (b02) and Green (b03) channels to obtain bathymetric information using the Stumpf (2003) method and Blue (b02), Green (b03) and Red (b04) channels when using the Lyzenga (2006) method. Calculation of natural logarithms (Stumpf, Lyzenga), coefficients of multiple regression (Lyzenga) and linear regression coefficients relative to the reference depth maps was conducted in the Scanex Image Processor. Nautical charts and data from direct acoustic bathymetric measurements were used as a reference map. The resulting accuracy in determining relative elevations and planned positions of individual underwater landforms is sufficient to make qualitative and quantitative assessments of transformation and planned displacement of hydrogenous forms.

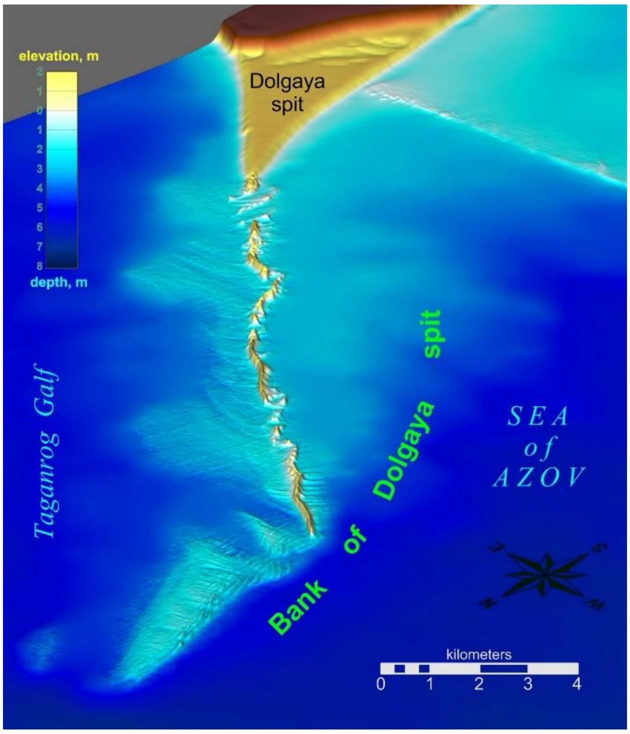

Fig. 7: 3D elevation model of the Dolgaya Spit geosystem (created from Sentinel-2 image, 16.10.2019)

Results and discussion

Structure of the shallow-island part of the Dolgaya Spit geosystem

The length of the shallow-island part is about 20 km. To describe the relief of the shallow-island part of the Dolgaya Spit geosystem, it is reasonable to distinguish between 'islands' – positive submarine or sometimes projecting over the water landforms outlined by a 1 m isobath and sometimes projecting above the water surface (Fig. 8, 9), 'shoals' – outlined by a 3 m isobath, and 'base' – outlined by a 5 m isobath.

The minimum width of the base (1.5 km) is found along the NE coast of the Dolgaya Spit, where it passes into the submarine flat-bottom land of the Taganrog Bay without pronounced boundaries. This indicates the longshore character of sediment migration in this area and the absence of transverse flow of sediment from the shore. D1 profile has a total base width of about 10 km (Fig. 8, 9). The total base width of the D4 profile is 8 km and that of D6 profile – 6 km. Near D7 profile, the base width decreases sharply to 3 km and its orientation and cross-section also change sharply (by 30-40°).

In general, the relief of the base is even but has a few distinctive elements. In sections D1-D7 extensive plumes of sediment directed into the Taganrog Bay can be traced 2-2.5 km NE of the axis of the shallow-island area. The orientation of the plumes indicates that the material is carried into the Taganrog Bay during the most severe storms. There is no evidence of a similarly large-scale migration of material in the opposite direction. The plumes are separated by narrows adjacent to the straits between the islands.

The width of the shoal zone is 250-500 m (Fig. 8). The greatest variety of landforms and their dynamics are to be found here. Four longitudinal sections can be distinguished according to a number of features (Fig. 8).

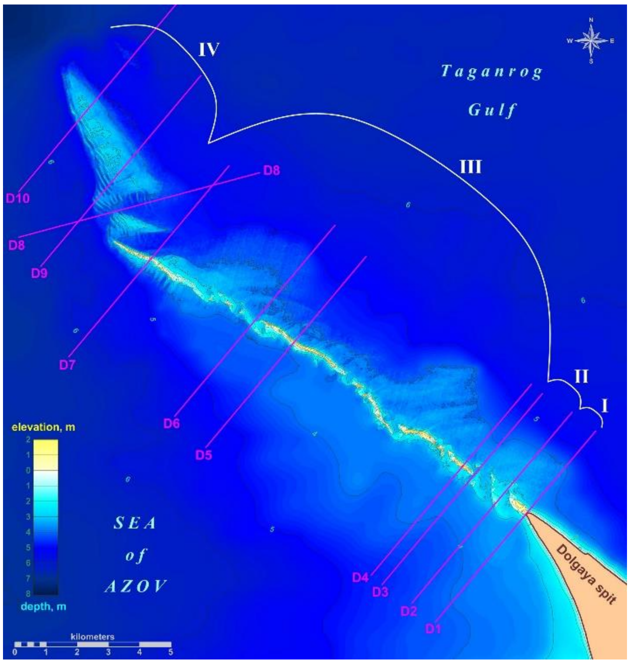

Fig. 8: Digital elevation model of the underwater part of the Dolgaya Spit (based on Sentinel-2 image of 16.10.2019)

