Coastal processes in the Russian Baltic (eastern Gulf of Finland and Kaliningrad area)

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Abstract: The results of both onshore and offshore monitoring of the coastal zone in the Russian Baltic reveal the high intensity and recent acceleration of coastal dynamics caused by an increasing frequency of extreme hydrodynamic events and anthropogenic impacts on the diverse geology. Stable coasts dominate in the eastern Gulf of Finland, but the local rate of shoreline recession is up to 2.0 m a⁻¹, reaching 5 m in one extreme storm event. The coastal zone of the Baltic Sea is diverse. The western coast of the Sambia Peninsula is controlled by anthropogenic influences linked to the exploitation of geological resources. The beaches advance when the supply of artificial sediments from opencast amber mines increases, whereas the shoreline retreat reaches 10–20 m a⁻¹ when the input is interrupted. Active landslides and beach degradation dominate along the northern coast of the Sambia Peninsula. Large areas of pre-Quaternary deposits, outcrops and boulders in the nearshore provide evidence of sediment deficiency offshore. The coastal geological hazards are dependent on climate. A comprehensive understanding of the main trends in climate change is important for predicting and mitigating future damage to the coastal infrastructure and for selecting adaptation strategies.

Thematic collection: This article is part of the Mapping the Geology and Topography of the European Seas (EMODnet) collection available at: https://www.lyellcollection.org/cc/EMODnet

Received 11 February 2020; revised 18 May 2020; accepted 2 July 2020

The Baltic Sea is an intra-European, transboundary water basin. The surrounding regions are densely populated and the drainage area is highly developed economically (Fig. 1b). Geological mapping of the floor of the Baltic Sea is one of the most interesting and challenging tasks in the EMODnet-geology project because the seamless maps are compiled by ten partner institutions from nine countries, each with a long history of different mapping approaches and classification techniques. From the perspective of the EMODnet-geology Work Package 4 (Coastal Behaviour), the most remarkable feature of the Baltic Sea is its great variety of coastal types. These are a result of differences in the geological structure of the various regions of the Baltic area and the diversity of land movement, with sinking southwestern and uplifting north-eastern coastal areas (Harff et al. 2011). The main geological features of the Baltic Basin are controlled by its position between the Fennoscandian crystalline shield, represented by Precambrian magmatic and metamorphic rocks, and the East European Platform, characterized by Phanerozoic sedimentary cover, the thickness of which increases by up to several kilometres from NE to SW (Siaupa and Hoth 2011). The hard metamorphic and magmatic rocks of the Scandinavian Shield outcrop along the northern coasts of the Gulf of Finland, the Gulf of Bothnia and the western Baltic Proper. Quaternary deposits are widespread along the southern Baltic coasts, but, in the areas where these are eroded, the coastal cliffs are composed of relatively easily erodible Ordovician and Devonian (in Estonia) and Paleogene–Neogene (in the SE Baltic, including the Kaliningrad area) sedimentary rocks. The rates of glacio-isostatic rebound along the Baltic coast vary from −1.5 mm a⁻¹ in the SE Baltic, to +10 mm a⁻¹ at the top of the Gulf of Bothnia (Harff et al. 2017). The impact of waves on the coastal zone of the Baltic Sea differs significantly depending on the geographical position, shoreline configuration and wave fetch.

The coastal zone of the Russian Baltic consists of two distinct areas: the easternmost part of the Gulf of Finland and the SE Baltic within the Kaliningrad area (Fig. 1b). The southern coast of the Russian Gulf of Finland experiences similar processes to the adjoining Estonian shores, whereas the skerries of the NW resemble much of the Finnish coast of the Gulf. The coasts in the Kaliningrad area consist of the high cliffs of the Sambia Peninsula and two significant sediment accretion bodies: the Vistula Spit, shared with Poland to the SW, and the Curonian Spit, the northeastern half of which lies in Lithuania. Both segments of the Russian Baltic are characterized by intense coastal erosion, with a wide spectrum of landslides evident on the coastal cliffs of the Sambia Peninsula.

The coastal areas and beaches of the two parts of the Russian Baltic are highly valuable from the perspective of both recreation and nature protection and are under great pressure from anthropogenic activity. The urgent need for an effective coastal protection strategy is recognized by the local authorities and is in the early stages of development. Such a strategy needs to be based on a clear scientific understanding of natural coastal processes, taking into consideration both marine and geological factors and identifying the main trends in the current and future evolution of the shoreline.

Our work aimed to identify the main trends in the evolution of the coastline and to calculate the rates of shoreline retreat or advance, mapping the coastal geology and identifying hotspots of coastal...
erosion. Our aim was to link the occurrence of different lithologies with different coastal behaviours, revealing the natural and anthropogenic driving forces of coastline dynamics, and to propose a strategy for coastal management and protection.

There is a long history of previous research in this region, with the first scientific investigation of the geology and coastal processes of the SE Baltic published at the beginning of the twentieth century. Abromeit et al. (1900) described the geomorphological features of the coastal zone and the problem of dune stability. Tornquist (1914) considered the problems of sediment drift and the impact of storms on the Curonian Spit. Based on field observations during the winter storm of 9–10 January 1914, he showed that the coastal system may lose twice as much material during a single extreme storm event as it accumulates over a whole year. Data on the geological structure of the Quaternary deposits and erratic blocks of Cretaceous rocks near the Curonian Spit were published in 1919 (Wichdorff 1919). The first map of the Quaternary deposits of the Kaliningrad Region was compiled by Vereisky in 1946 (Vereisky 1946). Complex hydrogeological investigations between 1958 and 1967 enabled the development of onshore geological, hydrogeological and geomorphological maps at a scale of 1:200 000 (Zagorodnyh and Kunaeva 2005). The first aerial survey of the SE Baltic coastal zone was carried out by the Atlantic Branch of the Institute of Oceanology (ABIO RAS) in 1960 (Boldyrev et al. 1990). Repeated bathymetric measurements – accompanied by sediment sampling, beach levelling, geomorphological observations by scuba divers, sampling of suspended sediment and measurements of hydrodynamic parameters (waves and current) – were carried out at the same time (Aibulatov et al. 1966). Further studies of the coastal dynamics of the Kaliningrad Region have been continued since 1972 by the Agency of Coastal Engineering, later reorganized as the Bureau Baltberegozashita (Boldyrev et al. 1990; Ryabkova 2000; Boldyrev and Ryabkova 2001).

