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Coastal dynamics of the eastern Gulf of Finland, the Baltic Sea: toward a quantitative assessment

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Abstract The easternmost part of the Gulf of Finland is characterized by intense coastal processes dominated by wave erosion. Reliable prediction of the coastal zone development, as well as effective strategy for coastal protection, demands a quantitative assessment of beach transformation and volume of sediment loss as a result of extreme storms. The main goal of this study based on results of terrestrial laser scanning was to establish volumes of eroded, transported, and redeposited sand during storm surge events that occurred between 2012 and 2017, and to verify a mathematical model of beach profile changes within key areas located in the Kurortny District of St. Petersburg (Gulf of Finland, Baltic Sea), where the longest set of levelling and terrestrial laser scanning was conducted. The resulting detailed 3D GIS models of coastal relief, based on high-resolution geodesic surveys, produced a highly reliable database of beachface transformation under the extreme storm impact and quantitative assessment of erosion volumes and sediment loss.

Keywords • coastal erosion • beach deformation • storm events • sediment loss • numerical modelling • terrestrial laser scanning

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INTRODUCTION

In contrast to the shores of the southern Baltic Sea (Harff, Meyer 2011; Uścińowicz 2003; Musielak *et al.* 2017 etc.) and Estonia (Orviku 1974; Tonisson *et al.* 2013 etc.) serving for a long time as the focus of numerous studies, the coastal zone of the eastern Gulf of Finland has not been considered as an area of active morphodynamics, and until recent years has not attracted the attention of researchers.

Recent advances in geological and geomorphological methodology and technology using multiple instruments such as aerial and terrestrial laser scanning, LIDAR, high-resolution video-survey using

unmanned aerial vehicle, georadar has provided data useful in 3D geomorphometric visualization of beach and escarpment surfaces, and quantitative access and monitoring of coastal deformation whole over the world (Abdulmuttalib 2006; Hobbs *et al.* 2010; Schmidt *et al.* 2013; Colenutt *et al.* 2015; Kim *et al.* 2017; Le Mauff *et al.* 2018 etc.).

In Baltic Region coastal studies based on airborne (ALS) and terrestrial (TLS) laser scanning have been successfully provided both for areas of active cliffs in unconsolidated sediments and accumulative sand coasts. 2 km-long section of the southern Baltic Sea cliff coast of Wolin Island (Poland), composed of unconsolidated Pleistocene sediments allowed cal-

culating volumetric changes of a coast in 2008–2012 (Dudzińska-Nowak, Wężyk 2014). The same study based on TLS was organized for the northern coast of Sambia Peninsula (Kaliningrad region, Russia) (Lugovoy *et al.* 2016).

Combining of ALS and TLS was used for monitoring of beach segment of the Pirita Beach (Tallinn Bay) (Julge *et al.* 2014). ALS flights, conducted in different altitudes and seasons, yield sub-decimetre accuracy for detecting contemporary coastal processes of Tallinn Bay (Grünthal *et al.* 2014). TLS, which provides fast and accurate acquisition of high-resolution spatial data, permitted to receive an information about the volume and size dynamics together with deflation/accumulation schemes and to compile 3D elevation maps for the Vistula Spit (southeast coast of the Baltic Sea) (Volkova *et al.* 2016).

The main goals of the reported study based on the results of terrestrial laser scanning (TLS) were:

- to estimate volumes of eroded, transported, and redeposited sand over the storm surges occurred between 2012 and 2017;
- to measure volumetric beach transformation during the storm surge of 5–7 December 2015;
- to verify the mathematical model of beach profile deformation within key areas located in the Kurortny District, where the longest set

of levelling and terrestrial laser scanning was conducted, and to produce a predictive model of future beach behaviour.

Study area. Coastal plain shoreline of the eastern Gulf of Finland, composed by Quaternary deposits (Petrov 2010), are characterized by very low rates of glacioisostatic uplift ($1\text{--}3\text{ mm year}^{-1}$; Harff *et al.* 2017) and a near zero rate of recent sea-level rise. This factor is typically expected to protect the coast from intense erosion.

However during past ten years, coastline of the eastern Gulf of Finland have been repeatedly impacted by erosional events. This includes the most valuable areas from recreational, economic and social points of view, such as the northern coastal zone within the limits of Kurortny (meaning “Resort”) District of St. Petersburg (Fig. 1) and part of southern coast between Lebyazhye village and St. Petersburg Flood Protection Facility. According to the results of coastal monitoring undertaken by A.P. Karpinsky Russian Geological Research Institute (VSEGEI), the remote sensing data show that the average rates of shoreline retreat within the Kurortny District are 0.5 m year^{-1} , the maximum rates reach 2 m year^{-1} (Sukhacheva and Kildushevsky 2006; Ryabchuk *et al.* 2009), whereas the berm or dune scarp retreat can reach 5 m during one extreme storm event (Tonisson *et al.* 2012).

