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Conditions of sand spits formation at the Northern Sea of Azov coast

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ABSTRACT

Term "spits of the Azov type" is encountered in the description of morphological features of sandy accumulative forms of sea coasts. This term is related to a system of several parallel spits in the form of narrow strips extended into the open sea over a few kilometers and formed under the influence of wind waves with acute incidence angles to the coastline. Term "spits of the Azov type" was introduced into everyday life by V.P. Zenkovich, who actively studied the shores of the Black Sea-Azov basin, as applied to the spit system of the northern coast of the Sea of Azov. It is shown in our work, based on a detailed analysis of the hydrodynamic regime of the Sea of Azov over the past four decades that wind waves with acute angles do not determine the features of the wave climate of the northern coast. The main factor in the development of spits from the open sea is wind waves that are normal to the coast, while the factor on the mainland side are coastal currents that are formed over the background of storm surges. Thus, the application of term "spits of the Azov type" to sea spits of the other coasts of the World Ocean formed by wind waves with acute angles of wave approach does not seem justified.

1. Formulation of the problem

First, a few words about the object of research. The Sea of Azov is a relatively small water reservoir belonging to the Atlantic Ocean basin. It is connected to the Black Sea by the shallow Kerch Strait. The surface area is about 39 thousand km^2 (which is comparable, for example, to the square of Lake Erie of the Great Lakes system); characteristic linear dimensions are length 360 km and width 180 km; the mean sea depth is 7.5 m, the maximum is 13.5 m (Dobrovolsky and Zalogin, 1982).

Below are some morphometric features of the Sea of Azov (Hydrometeorological Conditions, 1986; Fig. 1). The bottom of the central part of the sea is rather flat covered with soft silt with characteristic depths of 10–12 m. Alluvial sand spits are located over the coast from almost rectilinear and steep northern coast and continue in the southwest direction: Belosaraysk, Berdyansk, Obitochna, and Fedotova spits (Biryuch Island at the southern end of the spit is currently a continuation of the Fedotov Spit). The western coast is a sandy Arabat Spit with a width of several hundred meters in the south and up to 6–8 km in the north. The eastern shore is formed by a sandy bar; the most developed are Achuevsk, Yasensk, and Kamyshevatsk spits. Dolgaya Spit in the northern part of the sea separates the main part of the sea and the shallow, northeasterly elongated Taganrog Bay.

Sand bars are coastal bars or shoals attached at one end to the bedrock shore. There are many factors involved in the processes of formation and development of spits: features of the bottom geological structure (presence of bedrocks, species and sediments granulometric composition), sea level, wind loads (formation of coastal sand dunes), biological water productivity (carbonate sediments), anthropogenic stress (Riggs et al., 1995; Wang and Kraus, 1999; Simeoni et al., 2007; Allard et al., 2008; FitzGerald, 2015; Wernette et al., 2018). At the same time, the most important factor in bar transformation is the hydrodynamic effect under the influence of surface wind waves.

Recently, the issues related to the influence of the main wave parameters, in particular, the angle of wave approach to the coastline and the formation of coastal relief in general, have been quite intensely investigated. The bibliography of the problem is wide, we specially mention the works of (Ashton et al., 2001; Falqués and Calvete, 2005; Ashton and Murray, 2006a,b; Kaergaard and Fredsoe, 2013). The main research results are as follows. The morphological features of the coastline are largely determined by the variability of alongshore bottom sediment flows, which depend on the orientation of the coastline relative to the front of the waves approaching from the deep water. In the case of incidence angles exceeding 45°, flow instability leads to the formation of special coastal forms extended into the sea (capes, spits). At the incidence angles close to the normal to the coastline, local relief inhomogeneities are blurred, as a result of which the coastline becomes smooth. Here, we note that the previously mentioned 45° is the angle at which the alongshore flow reaches its maximum development. This is a debatable value and depends on the physical assumptions and simplifications of a particular theory.

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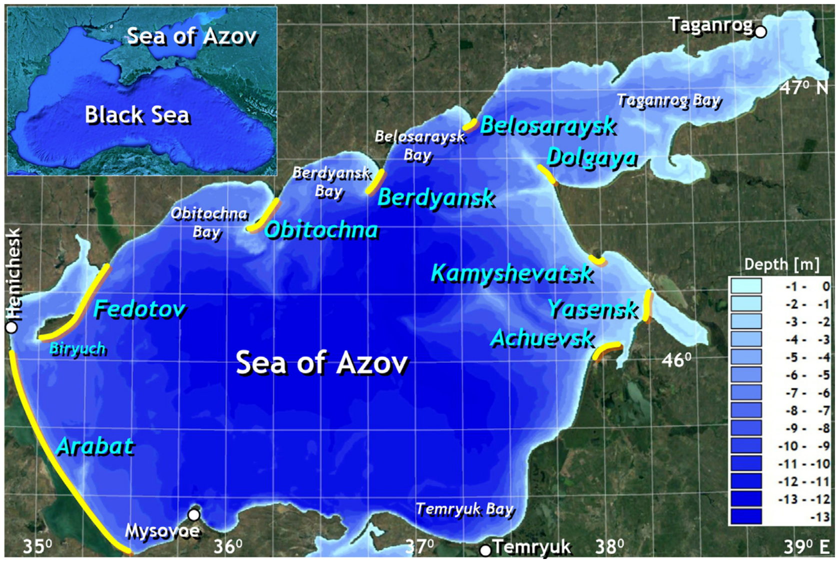

Fig. 1. Bathymetric map and morphometric features of the Sea of Azov.

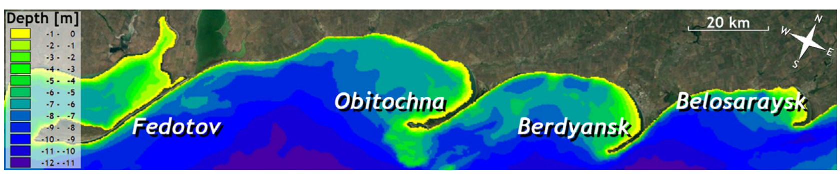

Fig. 2. Main spits of the "Azov type".

Investigations of the morphological features of accumulative forms on the northern coast of the Sea of Azov have strengthened the concept of the "Azov type" spits (Zenkovich, 1958, 1967). It is a series of spits in the form of rather narrow strips extended into the open sea for tens of kilometers with some common features: (1) the angle between the general directions of the spit and the coast is about 45°; (2) almost rectilinear eastern (from the side of the open sea) parts and concave western parts of the spits directed towards the main coast; (3) the tips of the spits are widened and bent towards the coast; (4) the bases of the spits are accumulative of triangular shape.

Fig. 2 shows the characteristic spits of the "Azov type": Belosaraysk, about 14 km long, Berdyansk (∼23 km), Obitochna (∼30 km), and Fedotova (∼45 km) spits.

The lengths of the spits notably increase along the northern coast from northeast to southwest. Dolgaya Spit is usually also mentioned among the spits of the "Azov type" (Krylenko et al., 2017; Kosyan and Krylenko, 2019), but it is located in the shallow Taganrog Bay; we will restrict ourselves to considering the spits in the basin of the main part of the Sea of Azov.

