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Baltica

BALTICA Volume 35 Number 2 December 2022: 125–139
https://doi.org/10.5200/baltica.2022.2.3

Genetic diversity of inlet systems along non-tidal coasts: examples from the Black Sea and Sea of Azov (Ukraine)

Oleksiy Davydov*, Viktoras Karaliūnas

Davydov, O., Karaliūnas, V. 2022. Genetic diversity of inlet systems along non-tidal coasts: examples from the Black Sea and Sea of Azov (Ukraine). *Baltica, 35 (2),* 125–139. Vilnius. ISSN 0067-3064.
Manuscript submitted 6 May 2021 / Accepted 15 August 2022 / Available online 14 November 2022

Abstract. In the coastal zone of the oceans, coastal barriers are quite widespread. Within their limits, inlets periodically arise and exist for a certain time, which is of great geological, hydrological, ecological, and navigational significance. Along the coasts where tidal fluctuations predominate, tidal inlets stand out, which are quite well studied in terms of genesis, morpho-, hydro- and litho-dynamics. Inland, semi-isolated marine basins, where tidal fluctuations do not reach a significant amplitude, are called non-tidal seas. Within the coastal barriers of non-tidal seas, channels periodically arise and develop, which are called breaches or prorvas. Breaches are quite often mentioned in the specialized literature along the coasts of non-tidal seas, but they have not been purposefully studied. In this article, we tried to analyze the conditions for the formation of prorvas within non-tidal seas based on many years of research. We have identified four hydrodynamic situations in which breaches are formed. The presented variety of situations allows us to identify and describe four genetic types of prorvas: storm-generated, storm-surge-generated, wind-stress-generated, and river-stress (fluvially induced). The presented article is the first attempt to analyze the genetic characteristics of the breaches.

Keywords: *coastal barriers; breaches; prorvas; storm surges; hydrometeorological fluctuations; accumulation forms*

✉ *Oleksiy Davydov* (svobodny.polet2012@gmail.com), https://orcid.org/0000-0003-2144-9627,*
Department of Geography and Ecology, Kherson State University, Ivano-Frankivsk, Ukraine;
Scientific department, National Nature Park "Biloberezhya Svyatoslava", Ochakiv, Ukraine

Viktoras Karaliūnas (viktoras.karaliunas@gamtc.lt), https://orcid.org/0000-0003-4237-5276,
Nature Research Centre, Institute of Geology and Geography, Vilnius, Lithuania

**Corresponding author*

INTRODUCTION

Tidal inlets are important morphodynamics elements along tidal coastlines, serving as conduits between the marine and back-barrier basins (Marine Geomorphology 1980; Gudelis 1993; Davis, FitzGerald 2004; Hayes, FitzGerald 2013; FitzGerald, Buynevich 2018). These are natural conduits for tidally driven water flow (tidal currents), as well as an exchange of biota, nutrients, and sediments. They also serve as important navigation routes and thus are often stabilized by jetties. However, there are many challenges related to their exploitation, especially due to their dynamics in space and time (Bruun, Gerritsen 1958; Zenkovich 1960; Shuisky, Vykhovanets 1989; FitzGerald 2015; FitzGerald, Buynevich 2018).

Tidal inlets are well studied along many parts of the world ocean and their dynamics, but not the origin, is a function of tidal flow (Hoyt 1967; Glaeser 1978; Fitzgerald 1996; Stutz, Pilkey 2001, 2011; McBride *et al*. 2013). Along non-tidal basins, inlets between coastal barriers are also present; however, less research has focused on these systems. In order to assess their characteristics and morphodynamic variability, this study presents datasets from the Ukrainian coast of the northern Black Sea (Fig. 1) and Sea of Azov coastlines and offers a comparative analysis of functionally non-tidal systems along the southeast Baltic Sea.

The aim of our study is the introduction of non-tidal inlets (prorvas) and definition of their genetic diversity through: 1) comparative analysis of previous research focused on tidal and non-tidal inlets; 2) investigation of regional characteristics of their structure and hydrodynamic function; 3) describe the genesis and variability of specific prorvas, and 4) synthesize the database to establish their typology based on genetic parameters.

DEFINITION OF COASTAL INLETS

In specialized literature, there are various names given to channels that are flanked on one or both sides by coastal barriers (as opposed to structural inlets): e*ntrance, inlet, a tidal inlet*, *breaches, prorvas (Russian/Ukrainian), and others* (Johnson 1919; Lucke 1934; Borisenko 1946; Zenkovich 1960, 1962; Bruun, Gerritsen 1958; Pravotorov 1966, 1968, 1970; Marine Geomorphology 1980; Shuisky, Vykhovanets 1989; Gudelis 1993; Fitzgerald 1996, 2015; Hayes, Fitzgerald 2013; McBride *et al*. 2013; Fitzgerald, Buynevich 2018; Fitzgerald, Miner 2021).

