Estonian Journal of Engineering, 2009, **15**, 3, 151–167 doi: 10.3176/eng.2009.3.01

Coastal processes in the Eastern Gulf of Finland – possible driving forces and the connection with nearshore development

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Received 1 April 2009, in revised form 22 June 2009

Abstract. The coastal zone of the Eastern Gulf of Finland is actively changed under the influence of complicated natural and anthropogenic factors. The easternmost part of the gulf, a valuable area for recreation, is characterized by very intense coastal processes and is dominated by erosion. Analysis of historical materials, archive aerial photographs and modern high-resolution satellite images together with on-land investigations have shown that the majority of the coast of the easternmost part of the gulf is being eroded and is retreating. A study in the nearshore (side-scan sonar profiling, accompanied by echo-sounding and sediment sampling) enabled the main geological reasons for the coastal erosion to be established.

Key words: Eastern Gulf of Finland, coastal processes, coastal morphodynamics, nearshore zone.

1. INTRODUCTION

Intensification of coastal processes is observed over the last few decades along many world coasts. Coastal erosion is already a widespread and serious problem in the Baltic Sea area (www.eurosion.org). The Workshop on Sea-Level Rise and Climate Change that concentrated on the changing processes and sustainable management of the low-lying coasts of the Baltic States, Poland and Russia, and was organized by the European Federation of Geologists in April 2008, has shown that the problem is very urgent for many Baltic countries [1].

Some scientists have suggested earlier that the main reason for the intensification of erosion processes is increasing storm activity both in the Gulf of Finland and over the whole Baltic Sea [2]. On the other hand, recent publications [3] reported no substantial changes in the wave regime and or variations of the annual mean wave height in the Northern Baltic Proper in the 1970s–1980s, based on long-term instrumental measurements [4] and visual observations [5].

However, it is usually impossible to explain active erosion of some coastal areas and the relative stability of adjacent ones using the general principles of coastal development in isolation. Only detailed analysis of the nearshore zone structure and processes provides evidence as to the cause of coastal problems.

For example, a long-term study of the coastal zone of the South-Eastern Baltic Sea within the Kaliningrad District revealed that the main reason for more intense erosion processes over recent decades in the coastal system between Cape Taran and Lesnoy* (Curonian Spit) is the sediment deficit [6–8]. The total loss of fine sediment annually in the coastal zone between Cape Taran and the Curonian Spit is estimated to be about 40 million m^3 (down to 12–15 m water depth) [7]. In the central part of Pirita Beach (Tallinn, Estonia) it was estimated that sediment loss of about 1000–1500 m^3 per year was caused by seaward sediment transport [9].

Intensification of the coastal processes in the Eastern Gulf of Finland was for the first time reported in [3]. The history of the descriptions and investigations of these coasts since the time of foundation of St. Petersburg [10–12], an analysis of the significant quantity of remote sensing data (1959–2008), collected by the Institute of Remote Sensing Methods for Geology (VNIIKAM) [13], shore-based field monitoring observations and marine geological studies (2004–2008), carried out by the A. P. Karpinsky Russian Research Geological Institute (VSEGEI), have enabled a number of aspects of coastal development to be determined. The spatial patterns of erosion, accretion and the transitional coastal zone, the rates of shoreline retreat and the primary reasons of coastal processes intensification have been examined. Some important features of the nearshore zone bottom relief and lithodynamics were mapped during VSEGEI investigations which have been carried out in the coastal zone of the Eastern Gulf of Finland [14,15]. The objective of this paper is to find links between the coast and nearshore development and to distinguish the geological reasons for the intensification of coastal processes.

2. MATERIALS AND METHODS

The Department of Marine and Environmental Geology of VSEGEI has undertaken sea-bed mapping, geological and geoecological investigations in the Eastern Gulf of Finland since 1980 [16–18]. Over the last decade, special attention has been given to the coastal zone [14].

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* Transliteration of Russian names into Latin alphabet is given according to the manuscript, presented by the authors.

Between 2005 and 2008, VSEGEI undertook multi-purpose research as a part of the project "Up-to-date assessment of mineral-resource potential, control over geological hazards and establishment of prediction development models of geological environment in the Baltic Sea and its coastal zone", funded by the North-West Department of the Federal Agency of Mineral Resources. The main objective of the project was to create an information system of geological hazards, geological structure and mineral resources of the Russian sector of the Baltic Sea. The system consisted of a GIS-atlas of geological and geo-ecological maps of the seabed of the Eastern Gulf of Finland and Kaliningrad area including the coastal zone (up to 10 km inland) at 1 : 500 000 scale, and a model of the coastal zone Cadastre [15]. The field observations along all the coast of Russian part of the Gulf of Finland were carried out and the zones of intense coastal line change were documented. Some were selected as key areas for detailed investigation (Fig. 1).

Within the key areas, a series of on land investigations and nearshore zone studies were performed. The repeated onshore observations included a detailed description and mapping of the coast, measuring beach morphological parameters, photographing specific features, describing the composition of coastal sediments, sampling sediments for grain-size (textural) analyses, and determining the condition of foredunes. The results of the field observations were analysed together with the outputs from the remote sensing data analysis (including aerial photos from 1990, with a resolution of 0.5 m, and Quick Bird space pictures from 2005, with a resolution of 0.64 m), and with navigation charts produced in the 19th and 20th centuries.

The shallow water areas of nearshore zone were studied using side-scan sonar profiling (CM2, C-MAX Ltd, UK) with a search swath of 100, 50 and 25 m using a working acoustic frequencies of 102 and 325 kHz. Within the northern coastal zone key area, 800 km of side-scan profiling (including 400 km of repeated survey) perpendicular to the shoreline was undertaken in 2005–2008. The distance between profiles (186 m for a range of 100 m) made it possible to construct an uninterrupted acoustic image of several investigated bottom areas. Repeated surveys of three areas of the nearshore zone (in front of the villages of Komarovo, Repino, and Solnechnoye) were used to study the development of bottom relief and sediment distribution. Along the southern coast, 75 km of side-scan survey were carried out.

