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The morphology of sand spits and the genesis of longshore sand waves on the coast of the eastern Gulf of Finland

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Abstract A study of the southern coastal zone of the eastern Gulf of Finland found sand spits up to 1100 m long and up to 200 m wide, with sand cusps 15 to 100 m wide moving eastward along the shoreline. Similar morphological forms have been described as long–shore sand waves associated with high energy coasts. This article presents the results of field geological and geomorphological studies and retrospective analyses of remote sensing data (air- and satellite photos of on–shore and near–shore parts of the coastal zone). The development of the long–shore sand waves in the study area is explained by the fact that prevailing waves induced by the westerly winds propagate almost parallel to the coast. It is shown that under these conditions the shoreline contours become unstable and any small perturbations to the shoreline extend these contours with time.

Keywords *long-shore sand waves, sand spits, coastal modelling, eastern Gulf of Finland.*

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INTRODUCTION

Traditionally the coastal zone of the easternmost (Russian) part of the Gulf of Finland has not been considered as an area of active of litho– and morphodynamics, but recent studies have shown that locally coastal processes can be quite active due to the combination of geological and geomorphic conditions, hydrometeorological and anthropogenic factors (Ryabchuk *et al.* 2007, 2009).

One such area with active lithodynamics is located in the southern coastal zone to the west of the Saint Petersburg Flood Protection Facility (Fig. 1). Sand spits of different shapes and size found here are among the most remarkable morphologic coastal forms of the eastern Gulf of Finland.

Large accretion forms are common features of the coast of the Baltic Sea. Many researchers have discussed the processes of formation and development of huge sand accretion forms in South–Eastern Baltic such as Curonian Spit, Vistula Spit, Hel Spit (Furmanczyk 1995; Badukova *et al.* 2006; Povilanskas *et al.* 2006; Bitinas *et al.* 2008; Žaromskis, Gulbinskas 2010). Along the Estonian coast several spits formed by pebbles and small boulders are described (Suursaar *et al.* 2005, 2008; Orviku *et al.* 2009).

In the easternmost part of the Gulf of Finland active sand accretion areas are the least common type of coast, and extending spits being even rarer. The coast of the Vyborg Bay area has many skerries, and the shoreline configuration is very complicated with many islands and narrow bays. The northern coast

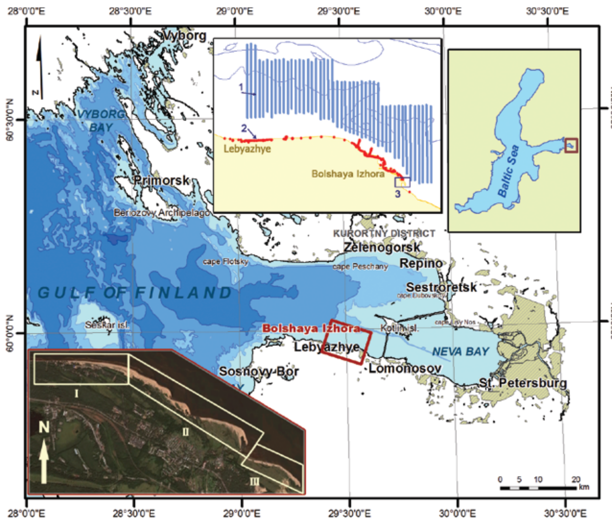


Fig. 1. The study area (red rectangle) in the eastern Gulf of Finland. 1 – side–scan and echo sounding profiles; 2 – offshore sampling stations; 3 – area of geo–radar study. I – III – coastal segments with different dynamics.

of the Gulf of Finland to the east of Cape Flotsky is largely open to the west and is strongly affected by storms. This, together with a sediment deficit results in active erosion with annual rates up to 2.5 m year^{-1}. Stable sand accretion areas are located in the bay heads of large bays of the southern coast (Luga Bay, Kopora Bay, Narva Bay) and in the sediment flow discharge area near Sestroretsk. There are also few small pocket beaches (Ryabchuk *et al.* 2011).

The studied coastal zone, in the vicinity of Bolshaya Izhora village is the only place in the Eastern Gulf of Finland where active development of sand spits is found. Very intense dynamics of the area was reported already by Kaarel Orviku (Orviku, Granö 1992). The geological description of the coastal zone and the preliminary result of A.P.Karpinsky Russian Geological Research Institute (VSEGEI) field studies were presented (Suslov *et al.* 2008). More recent studies using field observations and the analysis of modern and archived remotely sensed data (RSD) (aerial and high resolution satellite images) showed that the processes of growth and degradation of sand spits are accompanied by the formation of regular sand cusps along their seaward edges and by their movement eastward (Ryabchuk *et al.* 2009).

Different foreshore morphologies were described in Shepard (1952), Zenkovitch (1959), Dolan (1971), Davis (1978). Features with regular sinuosity less than a few hundred meters in wavelength, represented by alternation of horns and embayed areas are called *giant cusps* (Shepard 1952) (Fig2A). Having the same shape as beach cusps, these features are completely different as beach cusps are much smaller (up to 10 m and temporal scale of hours to a few days) and they are characterized by coarse sediment with respect to the adjacent beach area. Giant cusps do not display obvious textural patterns across their extent, they have

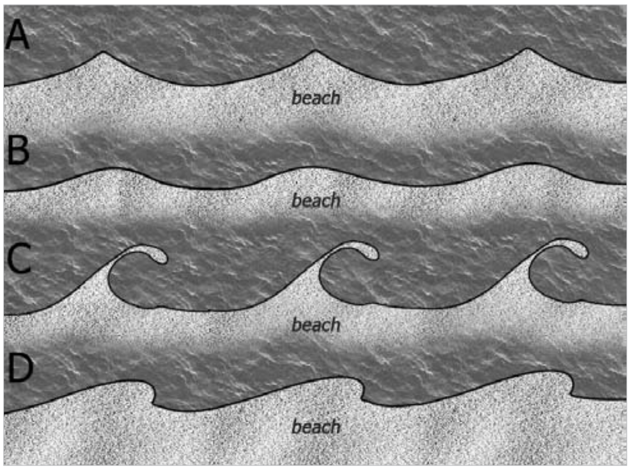


Fig.2. A – giant cusps; B – beach protuberances (Davis 1978); C – cuspate spits; D – long–shore sand waves.

along–shore wavelengths of tens to hundreds meters and generally exist on a temporal scale of weeks or months (Davis 1978; Davidson–Arnott, van Heyningen 2003).