Hydrological studies carried out by the ABIO RAS from 1980 to the late 1990s classified the near-bottom currents from the shoreline to the outer boundary of the coastal zone and determined the existence of sediment transport towards the east (Babakov 2002). The most recent overview of the coastal geology was presented by Zhidarev et al. (2012). The Laboratory of Coastal Systems of ABIO RAS has conducted coastal monitoring studies along the shores of the Kaliningrad area since the year 2000. Numerous annual cross-shore profiles have been measured using permanent concrete benchmarks as fixed points to calculate the rates of coastal erosion (Bobykina and Boldyrev 2008). The coastal zone and nearshore bottom dynamics of the Curonian Spit were analysed by Zhmoidsa et al. (2009).

The geology and geomorphology of the Eastern Gulf of Finland (EGoF) coasts have been studied since the 1920s (Yakovlev 1925; Markov 1931). Coastal processes were first investigated by researchers from the University of Leningrad in the 1970s (Barkov 1989). An overview of the geology, geological history and the first classification of the coasts of the EGoF area was presented by Raukas and Hyvärinen (1992). The first geological description of the Russian coast of the Gulf of Finland was published by K. Orviku in 1992 (Orviku and Granö 1992). The authors of the current paper have discussed some aspects of coastal zone dynamics (e.g. Ryabchuk et al. 2011a, b; 2014; Spiridonov et al. 2011; Kosyan et al. 2013; Sergeev et al. 2018). The current Fig. 1. (a) Morphogenetic classification and coastal dynamics of the Eastern Gulf of Finland. The measuring points are points of retrospective analyses of coastal escarpments and beach positions based on remote sensing data (rates in units of m a−1); relict uplifted Holocene marine terraces are terraces formed during the maximum of Holocene transgressions (Lake Ancylus and the Littorina Sea) and are mostly covered by sand; coastal types are morphogenetic coastal types (see Table 1). (b) Location map of the study area. FPF, St Petersburg Flood Protection Facility.
Coastal processes in the Russian Baltic

Table 1. Parameters of coastal dynamics for different coastal types of the Eastern Gulf of Finland based on the classification of Shepard (1948)

<table>
<thead>
<tr>
<th>Legend No.</th>
<th>Coastal type</th>
<th>Description</th>
<th>Average rate of cross-shore coastal dynamics (m a⁻¹) (number of measurements)</th>
<th>Average rate of longshore dynamics (spits, sand waves) (m a⁻¹) (number of spits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Skerries</td>
<td>Primary coasts: drowned glacial erosion coasts. Embayed coasts consist of hard rocks</td>
<td>0.05 (2)</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Sand accretion alluvial coast with delta</td>
<td>Primary coasts: river deposition coasts. Coasts consist of coarse-grained beaches and estuaries</td>
<td>0.1 (6)</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Moraine (boulder) erosion coast with local pockets of coarse-grained beaches</td>
<td>Primary coasts: glacial deposition coasts. Coasts consist of moraine deposits developed following erosional processes</td>
<td>−0.1 (69)</td>
<td>18 (2)</td>
</tr>
<tr>
<td>4</td>
<td>Erosion-dominated coast on Holocene marine terrace, straightening</td>
<td>Secondary coasts: wave erosion coasts. Permanently straightening coasts consisting of soft Holocene deposits, erosional processes are developed within marine palaoterraces</td>
<td>−0.25 (43)</td>
<td>47 (3)</td>
</tr>
<tr>
<td>5</td>
<td>Erosion-dominated coast on Holocene marine terrace, straightened</td>
<td>Secondary coasts: wave erosion coasts. Straightening of coasts is finished, coasts consist of soft Holocene deposits, erosional processes are developed within marine palaoterraces</td>
<td>−0.5 (4)</td>
<td>30 (1)</td>
</tr>
<tr>
<td>6</td>
<td>Sand accretion coast</td>
<td>Secondary coasts: marine depositional coasts. Accumulative processes are dominant as a result of sediment inflow</td>
<td>0.2 (9)</td>
<td>16 (1)</td>
</tr>
<tr>
<td>7</td>
<td>Sand accretion coast with cuspat e foreland</td>
<td>Secondary coasts: marine depositional coasts. Movement of beach sand spits is observed combined with accumulative processes</td>
<td>−0.7 (5)</td>
<td>14 (4)</td>
</tr>
<tr>
<td>8</td>
<td>Technogenic coast (with hard coastal protection structures)</td>
<td>No natural development of coasts due to technogenic impact (coastal protection)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The paper presents the first regional study based on a combination of comprehensive geological and geomorphological datasets and the results of long-term coastal monitoring.

**Materials and methods**

**Fieldwork**

The Russian Geological Research Institute (VSEGEI) has carried out geological mapping and research since the 1980s and there has been annual state (federal) monitoring of the geological environment of the Russian Baltic since 2011. The Regional Program of St Petersburg City Coast Protection Strategy development was carried out in 2015–16. The main methodological approach of coastal zone monitoring combines methods of onshore monitoring (e.g. remote sensing data (RSD), observations, levelling, terrestrial laser scanning (TLS), unmanned aerial vehicle surveys, ground penetration radar and profiling) and offshore surveys (e.g. sub-bottom profiling, sidescan sonar profiling, sediment sampling and submarine video survey; for some areas, also multibeam profiling). Offshore research has mapped the nearshore bottom to reveal areas of bottom erosion and an absence of recent sediment cover (sands or gravel). Engineering geological studies of coastal transects, from the shoreline to cliff edge, were carried out by VSEGEI in 2015–19. Five transects were monitored annually in the Kaliningrad coastal zone and three in the EGoF. Research included sediment sampling for grain size analysis, the determination of physical and mechanical properties, and strength testing of clays with portable penetrometer and field vane tests.

Annual monitoring measurements have also been undertaken in the SE Baltic by the State Budgetary Institution of Kaliningrad Region (‘Baltberegzoschita’) and the Atlantic Branch of the P.P. Shirshov Institute of Oceanology (ABIO RAS). Seventy regular ground marks were established in 2000–02 for repeat measurements and the number was increased to 285 marks in 2008. Monitoring includes measurements of the lithology, sediment characteristics and the relief of submarine coastal slope, beach and foredune dynamics. The 285 ground marks are installed at 500 m intervals and georeferenced (WGS-84, Baltic System of Heights 1977) along 145 km of coastline. Measurements are carried out both seaward and landward from the ground marks, with the datasets including the distance between the ground mark and the base and edge of the coastal escarpment, the foredune base and the shoreline. Comparative analyses of the results allows different parameters of the coastal zone dynamics to be distinguished. The precision of the measurements is at the centimetre scale, not exceeding several centimetres. As a result, a significant dataset has been collected for the last ten years (2008–18) for all coasts and for a period of 19 years (2000–18) for most of the representative coastal segments. These data can be used to analyse the main dynamic trends of the coast to identify the key driving forces (e.g. storm activity and frequency) and to calculate the sensitivity and vulnerability of the coast in relation to the geological properties. Coastal monitoring also includes the analysis of RSD, aerial laser scanning, aerial photographic surveys, the technical monitoring of coastal protection constructions, bathymetric surveys and sediment sampling of the nearshore bottom, together with analyses of geodesic, hydrometeorological, geological, environmental and hydrotechnical surveys and scientific publications.