Some of these are genetic, whereas others are functional (e.g., a breach is an ephemeral feature that may or may not become an inlet, whether tidal or non-tidal). In addition to being well established, there are also regional specifics of defining coastal channels based on their appearance of functionality. This causes some confusion, especially where non-tidal inlets, may appear identical to their tidal counterparts in many respects, especially on short-term timescales.

Based on an analysis of the vast tidal inlet literature (Allen 1972; Marine Geomorphology 1980; Shuisky 1986; Shuisky, Vykhovanets 1989; Gudelis 1993; Davis, FitzGerald 2004; FitzGerald *et al*., 2012; FitzGerald, Miner 2013; FitzGerald, Buynevich 2018, 2019), as well as our recent research along Pontic and Baltic coast, we offer the following broad definition of an inlet as a morphological element, sometimes ephemeral, which connect open marine basins to back-barrier water bodies (lagoons, bays, marshes, etc.) and are maintained by a complex interaction of storms, nearshore currents, as well as tidal and non-tidal (wind-driven and fluvial) forcing on the water level.

DIVERSITY OF INLETS ALONG BARRIER COASTS

Most of the world ocean is dominated by tidal coastlines, however, along some enclosed basins; similar currents may be initiated and maintained during storms (as an agent of origin for many inlets) and regional or local hydrometeorological fluctuations. Therefore, there is a difference between tidal and non-tidal inlets related to the energy fluxes, as well as periodicity and duration of key forcing factors. Traditionally, **tidal inlets** have attracted much attention and there has been intense research into the origin, structure, evolution, and anthropogenic influence on both the channels and associated tidal deltas (Lucke 1934; Bruun, Gerritsen 1958; Bruun 1966; Hoyt 1967; Nummedal et al. 1977; Hubbard et al. 1979; Oertel 1985; Inman, Dolan 1989; FitzGerald 1996, 2015; Sallenger 2000; Barnhardt et al. 2002; Hayes, FitzGerald 2013).

Non-tidal inlets were most often referred to as **breaches** (**prorvas** in eastern European literature; Borisenko 1946; Budanov, Ionin 1953; Zenkovich 1960). These are often differentiated from tidal inlets based on their origin, energy conditions, periodicity, and duration of morphogenetic parameters. However, there has been little attention paid to the origin and evolution of these features (Zenkovich 1962; Pravotorov 1966, 1968, 1970; Shuisky 1986; Shuisky, Vykhovanets 1989; Kotovsky 1991; Gudelis 1998; Buynevich 2007; Zhamoida *et al*. 2009).

CONDITIONS FOR NON-TIDAL INLET FORMATION

Most non-tidal seas are enclosed or semi-enclosed basins that have water-level fluctuations of reduced amplitude and are unrelated to tidal forcing due to their small sizes (Hydrometeorological… 2009, 2012). In addition to lakes, Baltic, Black, Azov, Caspian, and former Aral Seas are functionally non-tidal, making storm-induced surges and meteorological (pressure and, by extension, wind-induced) fluctuations important forcing mechanisms (Hünicke *et al*. 2015; Jarmalavičius *et al*. 2016; Davydov *et al*. 2019; Davydov, Chernyakov 2020). The influence of (pene-) contemporaneous or alternating wind stress fields and atmospheric pressure systems require wind speeds exceeding 12 m/s and pressure below 730–740 mbars. Meteorological fluctuations often have no periodicity, have varying duration, and may reach substantial amplitudes.

Along the northern Black Sea region, mostly focused along the coast of Ukraine, breaches (prorvas) form along a variety of coastal accumulation forms, but are most common along its northwestern margin (Fig. 1) characterized by specific morpho-structural, hydrodynamic, and sedimentological conditions. It is important to note that this part of the basin is characterized by maximum water-level fluctuations of 4.45 m, with 3.10 m of onshore stress and 1.35 m in offshore-directed flows (Davydov *et al*. 2019).

Such hydro-meteorological fluctuations characterize the back-barrier bays of the Tendra-Dzharylgach system (Fig. 1e) and this amplitude indicates an exchange of large water volumes (somewhat compara-

