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Modern state and dynamics of the Sea of Azov coasts

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ABSTRACT

Results: of the modern state researches of the Sea of Azov coasts and coastal processes influencing their evolution are presented. A multidisciplinary study of coastal processes allowed us to identify main types of coast evolution: abrasion, accumulation, and stability. Predominance of abrasion is the main feature of modern dynamics of the Azov shores. Not only the parent rock shores are subjected to erosion, but also accumulative forms are eroded. The eastern coast of the sea retreats most rapidly. The intensity of the abrasion and landslide processes is due to the weak resistance of the rocks composing the coast to the wave forcing. In particular, intense abrasion occurs in those parts of the coast where wave forcing is strong together with the surges caused by onshore winds, while the beaches are narrow or completely absent. At the same time, the percentage of beach-forming fractions in eroded soils is low, and the major part of the abrasion material in the form of suspended matter is transported to the deep parts of the sea. In general, the state and dynamics of the Azov coasts are influenced by abrasion-accumulative processes, sea level fluctuations, changes in the wind-wave regime parameters, and fluctuations in the biogenic beach-forming material volumes. The biogenic factor is the most important in the balance of deposits of accumulation forms (spits and bay-bars). Anthropogenic activity also affects the current state of the shores. The transport of beach-forming alluvial sediments into the sea is reduced because of the regulated river discharge. The natural evolution of onshore processes is disrupted during the development of the coast: agricultural activities, industrial and resort construction, removal of sand and shell material, construction of shore protection facilities.

1. Introduction

The coastal zones of the seas are among the most densely populated and economically developed areas in the world. Coastal areas are complex objects, including geographic, ecological, economic and social systems, and are sensitive to external influences. Erosion or accumulation processes have a significant impact on both the sustainability and evolution of coastal geo-ecosystems, as well as on the possibility of successful economic use of coastal territories. In turn, the intensive development of coastal resources and areas leads to an increase in anthropogenic pressure on the coastal zone. Changes in the position of the coastline of the sea, especially the retreat of the coast due to abrasion-landslide processes, changes the characteristics of coastal natural systems and causes significant economic damage. Currently, information on the state and dynamics of the coasts is necessary for effective spatial planning and sustainable development of any coastal areas.

The Sea of Azov is one of the smallest on the planet; it is situated in the eastern part of Europe. Its surface is 39 thousand km^2 and the average depth is about 7.4 m, the maximum depth is 15 m. The Sea of Azov is an inland sea. The narrow and shallow Kerch Strait connects this sea in the south with the Black Sea (Fig. 1). The boundary between the seas passes at the southern entrance to the Kerch Strait along Cape Takil – Cape Panagia line (Krylenko et al., 2017; Dobrovolsky, Zalogin, 1982; National Atlas of Russia, 2000).

In spite of the small size the Sea of Azov plays an important role in the economic development of the adjacent territories. The Sea of Azov and coastal areas are used for industrial, transport, commercial, agricultural, tourist and recreational and other activities. This is a transport route connecting industrial centers and large settlements of the Azov region with the ports of the Black Sea. The following ports are located on the coast of the Sea of Azov: Rostov-on-Don, Taganrog, Temryuk, Yeisk, Kerch, and Mariupol. The importance of the sea especially increased after the construction of the Volga-Don Canal in the 1950s and the unification of the Baltic, White, Caspian, Azov, and Black seas into a single water transport system. The mineral resources of the Azov Sea are of great importance: oil and gas, iron ores, glass sands, ordinary and other types of salt. The volume of predicted hydrocarbon resources in the Sea of Azov is about 1.5 billion tons of generalized fossil fuel (National Atlas of Russia, 2000). Before the beginning of large-scale economic development of the basin, the Sea of Azov was a reservoir

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Fig. 1. Sea of Azov. *Spits:* 1 - Tuzla, 2 - Chushka, 3 - Verbyanaya, 4 - Achuevskaya, 5 - Yasenskaya, 6 - Kamyshevatskaya, 7 - Yeskaya, 8 - Glafirovskaya, 9 - Sazalnitskaya, 10 - Chumbur-Kosa, 11 - Pavlo-Ochakovskaya, 12 - Beglitskaya. *Capes:* 13 - Panagia, 14 - Tuzla, 15 - Akhilleon, 16 - Kamenniy, 17 - Pekly, 18 - Kazantip, 19 - Zyuk, 20 – Khroni, 21 – Takil. *Water bodies:* 22- Kerch Strait, 23 – Taman Gulf, 24 – Dinskoy Gulf, 25 – Akhtanizovskiy Liman, 26 – Beysugskiy Liman, 27 – Yeskiy Liman, 28 – Berdyanskiy Gulf, 29 – Obitochny Gulf, 30 – Molochniy Liman, 31 – Utluksk Liman, 32 - Genichskaya channel, 33 – Chokrak Like.

with the highest biological productivity (70–80 kg/ha). In particular, it occupied the first place in the world among seas in terms of fish catch per unit area (Matishov et al., 2006; National Atlas of Russia, 2000).

