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Original article

Numerical Study of Hydrodynamic Regime of the Taganrog Bay Waters in the Sea of Azov

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Abstract

Purpose. The work is aimed at studying the hydrodynamic conditions of formation of the sand spits in Taganrog Bay of the Azov Sea from the viewpoint of the morphological features of spits.

Methods and Results. The analysis is based on the results of numerical modeling the hydrodynamic parameters of the entire Azov Sea over 42 years, from 1979 to 2020. The generated data array consists of the hourly spatial fields of bottom current speeds and directions, as well as the wind wave significant heights and directions of their propagation. A significant difference between the hydrodynamic regimes of the sand spits of the northern coast (Belosaraysk and Krivaya spits) and the southern coast (Ochakovsk, Chumbursk, Sazalniksk and Yeysk spits) has been found.

Conclusions. In the coastal waters of Belosaraysk and Krivaya spits (the northern coast), the frequency of currents from the east prevails. Beglitsk (the northern coast), Ochakovsk and Sazalniksk (the southern coast) spits are characterized by the predominance of currents from the west. In the region of Belosaraysk and Krivaya spits, the long-term mean velocities of the currents directed to the east are slightly higher than those of the currents directed to the west. In the areas of Beglitsk spit (the northern coast), as well as Ochakovsk, Chumbursk, Sazalniksk and Yeysk spits in the southern part of the bay, the eastward directed currents dominate noticeably, both in terms of mean and maximum speeds. In the coastal waters of Belosaraysk and Krivaya spits, both the mean and maximum heights of the waves propagating to the east slightly exceed those of the waves propagating to the west. As for Beglitsk, Ochakovsk, Chumbursk, Sazalniksk and Yeysk spits, the dominating westward direction of wave propagation is, on average, a characteristic feature, whereas the waves of maximum heights develop during the eastern storms.

Keywords: Sea of Azov, sand spits, hydrodynamic conditions, numerical modeling

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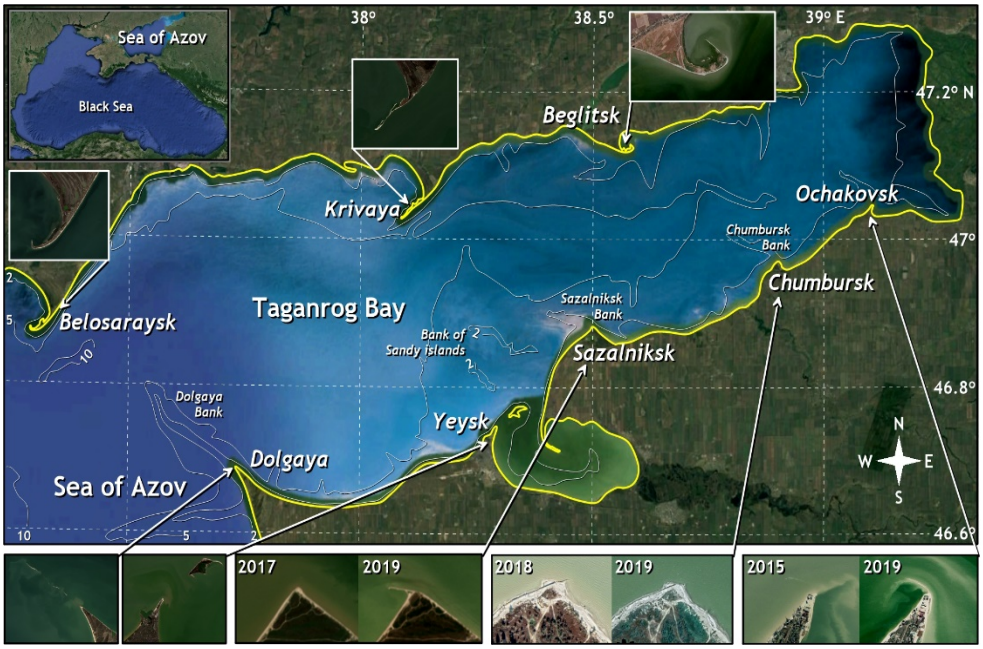
Introduction

Taganrog Bay is situated in the north-eastern region of the Sea of Azov. Taganrog Bay extends for 135 km in length and has a typical width of 30 km. In comparison to the main water area of the Sea of Azov, it is relatively shallow, with

an average depth of approximately 5 m [1]. The coastal zone of the bay, as well as the entire sea, is characterised by specific geomorphological forms, namely sand spits (Fig. 1).