Fig. 1 Location of study sites. Coastal accumulation forms along the northwest Black Sea margin of Ukraine where breaches (prorvas) are common: *a*) location of the Black and Azov Seas within Europe; *b*) position of the northwestern part of the Black Sea; *c*) spatial relationship and variously exposed key study regions; *d*) Tuzla Group (Bessarabian) Liman system; *e*) Kinburnska-Pokrovska-Dovgiy system; *f*) Bakalska Spit and prograded cuspate foreland; *g*) Tendra-Dzharylgach system (image source: *Google Earth*)

ble to a tidal prism of tidal inlets). This barrier system has a combined length of 130 km and width of 0.05–5.00 km, with an average elevation of 1.0 m (maximum >3.0 m; Zenkovich 1960; Pravotorov 1966; Davydov *et al*. 2018). These morphometric aspects, wave regime, and onshore-offshore water-level forcing result in periodic barrier overtop and overwash. This, in turn, leads to a formation of a spectrum of channels on and through the barrier (Shuisky *et al*. 1998; Davydov, Zinchenko 2019). Analysis of past research and cartographic materials along this part of the Balck Sea (Pontic) basin points to a systematic appearance of prorvas in this region (Fig. 1; Borisenko 1946; Budanov, Ionin 1953; Zenkovich 1960; Pravotorov 1966, 1968, 1970; Voskoboynikov, Brovko 1972; Shuisky 1986; Shuisky, Vykhovanetz 1989; Kotovsky 1991; Davydov, Chernyakov 2020). It is worth noting that their positions and formational factors may vary widely, suggesting an aspect of morphodynamic diversity. Within the smaller Sea of Azov, periodic formation of breaches has a regional accent, which explains their distribution along Dolgaya Spit, Obytichna Spit, Biryuchiy Island – Fedotova Spit, and northern Arabatska Strilka Spit complexes (Fig. 2).

A diverse suite of coastal barriers shown in Figure 2 is characterized by a wide range of morphological elements so that the formation of breaches is largely a function of hydrodynamic forcing. The sea of Azov is characterized by meteorologically driven fluctuations, with maximum amplitudes along the northeast and west margins. Within Taganrog Embayment, the total amplitude is 6.09 m (onshore: +2.51 m; offshore: -3.58 m; D`yakov, Fomin 2002). At Utlyutsky Liman, the amplitude is 4.12 m (+2.24 m; -1.88 m; Henichesk Hydrometeorological Station). Such fluctuations are the key causes of periodic breaching of Dolgaya Spit (Fig. 2b) at the mouth of Taganrog Embayment, as well as the formation and maintenance of channels through the Arabatska Strilka Spit complex (Fig. 2f). The latter is a complex landform represented by sections of antecedent (mainland) topography and welded bioclastic barriers. Its total length is ~110 km, width is 0.27–8.10 km, and a maximum elevation of 13 m along mainland segments and 5 m for barrier sections (Mamykina, Khrustalev 1980). This example demonstrates that breaching is rare despite hydrometeorological forcing, although some topographically low areas experience occasional overtopping, but without wholesale barrier breaching. However, the situation was different during the recent historic period. According to investigations by Shustov (1938), during the 19th and early 20th centuries, breaches existed in low-lying sections of Shchaslyvtseve and Strilkove settlements, near Arabat castle, and across the Salgir River mouth. The absence of breaches along Arabatska Strilka Spit over the past century suggests its trend toward aggradation (heightening). Such evolutionary trends may

Fig. 2 Accumulation forms and associated periodic breaches (prorvas) along the Sea of Azov coast: *a*) regional distribution of study sites; *b*) Dolgaya Spit (flying spit); *c*) Obytichna Spit (recurved spit); *d*) Biryuchiy Island – Fedotova Spit; *e*) close-up of Fedotova Spit and a relict (healed) breach; *f*) Arabatska Strilka Spit, along the northeastern Crimea Peninsula (image source: *Google Earth*)

be conditioned by anthropogenic activity as well. An example of such a tendency can be found at the tip of a large coastal barrier along the Baltic Sea coast – the Curonian Spit (Žaromskis, Gulbinskas 2018). It is ~100 km long (divided between Lithuania in the north and Russia in the south), 0.4–3.8 km wide, and reaches a maximum elevation of 67.2 m along the Great Dune Ridge. A protective foredune ridge varies in height between 3–15 m, largely constructed by human activity as a protection from storm surges. Its width and height preclude overwash, however, occasionally the protective dune is breached creating temporary surface channels, especially along its root at the Lesnoy settlement, Russia (Boldyrev *et al*. 1990; Boldyrev 1998; Gudelis 1998; Zhamoida *et al*. 2009; Sergeyev, Zhamoyda 2012; Bobykina, Stont 2015; Babakov 2018; Kalina 2019; Stont *et al*. 2019). Historically, the situation was different and over the past 500 years, there were a number of breaches, namely: 1497, 1630, 1642, 1673, 1680, 1706, 1714, 1790, 1791, 1792, 1796, 1895, 1899, 1967, 1983, 1990 (Boldyrev *et al*. 1990; Gudelis 1998). Therefore, persistent human influence resulted in the heightening of the protective foredune, reducing the probability of its breaching and backdune flooding. It is worth noting that stable sections of the Great Dune Ridge have experienced reactivation and deflation, but no breaching for >5,000 years (Gudelis, 1998; Buynevich *et al*. 2007).