The first section (profiles D1-D2) comprises the variable over-water distal of the main part of the Dolgaya Spit and a stable shoal (Fig. 8), which are adjacent to the root part of the Dolgaya Spit. This section is under a constant influence of longshore flow of sediment from the adjacent shore. The direction and extent of the distal part is determined by the volume of sediment discharged along the eroding NE shore and varies with hydrological conditions (Fig. 10). The distal has been eroding in recent decades. At present, the SW side of the distal is reinforced by a drop-fill rock (Fig. 11) and its variability has decreased. At the time of the survey – on 16.10.2019, the length of the distal and adjoining part of the shoal (up to profile D1) was about 650 m. The width of the uppermost part of the shoal was 300-350 m (2 m isobath), and 600 m (3 m isobath). The maximum elevation of the site (including the surface part) above the adjacent seabed was 4 m (Fig. 9).

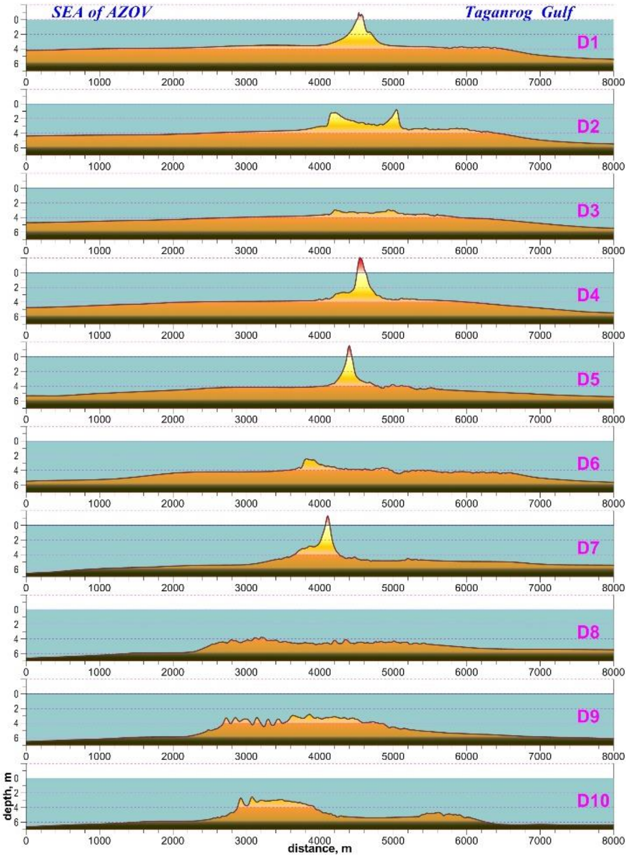

Fig. 9: Examples of transverse profiles of the shallow-island part of the Dolgaya Spit on 16.10.2019 (position of the profiles is shown in Fig. 8)