The spits are sandy with an admixture of shells. The sand zone with a predominant (more than 50%) fraction of 0.1–1.0 mm extends in a narrow strip along the entire coast to the depths of 2–6 m; it continues on the underwater coastal slope of the spits (Ecological Atlas of the Sea of Azov, 2011).

Zenkovich V.P. was one of the first to analyze in detail the morphological features and conditions of the formation of spits on the northern coast of the Sea of Azov. From his point of view (Zenkovich, 1958), the spit system is a consequence of the development of the coast, located at an acute angle to the resultant wind waves of the northeastern directions, prevailing throughout the year. According to Zenkovich, the fetch length of surface waves of the northeastern direction increases from Belosaraysk Spit, reaching several hundred kilometers near Fedotov Spit (in the monograph by Zenkovich (1958), an indicated fetch of 400 km is most likely a misprint; according to any approach to its assessment, a fetch not exceeding 300 km is sufficient). Note that in such situations, it is possible to focus only on the fetch of waves only as a first approximation. The importance of formation conditions of other waves (wind duration, flow stability, local bathymetry, sea level, presence of currents) is indisputable. Hence, according to Zenkovich, the resulting waves maintain approximately the same direction throughout the entire length, but the wave height increases. The consequence is an intense transport of bottom sediments along the bedrock coast and the body of the spits. Zenkovich concludes that each subsequent spit to the west gets more and more material and the bank, on which the sediments are deposited, should be longer and longer. Thus, the main cause for the formation of spits on the northern coast of the Azov Sea is the acute incidence angle of wind waves along the entire length of the study site considered. The concept of "Azov type" spits proposed by Zenkovich, which is widely used in modern literature, is now associated with such systems of spits (Ashton et al., 2001; Ashton and Murray, 2006a,b; Davydov, 2012; Serizawa et al., 2012; Murray and Ashton, 2013).

The idea that wind waves approaching the coast at an acute angle is the main factor in the formation of the Azov spits.

But we cannot state that this is the only explanation. An interesting idea was put forward by the British Captain Sherard Osborn, a member of the Royal Geographical Society. Based on numerous literary studies and on the results of observations during the Crimean campaign, Osborn makes an interesting conclusion (Osborn, 1857). The author writes that currents from Taganrog Bay (see Fig. 1), directed southwest of Belosaraysk Spit with velocities of 1.0–1.5 knots (i.e., 0.5–0.8 m/s), form in the course of time extensive Berdyansk and Obitochna spits and further; they meet the currents of the westerly winds and form extensive alluvial deposits of Biryuch Spit. In addition, Biryuch

Spit is a continuation of Fedotov Spit. By the way, it is surprising that in his rather lengthy work, Captain Osborne hardly mentioned a word about wind waves. Nevertheless, as follows from the above, that according to the opinion of Osborne, the system of the sea currents is the main cause of the formation of spits on the northern coast.

Thus, we can consider two (sufficiently substantiated for their time) points of view on the conditions for the formation of the Azov spits, based mostly on observations and indirect signs.

These factors determine the tasks of this work:

- to analyze the hydrodynamic regime typical for the sea waters of the northern coast of the Sea of Azov on the climatic time scale (the last four decades);
- to calculate the statistical characteristics of the parameters of currents, wind waves, and storm level rise, and also of the alongshore sediment flows in the coastal zone;
- to give a general assessment of the validity of the existing hypotheses of the formation of the Azov spits.

Below are the main factors that determine the hydrodynamic regime of the Sea of Azov: surface wind waves, sea currents, storm surges, and seiche level fluctuations. In the conditions of shallow and insignificant sea size, these factors are largely interrelated. The degree of development of wind waves directly depends on the sea level. In the Sea of Azov, with strong surges, the heights of the storm level rise can be comparable to the depths. In 1969, as a result of a strong storm in the area of Henichesk town, a two-meter offshore surge was observed, and in Temryuk, an almost three-meter onshore surge, i.e., the level imbalance between Henichesk and Temryuk was about 5 m (Shnyukov et al., 1994). Formation of ice cover is also an essential feature of the Sea of Azov, which, depending on the atmospheric conditions, can cover the entire water basin. The presence of ice, in turn, significantly transforms the fields of currents and waves. Thus, the complex nature of the formation of the hydrodynamic regime of the Sea of Azov is obvious.

The question of the conditions for the formation and transformation of the Azov spits is, naturally, in the climatic situation; therefore, we are interested in the climatic features of the characteristics of the hydrodynamic impact on the coast.

Owing to the geographical location, the interest to the study of the Sea of Azov was shown mainly by Soviet, and also by Russian and Ukrainian scientists. The list of publications on studies of interannual variations in the parameters of currents, waves, and storm surges is quite extensive (Matishov and Grigorenko, 2021, 2020; Fomin and Polozok, 2013; Ecological Atlas of the Sea of Azov, 2011; Dyakov et al., 2010; Fomin, 2002), and this is far from an complete list). We especially note the Fomin (2012), which presents the results of numerical modeling of wind wave fields in the period 1979–2010; climatic parameters of wind waves in the Sea of Azov were estimated. The atlas also contains depth-averaged fields of sea currents, which, unfortunately, are not climatic, since they are calculated only for specific specified directions and speeds of a uniform wind.

Note also that almost all studies do not take into account the real ice conditions in the Azov Sea. Obviously, strong winds in ice conditions do not necessarily lead to strong waves and significant surges.

In 2021, the authors of this article applied three-dimensional hydrodynamic and spectral wave models to estimate the climatic characteristics of sea currents and surface waves in the Sea of Azov over the period from 1979 to 2020 (Divinsky et al., 2021). The main approaches used in modeling are the following:

1. The data of the global atmospheric reanalysis ERA5, distributed by the European Center for Medium-Range Weather Forecasts (ECMWF, https://cds.climate.copernicus.eu), were used as the initial pressure fields, surface wind components, and ice concentration. Thus, our modeling was carried out taking into account the real ice situation in the sea basin, which significantly affects the estimates of the parameters of waves and currents during the ice period. The computational domain was limited by coordinates: latitude 45.25°–47.50° N, longitude 34.75°–39.50° E. The spatial resolution was the same in latitude and longitude (0.125 degrees), the time step was 3 h for pressure and wind, and one day for ice concentration.

2. The studies were carried out with the division of wind waves into two components: pure wind waves (hereinafter simply wind waves) and swell. As far as we know, the parameters of the swell in the Sea of Azov have not yet been estimated by anyone most likely because of the idea of the insignificance of swell waves in a relatively small, closed and shallow basin. However, we performed this work to fill in this gap for the completeness of study.

Thus, the available simulated data set includes hourly spatial fields: velocities and directions of currents in the Sea of Azov, integral characteristics of wind waves and swell (heights, periods, directions of propagation), and sea level. The array allows simulating the mean (climatic) values of hydrodynamic characteristics and assessing their impact on lithodynamic processes in the coastal zone of the Sea of Azov.

2. General characteristics of the hydrodynamic regime of the Sea of Azov

As previously mentioned, surface waves, sea currents and storm surges are the main factors of hydrodynamic impact on the sandy sediments of the Sea of Azov.

Climatic features of the distributions of mean values of significant heights of wind waves and swell over the period from 1979 to 2020 are shown in Fig. 3.