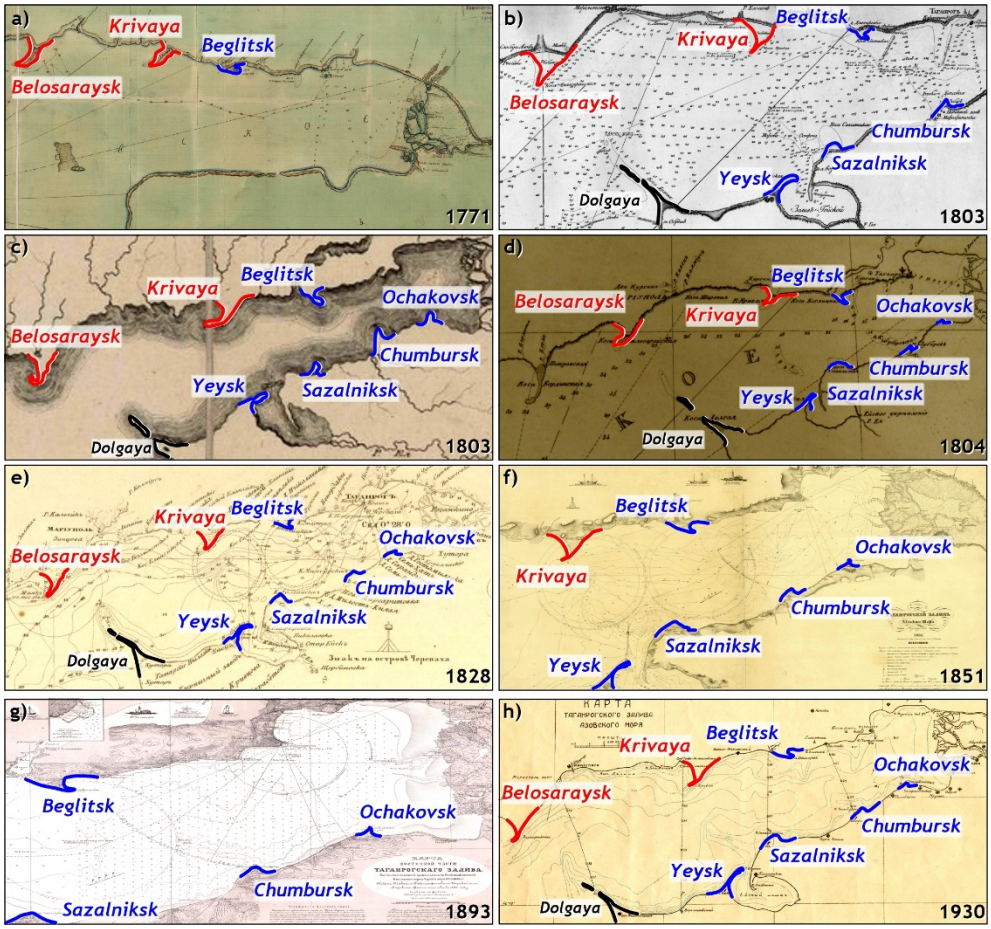


F i g. 1. Bathymetric map and morphometric features of Taganrog Bay in the Sea of Azov (*on the top*); examples of radical reshaping of spits (*on the bottom*)

On the northern coast, the spits of Belosaraysk, Krivaya and Beglitsk are the most developed, exhibiting significant extension into the open sea. The general direction of Belosaraysk and Krivaya spits is from east to west, whereas Beglitsk spit is oriented in the opposite direction. In the southern sector of the bay, the spits of Ochakovsk, Chumbursk, Sazalniksk and Yeysk are morphometrically oriented from west to east. However, the extremities of all spits, with the exception of Yeysk, may occasionally exhibit a tendency to extend in the opposite direction. The underwater extensions of these spits are also oriented from east to west, as is evident from Fig. 1, which illustrates the 2 m isobath. The distal portion of Dolgaya Spit, which directly borders Taganrog Bay on the southern side, bends either towards the bay or towards the open sea, depending on the prevailing hydrodynamic conditions.

It is noteworthy that a similar phenomenon was previously observed (Fig. 2). The spits directed from east to west are indicated in red in Fig. 2, while those directed from west to east are indicated in blue. The maps are ordered according to the year of publication.