The other common type of shoreline rhythmic features are described as *beach protuberances* (Fig.2B) after (Goldsmith and Colonell 1970) and have the same general aerial configuration as giant cusps except that the shore has a smooth "sine curve" shape (Davis 1978), whereas in giant cusps the apexes are peaked with the intervening areas smoothly curved. *Cuspate spits* (flying spits or "Azov type" spits) (Zenkovitch 1959) (Fig.2C) are elongated with an oblique angle to the shoreline. Rhythmic coastal features of wave–like shape—local disturbances to the otherwise mostly straight beach planforms—characterized by a wide accretion down–drift end and a narrow, erosion up–drift end, with the difference in beach width being of the order of 50–100 m were described by Davidson–Arnott and Stewart (1987) and are called *long–shore sand waves* (Fig.2D). These features have along–shore scales of the order of tens to thousands meters and a temporal scale of years to decades (Davidson–Arnott, van Heyningen 2003).

Long–shore sand waves were observed on sandy coasts with relatively high energy regimes (California, Long–Island, western coast of Denmark) as well as on the coasts of some large lakes such as Lake Erie (Thevenot, Kraus 1995; Davidson–Arnott, van Heyningen 2003). At the down–drift end of Long Point (14 km), a 40 km long spit in Lake Erie, seven to nine sand waves occur. They are 50–100 m wide at the down–drift end, range in length from 350 m to >1500 m wide, and migrate along-shore with rates of 100–300 m year^{-1} (Davidson–Arnott, van Heyningen 2003). Eleven long–shore sand waves with an average length of 750 m and amplitude (typical width) of 40 m were identified along Southampton Beach. A 16–month study calculated yearly average migration speed at 350 m year^{-1}. The migration rate was much higher under winter wave conditions and reaching an average of 1090 m year^{-1} (Thevenot, Kraus 1995).

Long–shore sand waves development was explained in different ways, e.g. by irregularity of the long–shore drift due to pulsed of river discharge or due to erosion of sand bars (Thevenot, Kraus 1995), by onshore migration and welding of inner near–shore bars, which is reinforced by refraction of highly oblique wind waves (Davidson–Arnott, van Heyningen 2003).

Ashton with co–authors, undertook a numerical simulation of coastline features, e.g. long–shore sand waves, and demonstrated that they are forming by large scale instabilities induced by high–angle waves. The spatial scales of long–shore sand waves can be up to hundreds of kilometres and temporal scales up to millennia (Ashton *et al.* 2001; Ashton, Murray 2006a, b).

The study area in the Eastern Gulf of Finland has hydrodynamic conditions essentially different from the areas discussed above. In contrast to areas where sand waves have been observed, the Eastern Gulf of Finland is a region of relatively low–energy. Calculated significant wave heights strongly depend on wind speed and do not on fetch. Under relatively calm conditions, the maximum significant wave height does not exceed 0.5 m. The highest (~1.5 m) waves are generally concentrated in the central part during severe storms. For the strongest westerly storms wave height reaches 2 m height (Kurennoy, Ryabchuk 2011). The difference in the magnitude of forcing factors for similar features is a good reason to study in detail the development of sand waves in the Eastern Gulf of Finland.

The main objectives of this study are to characterize the litho– and morphodynamics and to provide an interpretation of the features of the area based on of field observations and 30 years RSD data analysis using a mathematical modelling approach, with an aim to explain mechanisms which determine the long–shore sand wave's formation and their links to spit development.

MATERIALS AND METHODS

A geological survey of the Eastern Gulf of Finland seabed was undertaken by the Department of Marine and Environmental Geology of VSEGEI from 1980 to 2000. The survey resulted in a set of geological maps (Amantov *et al.* 2002; Spiridonov, Pitulko 2002; Spiridonov *et al.* 2007; Petrov 2010).

From 2004 to 2010 the VSEGEI undertook research to understand the geology and morphology of the coastal zone of the Eastern Gulf of Finland, including near–shore bottom and adjacent on–land areas (Ryabchuk *et al.* 2007, 2009; Suslov *et al.* 2008). Within the investigated area, annual field observations, GPS–surveys of the shoreline and systematic sediment sampling of the general appearance of the beach were undertaken. In 2008, sand spits in the vicinity of Bolshaya Izhora village were studied using a georadar SIR System–2000 (GSSI, USA). A 960 m long profile along the sand spit (20 m landward from the shoreline) and 5 profiles across the spit were measured (see Fig.1). To assist the interpretation of radar profiles, seven cores were drilled using a "Stihl BT 120" earth auger and sub–sampled at 10 cm intervals. Radiocarbon dating of sediments (3 samples) using dispersed organic carbon was performed at the Centre of Isotopic Research of VSEGEI using an ultra low level scintillation counter, Quantulus 1220. Radiocarbon data were converted into calibrated ages using Calib 5.0 (calib.qub.ac.uk/calib) and the Marine04 curve (Hughen *et al.* 2004).

Since 2004 annual studies of the bottom relief and the properties of sediments along four cross–shore profiles have been undertaken. In 2010 a levelling survey was carried out along the same profiles and along additional 10 onshore profiles across the easternmost spit. A PAL Automatic Level (CST/berger, Germany) was used for levelling surveys. Onshore and bottom samples were taken. Grain–size analyses of 34 onshore samples and 26 bottom sediment samples were carried out in the laboratory of VSEGEI (Department of Marine and Environmental Geology) using an analytical sieve shaker (AS 200 Retsch, Germany). Sediments were separated into 21 grain–size classes, and the main statistical parameters (Md, Ma, So, A) of size classes were calculated according to suggestions in Folk and Ward (1957).