It follows from Fig. 3 that the most intense waves develop in the central and relatively deep-water part of the sea, in which the mean significant heights of wind waves are approximately equal to 0.6–0.7 m. In this case, the zone of maximum waves is slightly displaced to the south, as a result of which the southern coast is the most subjected coast to the impact of wind waves. Swell waves are almost two times smaller than wind waves and also reach the biggest heights equal to 0.3 m in the center of the sea. The formed swell rapidly decays when the general wind direction changes. Swell with mean amplitudes of 0.2 m reaches the coast.

Application of three-dimensional hydrodynamic model with five vertical levels made it possible to obtain a climatic pattern of surface and bottom currents in the Sea of Azov (Fig. 4).

Fig. 4 clearly demonstrates the main properties of climatic circulation in the Sea of Azov:

- in the central part of the sea, an extensive cyclonic eddy dominates in the entire water column;
- in the western part of the sea, anticyclonic motion of waters prevails, and the surface currents are more pronounced in the western sector of this anticyclone, while bottom currents are more intense in the eastern sector;
- typical mean velocities of surface currents are 0.07–0.10 m/s, the typical velocities of the bottom currents are 0.05 m/s;
- the maximum mean current velocities, reaching 0.15–0.20 m/s in the upper layer, are observed in the coastal waters of the northern coast of the sea, and in the strait between the main basin and Taganrog Bay (Dolgaya Spit area).

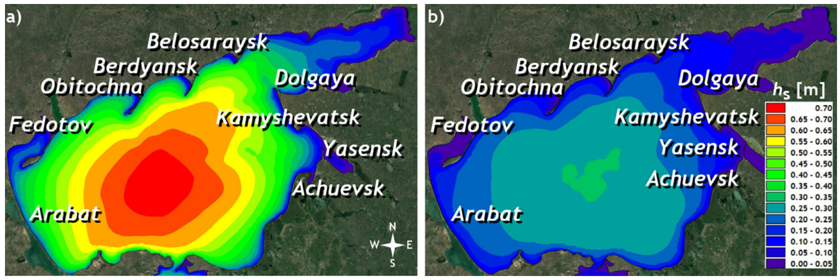

Fig. 3. Climatic fields of mean significant heights (m): wind waves (a); swell (b).

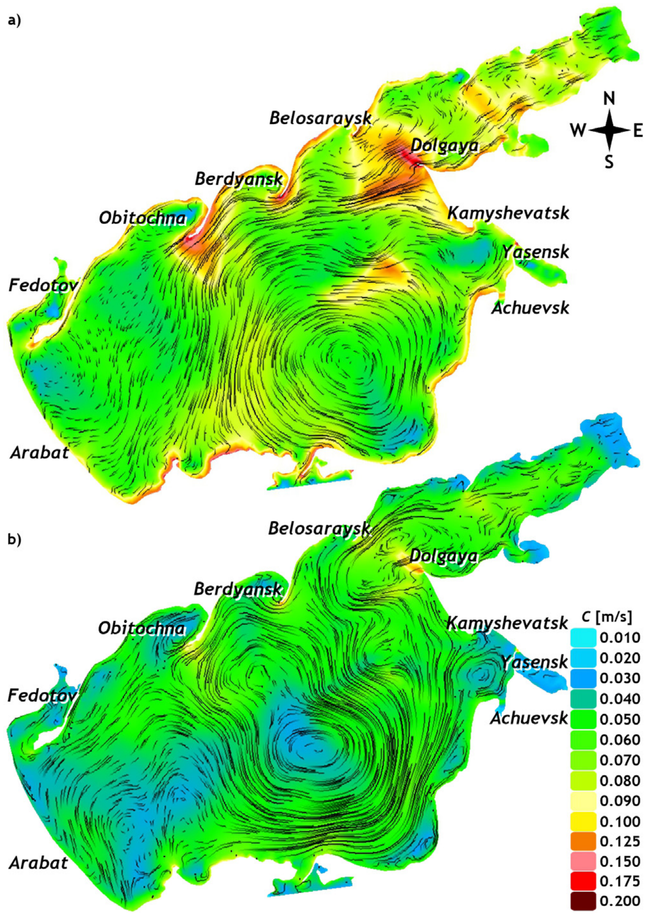

Fig. 4. Climatic fields of currents in the Sea of Azov (m/s): surface currents (a); bottom currents (b).

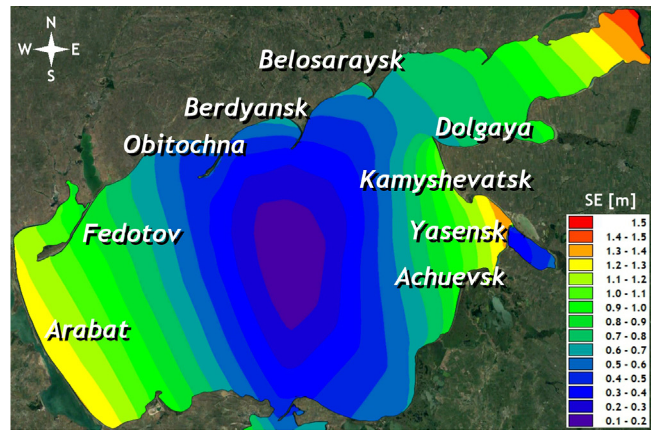

Fig. 5. Spatial distribution of annual mean maximum sea level elevations (m) in the basin of the Sea of Azov.

To some extent, the evidence of Captain Osborn (Osborn, 1857) can serve as a confirmation of this climatic pattern of currents. According to Osborne, six weeks after the successful operations of the British fleet against the Russian merchant ships passing south of Berdyansk, the entire Arabat Spit was covered with wooden debris. Analysis of the directions and velocities of currents (Fig. 4a) indicates a high probability of such events. We speak of "high probability", since specific, averaged over a certain period of time, current fields may differ from the climatic ones.

Storm surges are a feature of the hydrodynamic regime of the Sea of Azov; they are accompanied by significant sea level increase in the coastal zone. Annual mean maximum sea level elevations from 1979 to 2020 are shown in Fig. 5.

Since the direction of the surge waves in the shallow basin corresponds, in general, to the general direction of the wind, the spatial distribution of the heights of storm surges is a reflection of the climatic recurrence of wind situations in the basin of the Sea of Azov with a predominance of the northeastern winds. As a result, the largest surges are observed in the northeastern part of Taganrog Bay and in the southwest on Arabat Spit. It follows from Fig. 5 that a characteristic feature of the northern coast is the predominance of the storm surges on Fedotov and Belosaraysk spits compared to the surges on Obitochna and Berdyansk spits located between them. Naturally, what has been previously said applies to the mean climatic conditions.

Since the spits in the northern part of the sea are the object of our interest, we will proceed to a more detailed analysis of the hydrodynamic regime of the surrounding waters and estimate the fluxes of bottom sediments in the coastal zone.

3. Hydrodynamic and lithodynamic features of the northern coast of the Sea of Azov

Assuming the importance of the incidence angle of the waves, we will use the method described in Ashton and Murray (2006a,b), Kaergaard and Fredsoe (2013).