RESULTS – MORPHOGENETIC DIVERSITY OF BREACHES

Decades of field investigations along the Black and Azov Seas and extensive literature review (Shustov 1938; Borisenko 1946; Budanov, Ionin 1953; Zenkovich 1960; Pravotorov 1966, 1968, 1970; Voskoboynikov, Brovko 1972; Shuisky, Vykhovanets 1989; Kotovsky 1991) indicate several mechanisms of breach formation. These are based on periodicity (or episodicity), interaction, and patterns of specific forcing factors: 1) litho-dynamic (sediment transport) conditions along the seaward margin of the accumulation form (barrier island, spit, or baymouth barrier); 2) direction, intensity, and duration of storm phases; 3) amplitude, duration, and frequency of meteorological fluctuations, and 4) hydrologic regime of nearby river systems characterized by minor discharge. These factors may serve as sole breaching mechanisms or combine with other factors in a variety of ways.

Depending on the magnitude and relationships of morphodynamic factors along the Black and Azov Seas, we distinguish four mechanisms (genetic types) of breach formation and associated sand bodies (surge deltas) (see also Davydov, Karaliūnas 2020):

1) Storm-generated breaches (prorvas), which may persist as non-tidal inlets, occur along the distal portions of barrier spits (Fig. 3). The cause of their

Fig. 3 Evolutionary trends in storm-generated breaches (inlets): *a* – Bakalska Spit (NW Black Sea) in 1985; *b* – narrow portion leading to a spit terminus in 2006; *c* – breach (in 2013); *d* –breach (in 2020); *e* – Obytichna Spit (northern Sea of Azov) in 1986; *f* – spit terminus in 2013; *g* – breach near the terminus in 2014; *h* – breach (in 2020) (image source: *Google Earth*). Note the absence of surge deltas

formation is a function of the intensity and duration of storm events on barrier lithosomes in a regime of long-term reduction in longshore transport volume (Goryachkin *et al*. 2010; Goryachkin, Kosyan 2020).

This leads to erosional hot spots or segments, resulting in overall narrowing. In a regime of rising sea level and intensification of storm activity, such a scenario causes frequent overwash that ultimately leads to breaching. This type of channel normally does not have accumulative sand bodies (surge deltas) associated with it.

Storm-generated breaches formed during the past decade along narrow sections of Bakalska (NW Black Sea) and Obytichna (Sea of Azov) Spits (Fig. 3). As stated above, their formation took place in a regime of sea-level rise and erosion of the seaward margin (Goryachkin *et al*. 2010; Goryachkin, Kosyan 2020).

2) Storm-surge-generated breaches (prorvas) form in a regime of storm activity under substantial hydrologically forced water-level fluctuations along barrier coasts. Here, the overtopping and overwash are accompanied by incision and eventual transport of sediment into a back-barrier water body (bay or lagoon) as a surge delta (Fig. 4).

Field investigations and communications with local residents indicate that most overwash events do not culminate in breaching. This process is more complex and is a function of the intensity and duration of storm wave impact and water-level differential (hydraulic head) between the sea and the bay. During substantial lowering of the bayside water level, landward-directed surges overwash and may eventually incise a section of the barrier, leading to a breach. At the same time, large volumes of sediment are carried into a quiet water body, resulting in its deposition similar to a flood-tidal delta (element 3 in Fig. 4b, e; Hayes, FitzGerald 2013; FitzGerald *et al*. 2012; FitzGerald, Buynevich 2018). If this difference is small, ephemeral surge channels (washouts) may form above the fairweather sea level (Fig. 5). Their transformation into breaches depends on subsequent intensity and duration of storm activity and other hydro-meteorological conditions, such as wind-driven seiching.

During the process of breach formation, the re-equilibration of water level on either side of the barrier following the storm. If the onshore wind regime switches suddenly to offshore-directed wind stress, it may lead to a rapid water-level drop seaward of the erosional hot spot. In this scenario, newly formed surge channels and breaches experience intense compensational (reversal) currents, which are akin to ebb surges of their tidal counterparts, as excess seawater that entered the bay begins to return to the sea. It is these currents that for breaches, similar to tidal inlet formation, and eventually transport sediment seaward into frontal surge deltas (element 2 in Fig. 4 b, c).

Fig. 4 Storm-surge-generated breaches along Tendra Spit (NW Black Sea): *a* – regional view and position of the Iron Sign Breach (b); *b* – morphodynamic elements of Iron Sign Breach and associated surge deltas (1 – main channel and throat; 2 – frontal (seaward) surge delta; 3 – back (bayside) surge delta; 4 – surge spillover channels; 5 – delta islands (based on *Google Earth*); *c* – aerial view of the frontal surge delta (2); *d* – aerial view of the breach channel and throat (1); *e* – aerial view of the back delta with an island (5) (photos by author: AD).