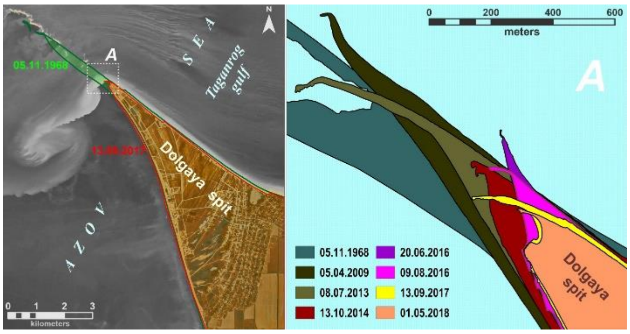

Fig. 10: Transformation of the distal part of the Dolgaya Spit

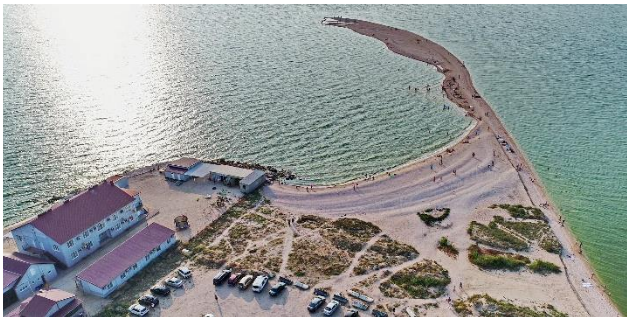

Fig. 11: Tip of the Dolgaya Spit on 22.08.2018

The next section between profiles D2-D3 (Fig. 8) on the accumulative body axis is 1700 m long and it is a zone of active water exchange occurring between the open Sea of Azov and the Taganrog Bay. In this area, the crest of the shallow-island part drops deeper than 3 m and is hardly expressed in the relief (Fig. 9). No islands have been formed here since 2014; in the preceding period, gullies in the accumulative body most often occurred here. The formation of gullies in this part probably prevents the rest of the Dolgaya Spit from destruction. The site formed crescentic positive landforms (Fig. 12) located at a 45° angle to the longitudinal axis of the accumulative body. They have an asymmetric cross-section profile (profile D2) reflecting predominance of sediment movement towards the bay. The elevation of these forms above the surrounding seabed is 2-2.5 m and they are separated by flat sections of the seabed (profile D3). The structure of this seabed relief in this area casts doubt on current existence of longshore flow of sediment from the tip of the main part of the Dolgaya Spit towards the shallow islands. Such flow may form when there is an excess of sediment. At this time there will be direct migration of sediment along the growing distal part of the spit all the way to the tip of the submarine shoal. However, when there is a shortage of sediment (as at present) the longshore inflow of material is insufficient to close gaps (gullies) and the dynamics of the site bottom relief is predominantly determined by lateral movements of the material.

The third (central) section is the longest at 13.75 km (Fig. 8). It is characterised by a chain of islands and well-defined submarine elevations, with periodically formed above-water parts, arranged clearly along the longitudinal axis. The elevation of the islands (including the above-water part) is 4-6 m above the surrounding seabed. The cross profile of the shoals is symmetrical and their width along the 3 m isobath is within 300-400 m (Fig. 9). The shoals are separated by more or less pronounced straits 100 to 500 m wide that cross or angle the axis of the shallow-island part. The bottom relief of most straits reflects the influence of powerful reverse flows of water masses. A narrow can be seen in the central part of the straits. At the exit from the straits, arc-shaped hills that mark areas of unloading of material discharged by the flow from the accumulative body can be clearly seen. These shapes are similar to bars situated near the mouth of a river. Characteristically, these bars are located on opposite sides of the straits, confirming the bimodal nature of the currents in them.

During periods of low hydrodynamic activity, when sediment is consolidated along the axis of the shallow-island area, the length of the island chain can vary from a few hundred metres to 2-3 km. The width of the emerging islands does not exceed 100 m, the height is up to 2 m at sea level. At the tip of the islands small hooks (locally called 'dzendziki') are formed, oriented in the direction of the prevailing current. The islands are the most 'ephemeral' element of the relief of the shallow-island part of the Dolgaya Spit. They can be formed and destroyed during a single storm, their configuration changes as currents change in the straits. Nevertheless, there is no doubt that even after complete destruction and under conditions of deficient longshore flow of sediment, islands re-form within a few years (Fig. 12). It is conceivable that the primary mechanism for consolidation of material within this section of the submarine-island part of the Dolgaya Spit is transverse movement of sediment close to the line separating the Taganrog Bay from the open Sea of Azov. This is indicated by the presence of pronounced straits between the islands at the time of their formation. It is only when sufficiently long islands have formed that local longshore flow of sediment is formed along them, lengthening the islands and gradually closing off parts of the straits. Characteristically, each of the islands lengthens simultaneously in both directions, bridging the straits. This contradicts the existence of a single longitudinal flow from the tip of the Dolgaya Spit to the NW. As the edges of the islands bend in the direction of the prevailing wave or current at a particular period, the junction point of the countercurrent flows is diverted from the axis along which the primary islands originated, and the entire island chain takes on a sinuous appearance (Fig. 12). In some cases, the development of surface accumulative bodies is observed, straightening the previously formed bend. As the islands lengthen, longshore currents intensify and they may also change the configuration of the shoals that serve as the islands` foundation. During storm surges there are breaks in the above-water part of the islands. Reconstruction of the junctions takes place under different hydrological conditions and the attachment of neighbouring islands may take place elsewhere.

To the south of profile D7 there are transversal ledges on both sides of the shoal, 150-200 m apart, with an average elevation of 0.5-1.0 m above the seabed. The ledges were presumably formed by the interaction of transverse (surge and seiche) and longitudinal currents that form along its sides. The presence of similar water motions caused by turbulence as large masses of water pass through can be seen in the structure of turbidity patches on satellite images (Fig. 13).