In the near–shore zone, over 100 km of side–scan sonar (CM2, C–MAX Ltd, UK with a working acoustic frequency of 325 kHz) and echo sounding (GP–7000F, Furuno, Japan) data were collected enabling 3D plotting of the bottom surface relief in water depths between 1.5 m and 12 m.

The results of field observations were analyzed together with available remotely sensed data (including aerial photos from 1989 and 1990, with a resolution of 0.5 m; Quick Bird space pictures from 2004–2007, with a resolution of 0.64 m) as well as navigation and topographical charts published in the XIX–XX centuries.

RESULTS: LITHO– AND MORPHODYNAMICS

The upper 50 m of geological sequence within the study area is comprised of Late Pleistocene and Holocene clays and sands. In the near–shore the thickness of Quaternary deposits increases as a paleo–valley 80 m deep is located along the shoreline (Spiridonov *et al.* 2007). The modern tectonic regime is characterized by low amplitude tectonic sinking with rates varying from 0 to 2 mm year^{-1}) (Yaduta *et al*. 2009).

Long–shore sand drift in an eastern direction at a 99% level of significance was established (Suslov *et*

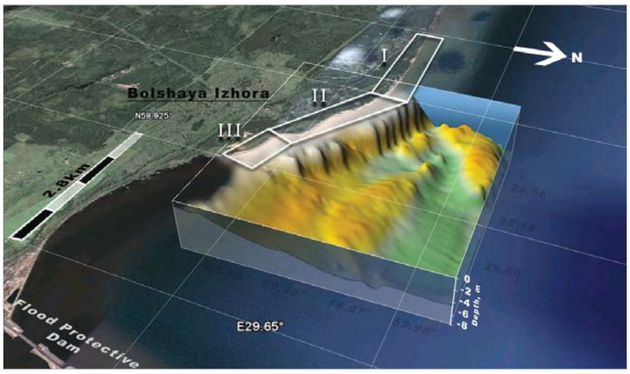


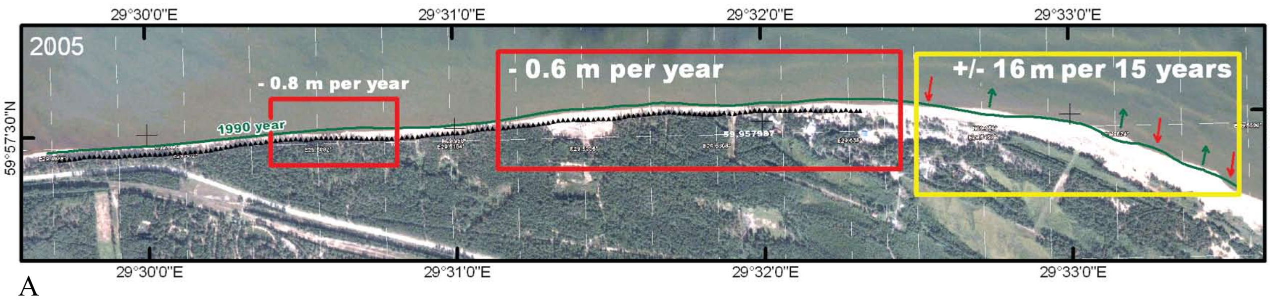
Fig. 3. The underwater topography of the nearshore terrace. I – III – coastal segments indicative of different dynamics.

al. 2008) using the MacLaren method (Mac Laren, Bowles 1985) and this accounts for the spatial changes in the grain–size. Also, in the area of sand spit growth the direction of the long–shore sediment flow is clearly morphologically determined by the shape of sand accretion forms and the eastward orientation of small rivers and rivulet mouths.

The surface of the near–shore bottom is covered by fine to medium grain–size sand. This material forms an along–shore sand terrace up to 2 km wide and up to 3-4 m thick. Seawards, the slope is relatively high (Fig. 3). The terrace is located in front of the sand spit area and is elongated 8 km to the west. The long–shore submarine terrace plays an important role in coastal development of the area. Firstly, submarine terraces recognized along the northern coast of the Eastern Gulf of Finland at the same water depth (4-5 m) (Ryabchuk *et al.* 2007) and most probably formed during the Late Holocene as a result of both coastal recession and sediment accumulation (Leontyev *et al.* 2010) may protect the shores from the most intense erosion events. Secondly, unlike the terraces of the northern coastal zone, the sand accretion terrace in front of Bolshaya Izhora village gradually transforms into a sandy near–shore coastal slope. Therefore, the terrace may be one of the sources of material for the sand spit formation.

According to dominating lithodynamic processes, the study area can be divided into three segments according to dominant lithodynamic processes: a straight coastal section elongated from east to west where intense erosion prevails (I in Fig. 1); the central part of study coastal zone between the shoreline orientation change and the River Tchernaya mouth where wide sand spits and long–shore sand waves are observed (II in Fig. 1); the sand spit to the east of the River Tchernaya, which is rapidly growing at its distal edge (III in Fig. 1).

To the west (I in Fig.1), along the straight coastal segment, sandy beaches are not wider than 10–12 m. Beaches comprise medium to poorly sorted (sorting value – the standard deviation of the relevant grain–size distribution (So) is about 1.5–2.6) medium–grained sands (mean grain–size ~ 0.47 mm), sometimes with a high gravel content (up to 25%). On the backshore, low cliffs (up to 5–7 m) were formed by the early 1980s



A

B

Fig. 4. Erosion of the coastal cliff to the west of Bolshaya Izhora village. A – rate of shore cliff erosion in 1990–2006; B – the coastal cliff (I at Fig. 1).