These sand-dominated bodies are formed largely from marine sediments and are roughly equivalent to ebb-tidal deltas that are best developed in mixed-energy barrier coasts around the world ocean (Hayes, FitzGerald 2013; FitzGerald *et al*. 2012; FitzGerald, Buynevich 2018).

During a prolonged cessation of storm activity, such water-level readjustment may take place over a longer period of time. In this case, the outgoing currents may be too weak to transport sediment through an incipient breach channel. Along the north-western Black Sea, this breach type commonly forms along very narrow segments of Bessarabian baymouth barriers (Tuzla group), Kinburnska-Pokrovska-Dovgiy system, and Tendra-Dzharylgach coast (Fig. 1). Temporal limits on the functionality (life cycle) of the breaches depend on a variety of factors and may last from several hours to decades. Along the Tuzla group barriers (Fig. 6), there is a systematic formation of storm-surge breaches that typically persist for only 2–3 years. This is likely due to the magnitude of longshore sediment transport that causes shoaling and infilling of the breaches in a regime of relatively weak forcing from the back-barrier basins (limans).

Along the Kinburnska-Pokrovska-Dovgiy system and Dzharylgach spit, this type of breach has formed during historical times, however, their life span also did not exceed several years.

Based on our observations during the past two decades, overwash has led exclusively to shallow washouts (Fig. 5). To explain this, we investigated both qualitative and quantitative aspects of the wind regime over the NW Black Sea region during the past 20 years. Based on synoptic data from regional weather stations, the number and duration of strong wind events have substantially decreased, and beginning in 2003, extreme surges have not occurred. Therefore, the absence of storm-surge breaches during this period is likely related to a regional reduction in wind stress.

Along the north-western part of the Sea of Azov, an extensive Fedotova Spit – Biryuchiy Island system reveals that during the 19th and early 20th centuries storm-surge breaches regularly formed and persisted along the central part of the Fedotova Spit (Fig. 2d, e). This is based on cartographic analysis and the current location of diagnostic fan-shaped landforms along the bayside, likely representing relict surge del-

Fig. 5 Field view of surge channels (washouts): *a* – Dzharylgach Spit (photo by author: AD); *b* – Kinburnska Spit (photo by V. Chaus). See Fig. 1 for locations of study sites

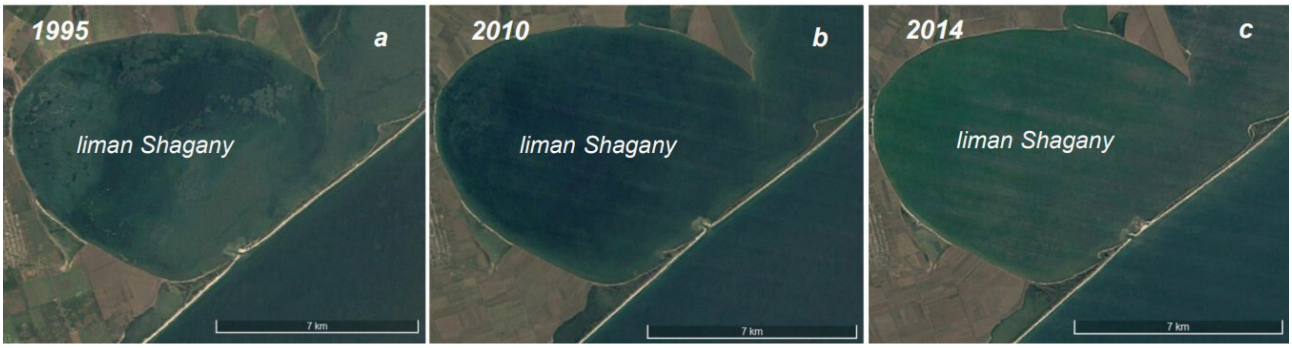

Fig. 6 Chronology of breach (prorva) formation across Shagany baymouth barrier (Tuzla group; see Fig. 1b for site location): *a* – breach near the root segment in 1995; *b* – a central breach in 2010; *c* – new breach formation in 2014 (based on *Google Earth*)

tas (Fig. 2e). Over the past 50 years, there were no breaches formed along this segment, only occasional overwash events. The most stable and long-lasting breaches (prorvas) of this type can be observed along the long and narrow part of the Tendra Spit (Fig. 7).

Analysis of cartographic materials along the eastern part of Tendra Spit for the period of 1865–1966 that a breach was formed seaward of Smaleny Island and it actively migrated eastward over a period of 20–25 years (Fig. 7a). Its width reached 600 m and maximum depth was 4.5 m. Field investigations in 2020 revealed relict nearshore accumulations, as well as lagoon islands associated with this historic channel.