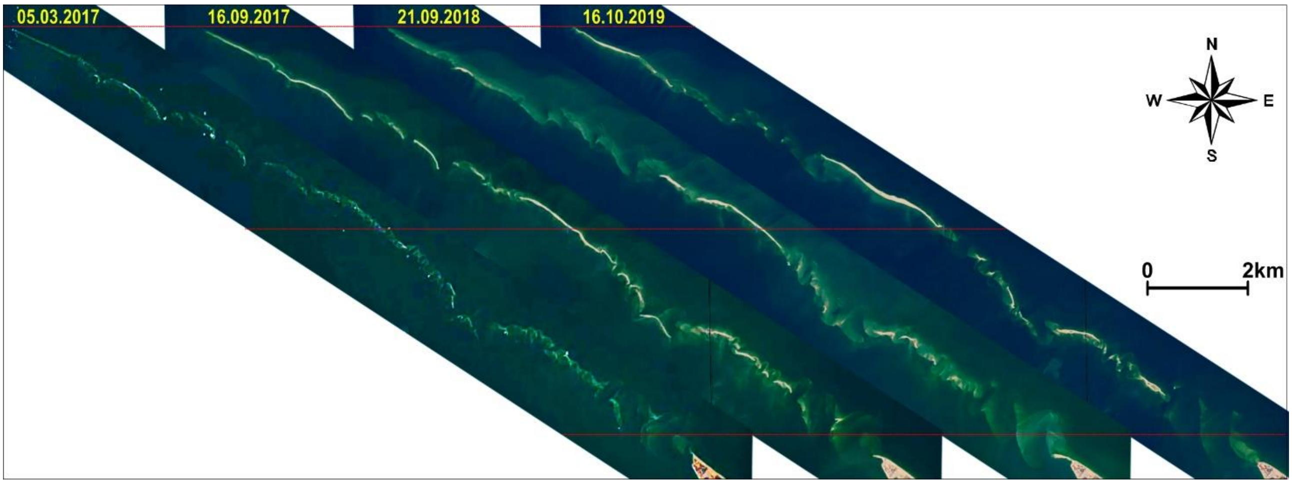

Fig. 12: Transformation of the shallow-island part of the Dolgaya Spit within two years

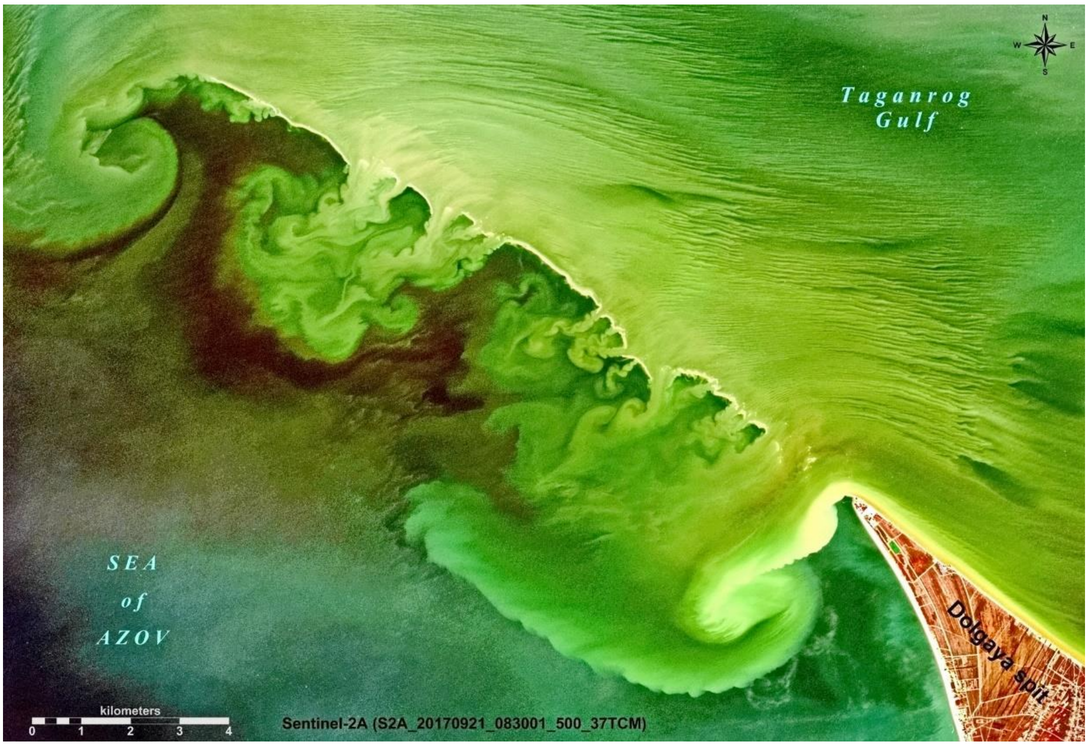

Fig. 13: (Sentinel-2 image fragment, 21.09.2017)

Near the northern tip of the shallow-island part of the Dolgaya Spit (Section 4) (Fig. 8, 14) there are underwater landforms indicating the presence of oscillatory movements of large water masses. These forms have been traced on satellite images since at least 2015. Over 6 km long and up to 3 km wide, there is a system of ridges perpendicular to the currents in the strait. There are up to 10 sub-parallel ridges traced (Fig. 9, 14), with a crest elevation of 1-1.5 m above the narrows separating them, the distance between adjacent ridges is 100-150 m (profiles D9-D10). The transverse profile of the ridges is close to symmetrical. To the east, smaller ridges or plumes are formed on top of these ridges and perpendicular to them. The distance between these ridges is about 50-60 m and the elevation above the bottom is about 0.3 m.

Relief formation mechanisms in the shallow-island part of the Dolgaya Spit

Analysis of the structure of the shallow-island part of the Dolgaya Spit, based on the digital elevation models obtained, revealed a number of characteristic features. Along the axis of the accumulative body there are shoals with a complex configuration and an abundance of drop-shaped or arc-shaped elements. Such hydrogenous bodies are formed by a combination of differently directed sea currents. The presence of depressions crossing or angling the longitudinal axis of the underwater-island part of the Dolgaya Spit indicates a much lesser influence of alongshore sediment transport from the main part, as compared to the transverse one.