Depending on the incidence angle in relation to the general direction of the coastline, we define four sectors of incident waves (Fig. 6):

$$-90^\circ < \Delta\alpha_1 < -45^\circ < \Delta\alpha_2 < 0^\circ < \Delta\alpha_3 < 45^\circ < \Delta\alpha_4 < 90^\circ.$$

In what follows, we will use two parameters that take into account the peculiarities of the climatic distribution of wave characteristics with respect to directions: A is the proportion of waves reaching the coast from one side of the normal (conventionally "left"); in Fig. 6, these are sectors $\Delta\alpha_1$ and $\Delta\alpha_2$; U is proportion of waves with very acute incident angles ($\Delta\alpha_1$ and $\Delta\alpha_4$), $U = U_l + U_r$. If the climatic recurrences for the indicated four wave sectors are approximately equal, then the resulting alongshore

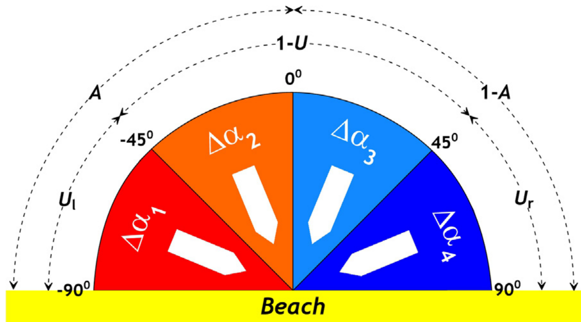

Fig. 6. Sectors of surface waves relative to the coast.

flux is usually insignificant; at the same time, the developing features of underwater relief are associated with the transverse motion of the bottom material. The predominance of waves of a certain direction (with respect to the normal), especially in the conditions of dominance of sharp approach angles, causes the formation of specific forms of the coastline in the form of spits elongated in the direction of the flow.

3.1. Hydrodynamic regime of coastal waters of the northern coast of the Sea of Azov

First, we estimated some statistical characteristics of wind waves and swell, velocities of the bottom currents, and the magnitude of storm surges over the climatic period (1979–2020) at selected points on the northern coast. The points are located on relatively straight sections of Belosaraysk, Berdyansk, Obitochna, and Fedotov spits, and also in the center of Arabat Spit at a depth of about 4 m. Fig. 7 shows the recurrence frequency of the directions of propagation of wind waves and swell at these points. The graphs reflect five statistical characteristics of the distribution: the median, two quantiles (10 and 90% of the distribution), and the minimum and maximum values.

Since there are no notable coastal landforms protruding into the open sea along the lengthy (more than 100 km) Arabat Spit, the data for this spit are presented for comparison.

It follows from Fig. 7 that in the coastal zone of Belosaraysk, Berdyansk, Obitochna, and Fedotov spits, wind waves of the northeastern and eastern directions significantly prevail in the annual cycle, corresponding to the incident angles of wave approach "to the left" of the normal to the coastline (sectors $\Delta\alpha_1$ and $\Delta\alpha_2$). At the same time, the waves with very acute approach angles dominate at Belosaraysk and Fedotov spits, while at Berdyansk and Obitochna spits, the angles are closer to the normal. Arabat Spit is characterized by the prevalence of wind waves normal to the coast (sectors $\Delta\alpha_2$ and $\Delta\alpha_3$).

The properties of spreading of swell in the basin of the Sea of Azov are related to its shallow water and small size, which limits the fetch of wind waves. Near Belosaraysk and Berdyansk spits, the swell with very acute incident angles (sector $\Delta\alpha_4$) is characterized by the greatest recurrence, near Obitochna and Fedotov spits, the swell normal to the coast is most frequent, and near Obitochna Spit, the "right" sector of waves with respect to the normal is dominating ($\Delta\alpha_3$); near Fedotov Spit, the "left" ($\Delta\alpha_2$) sector dominates. Near Arabat Spit, the frequency of occurrence is absolutely dominated by the eastern swell, which approaches the coast along the normal (sector $\Delta\alpha_3$).

Thus, keeping in mind the spits of the northern coast, it is possible to speak about the predominance of (climatic) waves with acute incidence angles to the coastline in relation to Belosaraysk and Fedotov spits for wind waves and Belosaraysk and Berdyansk spits for the influence of swell.

The wave heights typical for the four sectors are estimated below. Fig. 8 presents the statistical annual mean significant heights of wind waves and swell, determined for the climatic time scale.

The data in Fig. 8 show that the strongest waves develop in the coastal zone of Berdyansk Spit, where the mean long-term significant height of wind waves slightly exceeds 0.7 m. This indicator for Belosaraysk, Obitochna, and Fedotov spits is somewhat lower and amounts to about 0.50–0.55 m. The maximum values of wave parameters for all four spits are observed when the waves approaching from the eastern directions are close to the normal to the coast (sector $\Delta\alpha_2$). The waves comparable with these waves but with acute incident angles, are possible for Belosaraysk and Berdyansk spits under southerly winds (sector $\Delta\alpha_4$).

The heights of swell are several times smaller than the heights of wind waves. The greatest swell with heights of about 0.2 m has been modeled near Berdyansk Spit. In general, the southeastern and southern swell dominates along the northern coastline that arrive from "the right" of the normal to the coast (sectors $\Delta\alpha_3$ and $\Delta\alpha_4$4).

Near Arabat Spit, the largest wind waves and swell with heights of 0.50 and 0.15 m, respectively, are formed when the waves propagate from the east directed closer to the normal to the coastline.

Longshore bottom flows are most interesting in the structure of coastal currents; they are responsible for the redistribution of sedimentary material. Fig. 9 shows the climatic roses of bottom currents (9a), characteristics of the velocities of the currents directed "from the left" to the "right" relative to the normal to the coast (red arrows and graphs in Fig. 9b) and in the opposite direction (blue in Fig. 9b), as well as storm elevations of the sea level (9c).

It follows from Fig. 9a that the coastal zone of all spits is dominated by the currents directed from northeast to southwest (near Arabat Spit, from north to south). At the same time, near Belosaraysk Spit, formed in the strait between the main part of the Sea of Azov and the extremely shallow Taganrog Bay, both directions are almost equally probable. Further, when following along the northern coast, the recurrence of the northeastern currents (in terms of "from where") decreases quite significantly. Near Berdyansk Spit, this recurrence is about 55%, near Obitochna it is 45%, and near Fedotov it is 37%. The highest mean velocities, about 0.08 m/s, and maximum ones exceeding 0.5 m/s are observed near Berdyansk Spit during the action of the northeastern currents (Fig. 9b). Southwestern currents with velocities exceeding 0.30 m/s are most developed near Fedotov Spit. Near Belosaraysk, Berdyansk and Obitochna spits, the northeastern currents significantly exceed in intensity the southwestern ones. Near Fedotov and Arabat spits, the climatic characteristics of the velocities of currents in opposite directions are almost the same.

From the side of the open sea, all statistical characteristics of the heights of storm surges are minimal near Berdyansk Spit and increase to the southwest along the northern coast and to the northeast (Fig. 9c). This is due to the peculiarities of the spatial distribution of the maximum level elevations in the basin of the Sea of Azov (Fig. 5). Near Berdyansk Spit, the annual mean height is 0.35 m, at Fedotov Spit, it exceeds 1 m. The maximum surges with heights exceeding 2 m are possible near Arabat Spit. Note that the current (actual) sea level marks are taken into account when calculating the parameters of sea currents and surface waves in the Sea of Azov.