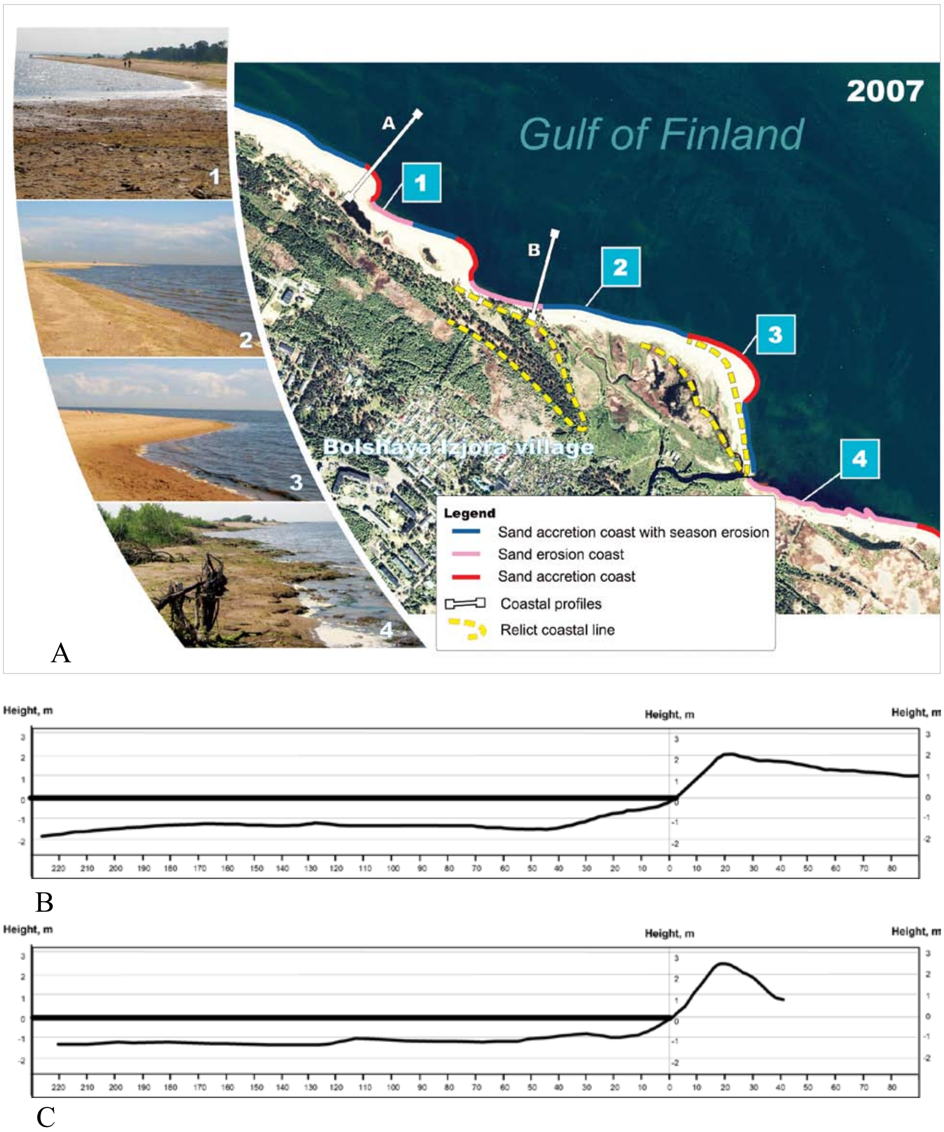


Fig. 5. Alternation of erosion, transit and accretion areas in the vicinity of Bolshaya Izhora village (A) and coastal profiles of accretion (B) and erosion (C) zones (II in Fig. 1).

(Orviku, Grano 1992) as a result of intense erosion. RSD analysis shows that the rate of shoreline retreat is up to 0.6 m year^{-1} between 1989 and 2007 (Fig. 4), and the erosion of sandy cliffs may be the second source of sediments for down–drift sand spit accretion area. The submarine coastal profile is steep near the shoreline (a depth of 1.5–1.8 m is reached at the distance of 7–10 m from the shoreline), but further offshore slope is more gentle and gradually transforms into surface of a submarine terrace. The smooth bottom surface comprises well–sorted fine–grained sands (mean grain–size ~ 0.14 mm, So ~ 1.5).

The coastal segment to the east (II in Fig. 1; in front of Bolshaya Izhora village) has much more complicated dynamics with long–term development of sand spits some hundreds meters long and some tens of meters wide. In the vicinity of Bolshaya Izhora village the maximal width of the area of relict sand spits and lagoons reaches about 500 m. The spits have separated from the open sea; small narrow lagoons are gradually becoming shallower and overgrowing with water plants. The coastal landscapes indicate that the coastal dynamics have been relatively unchanged for hundreds of years as demonstrated by the shape and size of relict spit (I in Fig. 5A). It is up to 10 m maximal height, 920 m long and up to 112 m wide. This relict spit is sub parallel to a recent sand body of the similar shape, located eastward (II in Fig.5A).

Along the seaward edge of the contemporary marine sand spit *long–shore sand waves* occur. An important feature of the sand cusps is an increase in the size (length and width at the down–drift end) in the eastern direction. The width of the down–drift end of the first (western) cusp is 15 m, with an adjacent strait shoreline segment 100 m long. The second cusp has an amplitude 30 m and length 250 m; for the third and forth (eastern) cusps these parameters are 70 m and 400 m and 100 m and 900 m, respectively (Fig. 6).