Analysis of aerial and satellite images spanning the past 55 years showed that a new channel – Babinska breach – formed during the 1970s (Fig. 7a). This breach was formed, actively functioned, and migrated eastward over nearly 50 years until its closure in 2019 (Figs. 7 and 8). It is worth noting that the closure of this system was likely a consequence of the opening of a fresh breach in the vicinity of the Iron Sign. This likely lead to redistribution of water masses, similar to tidal prism capture or piracy in mixed-energy systems (FitzGerald *et al*. 2012; Seminack, Buynevich 2013).

The history of the formation of multiple long-lasting breaches along this part of Tendra spit is worth discussing using an example of the Iron Sign system. During 2000–2013, ~3 km east of the active Babinska breach, there appeared a stable erosional hotspot along the shoreline. This resulted in the narrowing of the barrier, steepening of the underwater slope, and enhanced wave overtopping that eventually caused a breach in 2013 (Fig. 8b; (Davydov, Chernyakov 2020).

This original intensification of shoreline erosion is likely related to a long-term shift in sediment transport patterns. Tendra-Dzharylgach system is a classic winged foreland (Shuisky 1986), which is characterized by a divergence of longshore transport from the mainland, through bypass along narrow barrier sections, and terminating in massive recurved spits (Fig. 1e; Davydov, Zinchenko 2019).

Zones of sediment transport divergence are related to wave refraction patterns and source area morphology (Zenkovich 1962; Wright *et al*. 1999; Leontiev 2001). Convergence and divergence of wave approach and differentiation of nearshore transport vectors (direction and magnitude) affect the seafloor morphology and alongshore current patterns. Therefore, the divergence zone is directly related to regional wave

Fig. 7 Evolutionary history of Tendra Spit in the vicinity of Babin and Smaleny Islands during 1973–1995: *a* – formation of Babinska breach consisting of two channels (1973); *b* – easterly migration of the breach and formation of distinct recurred spits (1985); *c* – continued easterly movement with enlargement of recurred spits (1995) (based on *Google Earth*)

Fig. 8 Babinska breach and Iron Sign breaches during 2005–2019: *a* – stabilization of Babinska breach location; *b* – formation of a new breach in the vicinity of Iron Sign; *c* – closure of Babinska channel and an increase in complexity of the Iron Sign breach (based on *Google Earth*)

Fig. 9 Wind-stress-generated breaches within the Tendra-Dzharylgach system: *a* – site locations; *b* – Potievska prorva and surge delta elements; *c* – aerial view of the back-barrier features; *d* – view of the marine (frontal) side; *e* – Lazurnenska prorva and surge delta elements; *f* – aerial view of the back-barrier features; *g* – view of the marine (frontal) side. Morphological elements: 1 – main channel; 2 – seaside (frontal) surge delta; 3 – bayside surge delta; 4 – surge spillover channels; 5 – delta islands (photos by author: AD)

and wind climate and may shift alongshore both annually and over a longer term. Given this large-scale pattern of coastal behavior and the existing database of beach profiles along Tendra Spit, we argue that localize hotspots of divergence of longshore transport and shoreface erosion over decadal time scales may facilitate breaching.

3) Wind-stress-generated (seiche) breaches periodically appear at the root segments (attachment points) of large coastal accumulation forms (spits and baymouth barriers; Fig. 9). Their primary formation mechanism is wind stress directed over the back-barrier water body toward the backside of the barrier and the resulting water "set-up". Thus, it requires specific morphological and hydrodynamic conditions. The former is related to barrier integrity (continuity) and height, which facilitates the trapping of seaward-directed bay water volume. The latter is the result of water-level fluctuation amplitude, as well as the sufficient volume of the back-barrier water body. Such conditions exist within bays and lagoons that are sufficiently large and isometric (e.g., sufficient shorenormal fetch; Vykhovanets 1993; Buynevich 2007), as well as in embayments where such volume can be contributed from adjacent water bodies.

Along the Black Sea coast, breaches of this type form near attachment sections of Tendra and Dzharylgach. These are Potievska and Lazurnenska prorvas, respectively (Fig. 9). It is worth noting that these geographic names are given to all breaches formed at the corresponding sites during different time periods. During the 20th century, these channels were actively nearly constantly, with only temporary closures. However, at the beginning of the 21st century, Potievska prorva was closed during 2000–2007, leaving only a low sandy barrier with numerous storm-generated washouts. The process of breaching is assessed based on eyewitness accounts and an additional wind regime database from a nearby meteorological station.

Potievska Breach formation (2007): From 9 to 11 March 2007, Tendra Bay and the adjacent sector of the Black Sea experienced steady WNW wind, with a mean wind speed of 8–10 m/s (max: 14 m/s). Overnight on 12 March, the wind strengthened to 10–12 m/s, with gusts up to 18 m/s, based on the "Bekhtery" weather station 13 km from the breach. Based on personal records of M.B. Yatskevich (the park ranger of the "Potiev Boundary site" 3 km north of the prorva) and D.A. Chernyakov (former director of the Black Sea Biosphere Reserve), sometime ~7 am the ranger reported to the nature reserve about partial flooding at his house situated 130 m from the shoreline at an elevation of 1.8 m. At around 8:30 am, the ranger reported a drop in the water level to a mean annual value and suggested that a breach was formed.