The total beach recession in the period of 1990–

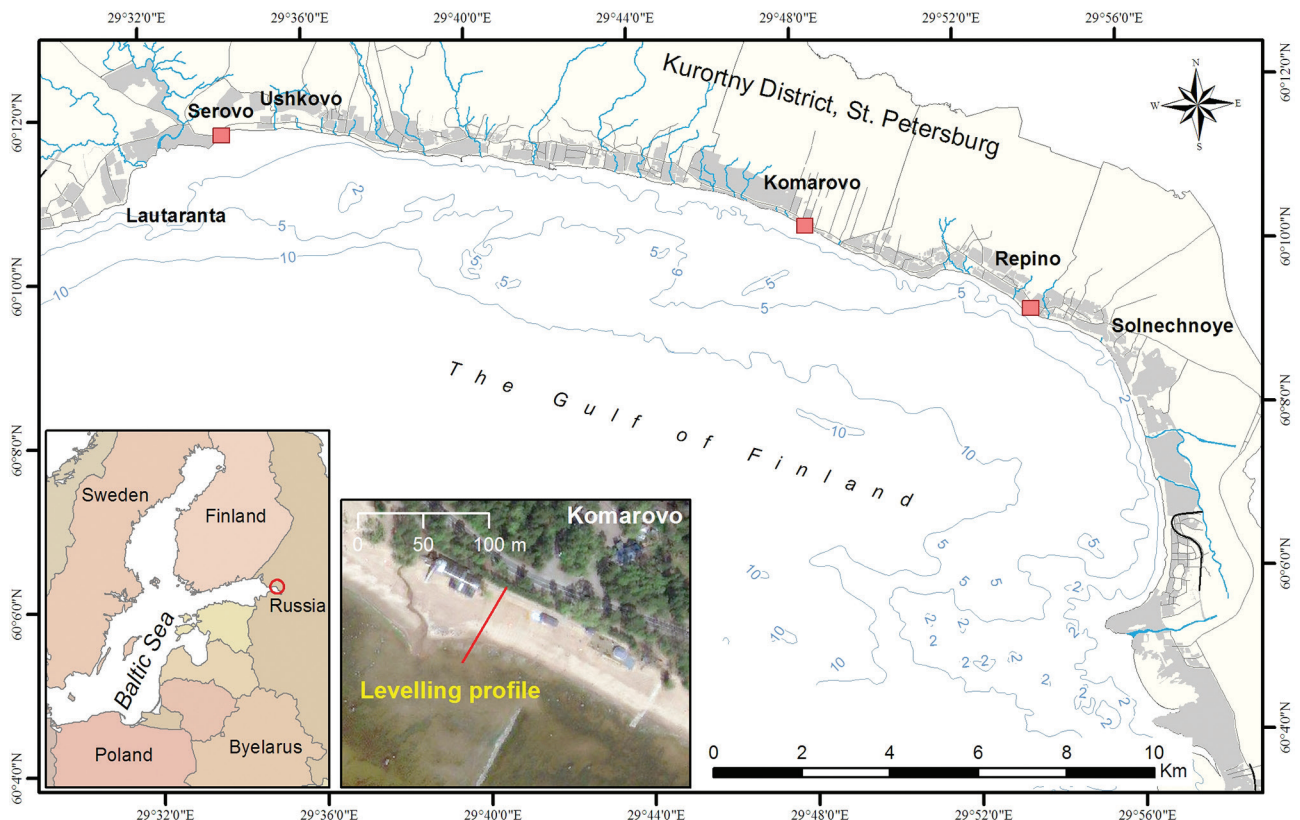


Fig. 1 Location map of the study areas of terrestrial laser scanning (red squares) along the northern coast of the eastern Gulf of Finland within the Kurortny District of St. Petersburg

2005 reached values as high as 25–40 m in the vicinity of Serovo, Ushkovo, and Komarovo villages. The recreation value of the coasts is reduced, especially within some areas of intense erosion that reached the upper part of nearshore coastal slope (shoreface). From the total length of about 45 km of this coastal zone, ~19 km is composed of boulders, formed as a result of glacial deposits (till) erosion (Kosyan *et al.* 2013).

Coastal monitoring reveals an acceleration of erosional processes during last ten years because of higher frequency of extreme storms. Significant loss of beaches, retreat of erosional scarp, damage to coastal dunes and recreational infrastructure initiated the St. Petersburg City Coast Protection Program, which has been developed in 2008–2016. Reliable prediction of the coastal zone dynamics, as well as effective strategy of coast protection demands an accurate quantitative assessment of beach morphodynamics and volume of sediment loss as a result of extreme storms.

Study area within Komarovo village can be subdivided into two parts separated by a small river. The eastern part is characterized by significant anthropogenic impact on beach morphology and presence of numerous recreational facilities (recreation area “Beach Paradise”). Western part of the study area remains in a natural condition. The beach is more than 30 m wide and consists of a beach ridge and berm. In the backshore, the foredune reaches a height of 2.0–2.5.

As the beach is heavily eroded within the boundaries of the recreation area (Ryabchuk *et al.* 2011, 2014), the coastal protection measures have been carried out since 2004 (e.g. construction of short groins with large boulders and breakwaters, local artificial beach nourishment, etc.). Coastal protection, as well as construction of wooden recreation facilities, have been executed without taking into account coastal dynamic processes and led to further beach degradation.

Previous research. The first research of coastal zone dynamics of the eastern Gulf of Finland has been carried out by scientists of St. Petersburg (Leningrad) University in 1975–1990 (Barkov 1991; Logvinenko *et al.* 1988). These studies included analyses of grain-size and mineral composition of the beach sediments, as well as first attempts at quantifying longshore sediment transport direction and volume.

In 1987–1990, field morphodynamic observations were carried out by Estonian scientists (as a contribution to “Geology of the Gulf of Finland” volume; Orviku, Granö 1992). The result of levelling and photo archiving provided the framework of this research a unique source of information for comparative analyses of coastal development along the eastern Gulf of Finland. Since 2000, VSEGEI has undertaken annual coastal observations in this coastal zone. Within Kurortny District sites it has included visual obser-

ations, beach sediment sampling, remote sensing data analyses, and since 2010 – onshore levelling and ground-penetrating radar imaging.

In the nearshore (depth: 3–10 m), the full coverage of side-scan sonar data was obtained in 2006–2015 (464 profiles, 107.3 km²), seismic-reflection subbottom profiling was carried out along 51 cross-shore profiles (total length: 124 km), two areas were studied using multibeam echosounder (3.14 km²), and 286 surface sediment samples were collected for textural analyses (Ryabchuk *et al.* 2011; Petrov, Lygin 2014).

Based on the results of statistics analyses of coastal monitoring and hydrometeorological data during 2004–2010, it was demonstrated that the most extreme erosional events occur within study area when three unfavourable conditions take place simultaneously: 1) long-lasting west or south-west storms; 2) high water level, and 3) the absence of stable sea ice (Ryabchuk *et al.* 2011). The results of coastal monitoring for 2011–2017 support this hypothesis. The extreme erosion events led to significant damage of the coastal dunes, which was observed in 2011, 2013 and 2015 – after severe autumn-winter storms of W, NW and SW directions, accompanied by water-level rise in the absence of ice (Fig. 2).

MATERIALS AND METHODS

Topographic profiles. Annual levelling has been carried out along 10 cross-shore beach profiles since 2010. A profile established in 1980s was chosen as a key reference for most frequent measurements (after each extreme storm) and modelling. Data of onshore levelling carried out since 2011 using optical level CST/berger SAL, were used for long-term analysis of coastal retreat in the Komarovo village. In 1988, 1989 and 1995 levelling was accomplished using Carl Zeiss Reductions Tachymeter Theodolite Dahlta 010 B. A reinforced concrete pole of electric power supply line was used as reference benchmark for all levelling profiles.