During the 20th century, the ecosystem of the Sea of Azov experienced severe anthropogenic stress. In the 1950–1970s, construction of reservoirs in the basins of the Don and Kuban rivers was implemented, the total flow of which has the greatest impact on the change in the average annual water balance of the Sea of Azov. After significant fluctuations in salinity associated with the anthropogenic withdrawal of fresh water to fill reservoirs and irrigation, the salinity of the sea stabilized at a level of 10–11‰ (Matishov et al., 2006). Chemical pollution occurs due to wastewater from industrial and agricultural enterprises located in drainage basin of the Sea of Azov, the transit transport of pollutants from the overlying sections of the Kuban and Don rivers, the washing away of mineral and organic fertilizers from agricultural lands, and the release of pesticides from wastewater from irrigation systems. Pollution by oil and petroleum products occurs from leaks of fuels and lubricants, cargo operations, emergency spills; this pollution is estimated at 7 thousand tons/year. Anthropogenic pollution intensified due to isolation and poorly flushing of the Sea of Azov. Fairway dredging regularly carried out near ports has a direct impact on the lithodynamics processes of the adjacent coasts. In future, significant changes in the structure of the economy and, correspondingly in the sources of pollutants in the Sea of Azov basin are unlikely. In general, in the second half of the 20th century, salinity and concentration of pollutants of the Sea of Azov increased, there was also an increase in the amount of dead fish, introduction of the Black Sea species of biota, a change in the species structure of brackish-water and freshwater aquatic organisms. At the present stage, an increase in the role of climatic factors and the relative stabilization of the negative anthropogenic impact are observed in the ecosystem of the Sea of Azov.

The coastal zone of the Sea of Azov is located in a zone of favorable climatic conditions for the development of the recreational complexes. Currently, the territory is used for organizing beach holidays, various types of tourism, medical and resort areas on the basis of mineral water deposits and therapeutic mud, designed for various population groups. The Sea of Azov is a unique natural object and a part of it became protected natural territories with various protected levels from international to local.

By present a large number of works devoted to the study of the shores of the Sea of Azov has been published. There are three stages in the history of the study of the Sea of Azov: descriptive-geographical from the time of Herodotus to the beginning of the 19th century, geological and geographical from the 19th century to the 1940s, and multidisciplinary from the middle of the 20th century to the present time (Datcenko, Nepsha, 2018).

The geological history, morphology, dynamics, and conditions of formation of the shores of the Sea of Azov were the subject of special studies; they are presented in summarizing scientific works (Zenkovich, 1958; Khrustalev, Scherbakov, 1974; Mamykina, Khrustalev, 1980; Dobrovolsky, Zalogin, 1982; Artyukhin, 1987; Kaplin et al., 1991; Shuisky, 2000; Eschenko, Shipilova, 2002; Matishov et al., 2006; Ivlieva, 2009; Krylenko et al., 2017). Theoretical and field studies have been carried out by the specialists of the Center for the Sea Coasts at the Southern Scientific Center of the Russian Academy of Sciences, Kubangidrovodkhoz, the Southern Branch of the Shirshov Institute of Oceanology, Russian Academy of Sciences, Marine Hydrophysical Institute, Institute of Geological Sciences, National Academy of Sciences of Ukraine, and other organizations. However, almost all of them are published in the Russian or Ukrainian languages and are almost not used by the world scientific community. The purpose of this work is to summarize the available scientific information on the current state and development trends of the Sea of Azov shores and to provide the possibility of this information use by specialists from other regions.

2. General characteristics of the Sea of Azov

The Sea of Azov is located in temperate latitudes and its climate is characterized by continental features. A very warm summer and moderately mild overcast winter is characteristic. Intense radiation heating of the shallow-water Sea of Azov in the warm season causes the high temperature of its surface waters. The average annual water temperature on the sea surface is 11°C. Changes in the magnitude of surface water temperature from season to season are greatly expressed. In winter, it has zero or close to negative values in almost all the sea. In summer, a uniform surface temperature of +24–25 °C is established almost throughout the sea. Maximum values (+32.0–32.5°) are observed near the coasts (Dobrovolsky, Zalogin, 1982; Climatic Atlas of the Sea of Azov, 2008).

On average, over a long-term period, 418 mm of precipitation falls annually on the surface of the Sea of Azov. The greatest number of it falls in the north-eastern (Taganrog Bay) and eastern (Primorsko-Akhtarsk) areas of the sea. The catchment area of the Sea of Azov is 630 thousand km^2. Two major rivers flow into the Sea of Azov: the Don and Kuban (they transport more than 90% of water inflow), in addition 25 smaller rivers flow into the sea (Climatic Atlas of the Sea of Azov et al., 2008). At present, the fluctuations in the discharge of the Kuban and Don rivers depend on the climatic factors and water consumption for irrigation. In the future, the large water reservoirs will continue intercepting a significant part of the river outflow.

The Sea of Azov belongs to non-tidal seas. The variations in its level are determined by the components of the water balance and neotectonic fluctuations. The annual course and perennial fluctuations in the level of the Sea of Azov are due to changes in the total water volume in the sea. These fluctuations are associated with changes in the relationships between the components of the water balance: river runoff, rainfall, evaporation and water exchange through the Kerch Strait with the Black Sea. The annual level variation is characterized by its increase in the spring-summer months and a decrease in the autumn and winter, an average range of oscillations of 20 cm (National Atlas of Russia, 2000). The main contribution to the input part of the water balance is made by the river flow (41%) and the inflow of water from the Black Sea (41%), and to the supply part - the flow of water to the Black Sea through the Kerch Strait (60%) and evaporation (39%) of the Sea of Azov, 2008).