Approximately at the same time, near the "Marine Boundary" site located near the present-day Potievska breach, eyewitness accounts point to extensive inundation of the barrier up to the Kefalne Lake basin, which is located 700 m from the bay margin. During this time, the seaside water level was 0.3–0.4 m above its mean annual position. At ~8 am, loud noise was heard from the region of the breach and the water began to recede gradually. During their afternoon inspection, park rangers discovered a new breach with a large shoal at its seaward end (pers. comm. with P.V. Tkachenko, the scientist at the Black Sea Biosphere Reserve).

The aforementioned sequence of events points to a pressure gradient (anti-barometer effect) or wind-stress (seiche-like) forcing as the main mechanisms of this type of barrier breaching. Like other types of inlets, these channel systems play an important role in water exchange between the marine and back-barrier basins. However, it should be noted that during extreme ("catastrophic") water set-up, existing breaches sometimes cannot accommodate the water volume, which can leave to additional breaches. Such a scenario occurred in 2007 near the Lazurnenska breach (Fig. 10).

Lazurnenska Breach formation (2007): During 23–24 March 2007, the Karkinit Bay region experienced east wind having a mean speed of 12–13 m/s, with a maximum of 20–22 m/s and gusts up to 40 m/s

Fig. 10 Breach formation near the attachment (root) segment of Dzharylgach Spit complex: *a* – Lazurnenska prorva and washout into Karkinit Bay to the west; *b* – formation of the washout; *c* – view landward; *d* – view seaward; *e* – lateral spillover channel (arrows show principal water flow directions; satellite images: Google Earth; field photos by author: AD)

(based on the aforementioned "Bekhtery" weather station 27 km from the current Lazurnenska breach). The action of the wind resulted in a strong stress field and set-up of ~1.5 in Dzharylgach Bay (behind the barrier attachment point), causing flooding of Lazurne settlement (Fig. 10). At this time, the water level on the seaward Karkinit Bay side dropped by 0.5 m. Under these conditions, the seaward-directed surge actively discharged through the open breach, eroding the bayside surge delta and moving large volumes of sand out into Karkinit Bay. The wind-generated surge that flooded the settlement followed a paved road toward Karkinit Bay where they breached the barrier forming a channel with a depth of >1 m (Fig. 10b–e).

It is worth noting that this event heavily altered the sediment transport dynamics along the Tendra-Dzharylgach shoreline. Much of the sediment exported into the nearshore was concentrated along the mainland section, thereby reversing a heavily erosional trend (Davydov *et al*. 2018). The differences in the genesis of the two breaches are determined largely by coastal morphology. Wind-stress breaches have relatively large and stable seaside (frontal) surge deltas (Fig. 9 d and g). Although their gross morphology may change during the year, they exist permanently, in contrast to storm-surge deltas. The bayside deltas are represented by extensive shoals that periodically emerge due to wind-driven water transport and typically have channels shallower than 0.5 m. Breaches of storm-generated type have greater depths both in the nearshore and in spillover channels.

4) River-stress (fluvially induced) breaches are defined along the regions of baymouth barriers associated with small river systems along the northern coast of the Sea of Azov. These include Berda and Obytichna Rivers (Fig. 11), as well as Bilosarayka, Kiltichiya, Lazovatka, and other streams characterized by low drainage conditions and distinct seasonal discharge. Similar features have been described in microtidal lagoons and estuaries of South Africa (Cooper 1990; Bond *et al*. 2013).

The baymouth barriers of small Azov basin rivers have developed under the active influence of marine processes, meteorological fluctuations, and longshore transport dynamics. This is the reason that over the long term, the fronting barriers represent relatively established landforms where breaches are absent and washouts are more characteristic features (see Fig. 11f).

Formation of this breach type requires substantial stress from the river channel on the backside of the barrier, which may be triggered by excess rainfall or active snowmelt. After a breach has formed, a seaside delta is deposited and has an ephemeral character for low-discharge systems (Fig. 11g) and is more stable for larger systems (Fig. 11c, e). A reduction in discharge and activization of incident waves and longshore transport lead to the formation of a longshore bar, which may be transformed into a barrier that eventually blocks the breach channel (Fig. 11h, j). Following breach closure, similar to ebb-tidal deltas, the frontal surge deltas are relatively rapidly reworked (into nearshore bars or ephemeral barrier salients) and largely disappear.