Terrestrial laser scanning (TLS). In 2012–2013, the laser scanning of the beachface was carried out along 500 m of the shoreline in Komarovo village in the framework of the Russian-Finnish project “Climate Proof Living Environment” (CliPLivE) of southeast Finland-Russia ENPI CBC 2007–2014 Programme. Measurements were conducted during two periods: October 2012 (period of beach stabilization) and November 2013 (immediately following several intense storms, e.g., so called “Saint Juda” hurricane). GIS analyses have shown that during each storm sand material is actively removed from the backshore (upper berm), followed by formation and rapid retreat of the foredune scarp (Ryabchuk *et al.* 2014).



Fig. 2 Cycles of coastal erosion and accretion caused by alternation of storm surges and normal hydrodynamic conditions (photos by D. Ryabchuk)

In 2015–2017, TLS was carried out in the frame of the project of General Coast Protection Plan development, undertaken by State Geological Enterprise “Mineral” together with VSEGEI within three beach areas of the Kurortny District (St. Petersburg). For Komarovo village site, TLS data were collected every summer from 2012 to 2017, for two other sites – from 2014 to 2017. TLS was also conducted before and after storm events of December 2015. This technol-

ogy allowed calculation of the volume of transported beach sand. The data of relief transformation formed the basis for establishing key parameters representative of the peak storm conditions. The 3D laser scanning covered the beach surface and the foredune ridge or scarp.

The length of a coastline scanning is about 400 m in Komarovo village, 190 m in Repino village and 150 m in Serovo village (Fig. 1). The laser scanning

data were used only on the beach surface without vegetation cover to avoid sediment surface calculation errors. The Komarovo village scanning site is characterized by the greatest number of TSL surveys and completeness of TSL data. The intersection areas of the annual TLS surveys in the Repino and Serovo villages are not sufficient to obtain reliable results for calculating volumetric changes. In this case, for the intersection zone of all surfaces, profiles were constructed based on the changes that took place from 2013 to 2017.

TLS was carried out by “Alpha-Morion Ltd.” using the terrestrial laser scanner “RIEGL VZ-400” (Austria) from twelve 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 Javad Legacy-E satellite. Post-processing was performed using “Pinnacle” software. Horizontal and vertical fixes of the position marks were made by a total station “LEICA TS06 Ultra (2)” (Austria).

Data processing. Cloud of XYZ points was imported to ArcGIS software. Gridding of XYZ data allowed to create a high-resolution (grid cell size: 10 cm) digital elevation model of the beaches for the subsequent surface analysis. The calculation of beach surface transformation was executed with the “Cut Fill” tool to calculate the difference between beach surfaces of each year of laser scanning. The result was a grid that contained large volume of data points showing erosion and accretion areas on the beach.

Numerical modelling. The model CROSS-P tested in the coastal zone of the Gulf of Finland (Leont'yev *et al.* 2015a, b) was used for calculation of the probable parameters of the storm and coastal profile changes. The model can both reproduce the erosion dynamics of the beach and reflect the main features of sand accumulation within a coastal profile. Coastal profile modelling allowed the estimation of the range of cross-shore profile changes during a storm event and to calculate the volume of material lost from the beach during the fairweather wave conditions. In addition, the model considers the overtopping of the foredune during the storm. The types of profiles predicted by the model are consistent with the known empirical criteria.

Forecast of coastal recession. The applied forecasting method is based on an assumption that the coastal profile behaviour is determined by the altering strong and weak wave impact. During extreme storm events, the material eroded from a foredune ridge or scarp is accumulated on the beach. In the period between the storms, the beach is eroded and redeposited sediments are transported away from the coast largely due to impact of the incident waves in the study region. To predict coastal recession, the wave-induced

bed deformations are simulated by using the model CROSS-P (Leont'yev *et al.* 2015a). Typical scenarios of storm events (including strengthening, maximum, and decaying stages) and averaged wave conditions between the storms are used as input in the model (Leont'yev *et al.* 2015b). A key parameter to forecast coastal recession is the frequency of extreme storm impacts. The greater the number of storms over a given time interval, the greater is the distance of coastal retreat.

Hydrometeorological database. Hydrometeorological analysis was based on the database of the State Institution “Saint Petersburg Centre for Hydrometeorology and Environmental Monitoring with Regional Functions”.

RESULTS

Storm parameters (2010–2017). As mentioned above, since 2010 the beaches within the study area have been affected by extreme erosion events that led to substantial damage to the coastal dunes during three time periods in the fall-winter of 2011, 2013 and 2015, when, due to warm fall, the ice cover in the eastern Gulf of Finland was absent. According to data of the State Institution “Saint Petersburg Centre for Hydrometeorology and Environmental Monitoring with Regional Functions”, during 24–28 November 2011, W and SW wind speed increased by 20–21 m s⁻¹. The water level rise outside the Flood Protection Facility reached 190 cm. It is important to mention that it was the first time when the water gates here were closed for protection of St. Petersburg and the Neva Bay coasts. As a result, the water level behind this protective structure did not exceed 135 cm, but outside (in our study area) flood level and, consequently, storm surge impact increased (Andreev *et al.* 2013).

On 29 October 2013, the “Saint Juda” hurricane with SW wind speed up to 20 m s⁻¹ reached the study area. According to modelling (www.meteo.pl), wave height in the open part of the gulf near Kurortny District was more than 3 m. Water level measured by weather stations in Shepelevo village and Primorsk was higher than average by 86 cm and 77 cm, respectively. According to visual observations, storm water surge within study area was 1.5–2 m.

In December 2015, cyclonic activity was very intense. During that month four active Atlantic cyclones have been observed that led to high sea-level rise and severe storms. During the most extreme storm of 5–7 December 2015, the wave heights in the open part of the gulf were 3–4 m (www.meteo.pl) and wind speed (during gusts) reached 23 m s⁻¹. According to visual observations, storm water surge within study area was 1.8–2.0 m.

Sediment texture. To calculate the beach profile dynamics, several textural characteristics of beach and shoreface deposits were analysed. Deposits of the Komarovo beach are characterized by medium-grained sand (0.5–0.25 mm) and change from fine (0.25–0.1 mm) and medium-grained sand at the upper part of the beach to coarse (1.0–0.5 mm) and medium-grained sand near the shoreline. On the underwater slope a thin layer of medium and fine sands covers escarpments of moraine and coarse deposits (including boulders, cobbles, and pebbles).

Deposits of beach surface at Serovo village are represented mostly by medium-grained sand with coarsening of mean grain size from the upper part of the beach (fine and medium-grained sand) to the shoreline (coarse and very coarse sand [1.0–2.0 mm]). The underwater slope deposits are represented by medium and coarse-grained sand.