**Retrospective analyses of topographic maps, aerial photographs and RSD**

Topographic maps at a scale of 1:25 000, based on late nineteenth century surveys and published in the early twentieth century, were used to determine the long-term trends of changes in the coastline of the EGoF. Digitization and geographical information system (GIS) analyses (ArcGIS 10.0) of 89 topographic map sheets at a scale of 1:50 000, published in the 1960s and covering most of the studied coastal areas, allowed us to trace specific relict coastal accretion forms that are currently located at different altitudes to reveal changes in the coastline. Georeferencing of these maps was carried out based on the position of the same objects (buildings, roads) that have been preserved since that time. We digitized four archival topographic maps published in 1908 and corrected in 1926 at a scale of 1:25 000 (Gr. Dirschkeim, Rauschen, Neukuhren, Palmnicken;
(Geographisches Institute 1908a, b, c, d)) to analyse the long-term coastal transformation of the Kaliningrad coasts. The results of retrospective analyses showed the high accuracy of the topographic maps, allowing us to trace the position of the coastal escarpment and to calculate its rate of retreat relative to modern satellite images from 2013 (available via Google Earth).

The recent coastal dynamics of the EGoF were studied using satellite imagery available via Google Earth for most parts of the coast. We used Landsat 1–7 images (cell size 80–30 m) for the period 1984–2005 and high-resolution satellite images with cell size of several tens of centimetres for the period 2005–18. We used aerial photographs from 15 August 1939 for analyses of RSD for the coastal dynamics of Kotlin Island. We used high-resolution aerial photographs from 1990 to analyse the southern coast of the Gulf of Finland near Bolshaya Izhora village. Analyses of the full set of satellite images enabled us not only to fix the initial and final points of the position of the coastline, but also to identify the dynamics of its transformation in relation to its geological composition, including the formation, mobility and destruction of sand spits and bars. The analyses for some of the most dynamic coastal areas are also based on annual field observations, levelling and retrospective analyses of very high-resolution satellite images available from earlier published studies (Leont’ev et al. 2011; Ryabchenko et al. 2018; Sergeev et al. 2018).

Terrestrial laser scanning

The TLS data were collected for the Sambia Peninsula coast in August 2016 and August 2017 using the TOPCON GLS-1500 system. The accuracy of the determination of distances and angles was 4 mm for 150 m of measurements and the angular accuracy was $2.9 \times 10^{-5}$ rad. The scanning system was equipped with a sensor system for self-calibration and the elimination of levelling errors, a collimator and a rotation system that started before each launch and did not require manual calibration (Topcon Inc. 2010). Co-registration of the TLS data was performed by the back-sight method using the target installed on the tripod and the GNSS receiver TOPCON GR-5. Differential correction was obtained from the internal network of the base stations. Digital elevation models were developed using ArcGIS 10.0 with the Natural Neighbor tool for the linear interpolation of point data to compare the results of the TLS point clouds. The GRID cell size was set at 0.1 m.

TLS was carried out in the EGoF coasts over the time period 2012–17 by Alpha-Morion Ltd using the RIEGL VZ-400 system from 12 stable points (scan positions). Geodetic referencing to the local coordinate system SK64 and the Baltic System of Heights 1977 was established using a Trimble R8 and the Javad Legacy-E satellite. Post-processing was performed using Pinnacle software. The horizontal and vertical fixes of the position marks were made using a LEICA TS06 Ultra (2") total station.

Data management and GIS

The results of the annual monitoring are collated as GIS maps. The results received in the frame of coastal monitoring in the SE Baltic are integrated within the Informational System of Kaliningrad Region using an online resource (www.bbz39.ru/ipas) for the development of a state coast protection strategy.

Results

Eastern Gulf of Finland

The Russian part of the Gulf of Finland shoreline, not accounting for the islands, is c. 520 km long (Fig. 1). A key feature of the EGoF is a very low rate of uplift (0–3 mm a$^{-1}$) and a near-zero rate of recent sea-level change (Gordeeva and Malinin 2014; Harff et al. 2017). The northern coast, from the Finnish–Russian boundary to the Beriozovy Archipelago, consists of skerries, with numerous islands and small barrow bays formed by igneous and metamorphic rocks and partly covered by till. The most widespread type of coast, formed as a result of the erosion of Late Pleistocene moraine, is characterized by erosion scarpas fronted by boulder benches in the nearshore zone. Our results indicate that the embayed coasts are straightening as the result of the accumulation of sediment. Sand accretion coasts with wide (50–150 m), stable sand beaches are observed in Narva Bay and in front of Sestroretsk town. The easternmost part of the studied coasts, within the mouth of the Neva River, has been largely transformed by technogenic processes.

About 70% of this coast (82 km over 118 km of shoreline) consists of embankments, coastal protection structures and other technogenic constructions. The St Petersburg Flood Protection Facility (FPF) (Fig. 1) has played an important part in the recent evolution of the coastline.

Hazardous floods have threatened the population of St Petersburg since its foundation and the earliest plans to protect the city date from just after the catastrophic flood of 1824. In 1858, in his report to the Russian Geographical Society, E. Tillo presented eight different potential projects for the defence of St Petersburg from floods (Tillo 1893). One of these proposed projects was developed in 1824–27 by Pierre Dominic Basen. There was no further development until after the Second World War, when discussions began again at a new, more technical level. As a consequence, construction work on a huge hydrotechnical structure, the FPF, began in 1979. The construction of the FPF was interrupted in the 1990s as a result of the need to carry out an ecological risk assessment, but it was continued in the late 2000s. The FPF, one of the largest hydrotechnical constructions in the Gulf of Finland (total length 25.4 km, height 6.4 m above the average long-term water level), has been fully functional since 2011 (Ryabchuk et al. 2017).