The described morphological features reflect different lithodynamic zones: transitional (straight coastal segments), accumulative (seaward protrusion at the distal parts of cusps), and erosional (concave sections of the shoreline, adjacent to the accretion areas to the east). Annual shoreline GPS–surveys have shown that the western cusp (Fig. 6) moved eastward 33 m since 2007 to 2009, and the adjacent cusp migrated by 26 m during the same time. Retrospective analysis 15 years of remote sensing data (1989 to 2004) shows shifts of 315 m and 200 m. The average annual shifts of cusps were 20 m year^{-1} and 13 m year^{-1} correspondingly. Such sand cusp movement causes the alternation of erosion and accretion along the coast (Fig. 5A). For example, on cross shore profiles located within down–drift parts of sand cusps, between 1990 and 2007 shorelines moved 80-110 m seaward, while in the erosion zone the shoreline moved 70 m landward (Fig. 6). It is important to keep in mind, as in such a case observations at a single point may give misleading results and for the proper understanding of coastal processes the entire system of cusps should be analysed in terms of planforms.

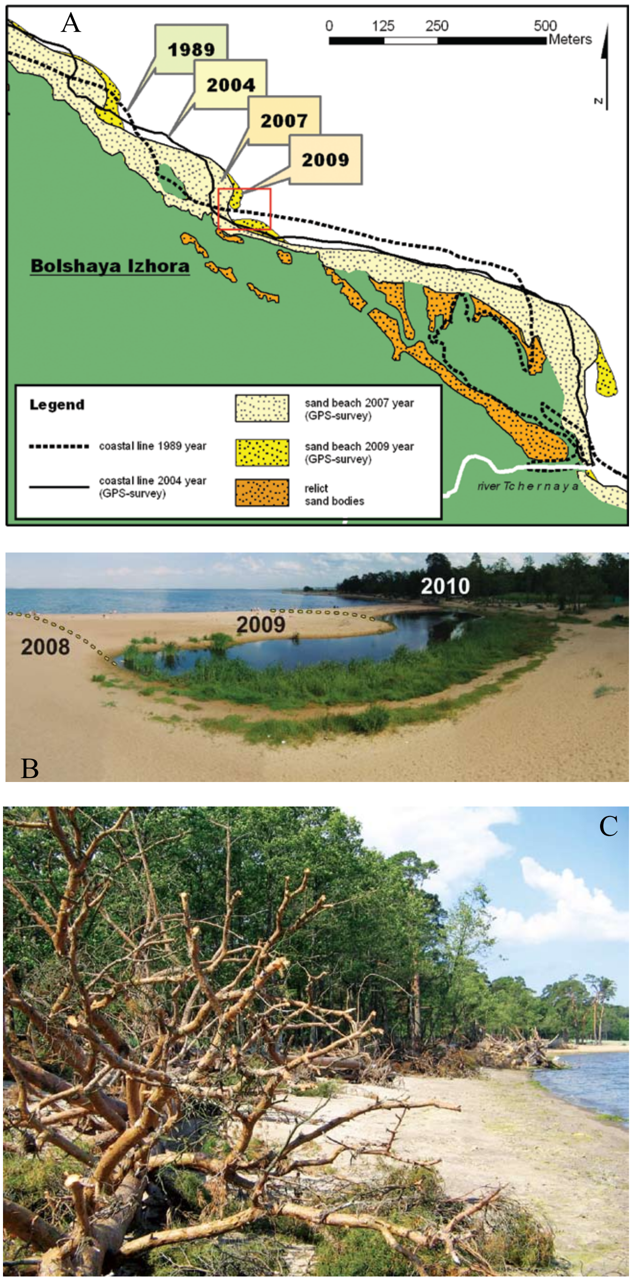


Fig. 6. Long–shore sand waves development based on remote sensing data analysis (II in Fig. 1). A – development of 500 m long sand accretion body from 1982 to 2007; B – forming of 50 m connected spit in 2009–2010 (red rectangle, Fig. 6A); C – area of active erosion after 2006–2007 winter storms.

Morphology and sediment data for the coastal profile, obtained annually for five years has shown that areas of sediment accretion, transit and erosion have some special features of note. At the "distal" ends of sand waves the width of the spits reach 70–80 m, with a height of 2 m (Fig. 5B). The sediments of the beach face have average 40–60% sand in the dominant class of 0.25–0.5 mm. The average grain diameter is 0.55 mm. The majority of the samples are represented by medium to poorly sorted sand (So 1.5–2.3). After storm events 0.5–1.0 m beach cusps of coarse–grained sand and gravel (up to 60% particles > 2.0 mm) form along the shoreline. On the eroding parts of the sand waves, low escarpments in the relict sand spits are located at a distance of 6–10 m from the shoreline (Fig. 5C). The grain–size of the eroding beach sands is similar to that of the distal part of sand waves (medium–grained sands, average diameter of 0.4–0.5 mm, So 1.59–2.83).

Submarine coastal profiles are very flat along the length of the spits (Fig. 5B, C), however, the shoreward 100 m of the eroding profiles is shallower than on accreting profiles. This can be explained by very high shoreline shift rate, due to which the coastal profile have not reached an equilibrium state. The near–shore bottom is covered by well–sorted (So 1.0–1.5) fine–grained (average grain–size 0.2 mm) sands; but along the shoreline outcrops of clay sediments are observed on the sea bottom surface.

Another set of coastal features n study area are sand spits that grow from initial shoreline disturbance, with the formation of elongated lagoon (so called *connected spits*). An example of these features are large (500 m long) accretion sediment deposits which formed as a result of sediment discharge in the eastern part of the study area, to the west of the Tchernaya River mouth, over the last 30 years (Fig. 7A). The topographic chart