Thus, if the climatic characteristics of hydrodynamic processes are available, it is possible to assess their influence on the alongshore transport of bottom sediments.

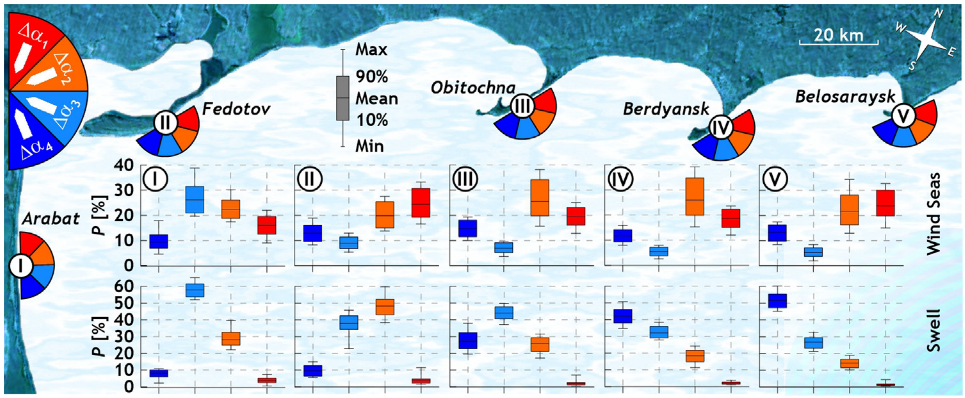

Fig. 7. Recurrence of directions of propagation (%) of wind waves and swell by sectors.

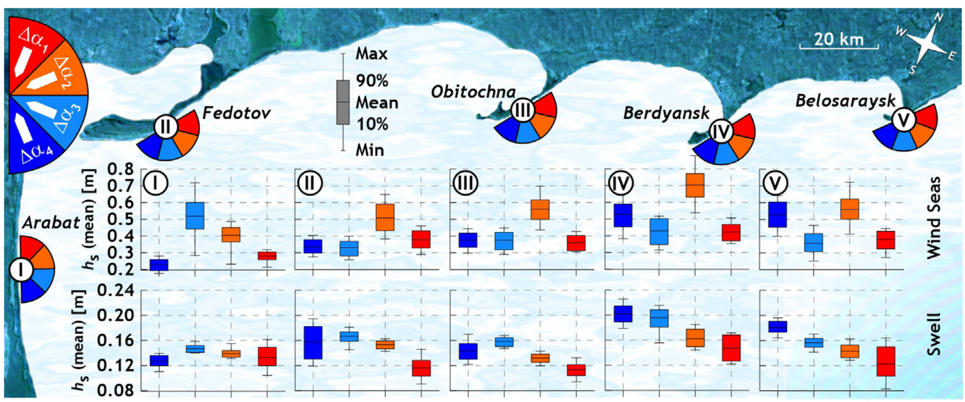

Fig. 8. Statistical characteristics of mean significant wave heights of wind waves and swell (m) over the period from 1979 to 2020.

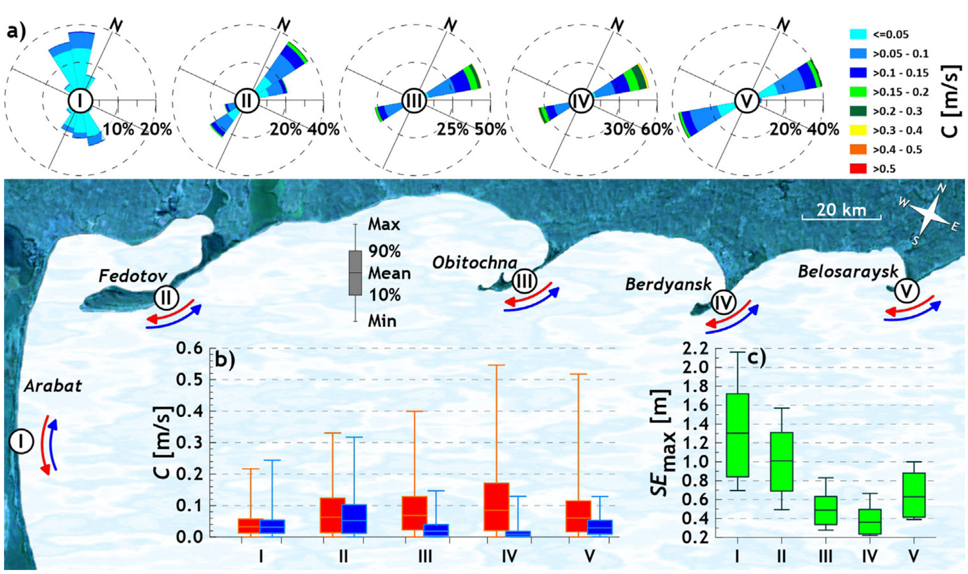

Fig. 9. Statistical characteristics: velocities of alongshore bottom currents, m/s (a); maximum level elevations, m (b).

3.2. Influence of the wave regime on lithodynamic processes in the coastal waters of the northern coast of the Sea of Azov

Going back to Fig. 6 and using the approach described in Ashton and Murray (2006a) for each spit, we estimate the proportion of waves reaching the coast from one side of the normal (conventionally "left") – parameter *A*, and the proportion of waves with acute incident angles – parameter *U*. Fig. 10 shows the results of similar calculations for wind waves and swell.

The calculations were carried out for each individual year over the period from 1979 to 2020. Climatic (mean) values are indicated in Fig. 10 by large circles (wind waves) and squares (swell).

The data shown in Fig. 10 show the following:

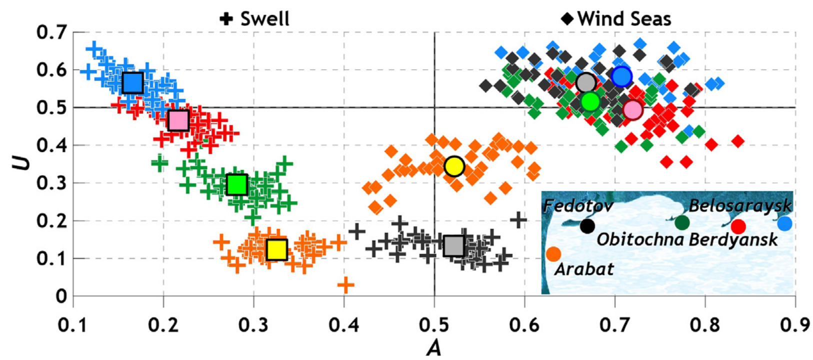

Fig. 10. Annual and climatic values of parameters A and U for the spits of the northern coast.