The FPF consists of 11 dams, six water sluices and two navigation gates (https://dambasph.ru/#intro). Its function is important in the protection of the city of St Petersburg from flooding, but in the 1990s there was a discussion about its possible impact on the environmental status of the EGoF and Neva Bay in particular. Consideration was given to the risk of increasing the pollution of water and bottom sediments with hazardous substances, such as heavy metals, as a result of the interaction of the FPF with waste water from St Petersburg. Testing and monitoring of the bottom sediments revealed no negative impact of the FPF, but instead indicated a generally decreasing trend in the concentration of hazardous substances since the 1980s (Ryabchuk et al. 2017). This decrease in heavy metal concentrations was attributed to decreasing anthropogenic loads in the 1990s and, since the 2000s, the efforts of the VODOKANAL State Enterprise to improve water treatment in St Petersburg (www.vodokanal.spb.ru/en).

Low coasts dominate within the EGoF. The average height of the recent marine terrace is 1–2 m, with the exception of 30 m high cliffs occurring in unconsolidated sediments near Krasnaya Gorka village. The coasts of the EGoF are exposed to the influence of multi-directional waves. The most dramatic impact on the coasts is caused by westerly and southwesterly waves associated with the prevailing wind direction (Ryabchuk et al. 2011a), with the coasts of the Kurortny region, Lebyazhye village, Kotlin Island and Narva Bay being the most vulnerable. The wave energy along these coasts increases during the autumn and winter (Kovaleva et al. 2017) when the unprotected and exposed coasts can retreat significantly. However, the erosive effects of the waves may be mitigated by the stable ice cover that usually forms in late November (Soloshchuk 2010), thus reducing the erosional consequences associated with storm surge events. The waves and currents induce the normal longshore and cross-shore transport of sediments during calm periods in spring and summer, which does not significantly reshape the beach profiles.
Based on RSD analyses, the coasts of the EGoF can be subdivided into four types: (1) erosion-dominated (foredune erosion or retreat of the coastal escarpment); (2) accumulative (beach aggradation, stable foredune); (3) intense longshore sand drift sufficient to develop sand spits and longshore sand waves; and (4) stable (skerries and technogenic) (Fig. 1). Combined analyses of monitoring observations and RSD have enabled the identification of the most dynamic parts of the EGoF coast as the shores of the Kurortny district of St Petersburg, the western coast of Kotlin Island and the southern coast of the Gulf between Lebyazhye and Bolshaya Izhora villages.

The average rate of retreat of the coastal escarpment within erosion-dominant coast is 0.25 m a\(^{-1}\). This increases locally to 1.5–2.0 m a\(^{-1}\) and, during severe storms, the escarpment can retreat landward by up to 5 m per storm (Ryabchuk et al. 2014). Such high-magnitude erosional events have recently become more frequent and have been observed four times since 2004. The coastal area of Kurortny district is exposed to the greatest erosion under the impact of westerly and southwesterly storms. The longest series of levelling measurements of the beach cross-sectional profile and the results of westerly and southwesterly storms. The longest series of levelling measurements of the beach cross-sectional profile and the results of

Repeated TLS surveys for Komarovo village showed that the average annual rate of erosion of the beach-face escarpment from 1988 to 2018 was 0.9 m a\(^{-1}\) (Sergeev et al. 2018). This long-term rate of erosion masks significant annual variations, whereby there may be 0 m of erosion over several consecutive calm years, followed by 5 m during an extreme storm event. Similarly, following a series of storms in 2011, the coastal cliff retreated landward by up to 6.5 m. We calculated the volume of sand as a difference between the beach surfaces for each year using only TLS data collected annually from 2012 to 2017. The total balance showed a reduction in beach sediments of 413 m\(^3\) along a 90 m segment. The average loss of sand as a result of storms over this five-year period was 4.5 m\(^3\) per metre of shoreline.

Analysis of RSD for the western coast of Kotlin Island over a time period of 76 years, using aerial photographs from 15 August 1939 and a high-resolution satellite image from 2015, shows that the alongshore transport of sand material and alignment of the coastal contours are dominant here, with the intense erosion of capes and the filling of small bays. The capes were eroded and sediment accumulation was observed in the eastern part of this coastal segment. The average rate of coastline retreat was 0.25–0.5 m a\(^{-1}\), reaching 1.2–1.6 m a\(^{-1}\) on the more exposed parts of the coast (Fig. 2b). The maximum rate of erosion of up to 2 m a\(^{-1}\) was recorded on the most western part of the island (Ryabchenko et al. 2018).

The coast to the west of Lebyazhye village (on the southern coast of the Gulf of Finland) differs from the neighbouring shores by the presence of an active coastal cliff up to 15–20 m high and composed of sandy sediments and boulder sandy loams (silty clay with boulders). Boulders and coarse-grained sand prevail on the surface of the beach. The lower part of the cliff is composed of sub-horizontal layers of boulder–pebble deposits. Several of these layers can be traced along the cliffs because of their large boulder content. The upper part of the cliff is composed of layers of sand, pebbles and gravel. The geotechnical properties of deposits are shown in Figure 3.

Repeated TLS surveys of the beach surface and coastal cliff in 2016 and 2017 showed that slope erosion occurs primarily due to intense landslides triggered by surplus rainfall. The volume of material displaced downslope reached 5.8 m\(^3\) for each metre of shoreline. An analysis of satellite images from 2005 to 2018 showed that the edge of the coastal escarpment retreated landward by 13 m (c. 0.8 m a\(^{-1}\)). Sand accretion is observed locally, mainly near the mouths of rivers, and results in the formation of stable beaches up to 100 m wide. There is no advancing sand beach within the study area.

The dynamics of the spit coast are the most active. Several small short-term sand spits (up to 100 m long) shifting in an easterly direction at an average rate of 30–60 m a\(^{-1}\) were observed within the northeastern coast of the Gulf of Finland between 2013 and 2018 (Fig. 1). Much larger sand spits up to 1100 m long and 200 m wide occur on the southern coast near Bolshaya Izhora village (Ryabchuk et al. 2011b). The special features of the geological structure of the coastal zone here include a sufficient volume of sand material, produced by onshore and offshore erosion of the Holocene sand terrace, which has resulted in the development of dynamic forms of coastal relief referred to as ‘alongshore sandy waves’ (Leont’ev et al. 2011). The shoreline contour of the seaward edge of the contemporary marine sand spit is characterized by a smooth curving shape. An important feature of the observed large sand cusps,
longshore sand waves, is an increase in their size, both length and amplitude, in an easterly direction. The amplitude of the cusps increases to the east from 15 to 100 m with straight shoreline segments down-drift. Comparison of RSD and annual field monitoring results showed that, over the period of observations from 2011 to 2018, the annual alongshore displacement of the ‘waves’ reached 8–20 m a\(^{-1}\) (Fig. 4). Although the beach is eroded from the west side of the protruding section of the coast (‘waves’), the whole sand wave feature is migrating along the coast in an easterly direction. Similar coastal forms are observed along the western shore of Kotlin Island. The development of these longshore sand waves is explained by the fact that the prevailing waves, induced by westerly winds, are propagated almost parallel to the shoreline.