The information, extracted from sonar data, was supported by sediment sampling and underwater video observations using a video-ROV Fish106M (Intershelf, St. Petersburg, Russia). Sediment sampling (216 samples) along the side-scan sonar profiles was undertaken using a grab-sampler and a small drag. Sediment sampling from the coastal slope, extending from the coastline to a water depth of about 2.5 m, was undertaken by divers. Altogether 168 samples were collected from 19 profiles.

In order to ensure efficiency and high quality of the results about the dynamics of coasts of the Eastern Gulf of Finland, a combination of the regionally oriented

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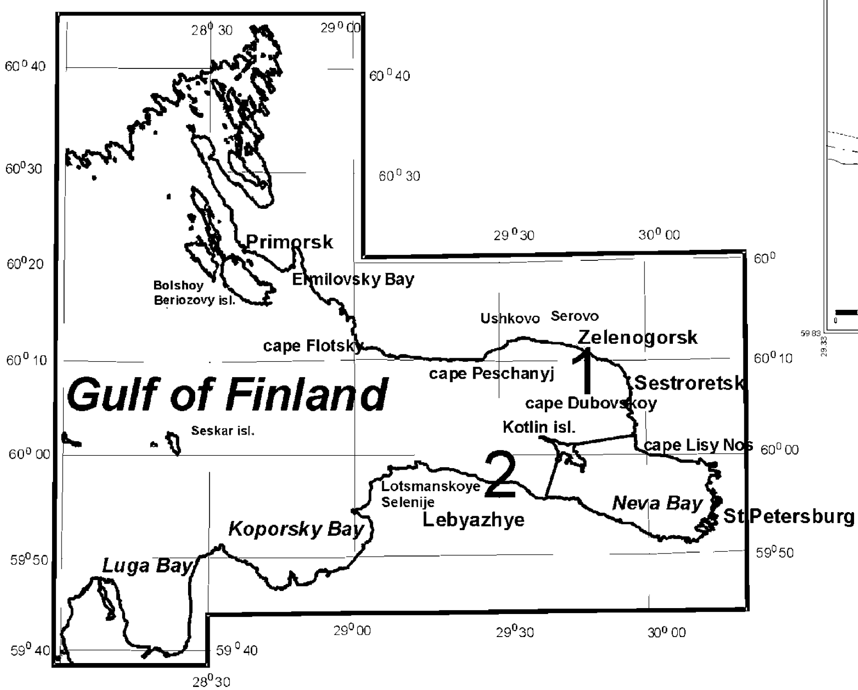

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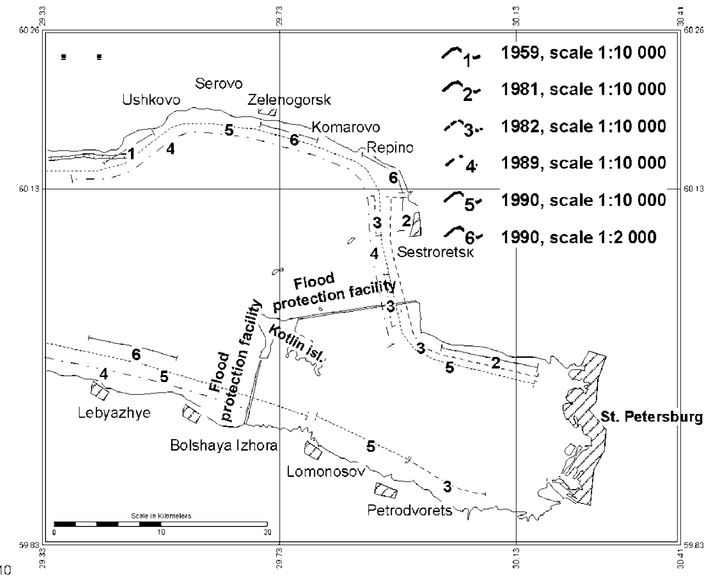

Fig. 1. (a) The study area and key areas: 1 – northern coastal zone of the Kurortny District; 2 – southern coastal zone adjacent to Lebyazhye village; (b) the scheme of the VNIIKAM remote sensing data survey.

knowledge base, field observations and analysis of modern and archival remote sensing materials (RSM) of coasts are used in the analysis. In particular, remote sensing data enable us to identify many features of the geological and geomorphological structure of coastal zones. The comparative analysis of the interpretation of multiyear RSM also enabled the identification of the presence, degree and direction of the variability of coast of the Eastern Gulf of Finland, and to forecast further changes to some extent.

Generally, for studies of the temporal change in coastal processes as well as for the prediction of future changes, it is necessary to take into account the effects of both natural and anthropogenic factors, such as:

– the effect of the use of water and other coastal resources (sand and gravel mining, land reclamation for settlements, dredging, construction and operation of ports, building of infrastructure for recreation etc.);
– change of the direction and intensity of long-shore streams of sediments owing to the construction of the flood protection facility for St. Petersburg and other hydraulic constructions;
– the overall water level rise of the World Ocean;
– downlift of land in St. Petersburg and in its vicinity (including the coasts of the Neva Bay);
– tectonic motions along fault lines, which can be accompanied by earthquakes.