- in climatic terms, wind waves directed from the northeast and east (i.e., "to the left" of the normal to the coast) dominate in the coastal waters of Fedotov, Obitochna, Berdyansk, and Belosaraysk spits; the swell of the southern and south-eastern directions dominate near Obitochna, Berdyansk, and Belosaraysk spits ("to the right" of the normal). Fedotov Spit is an exception, here the swell reaches the coast almost along the normal;
- the proportion of wind waves with acute incident angles to the coastline U is, on average, 0.5–0.6 for all four spits (Fedotov, Obitochna, Berdyansk, and Belosaraysk), in other words, waves with acute incident angles are not absolutely dominating. A variety of swell waves exists. On Belosaraysk and Berdyansk spits, 50%–60% of the swell waves approach at sharp angles; on Obitochna and Fedotov spits, this indicator decreases and is 30% and 12%, respectively;
- in the coastal waters of Arabat Spit, wind waves prevail, propagating along the normal to the coast, while neither the direction "to the left" of the normal, nor "to the right" are dominant.

We emphasize once again that all previous statements are related to the climatic, i.e., mean data over the last 42 years. The scatter of points in Fig. 10 demonstrates natural interannual variability with the allowance of the predominance of certain directions of waves in a particular year. Nevertheless, the position of the points relative to the mean is rather compact, which indicates the presence of the climatic features of wave dynamics in the coastal waters.

Ashton and Murray (2006b) developed an approach to the study of issues related to the influence of wave incidence angles on the evolution of the coastline and alongshore transport of bottom sediments. Assuming the superiority of the longshore sediment flow over the transverse one, the change in the coastline profile is expressed by the diffusion equation of the form:

$$\frac{\partial y}{\partial t} = -\frac{1}{D}\frac{\partial Q_s}{\partial \theta}\frac{\partial^2 y}{\partial x^2}, \quad (1)$$

where, x, y are coordinates in meters; D is sea depth in m; Q_s is longshore flux of sediments in m^3/s; θ is tangential angle of the coastline direction.

The sign of diffusion coefficient

$$\mu = -\frac{1}{D}\frac{\partial Q_s}{\partial \theta} \quad (2)$$

determines the degree of coastline development. The positive sign of μ provides evidence about the stability (smoothness) of the coastline, the negative sign indicates instability associated with the formation of features of coastal landforms protruded into the sea. The relative value of μ is also important, taking into account the degree of development of the coastline under the influence of surface waves with a certain angle of approach over a given period of time.

Each wave with its own incidence angle contributes to the longshore flow. The sum of the individual contributions μ_i gives the generalized diffusion coefficient μ_{net}

$$\mu_{net} = \frac{\sum_{i=1}^{n} \mu_i \Delta t_i}{\sum_{i=1}^{n} \Delta t_i}, \quad (3)$$

the sum of the absolute values of $|\mu_i|$ is the total diffusion coefficient μ_{gross}

$$\mu_{gross} = \frac{\sum_{i=1}^{n} |\mu_i| \Delta t_i}{\sum_{i=1}^{n} \Delta t_i}. \quad (4)$$

Following the terminology in Ashton and Murray (2006b) we introduce dimensionless "index of instability"

$$\Gamma = \frac{\mu_{net}}{\mu_{gross}}, \quad (5)$$

which varies from 1 to −1 and reflects the final (over a certain period of time) response of the coastline to external wave impact. In other words, the Γ-index indicates the predominance of processes that either lead to coastal stabilization or stimulate the formation of coastal relief inhomogeneities. If $\Gamma = 1$, we assume that the coast is quite stable, while lithodynamic processes associated with the restructuring of the coastline are affected by waves with incidence angles close to the normal to the coast. At $\Gamma = -1$, irregularities are formed, determined by waves with sharp incidence angles. A value close to zero indicates the absence of dominant wave direction.

Estimates of μ from Eq. (2) require an estimate of longshore flux of sediments Q_s. Ashton and Murray (2006a) suggest an updated presentation of widely used CERC formula (Coastal Engineering Research Center):

$$Q_s = K_2 T^{\frac{1}{5}} H_0^{\frac{12}{5}} cos^{\frac{6}{5}}(\phi_0 - \theta)\sin(\phi_0 - \theta), \quad (6)$$

where, $K_2 \sim 0.15$; H_0 is significant wave height; T is the period of most energetic waves, in our case, the period of the spectral peak; ϕ_0 is the incidence angle of waves.

Then, diffusion coefficient can be written as:

$$\mu = \frac{K_2}{D} T^{\frac{1}{5}} H_0^{\frac{12}{5}} \left\{ cos^{\frac{1}{5}}(\phi_0 - \theta) \left[\frac{6}{5} sin^2(\phi_0 - \theta) - cos^2(\phi_0 - \theta) \right] \right\}. \quad (7)$$

If a series of surface wave characteristics is available (heights, periods, directions of propagation) from model simulations at the points of interest on the coast, we can calculate index Γ.

Below are a few important comments:

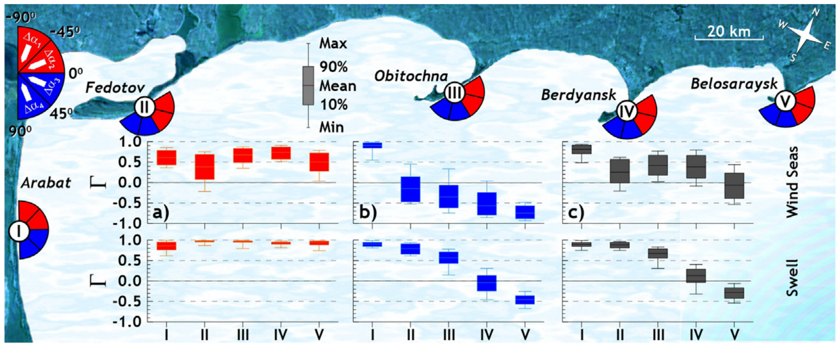

Fig. 11. Index Γ, estimated for wind waves and swell over sectors $\Delta\alpha1$ and $\Delta\alpha2$ (a), $\Delta\alpha3$ and $\Delta\alpha4$ (b), and also for directions of waves (c).

- unlike a simple analysis of the recurrence of waves (Fig. 10), parameter Γ, in addition to the direction of propagation, takes into account the wave height as a kind of analogue of the power law and, thereby, characterizes the energetic ability of the waves of these directions to induce transport of the bottom material;
- parameters of wind waves in formula (6) correspond to the values for deep water. In shallow water conditions and local inhomogeneities of the bottom topography, direction of wave propagation in relatively deep water may not correspond to the incidence angle at the shore, for example, due to refraction. In our case, the calculated points are at a depth of 4 m under the assumption that the wave front has been formed already.

Fig. 11 shows the statistical characteristics of the Γ-index, from the annual mean values over the period from 1979 to 2020 for all five spits. In our terminology, waves with very acute incident angles correspond to sectors $\Delta\alpha_1$ and $\Delta\alpha_4$; while angles close to the normal are related to sectors $\Delta\alpha_2$ and $\Delta\alpha_3$.

Parameter Γ calculated for the entire range of wave directions from $-90°$ to $90°$ does not contain complete information about the possible features of the wave climate with respect to directions, since when determining it there are no differences in sectors, for example, sectors $\Delta\alpha_1$ and $\Delta\alpha_4$, the waves from which generate alongshore flows in opposite directions. Hence, let us estimate three indices: for waves "to the left" of the normal to the coast, taking into account only sectors $\Delta\alpha_1$ and $\Delta\alpha_2$ (Fig. 11a), "to the right", taking into account sectors $\Delta\alpha_3$ and $\Delta\alpha_4$ (Fig. 11b), and the total index (Fig. 11c). Calculations are made separately for wind waves and swell.