The nearshore areas of the most heavily eroded segments of the EGoF coastal zone are fully covered by sidescan sonar profiling surveys. These surveys have revealed the occurrence of vast areas of boulder–pebble sediments, dominating at water depths of 0–5 m, along the northern coasts of the outer Neva Bay estuary, the nearshore of Kotlin Island and the submarine periphery of some capes. The results of these investigations have revealed a deficit of nearshore sediments (Ryabchuk et al. 2011a; Ryabchenko et al. 2018) and the results presented here support close links between the sediment balance offshore and the onshore rate of coastal erosion.

**SE Baltic**

The coasts of the Kaliningrad sector of the SE Baltic can be genetically subdivided into the erosion-dominated Sambia Peninsula shore and two accretion-dominated spits: Vistula and Curonian. Ten different coastal subtypes can be distinguished based on their morphology and recent processes trends (Petrov 2010).

The shape of the shoreline of the Sambia Peninsula (Fig. 5), with an alternation of capes and bays, is caused by long-term selective erosion of the coastal cliffs, which are composed of unconsolidated sandy and clayey Paleogene, Neogene and Quaternary deposits (Zhindarev et al. 2012). The height of the cliffs decreases gradually in the eastern and southern directions from 55 to 5–10 m. The

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Fig. 3. Monitoring (2016–19) of coastal cross-section of the southern coast of the Eastern Gulf of Finland near Lebyazhye village. (a) Description of cross-section (2018) with positions of samples. (b) Aerial photograph taken by an unmanned aerial vehicle. (c) Model of coastal relief with slope angles.
escarpments of both the western Sambia Peninsula, south of Cape Taran, and the northern Sambia, east of the Cape, are dissected by numerous ravines.

Cross-sections of the coastal escarpment show that the cliffs consist of alternating, relatively thin (1–10 m) layers of variable grain size sands, sandy loams (silts), clayey loams (silty clays), clays and coarse-grained sediments. The geotechnical properties of these layers differ slightly, but they are predominantly unconsolidated and easily erodible (Figs 6 and 7).

The cliff near the village of Donskoye has a very heterogeneous structure. Unconsolidated deposits of different grain sizes form many layers. The sands, as shown in Figure 6, vary in grain size from silty sands to coarse-grained sands. The clay layers of the cliff are thin with a moisture content of 23–26% and a density of 1.87–2.02 g cm$^{-3}$. The cemented sands of the upper part of the cliff, where the slope angle reaches 90°, are characterized by the highest level of hazard from mass movements.

The cliff in Filino village (Fig. 7) is composed mainly of medium-grained sandy sediments, which are densely folded in the lower part of the cliff, forming a vertical wall. The sands of the upper part of the cliff are more friable. The top 3–4 m are represented by silt with a high content of boulders and pebbles, a low moisture content (16.2%) and a density of 2.11 g cm$^{-3}$.

The wave activity in the SE Baltic Sea is caused by the shallow water and a semi-closed position and is determined by the direction of the winds and the interaction of waves with the seafloor (BACC Author Team 2015). A pronounced annual pattern of wind waves is observed: a decrease in wave height during the spring–summer period (0.6–0.7 m) and an increase in the autumn–winter period (0.8–0.9 m) (Różyński 2010; Zaitseva-Pärnaste et al. 2011). Storm waves (>2 m high) occur in <5% of all observations (Kelpšaitė et al. 2008). Southwesterly waves (1.4–1.8%), to which both the northern and western coasts of the Sambia Peninsula are exposed, have the highest frequency. Typical wave periods are 3–6 s (Kahma et al. 2003; Soomere 2008). There has been a significant increase in the occurrence of southwesterly winds from 15 to 25% during the last four decades, associated with a positive North Atlantic Oscillation index (Kelpšaitė et al. 2011). The air pressure is higher than average over the southern part of the North Atlantic or lower than average over the northern part of the North Atlantic when the North Atlantic Oscillation index is positive (Dailidiene et al. 2006). The modern evolution of the Sambia Peninsula coasts is driven by a complex system of currents, controlled by winds, their direction and the morphology of the underwater slopes (Babakov 2002). The most severe erosional events, accompanied by the transfer of nearshore sediments, are observed during short, but intense, storms of 1–2 days duration. The beach systems are partly regenerated between these storm events (Boldyrev et al. 1990).

Both the northern and western coasts of the Sambia Peninsula are characterized by active sediment dynamics (Fig. 5). The western coast of the Sambia Peninsula is an outstanding example of a positive anthropogenic impact on shoreline evolution, whereby...
large volumes of sediment are provided to the coast from mining activities. Early twentieth century topographic maps show an embayed shoreline. The shoreline was embayed to c. 150 m near Sinyavino settlement, c. 700 m near Yantarny and c. 300 m to the south of Okynevo (Fig. 8). Since 1958 the amber mining factory, located onshore in Yantarny settlement, annually dumped 1.5–4.5 Mt of clayey sand mining waste from the extraction of amber into the Baltic Sea (Bass and Zhindarev 2007; Bobikina and

![Diagram](http://qjegh.lyellcollection.org/)
Karmanov 2009). This dumped material was incorporated into cross-shore and longshore sediment drift. By the 1970s it had resulted in the formation of an 800 m wide and 5.5 km long anthropogenic accretion terrace and local foredune belt along the shoreline between Yantarny and Sinyavino. The volume of sediment accumulated in the terrace was c. 50 Mm³ of sand. As a result, the coastal cliffs have become inactive and overgrown by vegetation. Sediment dumping moved to Pokrovskaya Bay from 1971 and the anthropogenic accretion terrace between Yantarny and Sinyavino has begun to erode. The dumping of 20 Mm³ of sediments into Pokrovskaya Bay between 1971 and 1986 resulted in the total filling of the bay, shifting the shoreline to what was previously 9–10 m water depth and forming a protective beach in front of Pokrovskoye.

Sediment dumping was suddenly halted in 2000 due to the introduction of environmental restrictions. Coastal erosion has subsequently intensified along the whole western coast of the Sambia Peninsula, illustrating the sensitivity of the coastal zone to technogenic impacts. The sediment supply from even small onshore dumps, c. 100–200 m long, can initiate progradation of the coastline of up to 15–20 m per year and any attempt to illegally mine amber can trigger an acceleration of erosion. Landsat images for the study area from 1984 indicate that a wide technogenic terrace still existed at that time. Coastal erosion had decreased the width of the terrace by 2005, the sand spit was completely destroyed and an anthropogenic lagoon adjoined the Baltic Sea. The position of the shoreline was similar to that in 1936, with the exception of Sinyavino Bay, where it was positioned 150–200 m seaward. Sediment dumping from the amber factory resumed in 2007, with sediment volumes of 0.5–1.2 Mm³ annually. This reduced the retreat of the coastline to the south of Pokrovskoye village to 0.8–2.5 m a⁻¹.