One means to detect sites with the most intensive development of coastal processes is the retrospective analysis of remote sensing data. The VNIIKAM archive includes RSM for the examined region since 1959. VNIIKAM specialists carried out detailed examinations of coasts of the Eastern Gulf of Finland during 1989–1990 using RSM and traditional field observations. Airborne monitoring was carried out in the springtime, soon after ice melting (the period characterized by the maximum transparency of water) at scales: 1 : 50 000, 1 : 10 000, 1 : 5000 and 1 : 2000 (Fig. 1b).

By comparing images from the 1990s and from previous years, sites undergoing erosion or accretion were established and the rate of coastal change estimated. Alongshore sediment transport was examined. The magnitude and direction of littoral flow at a site depends mainly on the external forcing of sediment motion, primarily on the local wind-wave regime and the alignment of the coastal line with respect to the dominant direction of approaching waves. The prevailing direction of littoral flow in the Eastern Gulf of Finland is from west to east with the greatest sediment transport being along the northern coast, where there are relatively high waves.

Based, on the analysis of RSM and data of field survey, a study of the morphodynamics of beaches and their stability was carried out, with the goal to define typical coasts. The following satellite images were used: RESOURCE-F/KFA-1000 from 1989 (with a resolution of 5 m) and pan-chromatic images from LANDSAT/ETM from 2000 and 2002 (resolution 15 m).

3. RESULTS

From the geological point of view, the investigated coastal area has features related to its location at the boundary of the Baltic Shield and the Russian Platform. Geological processes caused by the Weichselian glaciation and the changes in continental, lacustrine and marine environments over last 14 500 years have played an important role in relief formation and sediment distribution [[18]]. The present gross morphology of the coastal zone in the study area was formed about 2–2.5 thousands years ago when Ladoga Lake waters burst out to the Baltic Sea and the Neva River was formed. Presently, the coastal zone of the Eastern Gulf of Finland is characterized by a litho- and morphodynamic regime partly caused by abrupt changes of sea-level during St. Petersburg floods. The most severe floods took place in 1777 (3.21 m above sea level), 1824 (4.21 m) and 1924 (3.80 m) [[2]]. During catastrophic storm surges accompanied by high storm waves, the rate of coastal erosion in some places along the coast reached 40 cm/h. On the other hand there is a very large difference between the hydrodynamics during the calm summer period and the stormy autumn and winter months. As a result, a mosaic-like superficial sediment distribution with alternating areas of erosion and accumulation is formed both at the coast and in the nearshore zone.

The most frequent winds that affect the shores of the study area come from the west and south-west directions and cause longshore sand drift to the east. An important feature of the coastal zone sediment balance is the effect of sediment starvation (deficit of material) [[14]].

Some parts of the Eastern Gulf of Finland coastal zone, such as the granite and glacial till skerries of the northern coast (between Primorsk town and Russian-Finnish border) or in large bays (Luga Bay, Koporsky Bay) of the southern coast, are relatively stable. A major part of the coast, however, is characterized by intense development. The most active erosion processes occur in the coastal zone of the easternmost part of the gulf, in the most valuable recreation area. The segments of the northern (Kurortny District) and southern (to the east from the Lebyazhye village) coasts, adjacent to the Protective Dam, were selected as key areas for detailed investigations (Fig. 1).

3.1. Northern coastal zone (the Kurortny District)

The Kurortny District of St. Petersburg is located along the northern coast of the Gulf of Finland, to the west of the St. Petersburg flood protection facility (Fig. 1). The development of the area for recreation began in the second half of the 19th century. The combination of sandy beaches, low vegetated dunes, pine forests and comfort climate was the driver of recreation tourism that triggered building of small picturesque resort towns with sanatoriums, hotels and yacht-clubs in this suburb of St. Petersburg. Over the same period of time, the beaches and coastal buildings suffered extreme storms and floods (Fig. 2).

(a) (b)

Fig. 2. Damage to the trees and buildings after the autumn flood of 1924 (www.terijoki.spb.ru).

Coastal erosion remains one of the most serious problems of the area. Analysis of historical materials, archive aerial photographs and modern high-resolution satellite images have shown that there are practically no advancing coasts with most sections of coast being eroded and retreating [[14]].

The remote sensing data analysis shows that the average rate of shoreline retreat from 1990 to 2005 was 0.5 m/yr, while the maximum rates reached 2–2.2 m/yr. The maximum landward shift (up to 25–30 m) of the shoreline has occurred along some sandy beaches in the vicinity of Serovo and Ushkovo villages. Sandy beaches with dunes in Komarovo village, which have a status of Nature Reserve, are characterized by alternating stable and eroded segments. The maximum distance of the shoreline retreat in that area is about 39 m. This retreat rate is particularly high in the light of recent attempts at beach nourishment. In 1988, along a 430 m long section of the coast at Komarovo, an artificial beach 50 m wide and 2 m high was created, with the total sand volume of 32 250 m^3. This artificial beach was an experimental type of coastal protection, which was evidently successful as it prevented even greater shore damage for two decades. However, the artificial beach is now completely washed away.

For some areas there is a possibility to compare the navigation charts for a period of more than 100 years (since the end of the 19th century) with remote sensing data and modern on-land observations. In the vicinity of Zelenogorsk (former Terijoki) town, since the construction of a yacht club harbour in 1910 that extends to about 100 m offshore from the shoreline, the sandy beaches to the east of the harbour have degraded and the shoreline has a retreat up to 90 m (Fig. 3).

The beach change can be traced by comparison of the navigation charts (1890, 1910, 1932) and air-photos (1929, 1959, 1990). After 1990 the shoreline did not change because the coast has been armoured by sea-walls and other “hard” types of the coastal defence. It is important to mention that this situation is typical for coastal development. Groins, perpendicular to the shoreline, are still the main type of coastal defence despite the well-known inefficiency of these structures in areas of sediment starvation. Vertical seawalls, also used in many coastal sections of the Kurortny District, enhance the wave impact and usually lead to intense erosion immediately seaward of the wall. Existing sea-walls themselves are currently in a badly damaged state (Fig. 4).