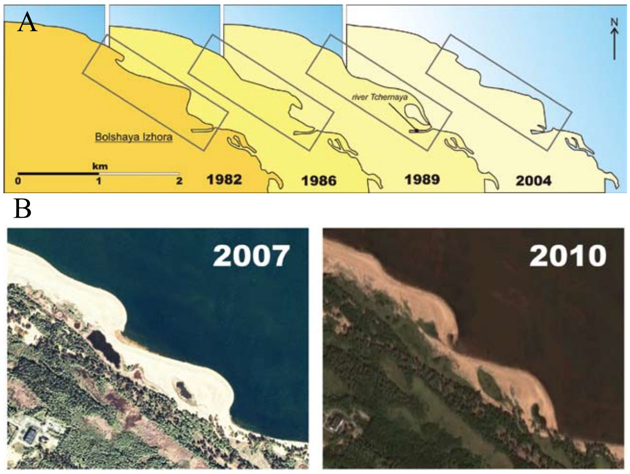


Fig. 7. Formation of connected spits: A – 500 m long sand body to the west of the Tchernaya River mouth; B – transformation of long–shore sand waves into connected spits (2007–2010).

from 1982 showed a smooth curve of the coastal line. The topographic chart from 1986 fixed the beginning of sand spit growth and lagoon formation. Aerial photography from 1989 showed the formation of a narrow sand bridge between the spit ridge and the river delta, and the lagoon being closed. The satellite photo and field GPS–study from 2005 showed that the sand spit was quite wide and a dry lagoon. By 2005 the sand body was entirely formed with the former lagoon being since 2009 a dry low space overgrown with grass and shrubs. It is interesting to notice that but the same process at a smaller scale was observed during 2008–2010

(Fig. 6B). Long-shore sand waves started to transform into connected spits (Fig. 7B).

To the east of the river mouth is located a spit with quite a complicated shape. The width of the spit varies from 30 to 90 m; its maximal height is 2.5 m. The length of the spit (in 2010) was 1100 m (Fig. 8, 9). Georadar profiling data confirmed by drilling showed

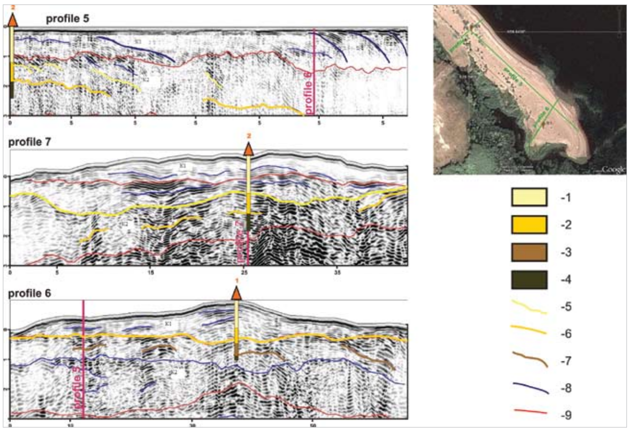


Fig. 8. Geo–radar profiles of the distal part of the spit. 1 – coarse–grained poorly sorted sands; 2 – fine–grained medium sorted sands; 3 – coarse–grained sands with pebbles and gravel; 4 – clayey black mud with remains of plants; 5 – 7 – geophysical boundaries confirmed by drilling; 8 – 9 – geophysical boundaries.

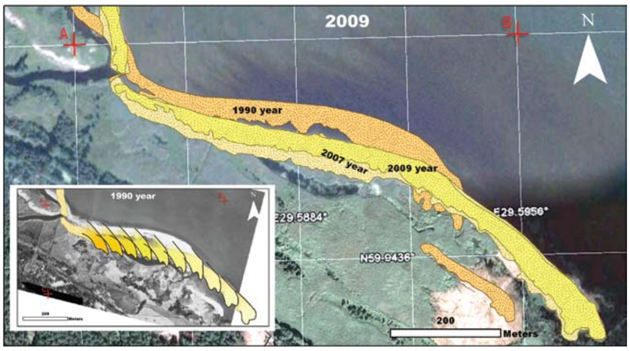


Fig. 9. Development of a hooked sand spit to the east of the Tchernaya River mouth.

the upper sediment layer of the spit comprising coarse–grained (average grain–size 0.7–0.9 mm), poorly sorted (So 2.7–3.46) sands.

The thickness of this sand layer varies from 150 cm at a distance of 10–12 m from the shoreline to 205–245 cm along the spit crest. The fine fraction component (<0.01 mm) is less than 0.2% and in some horizons the content of gravel is relatively high (8–26%). Some cores had layers of fine–grained (average grain–size 0.2 mm), better sorted (So 1.5–2.0) sand up to 0.5 m thick (Fig.8).

At the core interval 180–245 cm (depending of the core location) sands overlap black dense silty clays with a high content of organic matter and the remains of plants which are interpreted as relict lagoon marl. Along the western part of the sand spit, the same sediments are observed along the shoreline. They have outcropped here as a result of intense erosion. In front of the central part of the spit relict lagoon marl is outcropping on the sea bed about 100 m from the present shoreline, at the depth of 0.5–0.8 m (Fig. 10).

The distal end of the spit is still growing, while the western (attached) part of the spit is intensely eroded. Retrospective analysis of remote sensing data (Fig. 9) has shown that since 1990 the attached part of the sand spit shifted more than 100 m landwards. Erosion of the attached parts of spits accompanied by the growth

Fig. 10. Sand spits of different generation in the vicinity of Bolshaya Izhora village. 1 – modern sand spits; 2 – ancient sand spits; 3 – relict sand spits; 4 – relict lagoons; 5 – sites of sampling for ^{14}C dating. Pictures of relict lagoon marl.

of the distal parts is typical for many spits worldwide (Dolotov *et al.* 1964; Zhindarev, Khabidov 1998; Chen *et al.* 2002).

DISCUSSION – THE GENESIS OF THE LONG–SHORE SAND WAVES

It is possible to determine sand spits of different generations – recent and relict sand bodies. The oldest relict spits are overgrown by pine forest, and separated by low elongated swamps that probably are former relict lagoons (Fig. 10). Radiocarbon dating of four samples of relict lagoon mud (time interval are overgrown by pine forest, and separated by low elongated swamps that probably are former from 1800±170 ^{14}C years BP (414 ÷ 776 cal. years AD) to 2500±150 ^{14}C years BP (632 cal. years BC – 151 cal. years AD) showed that it was formed in the Post–Litorina time. It is improbable that these sediments could accumulate in that time in shallow water conditions near the coast of the open sea. Therefore these deposits are likely to be marl formed within small ancient lagoons separated from the sea by spits lately eroded and disappeared.