Development of onshore-offshore surges induced by storm winds is characteristic of the shallow Sea of Azov on the background of the seasonal fluctuations in the level. The sea level rise reaches 2–6 m above the long-term mean value (ESIMO, 2018). The most significant drifts and surges are observed in the Taganrog Bay and in the western part of the sea. In the Gulf of Taganrog and in the eastern part of the Sea of Azov, SW and W winds cause a surge of water, and NE and E winds cause swell. In the western part of the Sea of Azov, on the contrary, SW and W winds cause a surge of water, while NE and E winds cause a surge. Onshore surges can be catastrophic causing flooding of vast coastal areas.

The horizontal movement of water throughout the entire shallow Azov Sea is mainly due to wind. It causes drift currents and creates an increase in level near the coast, resulting in compensatory flows. In the pre-mouth areas of the Don and Kuban, there are stock flows. The resulting transfer of water, composed of multidirectional displacements, forms a circulation counterclockwise. It is well pronounced when the winds at a speed of 5 m/s and more. With weak winds, the pattern of currents is rather uncertain. A characteristic feature of currents is great variability in direction and velocity (Dobrovolsky, Zalogin, 1982).

The wave climate of the Sea of Azov is determined by a small area of the sea, shallow depths, and numerous bays. Winds of the eastern quarters are dominating in the winter seasons at the eastern coast, whereas western disturbances of air mass are typical for the warm seasons. The strongest storms in the eastern part of the sea are associated with western winds. The maximum wind speed reaches 28–34 m/s. Wind waves develop rapidly, but after 4–6 h of growth the waves cease. The largest waves in the central part of the sea reach a height of 3–4 m. The wave period does not exceed 4–5 s (Climatic Atlas of the Sea of Azov, 2008).

The Sea of Azov is a brackish water body. The hydrochemical regime is formed under the influence of the continental runoff, the vital activity of hydrobionts, temperature, atmospheric circulation, water exchange with the Black Sea and the Sivash Bay. Until 1952 (the beginning of the construction of reservoirs on the Don and Kuban rivers), the average salinity in the seas was 10.910,9‰. In the Taganrog Bay, the average salinity was 6.2‰. After the regulation of river flow and the implementation of water management measures in the basins of the Don and Kuban rivers in the period 1953–1989. the average salinity of the sea increased to 12.1, in the Taganrog Bay - to 7.5‰ (Kuksa, 1994). In the years 1993–2005 the salinity of the Sea of Azov stabilized in the range from 10 to 11‰, with an average value of 10.5‰ (Matishov et al., 2006).

In general, the Sea of Azov is characterized by low inertia of natural processes and fast response to changes in river flow and atmospheric circulation, which determine the high spatial and temporal variability of hydrophysical and hydrochemical parameters.

3. Characteristics of the coasts

3.1. Geomorphology and the Sea of Azov shores types

Geomorphological conditions of the coasts of the Sea of Azov are very diverse due to the manifestations of endogenous and exogenous factors. The Sea of Azov is located in the region of the newest platform flexure on the East European Platform, the Scythian Plate, and on the structures of the Alpine fold belt (from north to south). The following large geostructures are distinguished within the Sea of Azov from north to south: the North-Azov Trough, the Azov Ridge the Timashevsk Step, and the Indolo-Kuban flexure (Myslyvets, 2004). The complexity of the influence of endogenous factors is determined by the difference in the types of structures as well as in the directions of the coastal deformations at the neotectonic stage, during which the formation of the main elements of zoning occurred: large territories, regions, and to a large extent even sub-regions. The neo-structural features of the regions are confined to isolated blocks or their systems with the same type of the character of the newest motions during the Pleistocene (Chekunov, 1972).

The Sea of Azov belongs to the small epicontinental basins, in the development of which the subaerial stages played an important role. At the end of the Pleistocene, the Sea of Azov was a plain drained by the Don and its tributaries. The pre-Don valley is clearly manifested in the bottom topography of the Taganrog Gulf and in the central basin of the sea. The bottom of the Sea of Azov is broken by sublatitudinal and submeridional faults into separate blocks, the development of which determines the formation of specific morphological structures (Maev et al., 2009). The discrepancy between the plan of ancient tectonic structures and modern morphological structures indicates that the neotectonic, and in particular, the Holocene stage, which determined the formation of the sea depression superimposed on a more ancient structure, was the determining one in the development of the tectonic structures (Myslyvets, 2004, Ecological Atlas of the Sea of Azov, 2018).

The modern geomorphological shape of the Sea of Azov and its coasts was formed during the Holocene (the last 3 thousand years) under the influence of hydrodynamic and sedimentation processes against the background of descending tectonic motions and a general eustatic rise in sea level. The tectonic lowering speed was of up to 3 mm/year (Ecological Atlas of the Sea of Azov, 2018).

The shores are composed of continental rocks (mainly quaternary loess-like loams and scythian clays). Miocene and Paleocene limestones are widespread within the Kerch-Taman coast, (Kaplin et al., 1991; Khrustalev, Scherbakov, 1974). The main sources of terrigenous

material are the products of coastal abrasion and river alluvium. The bottom sediments consist generally of clayey silt, aleurite silt, silt sand, and sand. Clayey silts (fraction smaller than 0.01 mm) are most widely spread (Ivlieva, 2009).