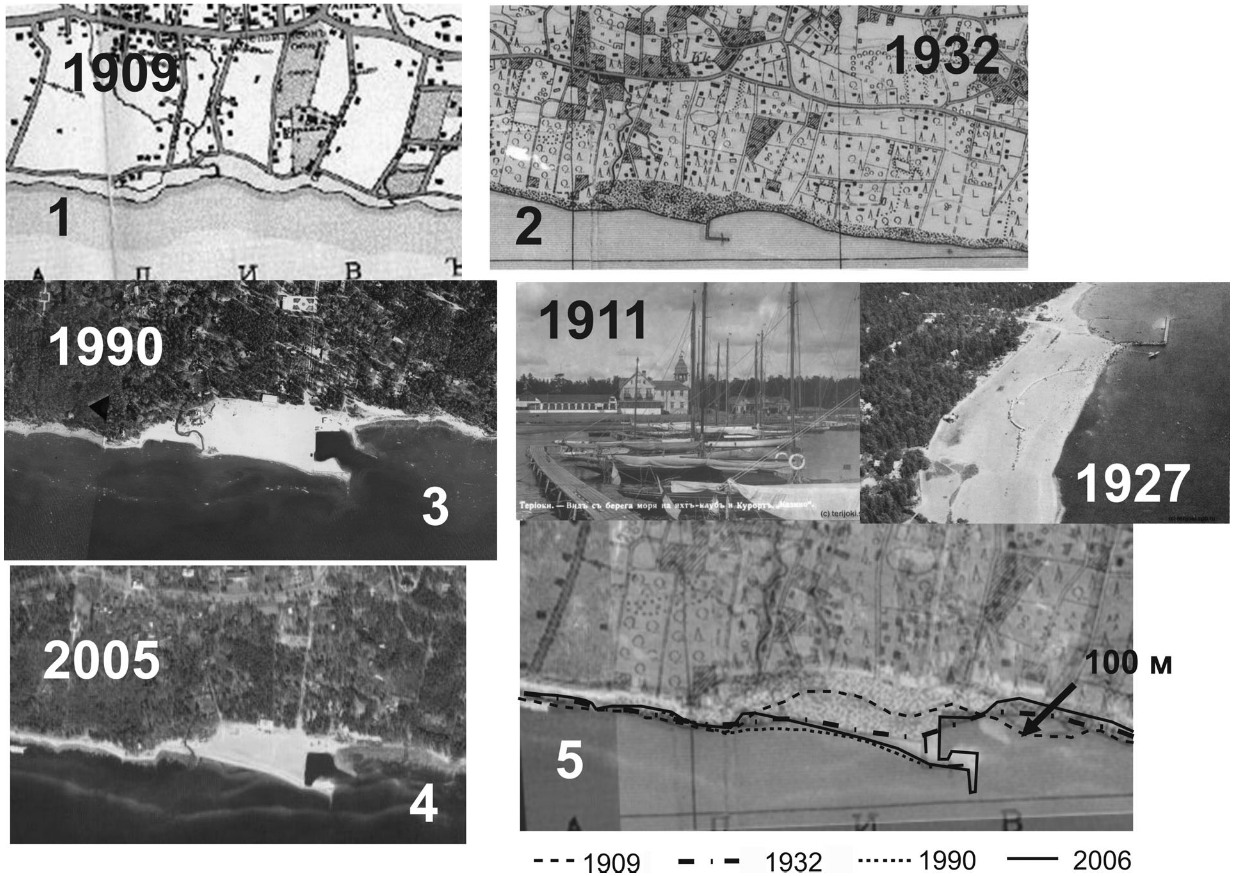

Fig. 3. Coastal development near Zelenogorsk (formerly Terijoki) town represented in maps of the sandy beach of Terijoki-Zelenogorsk from different years: 1 – 1909; 2 – 1932 (www.terijoki.spb.ru); 3 – aerial photo in 1990; 4 – satellite image in 2005 (Google Earth); 5 – shoreline change between 1909 and 2005.