Grain size distributions of samples of beach surface deposits at Repino village showed prevalence of coarse and very coarse-grained sands. On the shoreface of Repino village, a system of bars is composed by fine-grained sands; with pebble, boulders, and moraine deposits between bars.

Levelling. Study profile in Komarovo village is located in the area of experimental sand nourishment, undertaken in 1988 (Fig. 3). As it shown in Fig. 3, in 1987 the terrace width was approximately 9.5 m (distance from promenade) and the erosional scarp was very sharp and steep. Along a 430 m long section of the coast at Komarovo village, a 2-m-high artificial beach was created. The total amount of sand nourishment was 32250 m³ (Kosyan *et al.* 2013). In 1988, the beach-face escarpment moved 17.5 m seaward and during the first year (1988–1989) of artificial beach phase, the equilibrium profile attained a gentler slope and the scarp retreated to 3.5 m. According to surveys since 1989, the average annual rate of retreat of the terrace scarp was 0.86 m year⁻¹. The maximum rate of shore erosion was recorded in the 2011–2012 storm season and reached 6.5 m year⁻¹.

Terrestrial laser scanning. Comparative analyses of numerical relief surfaces having the largest intersection area (2012 and 2017), were carried out for the

area of 14.160 m² (417 m length of the beach). Spatial distribution of erosion and accretion areas is the same as for each TLS site (Serovo, Komarovo, Repino): intense erosion of backshore, foredune scarp, and mainland escarpment retreating, and deposition in the central and lower part of the beach. Total volume of eroded material in the period of 2012–2017 was 1.817 m³, with the volume of redeposited sand of 992 m³. Sediment loss reached 824 m³ (Fig. 4).

In order to analyse the sediment balance on the beach for each year, a shore segment (91 m longshore length, 2800 m²) was selected in the eastern part of the scanning area. This site was presented in all TLS surveys, which makes it possible to compare the inter-annual dynamics of volumetric redistribution of sand on the beach. The results of the comparison are given in the Table 1.

Storm deformation analyses based on TLS. The intersection area of TLS survey of August and December 2015 has 4000 m² (203 m longshore length) (Fig. 5). Results of calculation have shown that after storm of 5–7 December 2015, 915.2 m³ of sand was removed along the segment of the sandy beach. Coastal escarpment and foredune slope and crest (including coastal terrace surface behind the foredune) were most intensely threatened by erosion. Area of sand redeposition was located in the central part of the beach profile, where slightly convex surface (or ridge) was formed. Total volume of eroded sediment material was 465.1 m³, volume of deposited material – 453.6 m³, non-recoverable sediment loss – 11.5 m³. Length of sand escarpment retreat within the anthropogenically disturbed part of the study area was 2.5–3 m (Fig. 5C), while foredune slope in the adjacent (“natural”) part of the coast shifted 1.5 m landward, forming active scarp.

A similar situation was observed in Repino and Serovo villages TSL sites, where the coastal scarp was eroded by 2.0 m and 0.5 m, respectively, and part of the sandy material was deposited in the lower part of the beach (Fig. 5C). By September 2016, the sand from the lower part of the beach was eroded and partially moved to the upper part of the beach. As a result of gravitational slope processes, the slope of the coastal scarp was collapsed. The abrasion cav-

Table 1 Volumes of sand material displaced in the beach zone according to TLS data from 2012 to 2017

| Period | Sand accum. (m ³) | Sand loss (m ³) | Budget (m ³) | Area of sand accum. (m ²) | Area of sand loss (m ²) | Budget of linear meters (m ³ m ⁻¹) |
|-----------|-------------------------------|-----------------------------|--------------------------|---------------------------------------|-------------------------------------|---|
| 2017–2012 | 176.84 | 589.9 | –413.06 | 1032 | 1844.83 | –4.5 |
| 2017–2016 | 304.83 | 64.17 | 240.66 | 1992.58 | 843.1 | 2.6 |
| 2016–2015 | 60.71 | 451.79 | –391.08 | 672.66 | 2165.64 | –4.3 |
| 2015–2014 | 226.07 | 23.9 | 202.17 | 1916.75 | 528.59 | 2.2 |
| 2014–2013 | 114.82 | 318.84 | –204.02 | 831.42 | 1607.3 | –2.2 |
| 2013–2012 | 60.72 | 299.07 | –238.35 | 1001.83 | 1896.78 | –2.6 |

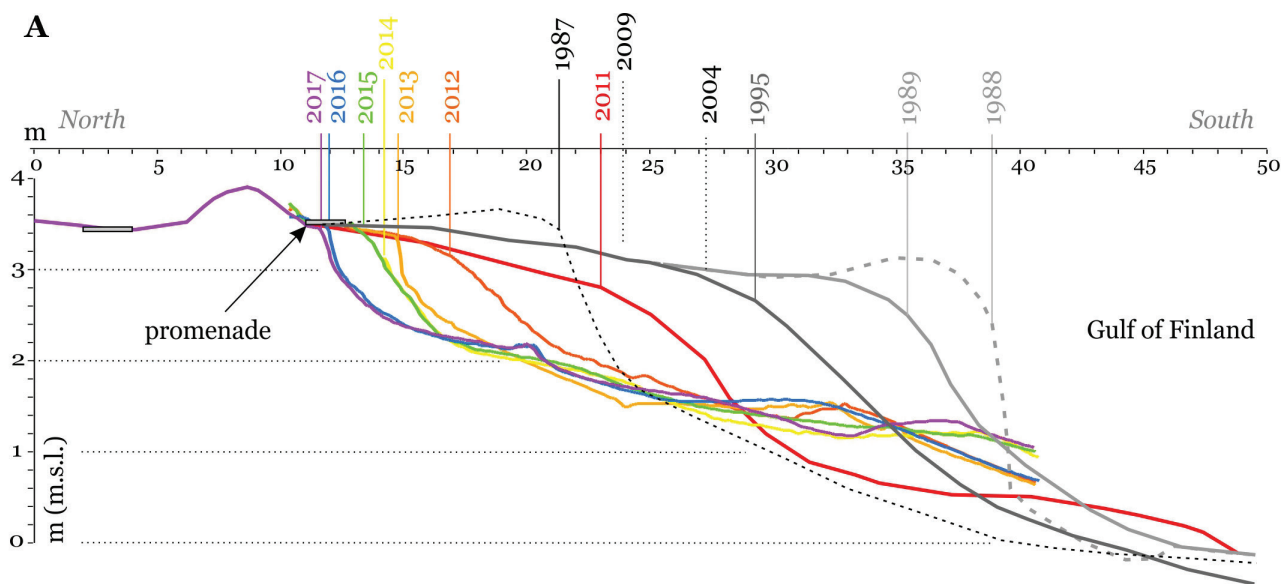


Fig. 3 Dynamics of beach erosion in the area of artificial beach backfilling performed in 1988 in Komarovo village. Levelling profiles from 1987 to 1995 according to K. Orviku data, from 2011 according to VSEGEI data (A). Series of photographs of the place of profiling (B) (1988–1990 photos by K. Orviku, 2003–2013 photos by D. Ryabchuk, 2015–2016 photos by A. Sergeev)

ity formed during the storm was partially buried. In the subsequent non-storm years, there was an insignificant flattening of the escarp without noticeable changes in the beach profile.