Arabatska Strilka Channels. Along the western part of the Sea of Azov, at the north end of the Arabatska Strilka spit, two channels – Tonka (Henicheska) and Promoina – form a large bayside shoal called Henicheska Delta (Fig. 11b; Davydov *et al.* 2019). Zenkovich (1962) defined this feature as a breach delta formed by a combination of surge and bidirectional currents. The earliest evidence of the Tonka (Henicheska) channel is found on the Black Sea folio map of Beninkazi dated to 1474. During this time, the channel has been functional, however, it began to shoal after the appearance of the Promoina channel in 1969. It formed as a result of breaching of the low-lying part of the Henicheska Delta following a series of winter and spring storms accompanied by extreme meteorological fluctuations (Vorovka 2016). Seaward of both channels is extensive shoals similar to ebb-tidal deltas or frontal surge deltas described in this study (Fig. 11b). The bayside contains a large dissected shoal reminiscent of a flood-tidal delta. The morphology of the Promoina, as well as the shoals associated with both channels, suggest that they conform to the definition of breaches. However, at this time it is not clear which of the four aforementioned breach types they represent and the research is ongoing.

DISCUSSION AND SUMMARY

The results of this study represent the first attempt at systematic classification and typology of breach channels, which periodically occur along non-tidal barrier coastlines. Our analysis of the literature synthesizing current research into characteristics and classification of **tidal inlets**, as well as the results of natural variability of non-tidal **breaches**, allow us to assess the differences and similarities in the general processes of formation, functioning, and closure of the two types of systems. The tidal fluctuations, as the key factor in maintaining (but not generating) **tidal inlets**, as well as hydrologic and sediment transport characteristics of the coastal compartments associated with these dynamic systems show a degree of recurrence and predictability. At the same time, the governing factors in non-tidal basins, such as storm waves and meteorologically driven water-level fluctuations, represent much less periodic and predictable events. Therefore, it is the periodicity and temporal forecasting ability that likely separates the genetic, morphological, and dynamic aspects of **tidal inlets** from non-tidal **breaches.**

Within most non-tidal basins, storm activity lacks clear periodicity and the temporal scales of events become relatively challenging to hindcast (reconstruct) or forecast. In the NW Black Sea region, storm events are accompanied by surges spanning hours to 2–3 days. It is this duration of uninterrupted wave activity that governs the intensity of nearshore energy fluxes, including those that generate breaches. The definition of a non-tidal inlet as a type of breach is a general one and reflects our understanding of these features as elements of coastal landforms. It is, therefore, open to further discussion. We did make an effort to differentiate **tidal inlets** and **breaches,** defining the latter as forming in functionally non-tidal basins and pos-

Fig. 11 Fluvially induced breaches along the Sea of Azov coast: *a* – locations of study sites; *b* – prorva and Henichesk Delta; *c–e:* breach through Obytichna River barrier: *c* – southeast channel in 2012, *d* – northwest breach in 2017, *e* – northwest breach and delta in 2020; *f–h:* breach through the baymouth barrier across the western distributary channel of Berda River: *f* – washout view in 2009, *g* – an open breach in 2014, *h* – a closed breach in 2020; *i–k:* breach through the baymouth barrier of the eastern distributary of the Berda River: *i* – a closed breach in 2014, *j* – partially blocked and deflected breach in 2017, *k* – active channel in 2020 (based on *Google Earth*)

sessing specific morphodynamic characteristics, although many elements are visually comparable with tidal systems. The genetic typology of the breaches is based on four hydrodynamic scenarios, all resulting in breaching of the coastal accumulation form (barrier island, spit, or baymouth barrier). They have been established based on extensive literature review, long-term field investigations, a compilation of eyewitness accounts, as well as analysis of coastal charts, aerial photography, and time-series satellite imagery.

The formation of storm-generated breaches (Types 1 and 2) is the result of prolonged wave action on barrier coast in a regime of reduced longshore sediment transport and varying degree of sea-level changes.

Wind-stress-generated breaches (Type 3), in contrast, are a product of water-level set-up in the bayside, especially by offshore-directed wind fields or near attachment points of large barrier complexes. River-stress breaches form as a result of the pressure from a small flashy river system onto the landward flank of the enclosing barrier (typically, a baymouth barrier). This study focused on the Black-Azov Sea region, with an example from the Baltic Sea, as a means of addressing the key aspects of historic and active breach formation and evolution (e.g., migration), both spatially and temporally. The preservation potential and geological legacy of former breaches (paleo-channelcut-and-fill structures and relict shoals; FitzGerald *et al*. 2012; Buynevich 2019) is beyond the scope of this study and is the focus of future research.

ACKNOWLEDGMENTS

This study was supported by Kherson State University, Ukraine. The authors are thankful to two anonymous reviewers for their valuable remarks and are especially grateful to Ilya Buynevich for reviewing the most recent version of the manuscript.

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