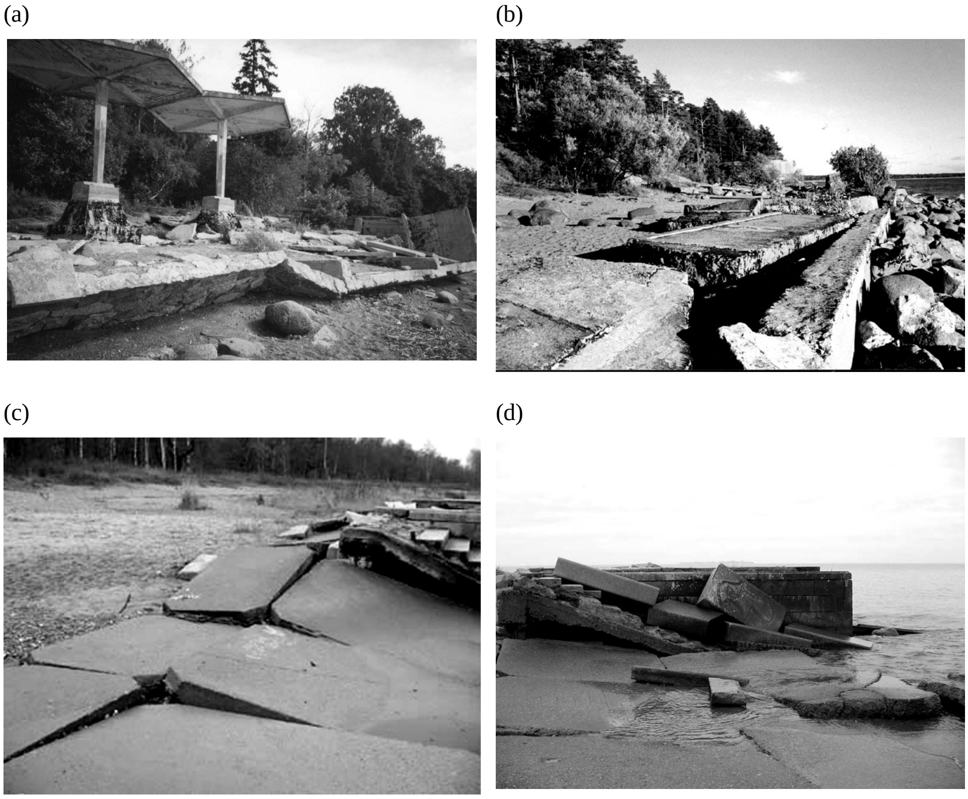

Fig. 4. Damaged seawalls in the Kurortny District of St. Petersburg.

3.2. Southern coastal zone between Lebyazhye village and the flood protection facility

The southern coastal zone between Lebyazhye village and the flood protection facility is an area of long-term sand accretion in the Eastern Gulf of Finland where the coasts are characterized by the sand spits of different sizes and shapes. In the vicinity of Bolshaya Izhora village the maximum width of the relict sand spits and lagoons is about 500 m. The recent VSEGEI investigations of lagoon mud (^{14}C analysis) have shown that sand spit formation has taken place over at least the last 2000 years [19].

According to many observations [2], the processes of coastal degradation became stronger during the 1970s and 1980s, in the vicinity of Lebyazhye and Bolshaya Izhora suburbs. The problem was first reported by the local authorities when a wooden cottage in Lotsmanskoye Seleniye village was destroyed as a result of coastal erosion in 1989. Orviku observed the event during his field expeditions to the Eastern Gulf of Finland in 1987–1990 (Fig. 5).

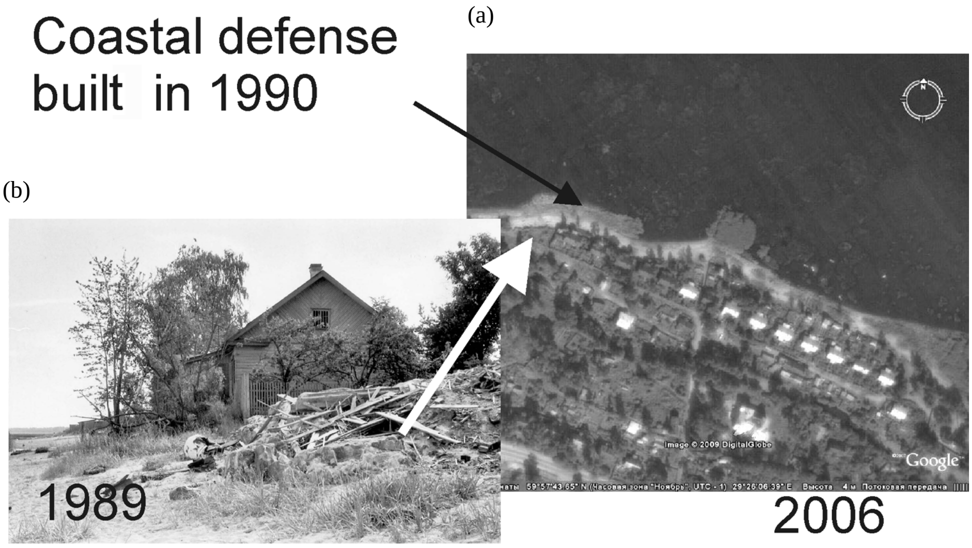

Fig. 5. Coastal erosion in Lotsmanskoye Seleniye village: (a) satellite image (Google Earth); (b) destroyed house. Picture by K. Orviku, 1989.

The analysis of aerial photos from 1975–1976 to 1989–1990 showed that sandy beaches to the west of Lebyazhye were eroded up to 30 m, and near Bolshaya Izora up to 70 m on a 200–330 m section of the coast [20]. A recent VSEGEI study has shown that the erosion processes are continuing.

The area in question is characterized by very active litho- and morpho-dynamic processes. The configuration of sand bodies has drastically changed since 1982. The eastern part of the sand body migrated up to 230 m. The maximum erosion rates are observed in the western part of accumulative sand spits, which were eroded about 80 m. According to navigation charts, air- and satellite photo analysis and GPS survey results, it is possible to establish different stages of formation of the new sand body. In the period 1982–1986 the sand spit grew in the eastern direction. Later on, the narrow sand spit grew at the mouth of a small river and formed a narrow lagoon between the spit and the former shoreline (1989). Finally, the spit became wider and the lagoon was filled with sand [20]. Sand drift in the eastern direction formed sandy cusps (Fig. 6) with a complicated pattern of areas of erosion, transition and accretion. In general, erosion processes, which led to the shoreline retreat, dominate.

One of the most actively eroded sections of the coast is located to the east of a small river. A part of sandy spit in its vicinity was shifted landward up to 10 m since 2004 and mud from the former inner lagoon outcropped on the marine side of the spit.