Storm deformation analyses based on coastal profile modelling. It is important to ascertain the parameters of the December 2015 storm in the studied

coastal area (eastern Gulf of Finland). Unfortunately, the water level and wave heights were not measured in the study area during the storm period. It is possible to estimate these characteristics by using the modelling of storm-induced bed deformation. Commonly, the coastal modelling aims to predict changes in the coastal profile for the known wave conditions.

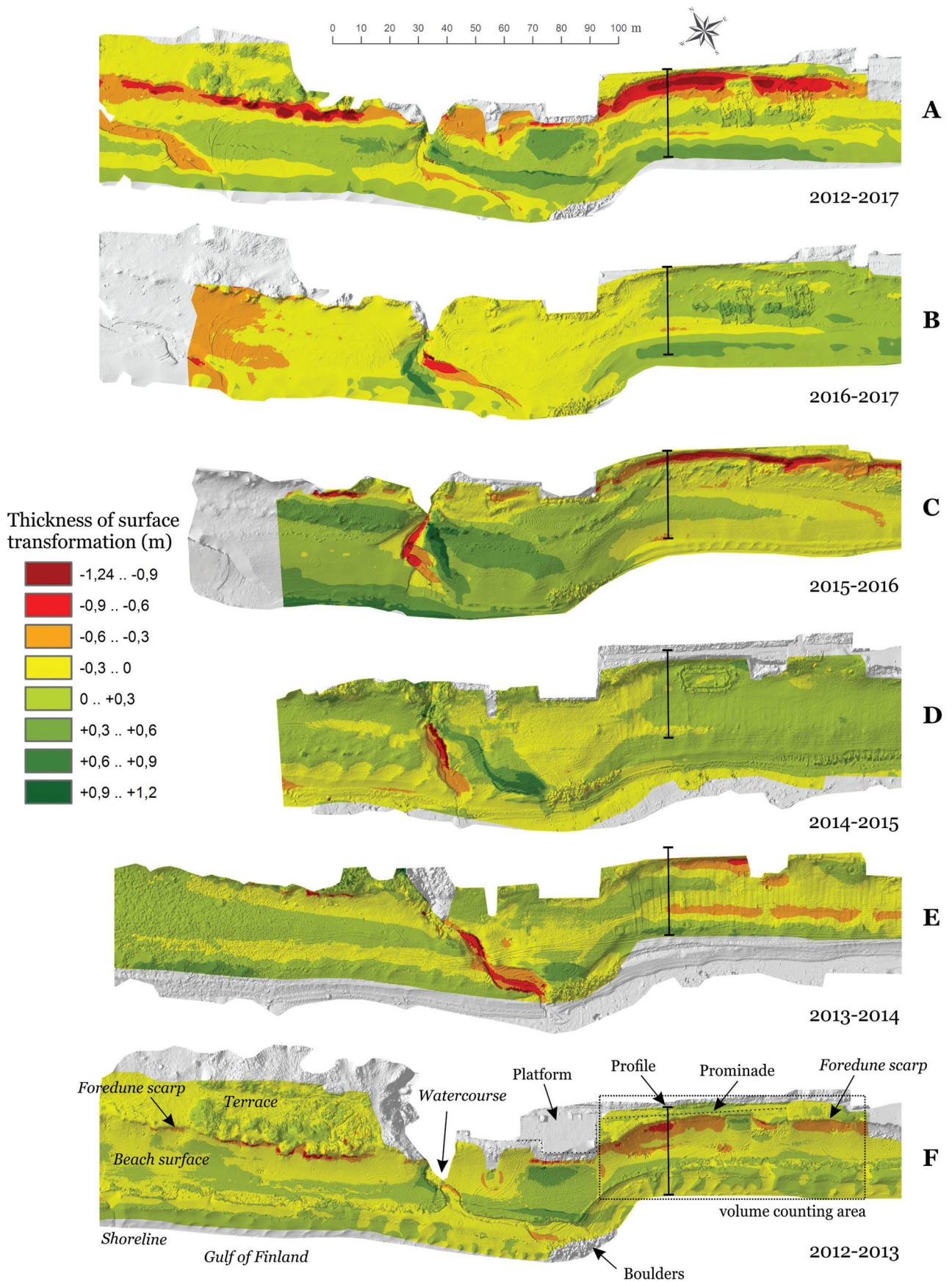


Fig. 4 The thickness of the deformation layer of the beach and foredune surfaces in Komarovo village from 2012 to 2017 according to the TLS. 2012–2017 (A). 2016–2017 (B). 2015–2016 (C). 2014–2015 (D). 2013–2014 (E). 2012–2013 (F)