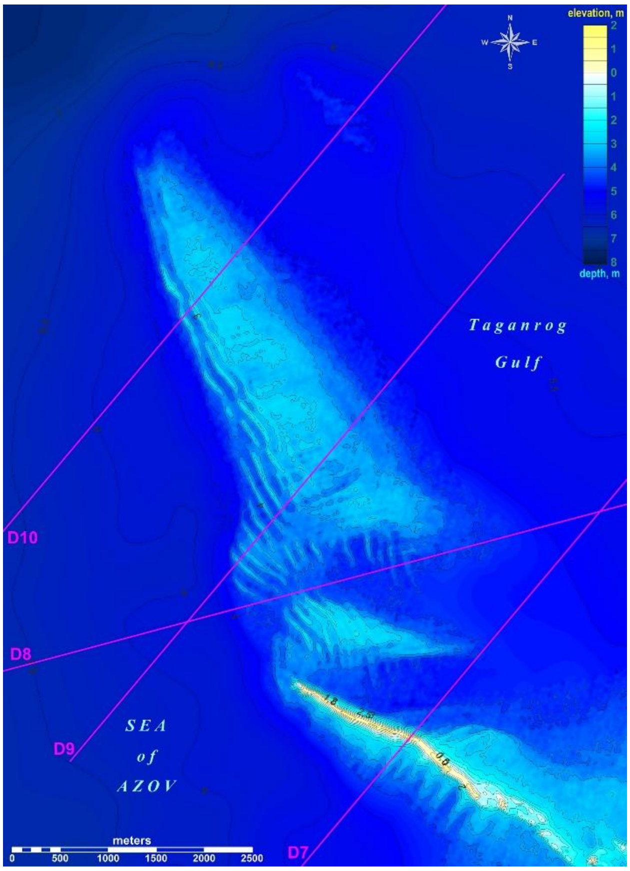

Fig. 14: Hydrogenous underwater landforms at the northern end of the shallow-island area (DEM based on Sentinel-2 image of 16.10.2019)

Along the adjacent shores, the alongshore currents can reach values of 0.4-0.6 m/s with the direction usually towards the tip of the spit. There are no beach-forming fractions in the original rock of adjacent shores (Kosyan, Krylenko, 2019). At the same time, potential capacity of sediment flow is very high. Accordingly, the role of longshore currents along the Dolgaya Spit is limited to the erosion of the root part and transport of sediment to the tip of the distal part of the spit. In addition, these currents, while continuing to move along the shallow islands of the Dolgaya Spit, consolidate the sediment previously carried onto the adjacent underwater slope by cross currents and storms.

The shoals and islands are formed mainly by shells, which has considerably greater mobility than mineral sands. The arrival of shell material from the underwater slope and its consolidation near the axis of the shallow-island part is determined solely by the nature of the waves. In addition, it is the waves that form the islands on the axis of the underwater-island area. Over the area of the Sea of Azov, the NE winds prevail in winter and SW – in summer. The shallow-island part of the Dolgaya Spit is exposed to waves from opposite directions – SW and NE. The strength of SW disturbances exceeds that of the NE swell, but the frequency of the latter, especially in winter, is higher. On the basis of available wave data (Shlyamin, 1977), at the entrance to the Taganrog Bay during the strongest SW storms shells mobilisation may occur from the entire area of the seabed adjacent to the shoal (depth - 6-11 m). On the side of the Taganrog Bay the supply of the shell material from the seabed is weakened: short waves cannot lift the shells from depths of 5-6 m. Thus, wave disturbance contributes to the flow of the shells from the open Sea of Azov to the Dolgaya Spit and its underwater shoal and its consolidation near the axis of the accumulative body.

The complex combination of factors at work determines the particular configuration and transverse structure of the islands that form along the axis of the accumulative body. The surface relief of the islands is represented by a series of shell beach bars extending along both shores (Fig. 15). The size (height and width) of the beach bars corresponds to the intensity of the wave from a given direction. There are often lagoons forming between the beach bars. As a rule, islands are formed independently of the state of the main part of the spit and are connected to it only in the presence of a significant excess of sediment brought in by longshore flow. Restoration of the lithodynamic connection alters somewhat the overall development of the area – the role of the longshore flow increases. At such times, the length of the main (shore-connected) part of the accumulative body increases due to its extension to the NW. Nevertheless, the influence of transverse sediment movement persists and the height and width of the beach bars on either side of the Dolgaya Spit continue to increase. In phases of sediment deficit the accumulative body divides into two almost independent parts once again – the main, predominantly over-water part and the shallow-island part, predominantly underwater. The observed disintegration of the single accumulative body is often perceived as its degradation, but this is only a phase of its development.

As the shallow-island part of the Dolgaya Spit acts as a barrier at the entrance to the Taganrog Bay, high sea level gradients occur over it as a result of up and down surges. Strong W-SW winds in Taganrog Bay produce a surge of up to 2-3 m. In contrast, during sustained NE wind there is a downsurge of up to 1-1.5 m. During the initial and final stages of the up and down surge cycle, currents of up to 1-1.5 m/s form in the straits. As a rule, these currents cover the entire water column, from the surface to the bottom. In general, such transverse water movement contributes to the formation of gullies in the shallow-island area and sediment transport to the adjacent underwater slope (Fig. 16).