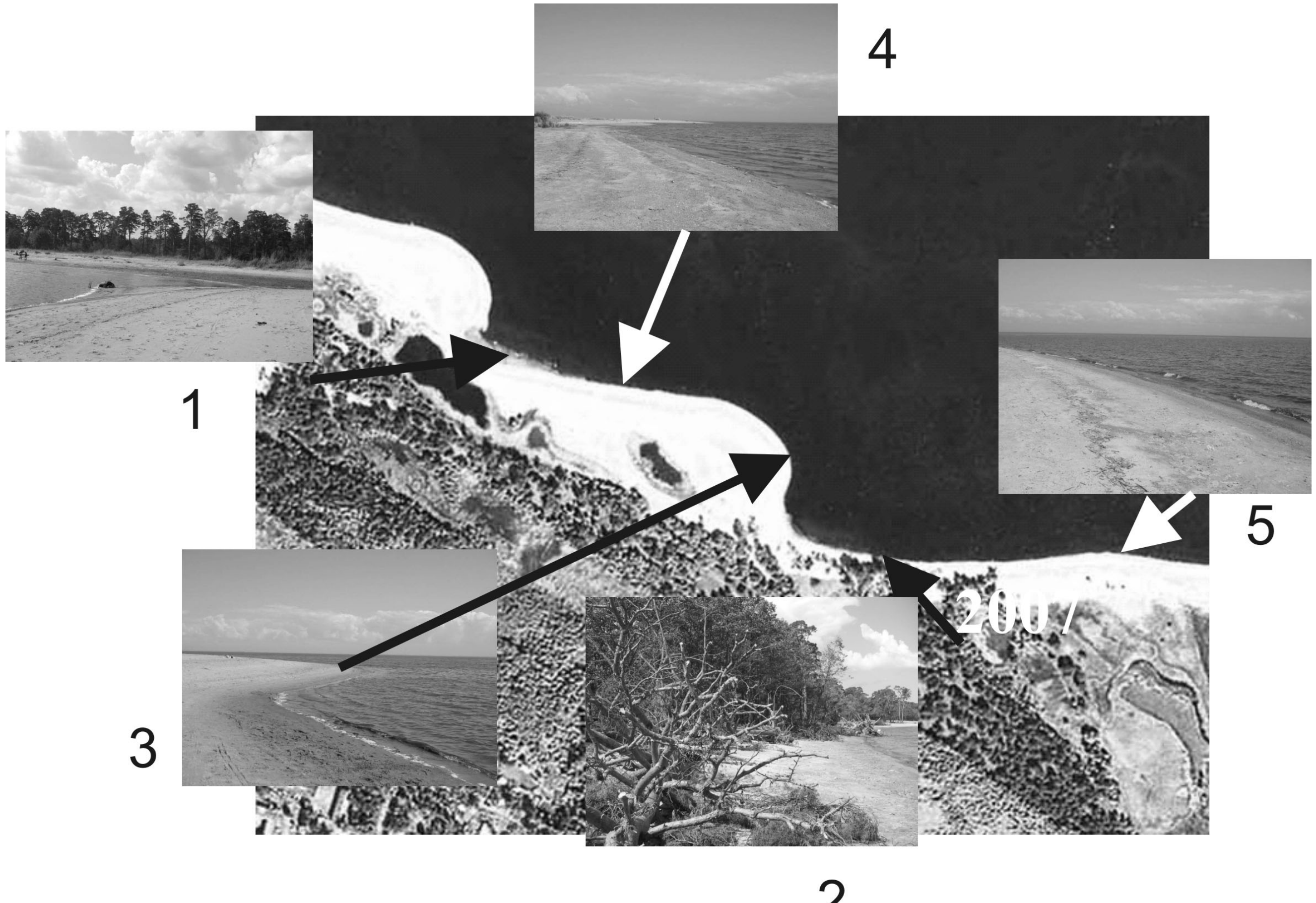

Fig. 6. Scheme of coastal changes with areas of erosion (1, 2), sediment transit (4) and accretion (3, 5).

4. DISCUSSION: REASONS FOR MORE INTENSE COASTAL EROSION

There are several reasons for intense coastal erosion within both investigated areas. Both the shore and the nearshore zones are entirely covered by up to 20–40 m thick Quaternary deposits, which can be easily eroded. Along the northern coast of the gulf, the Quaternary deposits are composed of glacial till, lacustrine-glacial deposits from local ice lakes and the Baltic Ice Lake, and Holocene (Ancylus Lake, Litorina and Limnea marine) sand and clays [[21,22]]. The most important feature of the litho-dynamic regime is a sediment deficit, "sediment starvation", partially caused by formation of a protective belt of cobbles, pebbles and boulders along glacial till coasts after an initial stage of fast erosion. The almost north-south orientation of the shoreline makes the coast sensitive to the western and south-western storms.

Field monitoring and observations from 2004 to 2007 have shown that the erosion processes have an intermittent, step-like nature. Periods of rapid, drastic changes are separated by much longer periods of stability. The most significant damage to sandy beaches and erosion of the dune system in last decade was observed during autumn and winter storms of 2006–2007 (Fig. 7).

The data presented for the coasts of the Eastern Gulf of Finland are consistent with similar observations of Estonian coasts. Over the last 20–30 years the most marked coastal changes have resulted from a combination of strong storms, high

(a) (b) (c)