The data in Fig. 11a indicate that alongshore currents formed by wind waves directed "to the left" of the normal have a smoothing, stabilizing effect on the coastline. These flows are determined by the predominant influence of waves with incident angles close to the normal. This pattern is most clearly manifested for Arabat, Obitochna, and Berdyansk spits. For Fedotov and Belosaraysk spits, in some years, a balance was observed between the contributions of waves with sharp incidence angles and directions close to the normal (index $\Gamma \sim 0$). In the same range of general directions ($-90°$-$0°$), wave sectors close to the normal are absolutely dominant for swell waves (Fig. 11a, lower part).

If we consider the alongshore flows caused by wind waves with directions $0°$-$90°$ relative to the coast, then the situation is opposite (Fig. 11b). For Belosaraysk, Berdyansk, Obitochna spits and, to a lesser extent, Fedotov Spit, wind waves with prevailing sharp incident angles (the Γ-index is close to -1) contribute to the development of coastline instability. For swell waves, acute incident angles are dominant only in the coastal zone of Belosaraysk Spit.

In a generalized climatic sense (Fig. 11c) for Arabat, Fedotov, Obitochna, and Berdyansk spits, coastline features are formed mainly under the influence of wind waves with incident angles close to the normal. The shape of Belosaraysk Spit is determined by the equivalent contributions of flows determined by waves with sharp incidence angles and close to the normal. The influence of swell waves with acute incident angles is most notable on Belosaraysk and Berdyansk spits, the influence of swells with angles approaching normally, on Obitochna, Fedotov, and Arabat spits.

Thus, the impact of wind waves on all spits, with the exception of, perhaps, the northernmost Belosaraysk Spit, can be considered as stabilizing, leading to smoothing of the coastline roughness. This is due to the dominance of wave directions close to the normal in the coastal zone of spits.

Using formula (6), we will estimate the annual volumes of bottom material transported under the influence of wind waves and swell. At the same time, we are not analyzing detailed studies requiring the determination of the transverse profiles of the bottom (to the depth of closure), and data on the granulometric composition of sediments, etc. Our task is to use the same method for all spits to get an idea of the volume of bottom sediments involved in alongshore transport, i.e., compare the scale of lithodynamic processes occurring on the northern coast of the Sea of Azov.

Fig. 12 presents statistical characteristics of the annual volumes of bottom sediments transported along each of the spits in two opposite directions; their total volumes are also shown.

The data in Fig. 12 show that the flux of sandy deposits directed from northeast to southwest along Berdyansk Spit, significantly exceeds all other fluxes developing on the northern coast. On average, annually wind waves and swell transport here (Fig. 12c) about 1400 m^3.

Returning to Fig. 12, we note some features of the bottom material dynamics:

- in the region of Berdyansk, Obitochna, and Fedotov spits, the alongshore flux directed generally from north to south, significantly exceeds the flux in the opposite direction; near Arabat Spit, the flux from south to north dominates; and near Belosaraysk Spit, the fluxes are almost equal;
- the volumes of the bottom material transported by the wind waves are several times (or even an order of magnitude) higher than the volumes generated by the swell. Nevertheless, in the area of Berdyansk Spit in some years, situations are possible when the fluxes from south to north, caused by the impact of wind waves and swell, are comparable in magnitude;
- the largest total volumes of transported sediments taking into account wind waves and swell (Fig. 12c) are observed near Berdyansk Spit with an annual mean value of 1400 m^3/year. Near Belosaraysk, Fedotov, and Arabat spits, this volume is almost two times smaller ($\sim$800 m^3/year). The smallest volumes are at Fedotov Spit ($\sim$500 m^3/year).

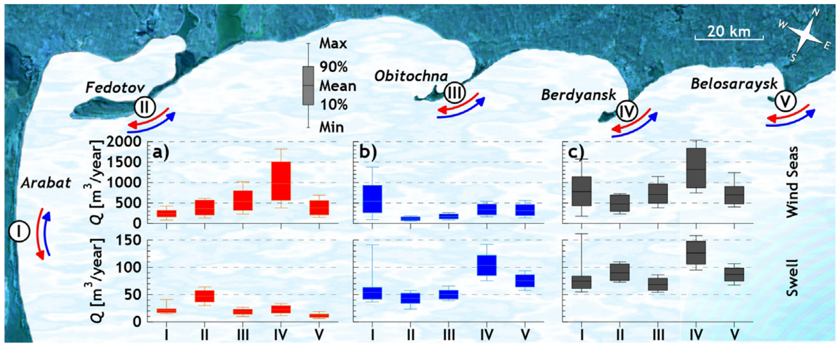

Fig. 12. Statistical estimates of the annual volume of bottom material transported along the spits in opposite directions (a, b), and their total volumes (c).

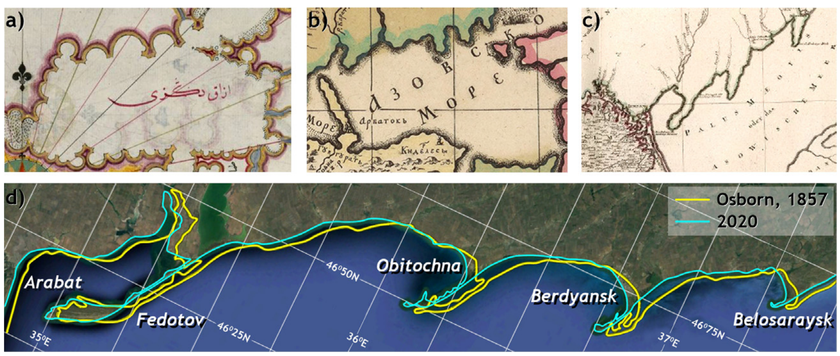

Fig. 13. Historical maps: Piri Reis, 1525 (a); Mengden, 1699 (b); Schraembl, 1787 (c); position of the coastline according to Osborn (1857), superimposed on a modern map (d).

We also note also that the inter-annual variability of fluxes is quite notable near Berdyansk and Arabat spits, as evidenced by the significant inter-quantile ranges of statistical distributions; the difference between 90% and 10% quantiles is about 800 m^3/year. Near Belosaraysk, Obitochna, and Fedotov spits, alongshore flows are climatically more stable, interannual fluctuations are much smaller here, and the difference between quantiles does not exceed 500 m^3/year.

4. Discussion

We are analyzing the object of this study, which is the spit system of the northern coast of the Azov Sea. The main morphological features of the system are: (1) the angles between the spits and the general direction of the entire northern coast are almost constant; (2) the lengths of the spits increase along the coast from northeast to southwest.