Fig. 15: Island relief (photo surf-shelter.ru)

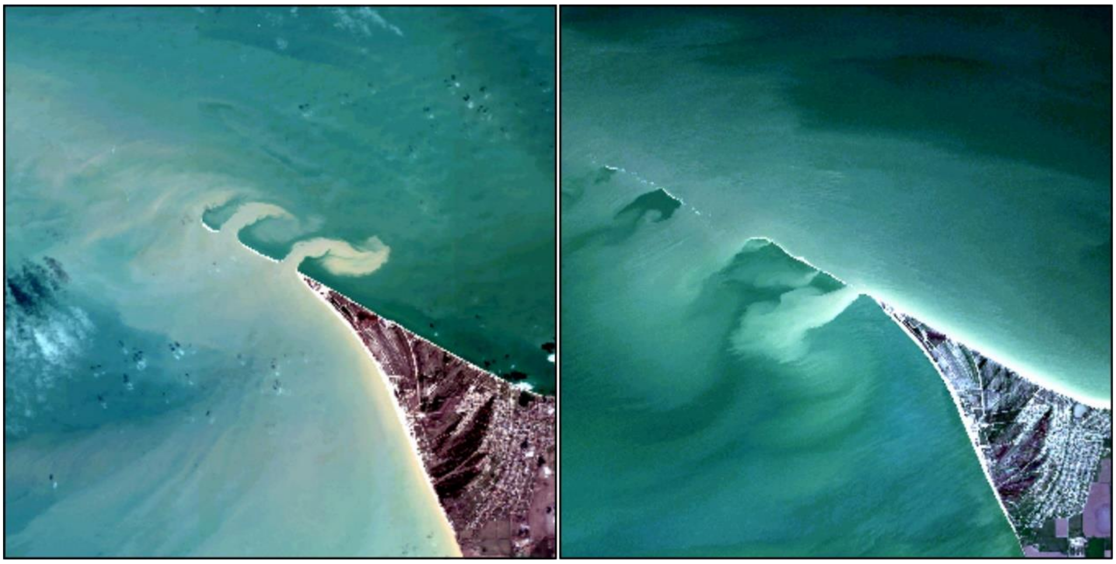

Fig. 16: Movement of water masses at the Dolgaya Spit. On the left – SW storm, eroding the SW coast of the Yeysk Peninsula and carrying sediment from the open Sea of Azov into the Taganrog Bay; on the right – NE storm, eroding the NE coast and carrying sediment into the open Sea of Azov

During the maximum development phase of the surge in the mouth of the Taganrog Bay, there are strong compensatory currents in the near-bottom layer directed from the Taganrog Bay to the open sea. During a field experiment in August 2000 at the exit of the Taganrog Bay at the end of the Dolgaya Spit there were intense near-surface and near-bottom currents with speeds of 60-90 cm/s and 40-60 cm/s respectively, directed in the opposite direction (Luk'yanov et al., 2001, Zakharevich, Sukhinov, 2001). A compensatory current originating in the near-bottom layer and covering a large area of the bottom of the Taganrog Bay contributes to the movement of the shells towards the underwater shoal of the Dolgaya Spit. After passing over the underwater shoal in the open sea, the near-bottom compensatory current quickly fades and sediment accumulates close to the shoal, in the zone of lithodynamic influence of waves of SW direction. Thus, the compensatory current is the driving force behind the process of shell transport from the bottom of the Taganrog Bay into the lithodynamic system of the Dolgaya Spit.

In addition to the processes listed above, the presence of a discharge current from the mouth of the Don towards the open Sea of Azov and alternating currents initiated by seiche should be considered. The process of island reshaping is also influenced by drifting ice.

Thus, the combined effect of wave action contributes to the influx of sediment into the lithodynamic system of the Dolgaya Spit from the open Sea of Azov. In addition, wave action promotes consolidation of sediment along the axis of the shallow-island area and formation of islands. The compensatory current, reinforced by the discharge current, contributes to the influx of sediment from the NE, from the side of the Taganrog Bay. The longshore currents, directed from the adjacent shores of the Yeysk Peninsula to NW, towards the tip of the Dolgaya

Spit and its underwater shoal, contribute to a gradual spread of sediment along the axis of the accumulative body and increase its length. The logical lithodynamic result of the combined action of the above phenomena was the quasi-stationary spatial position of the axis of the shallow-island part of the Dolgaya Spit. At the same time, the variety of acting factors contributes to a high variability and diversity of the hydrogenous forms that form along the axis of the accumulative body.

Sea level, the hydrological and wind-wave regimes and the sediment load are the main factors that determine the dynamic equilibrium of the shallow-island part of the Dolgaya Spit and its relief. The position of the accumulative body at the entrance to the Taganrog Bay is determined by the combined action of waves and currents of different genesis. Accordingly, a short-term change in any of these factors leads to a rapid transformation of the underwater relief. Variable water movements caused by surge and seiche phenomena contribute to the consolidation of sediment near the axis of the accumulative body, but at the same time can cause erosion in some areas. Waves contribute to the formation of islands and initiate longitudinal movement of sediment. If the current wind-wave climate and hydrological structure of the sea are preserved, the position of the underwater-island part will not change.