Fig. 2 illustrates stability of the above-mentioned features of the morphological appearance of Taganrog Bay over a period of at least 250 years.



F i g. 2. Historical maps of Taganrog Bay (source: internet archives papacoma.narod.ru; www.etomesto.ru)

Spatial positions of the main Taganrog Bay spits (excluding Dolgaya Spit) are summarized in the table.

General directions of the spits in Taganrog Bay

Coast	Spit	Direction
Northern	Belosaraysk	E-W
	Krivaya	E-W
	Beglitsk	W-E
Southern	Ochakovsk *	W-E
	Chumbursk *	W-E
	Sazalniksk *	W-E

* Direction of extremity E-W, W-E.

Let us point out once again that, with the exception of Beglitsk Spit, the sand spits of the **northern** part of Taganrog Bay (Belosaraisk and Krivaya) are oriented from **east** to **west**. The **southern** coast spits (Ochakovsk, Chumbursk, Sazalniksk and Yeysk), as well as Beglitsk Spit (the northern coast), are oriented in the opposite direction – from **west** to **east**. Thus, as follows from Fig. 1, 2, certain patterns in the development of the spits of the northern and southern coasts of the bay are found. Their study is the subject of the present paper.

The formation and transformation of sand spits is influenced by morphological factors such as bedrock conditions, sediment granulometric composition and the presence or absence of beach recharge, as well as hydrodynamic factors such as sea currents, prevailing wind waves and sea level. The morpho- and lithodynamic features of the sand spits of Taganrog Bay have been the subject of considerable research. A synthesis of the findings from numerous studies [2–8] reveals that the spits are predominantly composed of fine-grained sands and coarse silts, with the proportion of aleuritic silts increasing with depth. The underwater bases of the spits, which have been traced to depths of approximately 3–4 m, consist of sands with an admixture of shells and detritus. In general, as evidenced by the findings [3], the abrasion slopes of the northern and southern coasts of the bay exhibit typological similarities.

The most extensively studied hydrodynamic characteristics of the waters of Taganrog Bay are wind surges. These surges are associated to a significant extent with the developed system of sea level observations, with data being gathered from numerous hydrological posts located along the entire coast of the Sea of Azov [9–13]. The most notable characteristic of the bay is the considerable amplitude of wind surges. To illustrate, in Taganrog, the range of sea level fluctuations exceeded 6 m between the years 1882 and 1998 [14].

The wind wave regime of Taganrog Bay (as part of the Sea of Azov) has been the subject of detailed study [15–17], with estimates of the main parameters of wind waves (heights, periods and lengths) in the water area of the entire Sea of Azov. It is regrettable that the analysis does not take into account the ice cover, which partially or completely (depending on the severity of atmospheric conditions) covers the sea area from approximately November to March. The presence of ice has a direct impact on the conditions that facilitate the development and transformation of wind waves.

The parameters of sea currents in the Taganrog Bay water area, obtained by calculation, have been subjected to analysis in several scientific manuals [6, 15]. However, the main limitation of the data is that the current fields correspond only to specified directions and certain gradations of wind speed. Consequently, there is no information regarding the estimation of climatic conditions with respect to the characteristics of the currents.

Thus, assuming a certain morphological similarity between the sand spits of Taganrog Bay, the following aims of this study are defined:

– to analyze in detail the hydrodynamic regime of the Taganrog Bay waters;

– to identify possible factors that determine the general orientation of the spits on the northern coast from east to west, and on the southern coast, in the opposite direction, from west to east;
– to propose an answer to the question "Why doesn't Beglitsk Spit of the northern coast follow the general rule and is oriented from west to east?".

It is worth noting that the renowned Soviet researcher V. P. Zenkovich [1] noted that Krivaya and Beglitsk spits are rotated relative to each other "with an exact angle of 90°" (in reality, slightly more), but he did not inquire about the reasons for this phenomenon.

The main research method is mathematical modeling.