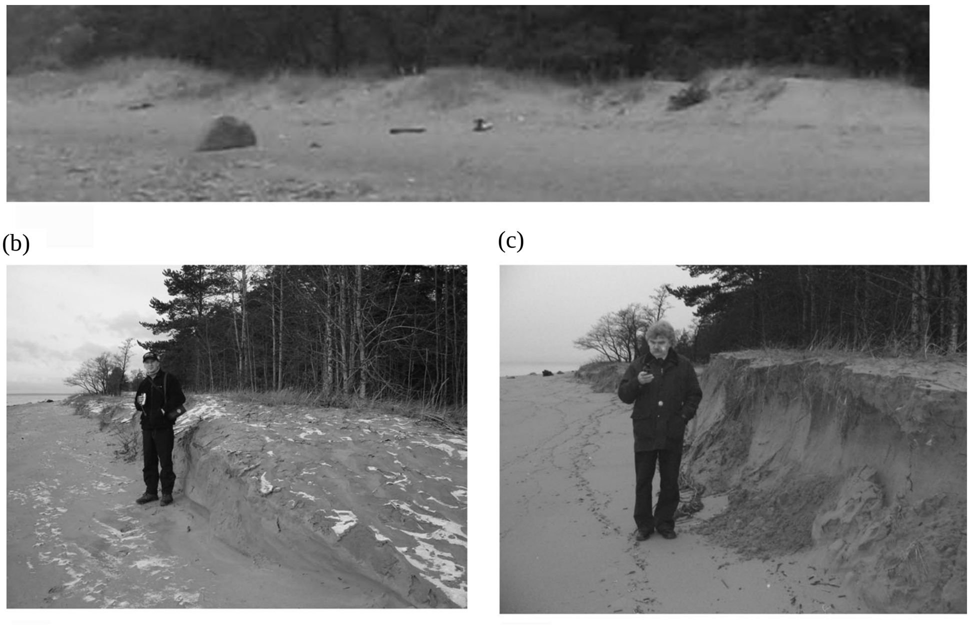

Fig. 7. Erosion of the foredune after autumn and winter storms accompanied by a sea-level rise in Komarovo Nature Reserve: (a) June 26, 2006; (b) October 24, 2006; (c) January 11, 2007.

sea levels induced by storm surge, and ice-free sea and unfrozen sediments during warm winters [21]. The weather and wave conditions during autumn and winter 2006–2007 on Estonian coasts were similar to those in the Eastern Gulf of Finland. Warm weather prevented the formation of the ice cover in the nearshore until late January. The on-land observations (Fig. 7) were undertaken after the floods, during which the water level in St. Petersburg was 2.25 m above the long-term mean.

Another important characteristic of the wind regime for the northern coast is a distinct anisotropy of strong WSW winds (>10 m/s) [23]. This feature is clearly demonstrated in data from Kotka (1961–2000) which is the most appropriate wind measurement site for the eastern part of the Gulf of Finland [23].

Marine geological investigation of the nearshore zone and analysis of the submarine coastal slope morphology of the northern coast of the Gulf of Finland within the Kurortny District made it possible to identify some pathways of sediment loss. The eastwards littoral flow weakens near Sestroretsk because of an orientation change of the coastline. As a result, an accretional beach, up to 140 m wide, is formed. The accretion area extends to the nearshore zone, where a very shallow submarine terrace surface, composed of fine-grained well sorted sands, has a system of sand bars and runnels. This is a relatively new formation. An analysis of remote sensing data suggests that the shoreline was not advancing in this area in the past. This formation has a steep offshore slope (water depth increase from 2 to 5 m along the distance of 100 m) of the narrow (about 500 m from shoreline) sand accretion terrace. It can be assumed that a substantial amount of material, brought to the terrace by the sediment flow, is transported seawards to the terrace foot.

Another potential pathway of fast loss of sediment from the nearshore is through erosion runnels. Such structures were discovered in this area for the first time in 2005 [14]. Erosion runnels are relatively shallow, canyon-like, elongated in the SW direction, bottom relief forms, oriented almost perpendicularly to the edge of the submarine terrace, and cut up to 30–50 cm into the bottom sediment. They are located at depths of 8–12 m. Repeated surveys have shown that these forms are very stable despite small relative depths. The erosion runnels were shown to exist over long sections of the coastline [14]. On the sediment surface of the troughs of the erosion runnels there are very distinct ripples (up to 20 cm high), orientated perpendicularly to the runnel direction and composed of coarse-grained sand. The distance between ripples crests is from 0.4 to 1 m (Fig. 8).

Along the northern coast between Cape Peschany and Repino village, the water depth along the terrace is about 4–5 m and its base is at the depth of 8–12 m. On the terrace surface there are sand ridges, stretching out at an angle of about 45° to the coast (Fig. 9). Repeated profiling of the submarine terrace and the comparison of our results with old nautical charts revealed the progressive erosion of the seaward edge of the terrace. As the terrace located at depths of 3–5 m effectively (albeit implicitly) protects the coast from wave impact through dissipation of a large part of the approaching wave energy, its erosion is rather dangerous for coastal stability.

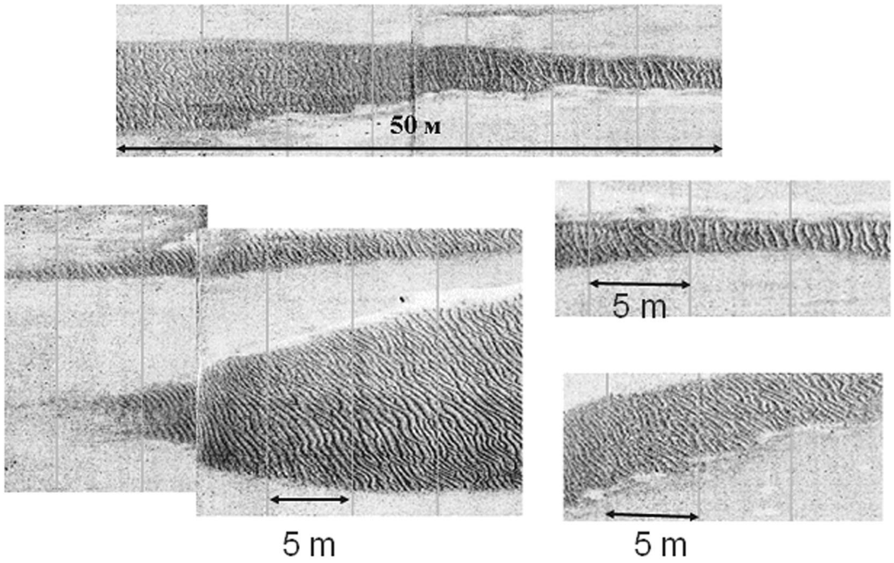

Fig. 8. Side-scan sonar images of erosion runnels.