When sea level is relatively stable (±1 m), the position of the accumulative body also remains unchanged. However, in the case of a short-term strong sea level rise (of more than 2 m, as during the surge in September 2014), the islands are destroyed. It is likely that if sea level rises significantly, possibly as a result of global climate change, the above-water part of the shallow-island part of the Dolgaya Spit will be completely destroyed, although the underwater part will retain its position in space. A drop in sea level can also have a significant effect, but only at values that cause a change in the configuration of the sea and its current regime. In this case, the change will manifest itself in a change in the orientation of the entire accumulative body, including the above-water and underwater parts.

Fluctuations in the total volume of sediment in the lithodynamic system of the Dolgaya Spit can cause changes in its relief. An increase in the amount of sediment will contribute to the growth of the surface parts and increase in the total length of the shallow-island part. Reduction in the amount of sediment will consequently cause the opposite process. At the same time, fluctuations in sediment volume have no effect on the position of the axis of the accumulative body in space.

Conclusion

The research carried out confirmed the assumption that there is a natural mechanism that determines both an extreme dynamism of the relief of the accumulative body in short periods of time and a high stability of the geosystem as a whole. A striking example of an accumulative body that exists due to such a mechanism is the Dolgaya Spit geosystem. On the one hand, it has the distinctive features of a free accumulative body influenced by longshore sediment flow. The configuration of its upper part is characteristic of many cuspate spits formed by two sediment streams converging at an acute angle. On the other hand, the shallow-island part develops under the influence of alternating transverse movements of water masses and waves from opposite sectors of the horizon. This influence favours the formation of a bar-like accumulative body, consisting of shoals and islands, located at the junction of two large water areas. The coexistence of signs of the bar and cuspate spit provides grounds for classifying the Dolgaya Spit not as a cuspate accumulative body (in particular as an Azov-type spit) but as a separate type of major accumulative geosystems, developing under the active joint action of transverse and longshore sediment flows.

In general, several features can be singled out for such accumulative geosystems:

1. They are located at the junction of two large water areas with opposing forces determining direction of sediment movement – waves, currents (drift, tidal, runoff, compensatory ones). The total power of all forces acting from each direction must be equal.

2. The initial (main) accumulation of sediment in the system is due to longshore sediment flow from the land side (sometimes there are two sediment flows).

3. During periods of sediment surplus, a single spit with an extensive above-water part is formed along the axis of the accumulative body. At this juncture the longshore sediment flow dominates along its coasts.

4. During periods of sediment deficit, the accumulative body is divided into a coastal body, with an above-water spit and longshore sediment flow, and a shallow-island body where transverse sediment flow predominates. During such periods, the lithodynamic connection between the above parts may weaken or even cease.

5. Within the shallow-island part in the zone of equilibrium of the forces acting on both sides, islands may form, representing two bars with lagoons enclosed between them.

6. The entire accumulative body system may gradually shift as the overall configuration of the adjacent shore changes or the balance of acting

forces changes, but the overall lithodynamic pattern of geosystem development remains unchanged.

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Author contribution

Conceptualization, Viacheslav Krylenko and Marina Krylenko; methodology, Viacheslav Krylenko; formal analysis, Viacheslav Krylenko; investigation, Viacheslav Krylenko and Marina Krylenko; writing—original draft preparation, Viacheslav Krylenko and Marina Krylenko; writing—review and editing, Marina Krylenko. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

References

Artyukhin, Yu.V., Artyukhina, O.I., & Rodionova, N.B. (2015). Yeisk coast: history and problems of development, natural foundations of reconstruction. Yeisk, 205 p.

Artyukhin, Yu.V. (1987). Genesis and dynamics of the 'Azov type' spits. *Geomorphology*, 3, 27–30.

Bespalova, L.A. (2007). Ecological diagnostics and assessment of the stability of the landscape structure of the Sea of Azov. Saint Petersburg State University, 32 p.

Budischev, I.M. (1808). Sailing Directions and the sea guide to the Sea of Azov. Saint Petersburg, 79 p. www.bookvoed.ru/files/3515/18/73/47.pdf

Chybicki, J. (2017). Mapping south Baltic near-shore bathymetry using Sentinel-2 observations. *Polish Maritime Research*, 24, 15-25. https://doi.org/10.1515/pomr-2017-0086

Fisher, R.F. (1955). Cuspate spits of St. Lawrence Island, Alaska. *Jour. Gool.*, 63(2), 133-142.

Hedley, J.D., Harborne, A.R., & Mumby, P.J. (2005). Simple and robust removal of sun glint for mapping shallow-water benthos. *Intern. J. Remote Sensing*, 26(10), 2107-2112. https://doi.org/10.1080/01431160500034086

Khrustalev, Yu.P., & Scherbakov, F.A. (1974). Late Quaternary deposits of the Sea of Azov and the conditions of their accumulation. *Rostov-on-Don: Publishing House Rostov University*, 154 p.