Materials and methods

The hydrodynamic regime of the Taganrog Bay water area is primarily influenced by three key factors: sea currents, wind waves, and sea level variations caused by storm surges and seiche oscillations. In conditions of reduced water depth, these factors are strongly interconnected. An increase in sea level results in a transformation of the fields of currents and waves. The collapse of storm waves by radiation stresses serves to adjust the magnitude and direction of currents, in addition to increasing the height of surges. The potential for ice to be present in the water area introduces an additional layer of complexity to the situation. From the perspective of simulating the ongoing hydrodynamic processes, it is evident that a separate calculation of the parameters of currents, waves and level is not entirely accurate. A more accurate methodology would be to analyse all processes within the context of a unified model. A comparable methodology was employed in the author's preceding work [18] on the investigation of the hydrodynamic regime of the entire Sea of Azov, using the following approaches:

1. Sea currents are calculated using the 5-layer σ-coordinate 3D ADCIRC model based on the solution of shallow water equations. Various modifications of the model have been effective in studies, particularly those examining extreme storm surges in the Sea of Azov (for example, in [9]).

2. Wind wave parameters are calculated using the MIKE 21 SW spectral wave model of the Danish Hydraulic Institute, which has been successfully applied to the conditions of the Azov and Black seas [19].

3. Fields of atmospheric pressure, surface wind components and ice concentration required for modeling are selected from the ERA5 global atmospheric reanalysis database. The time step is 3 h for atmospheric pressure and wind fields, and 1 day for ice concentration fields.

4. The calculation grid is formed based on a modern bathymetric map of the Sea of Azov [6].

5. The combination of models, taking into account the interaction of currents and waves, is carried out as follows: the height and current parameters determined

[1] Zenkovich, V.P., 1958. *Shores of the Black and Azov Seas*. Moscow: Geografgiz, p. 164 (in Russian).

in the hydrodynamic model are used in the spectral wave model to calculate wind wave parameters; radiation stresses generated by wave breaking processes and calculated by the wave model correct the current parameters.

The combined model is validated using available experimental data on the parameters of sea currents, wind waves and sea level. The data set comprises the results of measurements obtained using a range of specialist instruments, including tide gauges, RDI ADCPs and Vector-2 probes, as well as satellite observations.

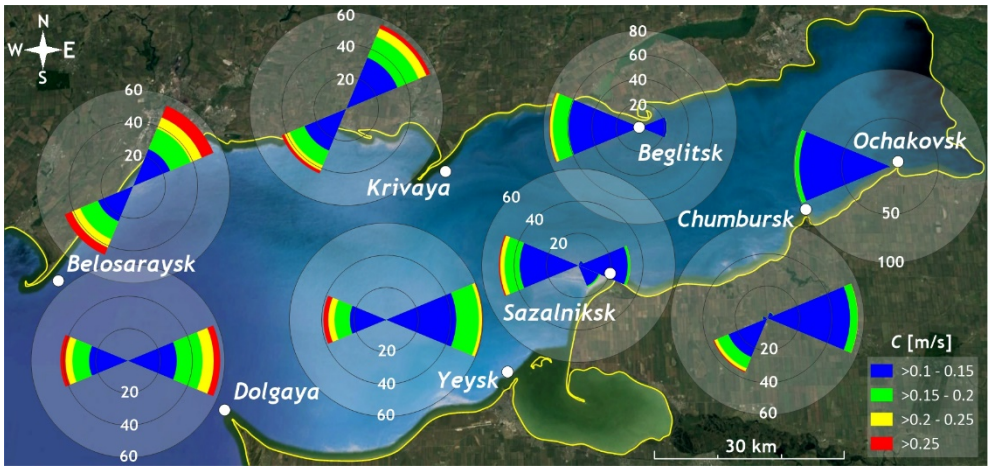
The calculations produced a database of hourly spatial fields of current and wind wave parameters covering the entire water area of the Sea of Azov, including Taganrog Bay. The calculation period was 42 years (January 1979 to December 2020).

Results and discussion

First, a few comments clarifying the features of the approach used to analyze the hydrodynamic impact on the coastal zone are to be made:

1. The data on the characteristics of sea currents and wind waves are used. Sea level fluctuations, or more specifically, storm surges, are not considered separately, since the surge process transforms both the current fields and the waves, which directly affect the bottom and coast deformations.