As to the physical causes that led to the formation of spits, the dominating opinion is that of Zenkovich (Zenkovich, 1958), who believed that the system of spits was formed due to the development of the coast located at an acute angle to the resultant wind waves of the northeastern directions prevailing throughout the year. From historical documents it was possible to establish that the same question was of interest to the British Captain Osborne a century and a half ago. While describing the hydrological regime of the Sea of Azov (Osborn, 1857), the author presents a very correct pattern of the general circulation of the sea and comes to the conclusion that sea currents are the main cause of the formation of the spits of the northern coast. We do not doubt anyone's competence but note that the researchers put forward their hypotheses, guided by the data of imperfect devices, eyewitness testimony, indirect signs, and also, in many respects, intuition. Modern analysis tools allow us to have a broader look at the problem taking into account the entire complex of interrelated hydro- and lithodynamic processes occurring in the coastal zone. In this work we performed: (1) analysis of the regime of currents and surface waves of the waters of the northern coast of the Sea of Azov over the climatic period 1979–2020; (2) calculation of the statistical characteristics of the parameters of currents, wind waves, and storm level rise, as well as alongshore sediment fluxes in the coastal zone; (3) general assessment of the validity of the hypotheses for the formation of the Azov spits. The main method is numerical simulation using modern hydrodynamic and wave spectral models.

Let us briefly describe the results:

- In the coastal zone of all spits, the prevailing currents are directed from northeast to southwest (near Arabat Spit, from north to south). At the same time, near Belosaraysk Spit, both directions are almost equally possible. When following along the northern coast, the recurrence of the northeastern currents (in terms of "from where") decreases. The highest mean velocities are approximately 0.08 m/s, and the maximum ones exceeding 0.5 m/s, are observed near Berdyansk Spit at the northeastern currents. Southwestern currents with velocities exceeding 0.30 m/s are most developed near Fedotov Spit. Near Belosaraysk, Berdyansk, and Obitochna spits, the intensity of the northeastern currents significantly exceeds the southwestern ones. Near Fedotov and Arabat spits, the climatic characteristics of the velocities of currents of opposite directions are almost the same;
- on the northern coast, the strongest waves develop near Berdyansk Spit; the average long-term significant height of wind waves slightly exceeds 0.7 m. Near Belosaraysk, Obitochna, and Fedotov spits, this indicator is somewhat lower and amounts to about 0.50–0.55 m;
- near four spits (Fedotov, Obitochna, Berdyansk, and Belosaraysk), the proportion of wind waves with acute incident angles to the coastline is on average 0.5–0.6, i.e., waves

with sharp incident angles are not absolutely dominant. There situation with swell there is variable. Near Belosaraysk and Berdyansk spits, 50%–60% of the swell waves approach at sharp angles; near Obitochna and Fedotov spits, this indicator is smaller and is 30% and 12%, respectively;

- it was found that in the climatic sense near Arabat, Fedotov, Obitochna, and Berdyansk spits, the coastline features are formed mainly under the influence of wind waves with incidence angles **close to the normal**. The shape of the northernmost Belosaraysk Spit is determined by the equivalent contributions of fluxes determined by waves with sharp incidence angles and close to the normal. The influence of swell waves with acute incidence angles is most notable near Belosaraysk and Berdyansk spits, the influence of swells with incidence angles close the normal is efficient near Obitochna, Fedotov, and Arabat spits.
- in the region of Berdyansk, Obitochna, and Fedotov spits, the alongshore flow, directed approximately from north to south, significantly exceeds the flow in the opposite direction; at Arabat Spit, the flow from south to north dominates, at Belosaraysk Spit, the flows are almost equal. The largest total volume fluxes, taking into account the impact of wind waves and swell, of transported sand are observed near Berdyansk Spit. Near Belosaraysk, Fedotov, and Arabat spits, this volume is almost two times smaller. The smallest volumes are at Fedotov Spit;
- the volumes of the bottom material transported by the wind waves significantly exceed the volumes transported by swell. Nevertheless, in the region of Berdyansk Spit, in some years, situations are possible when the flows from south to north, caused by the impact of wind waves and swell, are comparable in magnitude.

Thus, we draw a conclusion (an expected one) that neither wind waves nor the system of currents by themselves determined the existing morphological structure of the northern coast of the Sea of Azov.

Let us turn to historical documents. Maps compiled by Piri Reis (1525), Mengden (1699), and Schraembl (1787) are available. Maps are downloaded from open sources (David Rumsey Historical Map Collection, https://www.davidrumsey.com; project "Gallica" of the National Library of France, https://gallica.bnf.fr). Fig. 13 shows fragments of the maps of the northern coast of the Sea of Azov that are interesting; the map also show contours of the coastline (Osborn, 1857) superimposed on a modern map.

It is clear that the map of Piri Reis, 1525 (Fig. 13a) can be considered only from an artistic point of view, but, nevertheless, the author's desire to convey the features of the coastline with the scale of the protruding features is obvious. The maps of Mengden, 1699 (Fig. 13b) and Schraembl, 1787 (Fig. 13c) are more informative; they clearly show the system of spits extended into the sea. Captain Osborne's map (Fig. 13d) is somewhat surprising in its level of detail. Unfortunately, when processing the map, it turned out that comparing this map with the correct coordinate grid, corresponding to the modern one it was found that the coordinates of the points of the coastline themselves are indicated with a displacement, and this displacement is not constant in scale and direction. Even the points of the Black Sea coast, which, due to the low erosion of the areas, can be considered reference points, are several miles away from the modern ones on the Osborne map. Taking into account the Osborne's data, it turns out that Berdyansk and Obitochna spits retreated by 3–4 km, but, alas, there is no confidence in these values. Nevertheless, if one focuses not on quantitative indicators, but on a qualitative picture, it is seen that the displacement of the spits occurred almost without loss of shape. The eastern shores, facing the sea, remain relatively flat, while the western ones are indented and deformed. In addition, modern research suggests that the spits of the northern coast are shifting westward towards the mainland with a retreat rate of 0.1–4.8 m/year (Prokhorova et al., 2018), i.e., hundreds of meters per century.

5. Conclusions

We can conclude the following summarizing the work:

1. The impact of wind waves on all spits, with the exception, perhaps, of the northernmost one, Belosaraysk Spit, can be considered as stabilizing, leading to smoothing of the coastline irregularities. This is due to the dominance of wave directions close to the normal in the coastal zone of spits.
2. The strongest bottom currents are near Berdyansk Spit. The sea currents become weaker flowing along the coast to the southwest to Fedotov Spit. The currents turning around Berdyansk Spit contribute to the transporting material to Obitochna Spit and form a vast area of shallow water south of Berdyansk Bay. The hydrodynamic regime of Fedotov Spit is determined by the interaction of counter currents: cyclonic, occupying the main basin of the sea, and anticyclonic in the southwestern part. The coastal currents of the northernmost Belosaraysk Spit, located at the entrance to the shallow Taganrog Bay, are, in fact, reversible and are mainly caused by surge fluctuations.
3. For a long time (several centuries) the northern coast has been displacing westward towards the mainland. This happens for two reasons: first, due to the removal of material by wind waves with directions close to the normal from the eastern edges of the spits and, second, due to the accumulation of sedimentation in the western parts, caused by the effect of the local anticyclonic currents in the bays between the spits and the main shore. In other words, the main factor in the development of spits on the side of the open sea is wind waves that are normal to the coast, and on the side of the mainland, these are coastal currents that occur against the background of storm surges.
4. Application of the term "spits of the Azov type" to sea spits of other coasts of the World Ocean formed by wind waves with sharp incident angles of waves does not seem justified.

CRediT authorship contribution statement

Boris V. Divinsky: Conceptualization, Methodology, Software, Writing – original draft. **Ruben D. Kosyan:** Supervision, Software, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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