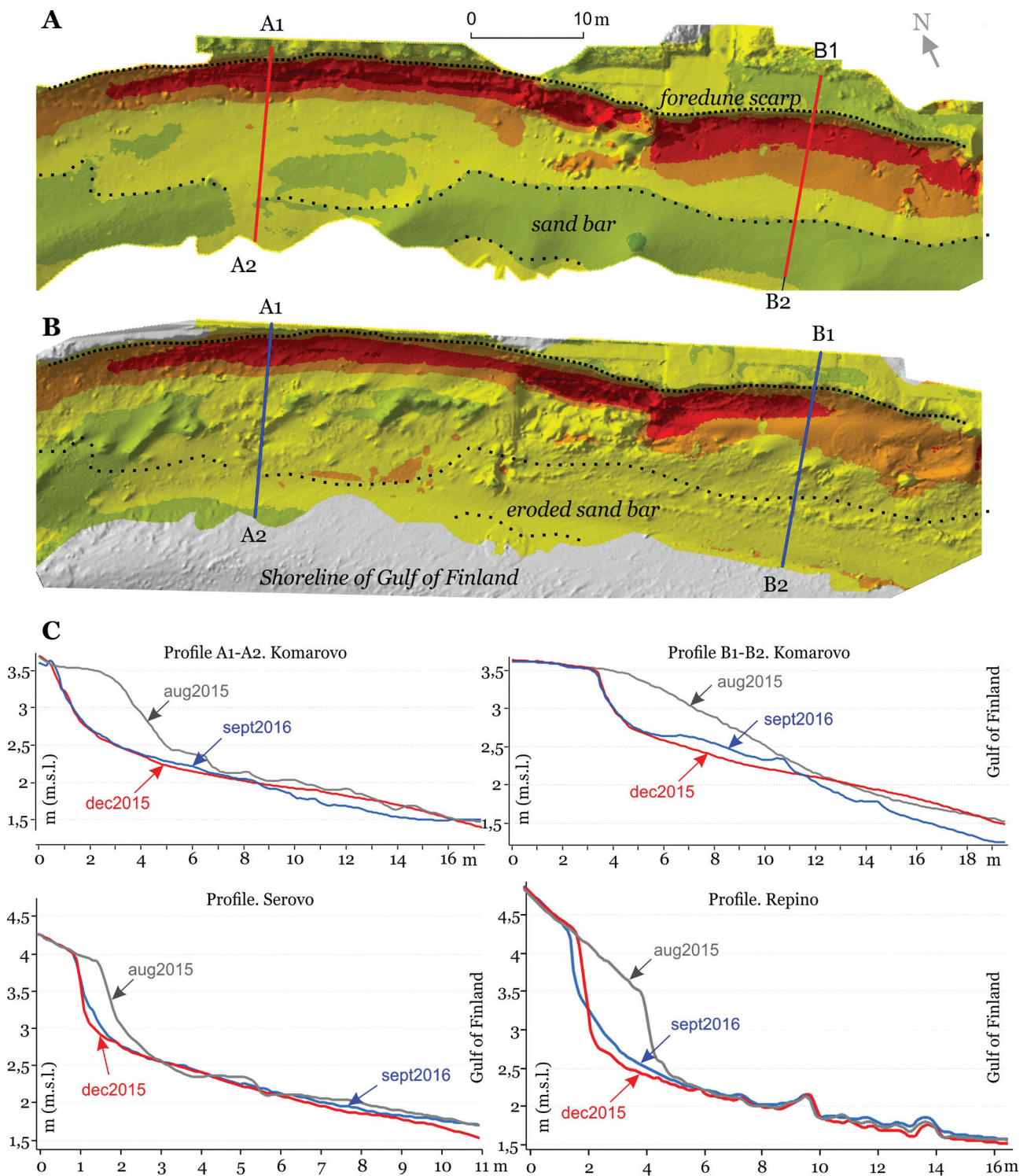


Fig. 5 Changes in beach sand thickness according to TLS data. For digital elevation model (DEM) before the storm in August and after the December 2015 storm (see Fig. 4 for legend) (A). For DEM after the December 2015 storm and in August 2016 (B). Deformation of the beach and foredune profiles in Komarovo, Serovo and Repino villages (C)

Dune erosion and recession are mainly observed during the peak of storm impact when the maximal water level is reached. Hence, this phase of storm is of special interest. First of all, we assume that wave heights and periods during the peak of the December storm could be close to parameters typical for severe storms in the eastern Gulf of Finland (Barkov 1991; Leont'yev *et al.*

2015a, b). With this assumption, the problem is simplified. Now the modelling of bed profile changes is only required for various heights of storm surge and different durations of the storm maximum. The required values of storm surge and durations would correspond to the condition of the closest coincidence of computed and observed displacements of the dune profile.

Calculations take into account that due to curvature of a coastline contour the waves come to Serovo village with a greater angle than to villages Komarovo and Repino relatively to the shore normal. Comparison of modelling results with observed data is shown at Fig. 6. Despite some deviations in the lower part of a beach, calculations faithfully reproduced the recession of the foredune. Thus, based on the obtained results, one can characterize the storm peak in December 2015 by approximate values given in the Table 2. Wave parameters (significant height and spectral peak period) refer to the open part of the Gulf of Finland.

DISCUSSION

Analyses of annual coastal escarpment retreat since 1989 allowed establishment of two important trends. First of all, it is obvious that the rate of coast retreat is not linear but uneven. For the years without extreme storm events, the mean rates of retreat are less than 0.5 m year^{-1} , whereas the average value for stormy years is 3.3 m year^{-1} . The other important feature of annual beach deformation is recent acceleration of coastal escarpment retreat, which has been 0.56 m year^{-1} in 1989–2009 and reached 1.45 m year^{-1} in 2009–2017.

Analyses of TLS results permitted to establish mechanism of beach morphodynamic response due to extreme storms. Comparison of relief surfaces over the years made it possible to identify the most dynamic zones of the backshore of the coastal zone. In the stormy years, a sharp degradation of the foredune and coastal escarpment is observed that is accompanied by sharp reduction in the thickness of sand deposits by 0.6–1.2 m in a narrow strip of the backshore. The surface of the beach in turn undergoes less noticeable transformations, mainly with a sediment thickness decreasing in the upper and lower parts of the beach to 0.3 m, and increasing of sand thickness to 0.3–0.6 m in the central and beachface zones in the form of a discontinuous bar. Separately in the scanning area, it is possible to distinguish the migration zones of the stream mouths, shifting by 60 m in different directions along the coast, with a predominant eastward direction.