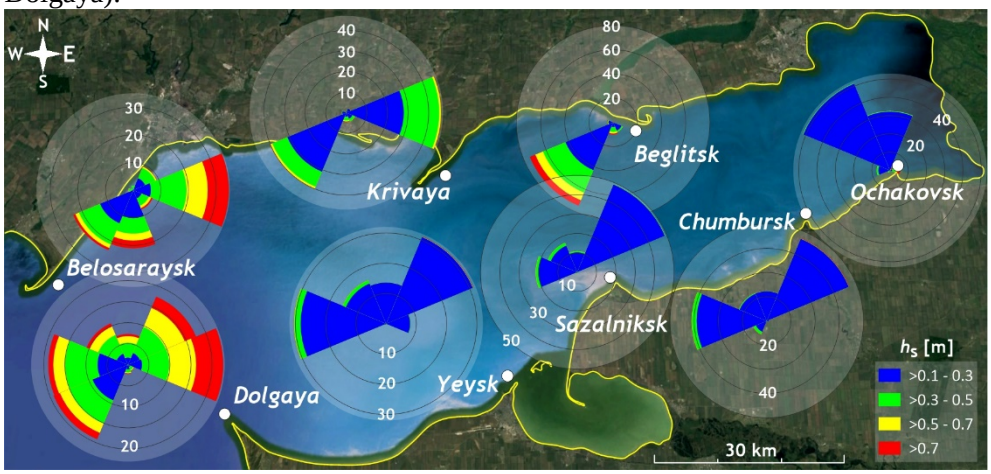
2. The use of a 3D hydrodynamic model allows a precise analysis of the bottom currents responsible for the initial suspension and redistribution of bottom material in the coastal zone of the sea.



F i g. 3. Roses of bottom currents (%) in 1979–2020

Figs. 3 and 4 show bottom current and wind wave roses (in terms of significant wave heights) at several points in Taganrog Bay. Due to the climatic predominance of relatively weak currents and waves, current velocities of less than 0.1 m/s and wave heights of less than 0.1 m were not included in the data used to construct Figs. 3 and 4. The repeatability of current velocities or wave heights and directions is

presented for three spits on the northern coast (Belosaraisk, Krivaya and Beglitsk) and five on the southern coast (Ochakovsk, Chumbursk, Sazalniksk, Yeysk, and Dolgaya).



F i g. 4. Wind wave roses (%) in 1979–2020

As shown by the data in Fig. 3, in the coastal waters of Belosaraysk and Krivaya spits, the frequency of northeastern bottom currents is one and a half times higher than the frequency of southwestern currents. Beglitsk Spit is characterized by the absolute dominance (almost 80%) of western currents. In the area of Ochakovsk Spit, the currents (with the speed of more than 0.1 m/s) are almost always directed from west to east. In the waters washing Chumbursk Spit, the frequency of eastern currents is somewhat higher than that of southwestern ones (55 and 38%, respectively), but strong currents with velocities exceeding 0.2 m/s are observed precisely in the southwestern sector currents. A similar picture is specific for Yeisk Spit (60% – eastern currents, 40% – western). In addition, Yeisk Spit has a high frequency of extremely strong (more than 0.25 m/s) western currents, amounting to almost 5%. In the area of Sazalniksk Spit, western currents are observed in 50% of cases, and eastern in 30%. Dolgaya Spit is characterized by the predominance of eastern currents (58%); strong currents can form both from the open sea and from the bay.

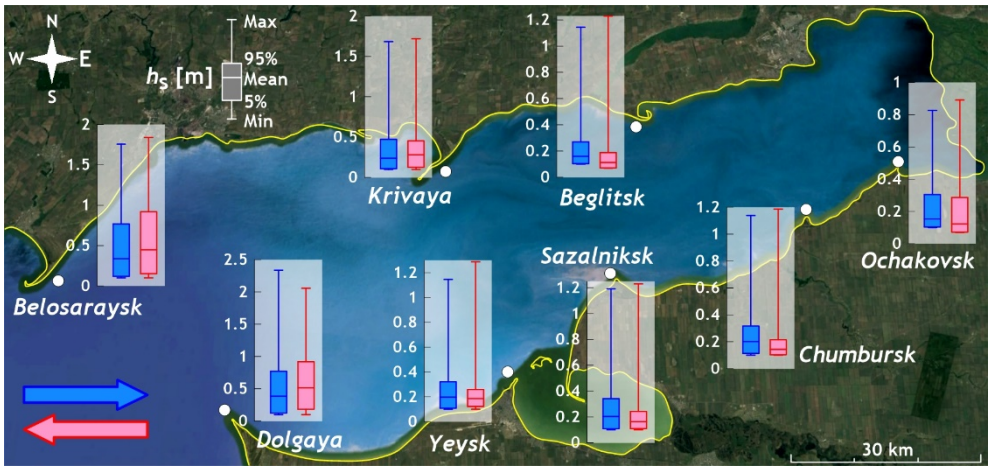
The degree of development of wind waves depends on many factors: strength, stability in direction and time of wind flow action, acceleration length and bathymetric features. In the present case, the strongest wind waves occur at the entrance to Taganrog Bay, as well as in the area of Beglitsk Spit (Fig. 4).