The role of biogenic processes (the state of benthic communities) is significant in the formation of the geomorphological structure of the coast. Shell detritus transported from the bottom of the sea participates in the formation of beaches and large accumulation forms; banks appear in the locations of stable colonial settlements of mollusks. The main factors affecting the distribution and amount of macrozoobenthos are the oxygen regime of the sea (the presence of dead fish) and the nature of sedimentation. Fluctuations in the salinity of the Sea of Azov within 9–14 are not a decisive factor due to the euryhalinity of the main species of benthic communities (Matishov et al., 2008).

The total length of the seashores of the Sea of Azov is about 1900 km (excluding Sivash and Molochny Liman bays). In general, the northern coast of the sea is plain, steep, with alluvial sandy spits. In the west, the Arabatskaya Spit separates Sivash Bay from the sea; the bay is connected to the sea by a strait. In the southeast, the delta of the Kuban River extends over 100 km with extensive flood regions, channels, and lagoons. In the northeast, the Taganrog Gulf, which is the largest gulf of the sea, intrudes over 140 km into the land, and the delta of the Don River is the top of the gulf.

There are various classifications of coast types. Usually, three types of coasts are considered in the Sea of Azov: accumulation, abrasion, and abrasion-landslide (Kaplin et al., 1991). Some authors distinguish (National Atlas of Russia, 2000) abrasion, abrasion-accumulation, and accumulation; a more detailed classification includes: abrasion-landslide, abrasion-landslide, ancient abrasion, accumulation-abrasion, initially accumulation, accumulation aligned, delta, dynamically neutral, anthropogenic (Datcenko, Nepsha, 2018). In this paper, in addition to the two main types of coasts development we identify: abrasion (abrasion-landslide and abrasion-landslide) and accumulation. The stable shores are characterized separately. There are currently no clear abrasion or accumulation processes. It is worth noting that in this case term “stable” is used in the sense of the relatively weak direct impact of waves on the coast (Kosyan, Krylenko, 2007; Mamykina, Khrustalev, 1980). Fig. 2 presents a generalized diagram of the Sea of Azov shores types, created on the basis of published materials (Ecological Atlas of Azov, 2018, Current state of the Crimea coastal zone, 2015, Krylenko et al., 2017; Kosyan, Krylenko, 2007), publicly accessible map services (Google Earth, Yandex Maps, Bing Maps) and own data of the authors.

3.2. Abrasion shores

The abrasion type of coast (Fig. 2) is widespread on the northern and north-eastern coasts of the Sea of Azov. Regional differences in the structure and dynamics of abrasion coasts within the sea are caused by the differences in the composition of rocks, initial relief and configuration of the original coast, and orientation relative to the prevailing waves. Most of the abrasion coasts of the Sea of Azov are composed of easily eroded rocks (Fig. 3): loess-like loams, loams, clays, and their various combinations.

If a cliff is 2–8 m high, abrasion coast with festoon dismemberment is formed in homogeneous loamy rocks, (Ecological Atlas of the Sea of Azov, 2018). For example, the coast between the Primorsko-Akhtarsk town and the beginning of the Yasenskaya Spit is of the abrasion type all over it entire length. The average height of the coastal cliffs is 4 m; the maximum height is 8 m. The coast has a festoon structure; the capes are formed by denser varieties of loams. The average abrasion rate over a long-term period is 1.0–3.6 m/year, and the maximum is up to 6.0 m/year (Kosyan, Krylenko, 2007). In general, the retreat rate of abrasion coasts formed by loess-like loams is 1.8–2 m/year, in some areas up to 5–6 m/year (Kosyan, Krylenko, 2007; Ecological Atlas of the Sea of Azov, 2018).

If a coastal cliff is 5–10 m high, and it formed by loess-like loams and underlain by more dense clay, conglomerates and sandstones; then niches and grottoes are formed by the influence of surge waves in the lower part of the cliffs (parts of the coast from Dolzhanskaya station to Kamyshevatskaya station, Berdyansk and Obitnoe gulfs, northern parts of the Taganrog Gulf) (Kosyan, Krylenko, 2007). The northern coast of the Taganrog Gulf has a length of abrasion coasts of about 100 km. The average speed of shore destruction is 0.1–0.5 m/year, the maximum speed is 2 m/year in the western part of the gulf (Ivlieva, 2009). If a cliff is higher than 10–15 m and its structure is relatively homogeneous, a steep wall is usually formed with collapses of loams at the basement (abrasion-landslide shore).

Strong storms combined with a surge increase in the sea level contribute to a strong restructuring of the abrasion coasts of easily eroded rocks in a short time period. For example, within a few hours of storm weather in the region of the Akhtarsky lighthouse, the abrasion-landslide shore retreated by 3–5 m (Peshkov, 2000). Under such conditions, the edge of the cliff at the Genichesky lighthouse displaced by 4 m. As a result of intense storms from 2002 to 2005, the eastern seacoast at a distance of 17 km south of the Dolgaya Spit retreated by 11 m (Matishov et al., 2006).

Fig. 2. Scheme of the coastal types. 1 – abrasion coast, 2 – accumulative coast, 3 – stable coast.

Fig. 3. Abrasion coasts composed of the rocks subjected to easy abrasion (photo by M. Krylenko).

Fig. 4. Typical coast of the northern Kerch Peninsula (left) and Kazantyp coast formed by bryozoan limestone (right) (photo by V. Krylenko).