Modelling studies by Ashton *et al.* (2001); Ashton and Murray (2006 a, b) and Falques (2006) lead to conclusion that a possible mechanism of the sand wave generation is associated with the impact of surface–water waves approaching the coast at a high angle. In such cases small initial perturbations of shoreline contour tend to grow over time. A simple explanation of this feature can be based on the equation of coastline evolution proposed by (Pelnard–Considere 1956)

$$\frac{\partial \chi}{\partial t} = \frac{1}{h_* + z_c}\frac{\partial Q}{\partial y}, \qquad (1),$$

which links the speed of shoreline displacement $\partial\chi/\partial t$ to gradient of long–shore sediment flux $\partial Q/\partial y$ (t is the time and the y–axis is directed along the coast, h_* is the water depth at the seaward border of the active coastal profile (closure depth) and z_c is the elevation at its upper boundary).

Using the CERC formula (Coastal Engineering Manual, 2002), sediment flux Q is proportional to the along-shore component of the wave energy flux F,

$$Q = KF\sin(\Theta+\delta)\cos(\Theta+\delta), \qquad (2),$$

where K is the proportionality constant, Θ is the angle between direction F and the normal to the general coast direction, δ is the angle of local deviation of shoreline contour from its general direction (Fig. 11a). The contour curvature and angle δ are supposed to be sufficiently small, allowing to the use of approximations $\delta \approx \sin\delta \approx tg\delta = \partial\chi/\partial y$. There are two limiting cases, when the angle of wave approach Θ is very small ($\sin^2\Theta \to 0$) and close to 90° ($\cos^2\Theta \to 0$). In other words, in the first case the waves propagate almost perpendicularly to the coast, while in the second case they run almost along the shore. The trigonometric function on the right in Eq. (2) can be expressed in the first case as $(1/2)\sin 2\Theta + \partial\chi/\partial y$, and in the second case as $(1/2)\sin 2\Theta - \partial\chi/\partial y$. Then Eq. (3) can be represented in the form of the diffusion equation,

$$\frac{\partial \chi}{\partial t} = \pm\nu\frac{\partial^2 \chi}{\partial y^2}, \qquad \nu = \frac{KF}{h_* + z_c}, \qquad (3),$$

where the signs "+" and "–" correspond to small and large angles Θ, respectively, and ν is the diffusion coefficient.

Let a small wave–like perturbation $\chi = a\sin ky$ of amplitude *a*, length λ and wave number $k = 2\pi/\lambda$ appear on the shoreline contour. Substitution of $\chi = a\sin ky$ into Eq. (3) leads to the equation for the perturbation amplitude *a*,

$$\frac{\partial a}{\partial t} = \mp\nu k^2 a. \qquad (4).$$

The general solution to this equation is

$$a = a_0\exp(\mp\nu k^2 t). \qquad (5).$$

Here a_0 is the initial value of *a* at the moment *t*=0 and the signs "–" and "+ " correspond to small and large angles Θ, respectively. The result (Eq.(5)) means that the shoreline perturbation will decay if the angle of wave incidence is small, and vice versa, it will grow with time if the angle is large.

Figs. 11b and 11c show schematically the variations in sediment flux *Q* along the shoreline for different wave approach angles. According to Eq. (2), *Q* reaches its maximum when $\Theta+\delta$=45°. Hence, if the angles are small, the increase in $\Theta+\delta$ along the contour results in growth of sediment flux, $dQ/dy > 0$ (Fig.11b). Accordingly the shoreline disturbance is suppressed by the sediment flux and the coastline tends to straighten.

Large values Θ lead to the opposite situation (Fig. 10c). An increase in $\Theta+\delta$ along the contour leads to a decrease in sediment flux, $dQ/dy < 0$, and such a trend favours sediment accretion and the growth of the perturbation amplitude.

Therefore, long–shore sand waves can naturally develop from small perturbations of the coastline if the

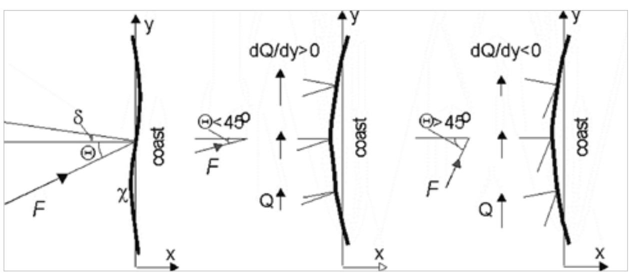


Fig. 11. (a) – definition sketch; (b) and (c) – changes in sediment flux in cases of small (b) and large (c) angles of wave approach to the coast.

resulting energy flux deviates from the shore normal at a large enough angle exceeding 45°. Such a situation can be observed under the conditions where winds blow predominantly along the coast and the majority of energy–carrying waves approach from the west.

In the area around Bolshaya Izhora village the westerly and south–westerly winds are the most frequent. In the eastern segment of the studied area the shoreline turns south. As a result, the waves come to the coast under at a very large angle, while a large amount of sand on the near–shore provides a source of material for the development and growth of shoreline structures.

The time t needed to form a sand wave of a given size is determined from Eq. (5) as

$$t = \frac{1}{\nu k^2} \ln\left(\frac{a}{a_0}\right), \qquad (6),$$

where the diffusion coefficient ν for a relatively small basin like the Gulf of Finland, is estimated to be about 10^3 $m^2 year^{-1}$ (Leont'yev 2005). The typical time scale of the process is the e–folding time t_e, during which the perturbation amplitude increases e times. With $a/a_0 = e$ it follows from Eq. (6) that $t_e = (\nu k^2)^{-1}$. Taking a typical length of the observed sand waves as λ=400 m (λ=400 m ($k = 2\pi/\lambda$=0.0157) gives t_e≈4 years. Therefore the period of sand wave formation estimated as the time needed for a one–order increase in amplitude (e^2–e^3 times) is (2-3)t_e or 8-12 years. This corresponds to the results of remote sensing analysis.