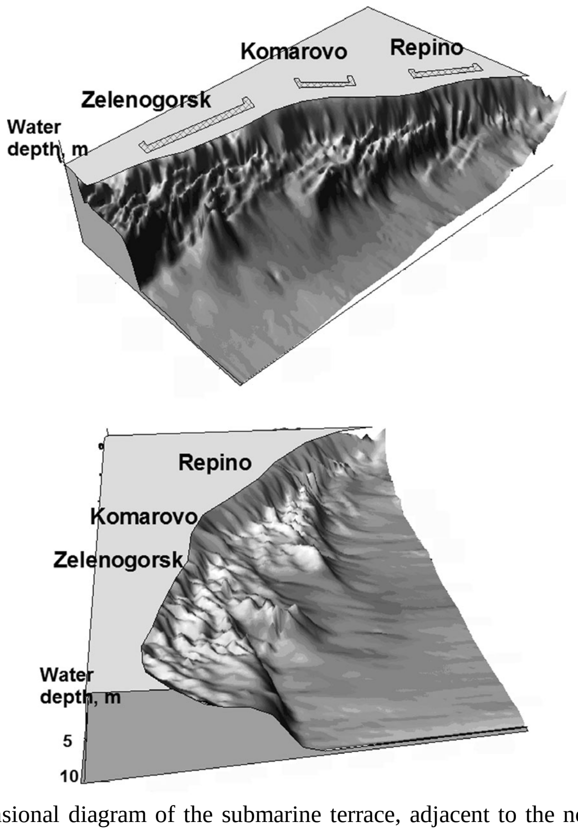

Fig. 9. Three-dimensional diagram of the submarine terrace, adjacent to the northern coast of the Kurortny District.

The reasons for intense erosion of the southern coast of the Eastern Gulf of Finland are not so obvious. The orientation of the coastline with respect to the dominant winds and a wide shallow water sand terrace (a source of sediment) jointly prevent the shore from significant erosion. The shoreward side of the underwater coastal slope is very gently sloping, with an average slope between 0.001–0.01 deg [20]. Most of the nearshore is shallow water area covered by sand, so sediment starvation should occur.

The shoreline orientation is such that strong NW winds may cause coastal damage. These winds, which are relatively strong and frequent in the Northern Baltic Proper, are unimportant in the inner part of the gulf [23].

The side-scan survey of the nearshore zone and grain-size analysis of the surface sediment allowed the sand masses to be differentiated according to their origin. Along the shore there is a sand accretion terrace up to 2 km long, seawards from which the depth increases relatively quickly. These sands can be divided into two types according to their grain-size characteristics, thickness and origin. Wave-derived accumulative sediments (up to 3 m thick) formed an accretion terrace in the nearshore zone. The other type of sand is formed as a result of submarine erosion of Late Pleistocene varved clays up to 30 cm thick (alternating varved horizontal layers of brown clays and grey silty layers) are located in the nearshore, whereas below the sand accretion terrace on the bottom surface there are traces of submarine erosion, indicating sediment transport in NW direction. At the lower part of the unit sandy layers, gravel grains of crystalline rocks and lenses of dry dense silt are observed. Grain-size analyses of the varved clays show that the finer layers consist of clay, while the coarser layers are silt. The average content of clay particles (less than 0.005 mm) is about 50%, silt fraction (0.05–0.005 mm) varies from 10% to 30%, and sand amounts to more than 20% [18]. As a result of long-term submarine erosion the clayey (and some part of the silty) fractions are removed, while the sand particles form the surface layer up to 30 cm thick.

Anthropogenic intervention as a possible reason for the intensification of coastal processes cannot be excluded. In particular, in the 1970s and 1980s underwater sand mining took place in so-called “London Shallow,” located to the east of Lebyazhye. As this area serves as a major source of sediment, transported alongshore for the southern coastal area, discussed in this paper, sand extraction may have resulted in a decrease in the magnitude of littoral flow.

ACKNOWLEDGEMENTS

The research was funded by the Committee of Nature Use, Environmental Protection and Ecological Safety of St. Petersburg City Government and grants from the Russian Fund of Basic Research 08-05-01023 and 09-05-00303-a. We are grateful to scientists from VSEGEI: Svyatoslav Manuilov, Yury Kropatchev, Elena Nesterova, Andrey Grigoriev and Gennady Suslov. We thank the captain and the crew of Research Vessel *Risk* for help and cooperation. We gratefully thank reviewers, Dr. Albertas Bitinas and Prof. Ruben Kosyan, for their helpful comments and Dr. Kevin Parnell for great help in polishing the final version of the paper.

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Rannikuprotsessid Soome lahe idaosas: mõjutegurid ja seos rannikuvööndi arenguga

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Soome lahe idaosa ranniku aktiivset arengut mõjutavad nii looduslikud kui ka inimtekkelised tegurid. Piirkonna idapoolseimas osas, väärtuslikus puhkealas, on rannaprotsessid väga aktiivsed ja domineerib erosioon. Ajalooliste vaatlusandmete ja aerofotode, nüüdisaegsete kõrglahutusega satelliidipiltide ning *in situ* uuringute alusel on näidatud, et enamikus Soome lahe idaosa randadest domineerib erosioon ja need rannad taganevad. Rannavööndis teostatud uuringute kompleksi (sh külgvaatesonari profiilide, kajaloodi andmestiku ja setteproovide analüüsi) alusel on esitatud ülevaade peamistest erosiooni soodustavatest geoloogilistest põhjustest.