In some regions of the Taman and Kerch peninsulas there are outcrops of poorly eroded rocks, as a rule composed of bryozoan limestone. On the Kerch Peninsula, such areas are large capes Zyuk, Kazantip, and a number of smaller capes of the Karalar coast (Fig. 4). The steepness of limestone slopes of Cape Zyuk are up to 45°; in the region of water edge they terminate with a steep active cliff approximately 10 m high. The shore in the region of Cape Kazantyp is finely indented and belongs to the abrasion type. The capes of the abrasion coast intrude into the water basin, and small bays intrude into the land by 30–150 m. The height of active cliffs is up to 10–20 m. Wave breaking holes and abrasion grottoes up to 5–8 m deep are found here. Sea kekurs are found in the coastal regions of the sea. Kekur is columnar or conic rocky butte of natural origin. According to the morphological characteristics, sea kekurs are remains of bryozoan limestone reef ridges. Their height varies from 2 to 4 to 10–20 m (Current State of the Crimea Coastal Zone, 2015). They reach a maximum height in the northeastern part of the peninsula, where storm winds, normal to the coast prevail. In the bays of the abrasion Kazantyp coast, narrow boulder-pebble or shell beaches are found. On the Taman Peninsula, the same bryozoan reefs form the capes of Tuzla and Panagia (Dikarev, 2018; Current State of the Crimea Coastal Zone, 2015). Cape Panagia was formed as a marine reef from bryozoan colonies, a chain of reef formations extending from the cape for many hundreds of meters into the sea. Reefs and surface cliffs mark the traces of the retreating coast.

Abrasion-landslide shores are widespread in the Kerch-Taman region (Fig. 5). The greatest extent of landslide phenomena exists in the northeastern part of the Kerch Peninsula and in the north of the Taman Peninsula. Landslides have a length of up to tens of kilometers. This subtype of the coast is confined to relatively elevated sections of the coast, at the basis of which Neogene sediments outcrop to the surface.

The most widely spread and continuously developing deep landslides are formed by several landslide terraces or steps, one above the other, with a high separation wall (Port-Katon village, Primorka village, Mariupol, Cape Achilleon, etc.). The landslide displacement rates depend on the morphology and characteristics of the lithological structure of the coastal land column, water saturation of the rocks, and the amplitude of the surge and surge fluctuations of the sea level and incidence angle of the waves to the coast. The annual mean retreat rates of landslide shores are usually smaller than that of the landfall coasts.

Abrasion-landslide shore between the Achilleon and Pekla capes (Taman Peninsula) extends over almost 30 km. The coastline forms two gentle sloping bays separated by Cape Kamenny. The cape was formed as a result of a large landslide massif of Chaudin thick-tiled sandstones towards the sea. The ancient landslide zone consists of several steps with a total width of up to 1000 m. The height of the protrusions is from 20 to 40 m and more. The overall slope is about 30°. The slope is cut by ravines (Kosyan, Krylenko, 2007).

As Cape Peckla is approached, the height of the parent rock coast increases to 50 m. The cape is formed of abrasion resistant marls (chalky clays). The width of the landslide zone of Cape Pecla is 200–300 m. The beaches are narrow, up to 5–10 m; they are composed of fine shell sand. The average abrasion rate is 0.5–0.6 m/year (Kosyan, Krylenko, 2007; Peshkov, 2000).

The western coast of the Kerch Strait north of Cape Takil is an extremely active region with a high speed of landslide motion and floods. The coastal protrusion with a height of 40–60 m and a length of 1 km cuts off the core of active anticline, which is composed of clay, and complicated by thrusts. It manifests itself in the relief as a large hill with a hanging relict valley on the top. The clays of the coastal ledge are dissected by a dense network of practically uncontaminated erosion intrusions up to 250 m long and 25 m deep, steeply inclined towards the Kerch Strait. Cones of clay and loam 1–3 m thick are located at the ends of these intrusions on a narrow beach. Some of them protrude into the water by 3–5 m. The abrasion rate on landslide regions is about 0.6 m/

Fig. 5. Abrasion-landslide shore, Taman Peninsula (photo by M. Krylenko).

year (Current State of the Crimea Coastal Zone, 2015).

3.3. Accumulation shores

Accumulation shores of the Sea of Azov are represented by spits, bay-bars of lagoons and estuaries (Fig. 2). They are formed in the mouth areas of the rivers. In the west, there is a very long (about 110 km long) Arabatskaya Spit that stretches along the entire western coast of the sea; it is composed almost entirely of shell material (Kaplin et al., 1991).

In the southeast, almost every bend of the parent rock coast ends with the formation of large spits (Chushka, Achuevskaya, Yasenskaya, Kamyshevatskaya, Dolgaya, Glafirovskaya, and Sasalnitskaya). The mouths of deep bays here are often blocked by sediments (the spits of the Akhtanizovsky and Beysug estuaries). Long coastal bars (Verbyanaya Spit) are formed along the sea edge of the Kuban River delta.

A special type of accumulative forms is common in the north: the Azov-type spits composed of quartz sand and shell. V.P. Zenkovich (1958) showed that multiple sand spits with rhythmic shapes may develop in shallow bodies of water, such as the Sea of Azov, and called them the Azov-type spits (Zenkovich, 1958). The Azov-type spits appear at small protrusions of the parent rocks, developing first due to the abrasion of the adjacent coast. The spits increase in the direction at an angle to the shore, than they block part of the shore from the prevailing disturbances. In the area of the wave shadow, the prevalence of secondary directions of waves is ensured and the onset movement of sediments to the root of the spit occurs (Zenkovich, 1958; Safyanov, 1996; Ashton et al., 2001).