Over the last ten years the average rate of coastal erosion of the Sambia Peninsula has been 0.5 m a⁻¹, but the rate and patterns of coastal dynamics differ significantly. The coast between the Baltic

Fig. 6. Monitoring (2016–19) of coastal cross-section of the western coast of Sambia Peninsula near Donskoye village. (a) Representative description of cross-section (2018) with positions of samples. (b) Aerial photograph taken by unmanned aerial vehicle. fg, fluvio glacial deposits; N1, early Neogene. (c) Model of coastal relief with slope angles.
Channel and Taran Cape can be divided into more than ten segments with different dynamics, with rates of shoreline shift from $-8.2$ to $+2.8 \text{ m a}^{-1}$ (Fig. 5). Recent rates of coastal erosion along most part of the western coast of the Sambia Peninsula are locally very high.

The recent rate of retreat of the coastal escarpment in the southern part of Pokrovskaya Bay reached $2.5 \text{ m a}^{-1}$ (2008–18), whereas the long-term rate is $1.4 \text{ m a}^{-1}$ (1936–2013). The coastal escarpment of Cape Peschany retreated by $6–16 \text{ m}$ between 2008 and 2018, with an average rate of retreat over this recent period of $0.6–1.6 \text{ m a}^{-1}$ and a longer term rate of $0.4–0.5 \text{ m a}^{-1}$ (1936–2013).

The technogenic terrace of Sinyavino Bay, formed by mining waste from the amber factory, is eroded according to monitoring levelling and retreated at a rate of $8.2 \text{ m a}^{-1}$ in 2008–18, although the coastal escarpment here is stable. The maximum rates of coastal retreat are observed near Donskoye village. The 15 m high escarpment to the north of Donskoye shifted landward by $80–100 \text{ m}$ along $800 \text{ m}$ of the coastline. The recent and longer term erosion rates are similar: $1.1 \text{ m a}^{-1}$ in the time period 2008–18 and $1.1–1.3 \text{ m a}^{-1}$ from 1936 to 2013.

An analysis of TLS results enabled us to demonstrate a mechanism for the destruction and retreat of the coastal escarpment. The escarpment is characterized by steep slopes and cliffs up to $40 \text{ m}$ high. TLS measurements for the $40 \text{ m}$ high cliffs with steep ($70–87^\circ$) slopes in the southern part of Donskoye village were made from 11 scan stations in August 2016 and 10 scan stations in August 2017 (Fig. 9). Analysis of the digital elevation model allowed us to obtain the volume of changes that occurred at this site over one year (Table 3). As a result of the high value of coastal land and intense erosion (average rate of shoreline retreat $0.25 \text{ m a}^{-1}$ and maximum rate up to $1.4 \text{ m a}^{-1}$), the total length of coastal protection structures on this stretch of coastline is $10.7 \text{ km}$. However, unlike the western coast, the technogenic impact on the northern coast of the Sambia Peninsula has not changed the main trends of the natural processes.

The coastal areas to the west of Filino village are susceptible to large landslides, several hundred metres in diameter, as a result of the combination of the heterogeneous cliff geology and hydrogeology. Dense ferruginized Paleogene sandstones crop out in the lower sections of the coastal cliffs (up to $10–12 \text{ m}$), whereas the upper part consists of unconsolidated Neogene sandy clay (Fig. 5b). The predominant process is cliff destruction caused by debris flows and landslides, together with erosion at the toe of the cliff. The long-term rate of retreat of the coastal escarpment is $0.1 \text{ m a}^{-1}$ (1936–2013) and instrumental measurements from 2008 to 2018 have shown the same rate of erosion. This is because a complex coastal protection project was implemented in Filino Bay from 1987 to 1991. The slope itself was engineered to a new shape, large volumes of sediment were used for beach nourishment and wave absorbers were constructed in the backshore. The programme included reshaping the height of the cliff up to $44–47 \text{ m}$. The most eroded part of the cliff, composed of Neogene sands, was removed and the residual material ($2.3 \text{ Mm}^3$) was dumped in the nearshore. This increased the width of the beach to the west of the dumping site at Filino Bay by up to $140 \text{ m}$ along a $2.5 \text{ km}$ segment and the beach at Primorye village was widened to $110 \text{ m}$. This sand also entered the longshore transport system and maintained the net sediment...
The geological structure of the coastal zone between Filino and Otradnoye villages is very different, with local capes formed of glacial till thought to be the remains of an end-moraine structure (Zhindarev et al. 2012). Glacial tectonics and selective denudation along this stretch of coast have resulted in the formation of several valleys perpendicular to the recent shoreline. At the present time these valleys are associated with intense landslides and surface runoff flow processes. Mass movement and erosional processes are very rapid within the coastal zones of Otradnoye village and Svetlogorsk town. Several coastal segments were straightened by various types of hard coastal protection structures in the 1960s to 1980s, but these have had a less positive effect since the beginning of the 2000s. The longer term (1936–2013) rate of retreat of the coastal escarpment is up to 0.3 m a$^{-1}$. Recent coastal protection measures have stabilized the escarpment.
The height of the coastal cliffs decreases between Svetlogorsk and Rybnoye villages as a result of the occurrence of a wide palaeriver valley and the longer term rate of retreat of the coastal escarpment reaches 0.2 m a$^{-1}$ (1936–2013), while the recent rate is reduced to 0.9 m a$^{-1}$ (2008–18). The recent rate of retreat decreases to 0.3 m a$^{-1}$ to the east, towards the Cape Kupalny escarpment, which consists of sandy and clayey loam (silty clay), although the longer term rate remains at 0.2 m a$^{-1}$. The long pier of Pionersky harbour, perpendicular to the shoreline, has caused the formation of a stable sandy beach to the east of the construction. Mass movement and erosion processes are very active from Pionersky to Cape Gvardeisky, with the exception of local areas with coastal protection structures. Here, the longer term rates of retreat of the coastal escarpment are 0.4–0.7 m a$^{-1}$ (1936–2013) and recent rates have increased to 0.9 m a$^{-1}$ (2008–18).

Offshore research on the marine periphery of the Sambia Peninsula has revealed the wide distribution of boulder bottom and pre-Quaternary deposits and a lack of sand material in the nearshore, so there is limited potential for the onshore movement of sand to maintain beach volumes (Petrov and Lygin 2014).