The wave regime of Belosaraysk Spit is determined by waves of eastern (33%), southwestern (23%) and southern (21%) directions. Krivaya Spit is characterized by the dominance of eastern (45%) and southwestern (31%) waves. In contrast to Belosaraysk and Krivaya, the third spit of the northern coast, Beglitsk, experiences the predominant influence of storms of southwestern direction. Ochakovsk Spit, due to its location and the shallowness of the coastal zone, is best protected from strong waves; northeasterly waves make the largest contribution to the formation of

the wave regime. For the next three spits of the southern coast of the bay (Chumbursk, Sazalniksk and Yeysk), the influence of northeastern waves prevails, but the strongest storms usually come from the west. In the area of Dolgaya Spit, strong waves are possible from almost all directions, except, of course, the southern and southeastern sectors.

Some statistical characteristics of the significant wave heights and bottom current velocities should be added. Figs. 5, 6 show box plots of the distributions of wave heights and current velocities, respectively, including minimum, maximum, and average values of the parameters, as well as 5 and 95 percent quantiles of the distributions. The distributions are constructed separately for alongshore currents, conditionally directed from west to east (blue boxes), and reverse currents from east to west (red boxes). For wave heights, the statistics are similar, the only difference being that the wave sector (‘west’ or ‘east’) is determined with respect to the normal to the shoreline.

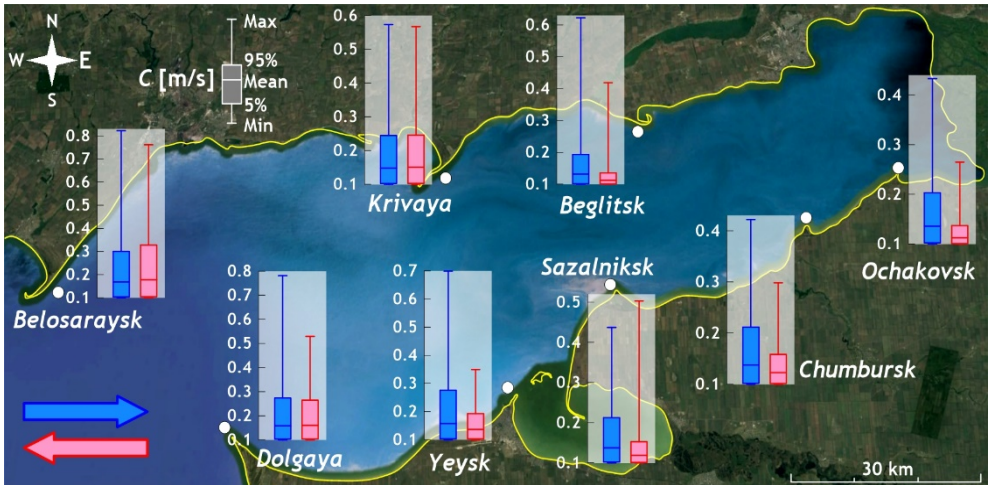
Wind waves are most developed in the strait and on the northwestern coast of the bay (Fig. 5).



F i g. 5. Statistical characteristics of the distributions of significant wave heights (m) in 1979–2020

In the coastal waters of Belosaraysk and Krivaya spits, the wave heights of the eastern directions are observed to be higher than the average, with maximum wave heights for western direction swells also exceeding the norm. The spits of Beglitsk, Ochakovsk, Chumbursk, Sazalniksk and Yeysk are subject to comparatively weaker swells. The data indicate that, on average, these spits are subject to a predominance of western swells. However, it is notable that swells with maximum wave heights develop during eastern storms. In contrast, at Dolgaya Spit, the average wave height for eastern swells exceeds the average height characteristic of western swells. Nevertheless, maximum waves develop during storms coming from the west, from the open sea.