High content of the shells supplied from the sea bottom is a characteristic feature of the structure of the Sea of Azov spits. Approximately 85–99% of the Dolgaya Spit material is shell detritus; the shell content of the Chushka Spit is 63%. According to the data (Mamykina, Khrustalev, 1980) in the end of the 20th century, the amount of accumulated nutrient material in the Sea of Azov was 2.7 billion m^3, which was almost two times greater than the accumulated amount of terrigenous material. This fact indicates the importance of the nutrient source of sediment for the state of accumulative forms of the region.

The Arabatskaya Spit, which is more than 110 km long (Fig. 2), separates the largest bay of the Sea of Azov (Sivash). This shallow lagoon-type bay in the north is connected to the sea by two channels: the Genicheskoy and Nameless. The Arabatskaya Spit is a narrow (from 270 m to 7 km), low, and long peninsula (Vorovka et al., 2010) composed mainly of sand and shell material based on specific remains of the Quaternary bedrock. It is namely the outcrops that create elevated areas in the form of projections of the coastline from the Sivash side.

These protrusions are subjected to abrasion at the average rates of 0.1–0.5 m/year. Despite the dominating role of the exogenous coastal processes, the formation and development of the spit relief are also influenced by the latest tectonic motions. In the central part of the Arabatskaya Spit, the decrease in the Earth's surface is 2.8 mm/year, and in the southern part it is 3.7 mm/year. These descents contribute to the relative sea level rise (Shuysky, 2007) in this region.

The coastline of the Arabatskaya Spit is straight on the Sea of Azov side. The beach is located along the entire length from the root part in the south to the Tonkiy Strait in the north. The width of the beaches is 20–50 m. They are composed of shell detritus with a low content of sand and fine gravel. The surface of the beaches is flat and not complicated by secondary forms (Shuysky, 2007). There are several dozens of depressions of various sizes in the central and northern parts of the spit in the back of the modern beach. The depressions were formed during the extraction of shell material from the ancient coastal ridges. The relief of the seaside part has been disturbed in the northern part of the spit when the recreational facilities were built. The coastal ridge is actually destroyed in many regions. Under the conditions of reducing the reserves of shell rock as the main source of sediments against the background of the current relative sea level rise, erosion processes (due to storms combined with wind surges) affect many regions of the sea shore of the Arabatskaya Spit. In general, the seashore retreats with average speeds of 0.1–0.3 m/year (Shuysky, 2007).

The following large spits are located on the northern coast of the Sea of Azov (they are more than 10 km long): Fedotov, Obitochnaya, Berdyansk, Belosaray, and Krivaya spits. There are also small spits (1–5 km long): Beglitskaya, Samsonova, Bezymyannaya, Shirokinskaya, Lyapinskaya, as well as the bay-bar of the Molochny estuary (Nepsha, 2014; Prokhorova et al., 2018) (Fig. 6).

There is an interesting line of four large spits: Krivaya (13 km), Belosarayskaya (18 km), Berdyansk (30 km), and Obitochnaya (40 km). They are characterized by the presence of a triangular base, an extended base and a thin isthmus connecting these parts of the forms. These are the Azov-type spits, which extend from the northeast to the southwest. The southeastern coast of the spits is rectilinear, while the northwestern one has complex shapes with small bays and lagoons. The surface of the spits is slightly wavy. Numerous salt lakes exist near the basements of the spits.

Fig. 6. Spits of the Sea of Azov type on the northern coast of the Sea of Azov.

Erosion dominates on the southeastern side of the spits composed of quartz sand and shell. Accumulation of sand-shell and clay-aleurite material occurs on the northwestern shore. The underwater slope of the spits on the southeastern side is rather deep. Beaches up to 25 m wide are located along it. Extensive shoals with depths of less than 5 m are located along the western and northwestern coasts of the spit (Matishov et al., 2006; Prokhorova et al., 2018). Along the western coast there are extensive areas covered by near-water vegetation.

The natural relief of the spits in some areas is disturbed by dykes, embankments for roads, drainage channels, artificial increase of built-up areas, former mining pits for excavations of sand, which are now filled with water. From the beginning of the 1980s up to the present, erosion processes with an average speed of 1–3 m/year have been prevailing in the distal parts of the spits (Prokhorova et al., 2018; Datsenko, Nepsha, 2018).

The Dolgaya Spit is located at the entrance to the Taganrog Gulf; it is adjacent to the northwestern tip of the Eisk Peninsula and it is one of the largest accumulative bodies on the Russian coast of the Sea of Azov. Its length is currently 9 km. In addition, there is an underwater bank 24 km long (from the modern tip of the spit); islands are formed from time to time over a distance of 16 km along the axis of this bank (Krylenko et al., 2018). The body of the spit is composed mainly of shell material. The Dolgaya Spit has two shores: the northeastern (the Taganrog Gulf) and southwestern (the open Sea of Azov) that are significantly different in composition and processes that take place here. The coast of the spit from the side of the Taganrog Gulf is a low abrasion protrusion, developed in the ancient accumulative sediments. Up to the end of the spit, the accumulative coast is represented by a full-profile beach. The width of the beach varies from 5 to 10 m (at a junction with the original abrasive coast) to 50–70 (in the central part of the spit) (Krylenko et al., 2017).