**Discussion and recommendations for coastal protection**

Analyses of archive maps, RSD and monitoring measurements reveal high erosion rates within the most valuable, from a recreational point of view, segments of the coast of both Russian sectors of the Baltic Sea. Moreover, a comparative study of longer term and recent rates of erosion in the SE Baltic Sea and monitoring observations in the EGoF coastal zone show a recent acceleration of coastal erosion within most parts of the study area. The geological and geomorphological factors determine the long-term evolution of the coastal zone. The most important prerequisite for the relatively rapid coastal erosion in the Russian Baltic is the geological composition and properties of the coastal deposits.

The coasts of the EGoF mostly consist of easily erodible Quaternary deposits (clays and sands). They have evolved under an overall deficit of sediment in the nearshore region, which is partially augmented by numerous boulder belts formed as a result of the erosion of glacial till. The coastal cliffs of the SE Baltic are composed of unconsolidated sandy and clayey Paleogene, Neogene and Quaternary deposits. The relatively small thickness of the layers (1–10 m), the changeable grain size composition (alternating clayey sands, sands and sandy clays, clays and coarse-grained sediments) and multiple points of spring water discharge from three aquifers in Neogene deposits predetermine the conditions for active mass movements. Coastal erosion, coupled with surplus rainfall, is one of the most important triggers of landslides. The main driving forces of the cliff landslides are wave erosion at their foot, frost weathering and precipitation. Fluvial processes, in which temporary waterways in the coastal ledge, fed by precipitation, produce channels, wash away material and cause instability of the gulley walls. The results of offshore investigations have shown a significant deficit of sediment in the nearshore of both study areas; this is one of the most important causes of active coastal erosion.

Analysis of extreme water levels for the whole Baltic Sea showed that the amplitude could reach 3 m for the SE Baltic and 3.5 m for the EGoF for the period 1960–2010. The EGoF experiences the most dangerous storms as a result of particular atmosphere movements (Wolski et al. 2014). The geographical distribution of the storms across the Baltic Sea shows a higher occurrence of storms (>300 for the period 1960–2010) in the EGoF than in the SE Baltic (100–200 for the same time period) (Wolski et al. 2014).
We analysed archival wind data (velocity, direction, gusts) and storm wave generation to demonstrate these changes. Waves more than 1–1.2 m high were accepted as the threshold for coastal storm waves (Boccotti 2000). Data from Kronstadt meteorological station (https://rp5.ru) for the EGoF for the period 2010–19 showed that storm events of >6 h duration with wind speeds >5 m s⁻¹ were sufficient to produce storm waves 1–1.2 m high (Ryabchuk et al. 2011a) (Fig. 10a). There was no significant increase in storm activity during this period and the maximum storm frequency of 30% occurred in 2019, with an average number of storm events in the EGoF of 16% per year.

Data from the D6 platform station in the SE Baltic for the period 2010–19 showed that storm events >6 h duration with wind speeds >12 m s⁻¹ were required to produce storm waves higher than 1–1.2 m (Bobykina and Stont 2015; Figure 10b). There was no significant increase in the occurrence of storm events in the SE Baltic in the time period 2010–19. The peak number of events over ten years was observed in 2014 (2%). The average occurrence for intense events was 0.7% per year.

An increase in the frequency of strong storm events has been noted for both the SE Baltic Sea and the Gulf of Finland in recent decades (Soomere et al. 2007; Ryabchuk et al. 2011a; Wolski et al. 2014; BACC Author Team 2015; Bobykina and Stont 2015). They occur up to four times in every ten years for the EGoF, whereas in the second half of the twentieth century such events occurred only once in every 25 years (Barkov 1989). The impact of this increased storm activity on the coasts of the SE Baltic Sea is reflected in the destruction of coastal protection structures and flooding of inland territories as a result of the erosion of the foredune ridge (Stont and Bobykina 2013; Ryabchuk et al. 2011a; Danchenkov and Belov 2019; Danchenkov et al. 2019; Stont et al. 2019).

Based on the VSEGEI monitoring observations, the most extreme erosion events in the EGoF are controlled by a specific combination of long-lasting westerly or southwesterly storms, which bring high waves to the area in question, high water levels and an absence of stable sea ice during such events. A drastic reduction in beach material was observed after extreme erosion events in the Gulf of Finland (Eelsalu et al. 2015; Sergeev et al. 2018). Based on the TLS data used to assess sand losses after storms, the depth of beach and foredune sediments was reduced by up to 0.9–1.2 m in a single autumn–winter storm event (Sergeev et al. 2018).

Wave activity is still the major driver of coastal processes in the SE Baltic (Kelpšaitė et al. 2011). The Sambia Peninsula has historically been considered as a source for bidirectional alongshore sediment flows (Harlf et al. 2017). Most of the storms are associated with west–NW–north wind directions, the frequency of which is increasing (Kurennoy and Kelpšaitė 2014) and for which the fetch length is at a maximum for this part of the sea. The wave heights in the shallow water along the cliffs of Sambia Peninsula can reach significant values as a result of the large bottom slopes (0.01–0.2 rad), whereas the dissipation of wave energy is much more significant in the accumulation region of Pokrovskoye settlement where the slopes have much lower angles (0.005 rad). Thus steeper bottom slopes, caused by sediment deficits on the underwater coastal slope, lead to a greater energy content of storm waves. These, combined with surge phenomena, increase erosion on the shores of Sambia Peninsula.

Nearshore sand mining, which took place in the nearshore in the 1960s–1990s, and damage to the coastal dunes are the main negative technogenic factors in the evolution of the coastline. The construction of the St Petersburg FPF was an important anthropogenic factor influencing coastal dynamics. The sea-level is a crucial factor influencing the intensity of coastal erosion. The main aim of the FPF is to decrease the water level within Neva Bay during floods. Closing the FPF gates prevents a rise in sea-level within Neva Bay during hazardous westerly cyclones, but at the same time