The mechanism of redistribution of sand on the beach for one annual cycle is expressed in gradual smoothing of the coastal profile, landward displacement of the coastal escarpment edge, relative increasing of the beach width and gradual rising of the coastal escarp foot above sea level. Furthermore, noticeable deformations of the coastal profile occur exclusively in stormy periods, while in the non-storm seasons, the beach profile remains almost unchanged. Sand accumulation occurs mainly through the activ-

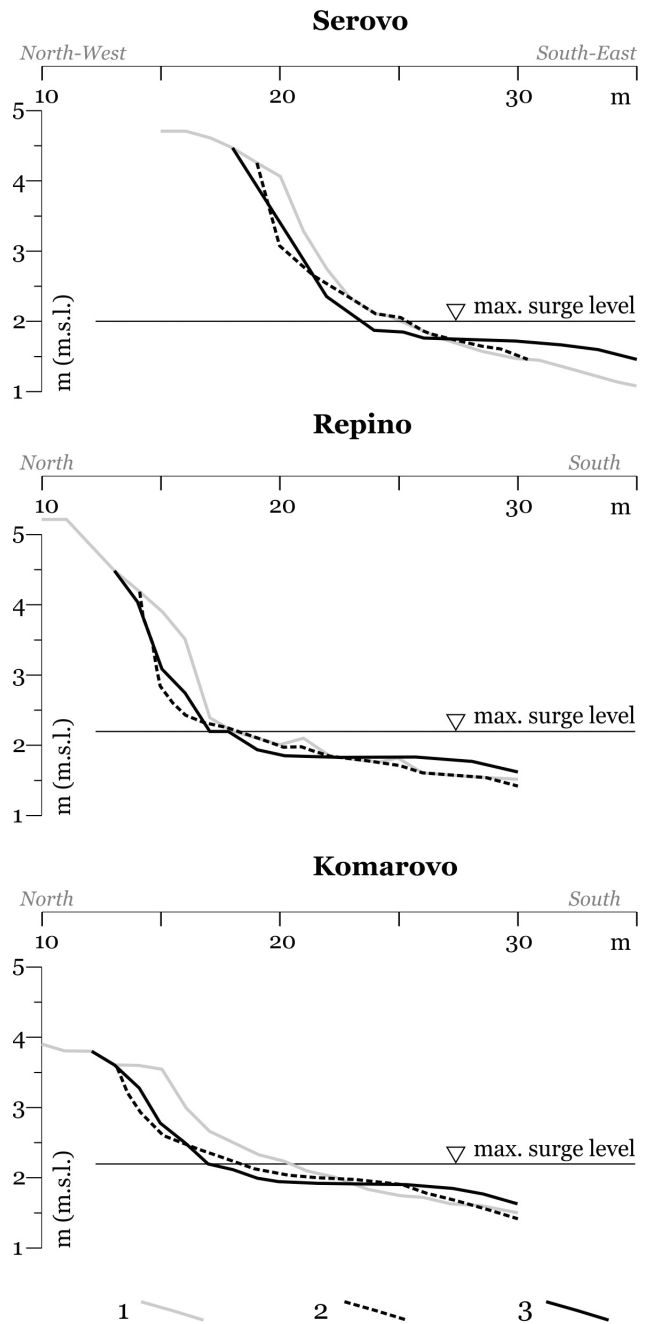


Fig. 6 Comparison of observed and computed changes of beach profiles of Komarovo, Repino and Serovo due to the storm in December 2015. 1 – August 2015, 2 – December 2015 (observation), 3 – December 2015 (calculation)

Table 2 Probable parameters of the storm peak in December 2015 in the eastern Gulf of Finland

| Coastal profile location | Wave height (m) | Wave period (s) | Max. water level (m) | Duration (h) |
|--------------------------|-----------------|-----------------|----------------------|--------------|
| Komarovo and Repino | 1.6 | 5.4 | 2.2 | 2 |
| Serovo | 1.6 | 5.4 | 2.0 | 2 |

ity of fairweather waves, the accretion of sand on the berm, and accumulation of sand in the swash zone in the form of a longshore bar.

Immediately after the storm, almost all sand eroded from the foredune or berm scarp (Buynevich *et al.* 2014) is deposited in the lower part of the beach in the form of a bar, followed by its removal from the beach, and partial movement to the upper part of the beach. It is important to mention that results of numerical modelling demonstrate the same mechanism of storm beach profile transformation.

The long-term trends of coastal dynamics are caused by regional geology, glacioisostasy, and neotectonics. Upper part of the coastal geological sequence consists of easily erodible Quaternary deposits represented mainly by Holocene marine sands and Late Pleistocene sandy and clayey glacial deposits. Due to high content of coarse-grained material (boulders, cobbles) washed out from moraines, a belt of stones of various size is formed on the beachface and in the nearshore, which in turn causes sediment deficiency and reduces ability for self-restoration of the coastal zone after extreme storms (Ryabchuk *et al.* 2011). Interpretation of the nearshore side-scan sonar images of the entire study region revealed the development of vast surfaces of covered by boulders and pebbles, indicating sediment deficiency.

As it was mentioned above, the most extreme erosion events are controlled by a specific combination of long-lasting western or southwestern storms that bring high waves, high water level, as well as absence of stable sea ice. A projected increase in the frequency of these conditions may be linked to acceleration of sea-level rise within the study area. According to a datum obtained by a Kronshtadt gauge measurement, the rate of sea-level rise from 1835 to 2005 is $0.56 \text{ mm year}^{-1}$ (Gordeeva, Malinin 2014). At the same time, during a large part of this interval (1836–1945) the level was stable but after 1946, began to rise quite rapidly up to 1.9 mm year^{-1} . The frequency of extreme water level rises plays even more important role in the intensification of coastal erosion, due to insufficient time for equilibrium profiles to be re-established. The annual maximum values of sea level have significantly increased along the coasts of the Gulf of Finland during the past 70 years, especially during the second half of the 20th century (Johansson *et al.* 2001).

The studies of ice conditions in the Baltic Sea (Jevrejeva *et al.* 2004; Sooäär and Jaagus 2007; Zaitseva-Parnaste, Soomere 2013) have identified a clear decrease in the duration of the total ice period during the last century. Ecosystem modelling of the expected regional climate change according to greenhouse gas emission scenarios A1B and B1, for the period 1960 to 2100 (Neuman 2010), showed a much reduced sea-ice cover in winter. By 2100, the sea-ice cover period can be reduced in the Gulf of Finland by 1.5–2.0 months, with ice thickness decrease by 20–30 cm.

There is some evidence about the increase in storminess in the western part of the Gulf of Finland (Soomere *et al.* 2008). Relatively high stages of storminess occurred during the 1920s–1940s, 1980s–1990s, and likely since 2010. Despite the absence of evidences of general increasing long-term trends in storminess, wherever such a trend was observed, it has occurred as a winter-time increase accompanied by a shift of the stormy season from fall to winter (Suursaar *et al.* 2015).

However, reliable forecast of storm activity and extreme sea-level rise frequency for the Baltic Sea and Gulf of Finland is still lacking (The BACC Author Team 2008). That is why numerical modelling was based on two scenarios of possible extreme storm frequency: 1) once per decade and 2) four per decade, which corresponds to field observations over the past 10 years.