Kosyan, R.D., & Krylenko, M.V. (2019). Modern state and dynamics of the Sea of Azov coasts. *Estuarine, Coastal and Shelf Science*, 224, 314-323. https://doi.org/10.1016/j.ecss.2019.05.008

Krylenko, V., Aleinikov, A., Krylenko, M., Beliaeva, N., & Moiseeva, N. (2019). Possibility of the underwater topography studying of large accumulative forms according to Sentinel-2 data. *Proc. of SPIE*, 11174, 111741P. https://doi.org/10.1117/12.2532292

Krylenko, V., & Krylenko, M. (2017). Long-term Dynamics of the Dolgaya Spit Coast. *Proc of the XIII International MEDCOAST Congress on Coastal and Marine Sciences, Engineering, Management and Conservation*. Mugla: MEDCOAST Foundation, 2, 839-848.

Krylenko, V., Krylenko, M., & Aleynikov, A. (2019). Revision of the coastline length of the Azov Sea according to remote sensing data. *Proc. of SPIE*, 11174, 111741B. https://doi.org/10.1117/12.2532690

Krylenko, V., & Krylenko, M. (2018). High-precision relief survey of the Bakal spit. *Environmental safety of the coastal and offshore zones of the sea*, 4, 65-72. https://doi.org/10.22449/2413-5577-2018-4-65-72

Luk'yanov, Yu.S., Tsytsarin, A.G., Sukhinov, A.G. (2001). Investigation of hydrophysical and hydrochemical fields for the purpose of monitoring marine water bodies. *Physical problems of ecology*, 8, 15-22.

Lyzenga, D.R., Malinas, N.P., & Tanis, F.J. (2006). Multispectral bathymetry using a simple physically based algorithm. *IEEE Transactions on Geoscience and Remote Sensing*, 44(8), .2251-2259. https://doi.org/10.1109/TGRS.2006.872909

Mamykina, V.A., & Khrustalev, Yu.P. (1980). The Sea of Azov Coastal zone. *Rostov-on-Don: RSU Publishing House*, 176 p.

Matishov, G., Polshin, V., Kulygin, V., Titov, V., Kovalenko, E., & Sushko, K. (2020). New data on the structure of the Dolgaya spit of the Sea of Azov (drilling, study of outcrops, malacofauna). *Science in the South of Russia*, 16, 3, 26–39. https://doi.org/10.7868/S25000640200304

Matishov, G., & Polshin, V. (2019). New result on the history of the Azov Sea in the Holocene. *Reports of the Academy of Sciences*. 15, 1, 42–53. https://doi.org/10.7868/S25000640190105

Matishov, G.G., Gargopa, Yu.M., Berdnikov, S.V., & Dzhenyuk, S.L. (2006). Patterns of ecosystem processes in the Sea of Azov, M.: *Nauka*, 304 p.

Papacoma http://papacoma.narod.ru/maps-index.htm [Accessed: 15.11.2020]

Price, A.W., & Wilson, B.W. (1956). Cuspate Spits of St. Lawrence Island, Alaska: A Discussion. *The Journal of Geology*, 64, 1, 94-98. https://doi.org/10.1086/626321

Rosen, P.S. (1982). Cuspate spits. In: Beaches and Coastal Geology. *Encyclopedia of Earth Sciences Series*. Springer, New York. https://doi.org/10.1007/0-387-30843-1_143

Rosen, P.S. (1975). Origin and processes of cuspate spit shorelines, in L. E. Cronin, ed., Estuarine Research. *New York: Academic Press*, 2, 77–92. https://doi.org/10.1016/B978-0-12-197502-9.50010-1

Sentinel Online technical website. Available at: https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-2-msi/level-1c/product-formatting [Accessed: 10.01.2020]

Shlyamin, B.A. (1977). Waves on the Sea of Azov. *Trudy GOIN*, 16, 45-47

Stumpf, R., Holderied, K., & Sinclair, M. (2003). Determination of water depth with high-resolution satellite imagery over variable bottom types. *Limnol. Oceanogr.*, 48(1), 547-556. https://doi.org/10.4319/lo.2003.48.1_part_2.0547

Sukhomlin, A.M., 1854 (2017). Sailing directions of the Sea of Azov and the Kerch-Yenikalsky Strait. Nikolaev, 4, 96 p.

Traganos, D., Poursanidis, D., Aggarwal, B., Chrysoulakis, N., & Reinartz, P. (2018). Estimating satellite-derived bathymetry (SDB) with the Google Earth Engine and Sentinel-2. *Remote Sens.*, 10(6), 859-877. https://doi.org/10.3390/rs10060859

Zakharevich, V.G., & Sukhinov, A.I. (2001). Mathematical modeling is a universal methodology for analyzing and forecasting the ecosystem of the Sea of Azov. *Proceedings of the Southern Federal University*, 20 (2), 3-13

Zenkovich, V.P. (1967). Processes of Coastal Development. *Oliver and Boyd*, Edinburgh, 738 p.

Zenkovich, V. P. (1959). On the genesis of cuspate spits along lagoon shores. *Jour. Geology* 67, 269–277

Zenkovich, V.P. (1958). Shores of the Black and Azov Seas. *M.: Geografizdat*, 359 p.

Zimin, M., Moiseeva, N., Belyaeva, N., Aleynikov, A., Savostin, A., & Perminova E. (2018). Bathymetric mapping in the coastal zone based on Earth remote sensing materials. *RRW by SCANEX R&D Centre*, 91 p.