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<table>
<thead>
<tr>
<th>Coastal Type</th>
<th>Description</th>
<th>Legend No.</th>
<th>Rate of cliff dynamics (m a⁻¹)</th>
<th>Number of measurements for the period 2008–18</th>
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<tbody>
<tr>
<td>Active erosion cliff, active with loose material</td>
<td>Active erosion cliff with loose material</td>
<td>1</td>
<td>Average (mean): -0.24; minimum: -0.7; maximum: -1.1 (26)</td>
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<tr>
<td>Active erosion cliff, active with massive material</td>
<td>Active erosion cliff with massive material</td>
<td>2</td>
<td>Average (mean): -0.24; minimum: -0.7; maximum: -1.1 (26)</td>
<td>2</td>
</tr>
<tr>
<td>Active erosion cliff, active with massive material</td>
<td>Active erosion cliff with massive material</td>
<td>3</td>
<td>Average (mean): -0.1; minimum: 0; maximum: 0.1 (8)</td>
<td>2</td>
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<td>Active erosion cliff, active with massive material</td>
<td>Active erosion cliff with massive material</td>
<td>4</td>
<td>Average (mean): 0; minimum: 0; maximum: 0.1 (8)</td>
<td>2</td>
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<tr>
<td>Active erosion cliff, active with massive material</td>
<td>Active erosion cliff with massive material</td>
<td>5</td>
<td>Average (mean): 0; minimum: 0; maximum: 0.1 (8)</td>
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<td>Active erosion cliff with massive material</td>
<td>6</td>
<td>Average (mean): 0; minimum: 0; maximum: 0.1 (8)</td>
<td>2</td>
</tr>
</tbody>
</table>

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Table 2. Parameters of coastal dynamics for different coastal types of the southeastern Baltic based on the classification of Shepard (1948).
the water level on the outer side of the FPF (to the west of the construction) is higher than under natural conditions. As a result, the influence of the FPF on coastal stability varies with location. Neva Bay has been much better protected from erosion since the FPF began operation in 2011. By contrast, the coastline outside the FPF has experienced more severe effects from waves associated with increased water levels outside the FPF during storm surges.

The earliest coast protection measures in the EGoF, which aimed to stop erosion and protect sandy beaches, began at the end of the nineteenth century. The hard engineering structures, mostly groynes emplaced perpendicular to the shoreline and sea walls without sand nourishment, were not effective as a result of the deficit of sediment. Most of the structures are badly damaged and have intensified beach erosion with, in some instances, a full loss of sand material both on land and offshore. As a consequence, they have not protected the coast and have, in fact, reduced its recreational value. The first Coast Protection Plan for the most eastern part of the Gulf of Finland, the General Scheme of Coast Protection, was developed in the late 1980s, but was not realized. The only successful attempt at the protection of this part of the coast was an experimental beach nourishment scheme in Komarovo village in 1988 (Sergeev et al. 2018). The effect of that sand nourishment is now depleted.

The first coastal protection structures along the Sambia Peninsula coast, mostly groynes perpendicular to the shoreline, were constructed before the Second World War. Their effectiveness has decreased over time, together with a growing deficiency of sediment in the nearshore. Hard coastal protection constructions (sea walls) have been the main method of minimizing erosion since the 1960s. These constructions have prevented some emergency situations in the coastal resorts, but, at the same time, they have initiated a deficit of sediment that has decreased the width of the beach and accelerated the erosion of the adjoining coastal segments.

The results generated in this study were recently incorporated into the Coast Protection plans of Kaliningrad Region and St Petersburg City. The coasts of the Sambia Peninsula can be protected using complex engineering structures—that is, sand nourishment with the construction of artificial beaches to prevent the impact of storms on the base of the escarpment and to compensate for the deficit of sediment; wooden groynes perpendicular to the shoreline to decrease the erosion of the artificial beaches and gabions at the base of the coast escarpment and stabilization of its slope to prevent landslides. These complex coastal protection measures started in the resort towns of Zelenogradsk and Svetlogorsk in 2016–19 within the framework of the development of the State Program of Kaliningrad Region.

The St Petersburg City Marine Coast Protection Program was developed in the EGoF in 2015–16. This is based on both the Master Plan of St Petersburg city and the analyses of distribution of coastal erosion hotspots, erosion rates, coastal zone geology and morphology, and existing coastal protection constructions. The Program has identified five areas of high priority for coastal protection within Kurortny district (to the west of the FPF), two areas on the west coast of Kotlin Island and six areas within Neva Bay. The key mode of coastal protection is sand nourishment, together with groynes or wave-breakers within the most heavily eroded and most valuable coastal segments. Unfortunately, realization of the Program has been postponed due to legislation and financial problems.

**Conclusions**

A comparative analysis of historical data (since 1936) and recent coastal monitoring measurements for the last ten years shows an acceleration of coastal retreat of up to 1.4–1.6 m a⁻¹ in both Russian sectors of the Baltic Sea. This activation of hazardous exogenous geological processes in coastal zones during the last decade is related to climatic changes and sediment deficits. A combination of tectonic (vertical movement of the Earth’s crust), geological (geotechnical properties of coast-forming deposits) and geomorphological factors controls the long-term evolution of the coastal zone. The coasts of the EGoF and the coastal cliffs of the Russian SE Baltic are mainly formed of easily destructible clastic deposits of different grain sizes (clay, silty sand and mixed sediments). Coastal erosion at the toe of the slope—coupled with surplus rainfall, numerous groundwater outlets and frost weathering—is the main trigger of landslides. Anthropogenic influences have recently become an important factor, both negatively and positively affecting the evolution of the coastline, and comparable in potency to natural processes, especially in the Kaliningrad Region.

The short-term, but most extreme, erosion in the coastal zone is associated with long-duration storms combined with higher levels of surge water. Such storms occur most frequently during the autumn–winter period and cause significant erosion where stable sea ice is absent. The frequency of such storm events has recently increased as a result of the warming climate. Monitoring of coastal geological processes and forecasting of the main trends in the evolution of the Baltic coast of Russia are very important in informing plans for coastal protection measures and to help ensure the future sustainable development of Russia’s coastal territories.

**Scientific editing by Cherith Moses; James Lawrence**

**Acknowledgements** This paper was prepared within the frame of the EMODnet-geology project. We are grateful to the reviewers for very useful and important comments and to Cherith Moses for helping to improve the English in our paper.

**Author contributions** DR: conceptualization (lead), investigation (equal), methodology (equal), writing – original draft (lead), writing – review and editing (equal); AS: conceptualization (equal), data curation (equal), investigation (equal), methodology (lead), software (equal), visualization (lead), writing – original draft (supporting), writing – review and editing (supporting); EB: investigation (equal), methodology (equal), writing – original draft (equal); VK: data curation (equal), investigation (supporting), methodology (supporting), writing – original draft (supporting); IN: data curation (equal), investigation (equal), methodology (equal); OK: investigation (supporting), writing – original draft (supporting), writing – review and editing (equal); LB: data curation (equal), investigation (equal); VZ: conceptualization (equal), investigation (equal), writing – review and editing (equal); AD: data curation (equal), investigation (equal), methodology (equal), writing – original draft (supporting), writing – review and editing (supporting).
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