The width of the beach here does not exceed 5 m. The site is characterized by one-sided removal of erosion products towards the distal part of the Dolgaya Spit. Analysis of the images taken over a long time in the period 1968–2018 showed that the long term retreat of the coast is observed over the entire northeastern coast of the spit, the speed of which varies depending on the current hydrodynamic situation in the range of 0.5–1.0 m/year to 4–5 m/year. Further, up to the end of the spit, the accumulative coast is represented by a full-profile beach. The width of the beach varies from 5 to 10 m (at a junction with the original abrasion coast) to 50–70 (in the central part of the spit) (Krylenko et al., 2017). The overall width of the spit decreases with the approach to the tip of the spit. Erosion was found in the root part of the spit and near its tip. The distal part of the spit constantly changes its form depending on the hydrodynamic conditions and the amount of biogenic material. The distal part of the spit has been degraded from the middle of the twentieth century, which terminated in its almost complete disappearance in 2014. During the storm on September 24, 2014, the distal surface part was eroded completely, and the length of the spit decreased by 300 m (Krylenko et al., 2018).

A characteristic feature of the accumulative shores of the Sea of Azov, like most accumulative shores in the world at the present stage of development (Luijendijk et al., 2018), is their susceptibility to erosion and retreat of the coastline.

3.4. Stable shores (not subjected to wave forcing)

Stable shores of the Sea of Azov, as a rule exist in bays, estuaries, and regions blocked by spits in the deltas of the Kuban and Don rivers (Fig. 2). These are the regions protected from wave action, where abrasion and accumulative processes are not clearly manifested. The shores are usually low, often covered with reeds and protected by shallow waters.

Stable coastal regions composed of loose rocks in the Taganrog Gulf are up to 10 m high (Fig. 7). The stable shores of the Taman and Dinskoy gulfs are usually low as can be seen in Fig. 7. The Dinskoy Gulf is large, but due to its extreme shallowness the waves almost do not develop here. The bottom of the Dinsky Gulf is muddy and overgrown with reeds. Erosion of the coast occurs only under the conditions of storm surge. The low, sandy shores of the Akhtarsky liman-lagoon are almost completely overgrown with reeds. In the eastern part and the northeastern part of the Yeysky liman-lagoon, the dead cliff is also separated from the edge by reeds. The coast is stable, but subjected to surge forcing (Kosyan, Krylenko, 2007). This type of coast with wide shoals and extensive underwater slopes is found on the western coast of the Sea of Azov and in the Sivash Gulf (Datcenko, Nepsha, 2018).

4. Shore protection structures and anthropogenically transformed shores

Active abrasion processes and high dynamics of the coastline cause the necessity of various shore protection structures on the Azov shores. As a result of the analysis of modern satellite images, more than 900 hydrotechnical (coastal, protective and all that) structures normal to the coastline were found. Blocks of rock spurs became of the greatest use on the shores of the Sea of Azov especially in recent decades (about

Fig. 7. The coast of the Taganrog Gulf at the mouth of the Don River (left); characteristic shore of the Dinskoy Gulf (right) (photo by V. Krylenko).

Fig. 8. Tuzla spit.

350 constructions). Most often they are used to create artificial beaches or bulk areas.

There are also protection facilities made of construction garbage and concrete spurs (about 250 constructions). Such facilities are used for the local strengthening of private property areas (residential, recreational, small industrial plants) due to the lack of a unified shore protection plan. Much less often, they are used for the creation of large artificial recreational beaches; combinations of stone blocks and tetrapods with dumping of beach-forming material are used. Concrete piers are most often used to protect the waters of ports and other harbors, sometimes they are additionally enhanced by dumping large stones or installing concrete products (tetrapods, hexabits, etc.) from the sea side. Concrete walls, sheet piling or pile fences are used for the organization of the inner harbor areas.

Concrete boulders traditional for the USSR period are widespread, sometimes being at the same time a protective structure and a pier (Peshkov, 2000). Many of the 150 existing groins are now almost destroyed.

About 50 sites with continuous coastal construction as private boathouses combined with rooms for living or other buildings can be considered a special anthropogenically transformed type of the regions (Goryachkin, 2016). Dumping debris, barricades of metal structures, and car tires are usually used for the protection of such areas. Similar methods of shore protection are also used to preserve private territories or objects located very close to the edge, most often without permission for buildings violating the legal regulations (Goryachkin, 2016).

Dumping along coastal dams (berms) immediately along the coastline or at the back of the beach is used to protect against erosion of industrial or transport facilities. Their length is hundreds of kilometers.

The western coast of the Kerch Strait is strongly transformed. There are harbours of ports and shipbuilding enterprises protected by concrete piers. In addition, about 20 stone blocks and 10 concrete piers are located here. In addition, breakwater walls of embankments and sections with “handicraft” shore protection have a considerable length. The Tuzla Spit composed of quartz sand, shell, and pebbles is a large anthropogenically transformed accumulative form of the Kerch Strait.

During a strong southern storm in 1925, the sea near the Taman coast broke through the spit, and the spit turned into an island, separated from the Tuzla Cape by a strait (Zenkovich, 1958). The sediment deficit was accompanied by the intensification of erosion and the general narrowing of the root part of the spit. Erosion niches were formed, and the accumulative form broke up into separate islands. Since the Tuzla Spit was in the critical state, it was strengthened in 2003 by a dam. The total volume of material in the body of the dam was 580,000 m^3. Observations showed that by the mid-2005s, due to the attachment of shoals and supply of shell material from the bottom, a beach with an average width of 7–8 m and in some places up to 18–20 m began to form on the sea side of the dam.