Figure 7 shows results of modelling of the decadal transformation of the initial coastal profile measured by levelling in the summers of 2011 (Fig. 7A) and 2017 (Fig. 7B). Model based on scenario of average storm frequency for 20th century has shown the distance of coast retreat, that was achieved already after the extreme storms of fall-winter 2011 (Fig. 7A). Since that time, the coast was affected by two series of extreme storms (2013 and 2015). Therefore an “optimistic” scenario is unlikely.

Farther (landward) part of the coastal profile according to modelling is characterized by slower predicted rates of escarpment retreat due to wave impact reaching the 1-m-high relict beach ridge. In the case of realization of the scenario based on frequency of extreme storms 4 per decade, by 2027 the coastal escarpment will retreat ~7–8 m from the 2017 position and will ultimately reach the highway (Fig. 7B). Sediment deficiency in the nearshore, significant rates of measured coastal escarpment retreat, sediment volumes loss during extreme storms, and the results of numerical modelling demonstrate urgent necessity of scientifically guided sand nourishment campaigns as a basic principle of a “soft” coastal defence strategy.

It is well known, that the height of storm surges in the Gulf of Finland increases towards the Neva Bay. Hence, the maximal water level rise in Komarovo and Repino should be higher than in Serovo site. This trend is also seen in Table 2.

CONCLUSIONS

Monitoring study of 2011–2017 has supported the earlier hypothesis of Ryabchuk *et al.* (2011) that the extreme erosion events occur within study area when three conditions coincide: long-lasting western or southwestern storm winds and waves, high water

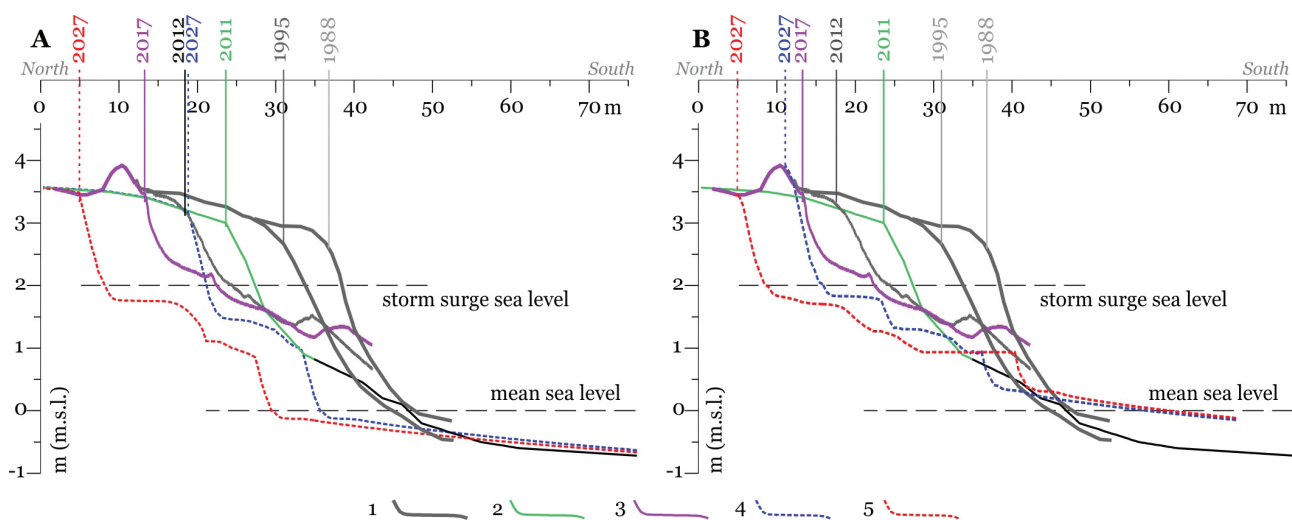


Fig. 7 Prediction of the coastal zone development for Komarovo village for the next 10 years. Calculated from profile measured in 2011 (2011–2027) (A). Calculated from profile measured in 2017 (2017–2027) (B). 1 – observed beach profiles 1988–1995, 2 – observed beach profile of 2011; 3 – observed beach profile of 2017; 4 – modelling beach profile of 2027 (extreme storms 1 per 10 years); 5 – modelling beach profile of 2027 (extreme storms 4 per 10 years)

level, and the absence of stable sea ice. During the past decade, such conditions have been observed in the eastern Gulf of Finland four times: during late fall-winter 2006–2007, 2011, 2013 and 2015.

According to the results of levelling, the rate of annual coast retreat is uneven. It is less than 0.5 m year⁻¹ during low storminess periods, whereas for stormy years it is 3.3 m year⁻¹. So the infrequent events of structural erosion occurring in relation to certain extreme events give rise to a clearly pronounced step-wise manner of coastal development in this area. An important feature of annual beach transformation is recent acceleration of annual coastal escarpment retreat, which has been 0.56 m year⁻¹ in 1989–2009 and reached 1.45 m year⁻¹ in 2009–2017.

Results of TLS data analyses allowed quantification of the volumes of sedimentary material that is eroded, transported, and redeposited as a result of extreme storms. Detailed 3D GIS models of coastal relief, compiled based on high-resolution geodesic surveys, allowed establishment of a highly reliable database of beachface transformation under the extreme storm impact and quantitative assessment of erosion volumes and sediment loss. In the stormy years, pronounced degradation of the foredune and coastal escarp was accompanied by a sharp reduction in the thickness of sand deposits by 0.6–1.2 m in a narrow strip of the backshore. The surface of the beach in turn undergoes less noticeable transformations, mainly with sediment thickness decreasing in the upper and lower parts of the beach to 0.3 m, and increasing to 0.3–0.6 m in the central and shoreline zone in the form of a discontinuous bar.

Results of numerical modelling of coastal profile development show the same mechanism of storm

beach profile behaviour. Mathematical modelling was used to forecast the future coast development. In case of realization of the “pessimistic” scenario of extreme storm frequency, by 2027, the coastal escarpment will retreat approximately 7–8 m from the 2017 position and will reach the highway. Based on the integrated analysis of coastal zone morphodynamics (e.g. sediment deficiency in the nearshore, significant measured rates of coast escarpment retreat, and sediment volume loss during extreme storms), as well as the results of numerical modelling, we recommend artificial sand nourishment as the main “soft” coastal defence method to mitigate sediment deficit and to prevent future erosion.

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