Eq. (5) shows the shorter is the perturbation length λ (larger k), the faster is the growth of the shoreline disturbance. The reason is that the gradient of sediment flux along the shorter structure is higher (Fig. 11c). However Eq. (5) only describes processes with spatial and temporal scales exceeding a certain threshold with small disturbances smoothed out by local processes. The optimal sand–wave length probably is a result of the equilibrium of many factors which control the regional coastal zone dynamics. A deviation to one side or the other will lead to decay of the mechanisms supporting this development.

The results derived from the above simple model are consistent with the analyses of RSD and hydrometeorological data. Unfortunately, there is a lack of wind and wave statistics for the study area. The only available data were published in a reference book "Climate of Leningrad", published in 1982. The probability of occurrence of strong (speed >5 m s^{-1}, with gust speed exceeding 15 m s^{-1}) westerly and south–westerly winds in study area is 31.4% and the probability for easterly and north–easterly winds is 13.9% (Climate of Leningrad, 1982), so the frequency of winds, which induce long–shore sand waves development are about three times more than the frequency of winds, that cause suppression of shoreline disturbances. Over the last decade wave–like shoreline contours were observed for the first time in 2004 and the long–shore sand waves have become more evident in 2006–2007. According to the data from the State Institution "Saint Petersburg Centre for Hydrometeorology and Environmental Monitoring with Regional Functions", in 2000–2004 and in 2007–2009, the frequency of occurrence of westerly and south–westerly, and easterly and north–easterly winds was close to the average annual. On the other hand, at Lomonosov settlement (southern coast of the gulf, at the distance of 10 km from study area) in 2004 of 18 cases of strong winds there were 8 cases of westerly and south–westerly and just 2 case easterly wind. In 2005 from 30 stormy days 21 wind directions were westerly and 3 days of easterly and north–easterly winds. In 2006 westerly and south–westerly storms were 5 times more frequent than easterly and north–easterly storms (20 cases to 4).

The properties of wave fields are mostly governed by the properties of wind over the entire fetch area, that is, by spatial wind patterns over most of the northern Baltic Proper and the Gulf of Finland the lack of local wind and wave data are found from the results of recent studies and reanalyses of wind and wave properties in the Gulf of Finland, undertaken by Estonian authors. The most important changes in regions adjacent to the study area are connected with changes in the directional structure of winds. Namely, during the last 40 years there has been significant increase in the frequency of south–westerly winds and decrease of southerly and easterly winds over all of Estonia (Kull 2005).

Visually observed wave data sets recorded at Narva–Jõesuu in the Narva Bay showed a substantial turn in the predominant observed wave propagation direction. The duration of wave events generated by south–westerly winds was clearly longer in comparison to northerly and north–westerly directions (Raamet *et al.* 2010).

There is evidence that there is an increase in storminess both in the Baltic Proper (Orviku *et al*. 2003; Jaagus *et al*. 2008), and in the western part of the Gulf of Finland (Soomere *et al*. 2008). Recent analysis (Soomere, Räämet 2010) and numerical simulation of wave conditions for 1970–2007 also show an increase in the extreme wave conditions in the eastern Gulf of Finland. Such changes may be responsible for a large part of the intensification of coastal processes in the Neva Bay area (Ryabchuk *et al.* 2010) and confirm the changes in wind directions traced in the vicinity of Bolshaya Izhora village.

CONCLUSIONS

This study describes the litho– and morphodynamic features of sand spits and the genesis of the long–shore sand waves, moving in the direction of sediment flow along the southern coast of the easternmost part of the Gulf of Finland in vicinity Bolshaya Izhora village.

The predominant direction of long–shore sediment flow is to the east. Surface sediments in the near–shore zone of study area are represented by sands of different grain–size characteristics, thickness and origin. Along the shore there is up to 2 km long accretion terrace, seawards from which the depth increases relatively fast. There are two sources of material for sand spit formation – erosion of the submarine sand terrace and erosion of sandy coastal cliffs up–drift of the accretion area.

The coastal segment in front of Bolshaya Izhora village has complicated dynamics with long–term development of sand spits some hundreds meters long and some tens of meters wide. In the vicinity of Bolshaya Izhora village the maximal width of the area of relict sand spits and lagoons reaches about 500 m. The spits have separated from the open sea; small narrow lagoons are gradually becoming shallower and overgrowing with water plants. Radiocarbon dating shows sand spit formation has occurred for at least the last 2500 years. Long-shore sand waves occur along the seaward edge of the contemporary marine sand spit. An important feature of the observed sand cusps is an increase in size (both length and amplitude) in the eastern direction. The amplitude of the cusps grows to the east from 15 m to 100 m with down–drift strait shoreline segments from 100 m (in the west) to 900 m (in the east) long. The sand cusps migrate in an eastern direction with an average rate from 15 to 20 m year^{-1}.

The reason of the long–shore sand wave's development is explained by the fact that prevailing waves induced by the westerly winds propagate almost parallel to the shore. In this case the shoreline contours are unstable and small perturbations tend to grow over the time. If the sand volume in the near–shore zone is large enough, these perturbations can transform into sand "waves", migrating in the direction of sediment flux. The size of sand waves in the Eastern Gulf of Finland matches the size of similar structures on the Atlantic coast of Long Island (Thevenot, Kraus, 1995). However, in the latter case of high–energy coastal environment both the long-shore sediment flux and the migration speed are ten times greater.

A possible reason for the recent development of sand waves within study area may be the increase in the frequency of south–westerly winds and decrease in southerly and easterly winds established for adjacent western part of the Gulf of Finland (Kull 2005).

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