At the same time, the material began to move along the main stream in the direction of the depression between the head of the dam and Tuzla Island. In order to avoid sediment leakage, two stone-filled blocks of 25 m length each were built in 2004 at the end of the dam. The width of the beach at its head part gradually reached 30 m in some places (Krylenko et al., 2017). The restoration of the root part of the Tuzla Spit significantly reduced the penetration of storm waves from the Black Sea. As a result, the abrasion rate of the northern shores of the Taman Bay was significantly reduced. At present, the Crimea Bridge connecting the Kerch and Taman peninsulas passes through the Tuzla Spit and Tuzla Island (Fig. 8).

Shore protection works in the town of Primorsko-Akhtarsk were performed in 1956–1970 in the form of a concrete vertical wall with a resistant support at the base and a parapet along the top protecting the embankment. The total length of the enhanced section of the coast is 4 km. The protecting facilities were built from iron plates installed

between the rows of piles interconnected in a single design monolithic cap bars (Peshkov, 2000). At present, the coast near the town of Primorsko-Akhtarsk is protected by 20 concrete groins of various sizes, 5 stone blocks, and side structures. In the central part there is a gravel-sand beach up to 35 m wide.

The Yasenskaya Spit (Fig. 1) is composed of shells, its total length is about 14 km and its width ranges from 0.2 to 2 km. From 1948 to 2005 the total area of erosion of the marine part of the spit amounted to 2.4 million square meters; the volume was about 2.5 million m^3. The maximum retreat of the shore edge was up to 12–15 m per year (Vostrikov, 2006). The Yasenskaya Spit is fortified with a stone berm construction near its beginning. The width of the berm is 6 m, its height is 1–1.5 m. In 2005–2006 by the order of the gas company the Yasenskaya Spit was reinforced with an anti-surge dam and a wave breaking sloping beach of shell material with a total volume of about 10,400,000 m^3 over a distance of 10 km (Peshkov et al., 2005).

In the early 1980s, the natural sandy bay-bar that separated Lake Chokrak was broken as a result of extreme wave action. In 1984, the construction of a 0.9 km long dam was completed. In the late 1980s and mid-1990s erosions of the natural beach and the dam body in its northwestern part were observed. In 2001–2013 the width of the surface of the beach increased at this site by 10–11 m and the erosion of the dam completely stopped. Now the state of the dam is satisfactory (Current State of the Crimea Coastal Zone, 2015).

Areas with shore protection or other hydro-technical structures of any type are unevenly distributed along the seashore. As a rule, shore protection is located within the settlements or along transport routes. There are extensive areas of abrasion and accumulation shores without the presence of any artificial structures influencing the natural motion of sediment or wave forcing. Such sites include the Arabatskaya Spit (about 110 km), the adjacent section of the Kerch Peninsula (about 120 km), the western side of the Fedotova Spit, the coast of the southeastern part of the sea, where single structures are found over tens of kilometers of the coast. Agricultural territories are almost not protected anywhere.

Shore protection facilities are used mainly on the abrasion shores. The eroded accumulation forms are protected only if there are economic or transport objects on them (Berdyansk, Chumbur-Kosa, Yasenskaya, Verbyanaya, and Tuzla spits). Often, the construction of various shore protection structures is carried out spontaneously and chaotically, without appropriate project documentation, without state project plans, without analyzing the efficiency of coastal protection by various constructions.

5. Conclusions

The domination of abrasion is a feature of the modern dynamics of the shores of the Sea of Azov. Not only the native shores are subjected to erosion, but also accumulation forms. The average abrasion rates of the coast are within 0.3–2.0 m/year (Ecological Atlas of the Sea of Azov, 2018). The coast of the eastern coast in the region of Primorsko-Akhtarsk and the Yeisk Peninsula retreats most rapidly. The abrasion and landslide processes are caused by the weak resistance of the rocks composing the coast to the wave forcing. Particularly active abrasion processes occur in those parts of the coast where the wave forcing occurs together with the surges, in the regions with a small width of the beaches or their complete absence. At the same time, there are little beach-forming fractions in eroded soils, and most of the abrasion material in the form of suspended matter goes into the deep part of the sea. This causes high rates of coastal abrasion, even with relatively weak wave forcing.

In general the state and dynamics of the Azov coasts are determined by abrasion-accumulative processes, sea level fluctuations, changes depending on the wind-wave regime parameters and fluctuations of the biogenic beach forming material volumes. The biogenic factor is especially important in the balance of deposits of accumulation forms (spits and bay-bars).

Anthropogenic activity affects the current state of the shores of the Sea of Azov. The transport of beach-forming alluvial sediments into the sea is reduced as a result of river discharge regulation. The natural evolution of onshore processes is disrupted during the direct economical development of the coast: agricultural activities, industrial and resort construction, removal of sand and shell material, construction of shore protection structures.

The density of shore protection structures is highest on the northern coast of the sea, where there are many settlements, recreational, industrial, and transport facilities. Conducting shore protection measures not always leads to the stabilization of the coast. Coast protection is often performed without taking into account the width of the existing beaches and the influence of the designed structures on the adjacent coastal regions. As a result, in some areas, the shore-protective structures were completely or partially destroyed. In the economic development of the coast, absolutely no attention has been paid to the preservation of the coastal landscape. Most authors point out that it is necessary to monitor and create a modern integrated management and development scheme for the shores of the Sea of Azov.

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