The strongest bottom currents with maximum velocities of ~ 0.8 m/s are formed in the western part of the bay (Fig. 6).



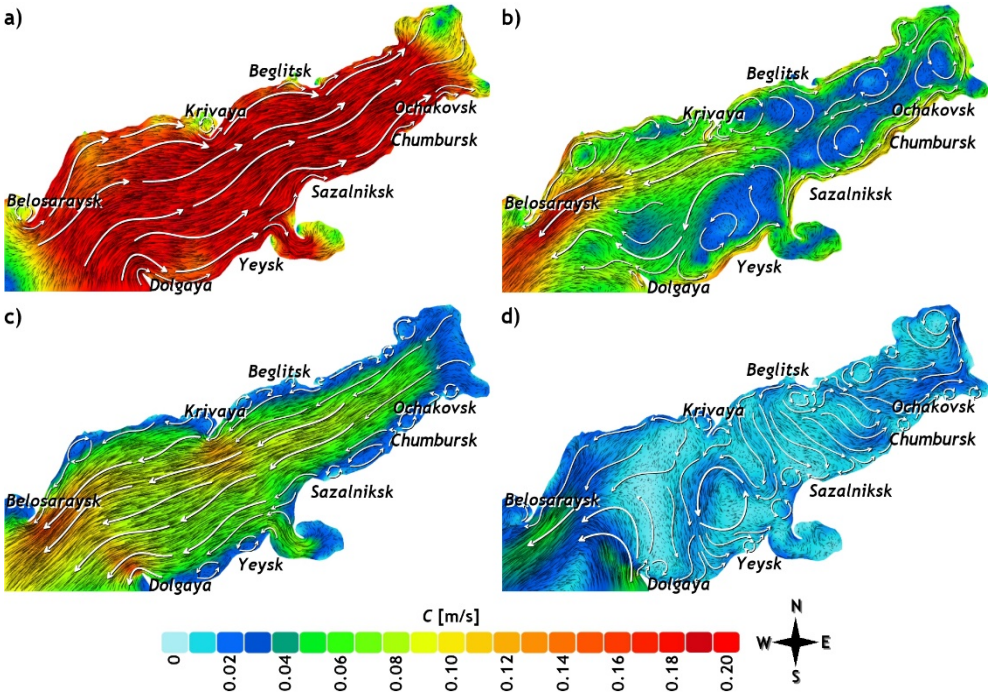
F i g. 6. Statistical characteristics of the distributions of bottom current velocities (m/s) in 1979–2020

In the coastal waters of Belosaraysk and Krivaya spits, the western and eastern water flows are almost comparable in speed. However, the average long-term values of the current velocities of the eastern flows slightly exceed those of the western directions. In the area of the northern coast of Beglitsk Spit, as well as Ochakovsk, Chumbursk, Sazalniksk and Yeisk spits of the southern part of the bay, the dominance of currents from the west is evident, both in terms of average and maximum velocities. It is noteworthy that the water regime near Sazalniksk Spit exhibits a distinctive pattern, with the highest velocities occurring in the eastern currents. In the vicinity of Dolgaya Spit, the mean velocity of the eastern and western currents is equal, yet the maximum velocities of the flows are indicative of the currents from the main sea area to Taganrog Bay, exceeding the current velocities in the opposite directions by approximately 50%.

It should be noted that the spatial position of Taganrog Bay, namely its elongation along the WSW – ENE line, corresponds to the directions of the prevailing winds over the bay, which contribute to the development of surge phenomena and largely determine water circulation. As an example, Fig. 7 shows schematic maps of the magnitude and direction of bottom currents during the passage of the strong SW storm *(a)*; weakening of the SW storm *(b)*; development of the NE wind *(c)*; weakening of the NE wind *(d)*.

As shown in Fig. 7, *a*, during the passage of the SW storm, a uniform SW to NE bottom current caused by the surge is established throughout the bay. In the bays between the main bodies of Belosaraysk and Krivaya spits and the mainland, small cyclonic eddies form, causing water movement in the opposite direction. As the SW wind weakens (Fig. 7, b), the eddy gives way to a surge and the circulation in the bay is significantly restructured. Belosaraysk, Krivaya and Dolgaya spits are under the influence of NE to SW currents, while Beglitsk, Ochakovsk, Chumbursk, Sazalniksk and Yeysk are under the influence of SW to NE reverse currents.

The NE wind development (Fig. 7, *c*) near Belosaraysk, Krivaya, Sazalniksk, Yeysk and Dolgaya spits forms the alongshore flow directed towards the open sea. In the same situation, a local circulation of water is formed near Beglitsk Spit: in its western part the flow is directed to the SW, in its eastern part – to the NE. In the coastal zone of Ochakovsk and Chumbursk spits, the alongshore flow is oriented to the NE. The weakening of the NE wind (Fig. 7, *d*) leads to a weakening of the currents in almost the entire water area of the bay, with the exception of the strait waters, where significant currents develop only near Belosaraysk (SW-directed) and Dolgaya (N, NE-directed) spits. In the coastal waters of the remaining spits, local current systems are formed, usually consisting of countercurrents.



F i g. 7. Velocity fields (m/s) of bottom currents in Taganrog Bay under conditions of: a – strong SW wind; *b* – weakening of SW wind; *c* – strong NE wind; *d* – weakening of NE wind

It should be noted that the diagrams in Fig. 7 serve only to illustrate specific hydrodynamic situations and do not represent the full diversity of possible current structures in the bay. At the same time, Fig. 7 gives an idea of an important feature of the bottom circulation of waters: directly in the coastal zone, or more precisely in small bays between spits, countercurrents can form in relation to the general water flow in the main channel of Taganrog Bay.

Conclusions

The focus of our study is the spatial position of the sand spits of Taganrog Bay of the Azov Sea. The general direction of Belosaraysk and Krivaya spits of the northern coast is from east to west, while Beglitsk is the opposite, from west to east. The spits of the southern part of the bay, such as Ochakovsk, Chumbursk,

Sazalniksk and Yeysk, are also stretched from west to east. Accordingly, several legitimate questions arise:

1) What factors contribute to the orientation of the northern coast spits from east to west and the southern coast in the opposite direction, from west to east?

2) Why does Beglitsk Spit on the northern coast not follow the general rule and is directed from west to east?

We address these questions from a hydrodynamic perspective, examining the climatic characteristics of sea currents and wind waves that directly influence coastal formation and transformation. The potential impact of spits on the lithodynamic relation, as well as the possibility of human-induced alterations to the coastal zone (sand extraction, construction of protective structures) have not been considered.

The analysis was conducted using the results of numerical modeling of the hydrodynamic parameters of the entire Sea of Azov over a 42-year period (1979–2020). The generated data array comprises hourly spatial fields of velocity and direction of bottom currents, as well as significant heights and directions of wind waves.

As a result of the work carried out, it has been established that

1. The coastal waters of Belosaraysk and Krivaya spits (northern coast) are characterised by the recurrence of currents from the east. In the case of Beglitsk (northern coast), Ochakovsk and Sazalniksk (southern coast) spits, the dominance of currents from the west is a distinctive feature. In the waters adjacent to Chumbursk and Yeysk spits (southern coast), the recurrence of eastern currents is somewhat higher than that of southwestern ones. However, strong currents with velocities exceeding 0.2 m/s are observed with precise regularity in conjunction with currents from the west.

2. In the coastal waters of Belosaraysk and Krivaya spits (northern coast), the mean long-term values of the current velocities in the eastern directions are slightly higher than those in the western directions. In the area of Beglitsk spit of the northern coast, as well as Ochakovsk, Chumbursk, Sazalniksk and Yeisk spits of the southern part of the bay, the dominance of west currents is notable, both in terms of average and maximum velocities. However, a slight exception can be observed in the water regime near Sazalniksk spit, where the highest velocities develop with eastern currents.

3. In the coastal waters of Belosaraysk and Krivaya spits (northern coast), the height of waves originating from the east is greater than both the average and maximum heights of waves from the west. The spits of Beglitsk (northern coast), Ochakovsk, Chumbursk, Sazalniksk and Yeysk (southern coast) experience the dominance of western direction waves on average. However, waves with maximum wave heights develop during eastern storms.

It can be concluded that the hydrodynamic regime of the sand spits on the northern (Belosaraik, Krivaya) and southern (Ochakovsk, Chumbursk, Sazalniksk and Yeysk) coasts is significantly different. The climatic characteristics of the waves (to be more precise, in relation to the normal to the shore) and currents

of Beglitsk Spit in the north of the bay are similar to those of the southern coast spits, which most likely explains its elongation from east to west.

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