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Contemporary Dynamics of the Sea Shore of Kaliningrad Oblast

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Abstract

The article presents estimations of coastline retreat and advance in Kaliningrad Oblast at 85 monitoring points for a ten-year period of 2007–2017, based on monitoring data supplemented with satellite image analysis. The mean annual rate of coastline retreat and advance was estimated in general for each of the four major morpholithodynamic segments of the coastline: the Vistula (−0.2 m/year) and Curonian (−0.4 m/year) spits, as well as the western (−0.5 m/year) and northern (−0.2 m/year) shores of the Sambia Peninsula. The analysis of the shore protection measures implemented in Kaliningrad Oblast from 2007 to 2017 showed that the length of protected shore segments increased by 30% to 14.5 km, which is 10% of the total coastline. The obtained scheme of long-term mean annual rates of coastline retreat and advance clearly demonstrates an uneven distribution of eroded segments along the shores of Kaliningrad Oblast, however the sea shore of Kaliningrad Oblast is mainly susceptible to erosion (44%). Accumulative segments of the shore make up only 17% of the total coastline, and the remaining 39% of the shore is relatively stable. The results obtained demonstrate that the long-term mean annual rate of coastline retreat has decreased to −0.3 m/year from −1 m/year in the earlier period of 2000–2010. The general condition of the entire coastline of Kaliningrad Oblast can therefore be described as relatively sustainable]. The changes are related to several factors, such as an increase in the length of protected shore segments, the resumption of sand pulp dumping in the beach area by the Amber Mining Plant, and an increase in the amount of analytical data from an expanded local monitoring network.

Key words: sea shore, coastline retreat and advance, foredune, erosion, protection

1. Introduction

The sea shore of Kaliningrad Oblast is 145 km long (Fig. 1) and it has a significant recreational potential. It holds some federal resorts (Svetlogorsk-Otradnoye and Zelenogradsk), seaside resort towns (Baltiysk, Yantarnyy, Donskoye, Filino, Primor'ye, Lesnoye, Poinerskiy, Zaostrov'ye, Kulikovo, Sokol'niki, Priboy), and some conservation areas, including a natural reserve park at the Curonian Spit. However, the coast of

Fig. 1. Kaliningrad Oblast coastline with four major morpholithodynamic segments (a): the Russian part of the Vistula and Curonian spits, the western and northern shores of the Sambia Peninsula. The location of emergency cites (Table 1) and coastal segments protected by engineering structures are marked in panel (b), see legend

Kaliningrad Oblast suffers from coastal erosion and cliff abrasion. The coastal erosion is caused, in the first place, by sand deficiency at the bottom slope. The same factor accounts for the weak development of sandy beaches (Boldyrev et al 1992).

Nearly half of the sea coastline in Kaliningrad Oblast (73 km) is under erosion, and the rest is subject to alternating processes of accumulation and erosion (State Report 2018).

The estimations of rates of coastline retreat and advance in the entire Kaliningrad Oblast made by different authors vary, but all fall within the range of 0.4–1 m/year (Boldyrev, Ryabkova, Zhindarev, Bass, Bobykina, Burnashov, Chubarenko et al, Ryabkova and Levchenkov 2016), which is related to the analysis of different time spans and use of different methodology. Under rate of coastline retreat and advance for entire shore we suppose the arithmetic average of mean annual rates of coastline movement (negative values for retreat and positive values for advance) at all points of measurements.

For example, with time the quality and quantity of monitoring data have improved. Since 2000, regular observations (Bobykina and Boldyrev 2007, 2008, Bobykina and Karmanov 2007, Bobykina et al 2016) have been carried out in all four geomorphological segments (Scheme 1999) of the sea shore in Kaliningrad Oblast: the Baltiyskaya Spit (the Russian part of the Vistula Spit) – 25 km; the northern and western shores of the Sambia (Kaliningrad) Peninsula – 36 and 37 km, respectively; and the Russian part of the Curonian Spit – 47 km (Fig. 1).

Different research periods were characterized, on the one hand, by different storm activity, and on the other hand, by changes in the operational activity of the Kaliningrad Amber Mining Plant, which has a considerable impact on the western shore of the Sambia Peninsula due to the dumping of sand pulp from the washing of amber deposits (Bass and Zhindarev 2004, Burnashov et al 2010).

For example, the mean annual rate of coastline retreat for the entire coastline of Kaliningrad Oblast in 2000–2010 was about 1 m/year (the Amber Mining Plant did not work until 2007). An estimate of the mean annual rate of retreat for the Sambia Peninsula for the same period, excluding its western shore (where the Amber Mining Plant is located), was much less: 0.6 m/year From 1960 to 2000 (when the Amber Mining Plant operated intensively) the advance of the coastline at the western shore of Sambia Peninsula was so high, that the mean annual coastline movement of entire shore (formal arithmetic average) of the Sambia Peninsula was positive (+1.3 m/year), but without the western shore, it was negative (−0.55 m/year) (Burnashov et al 2010, Burnashov 2011).

Since 2007, when the Amber Mining Plant resumed operation, the sand pulp has been dumped again in the beach area of Pokrovskaya Bay at the western shore of the Sambia Peninsula. It is about 1 mln m^3 per year, which has undoubtedly influenced contemporary coastal dynamics.

Along the coastline of Kaliningrad Oblast, 7 local emergency sites have been identified, 6.5 km long altogether (Burnashov 2011). The coastal erosion rate at those sites exceeds the long-term annual values, and there is a threat of damage or destruction to buildings situated immediately on the sea shore (Table 1, Fig. 1).

Along with natural storm activity, the development of shore protection structures also influences the overall dynamics of the shore in Kaliningrad Oblast, particularly the shore of the northern Sambia Peninsula (Boldyrev et al 1990, Kirlis 1990). They preserve the shore from erosion, but at the same time decrease the volume of natural sediment supply to the coastal area (Boldyrev, Ryabkova 2001).

At present, the existing shore protection structures belong to Baltberegozashchita, a state budget organization of Kaliningrad Oblast, which has been specializing in coastal protection in Kaliningrad Oblast since its foundation in 1972 (it was founded and is controlled by the Kaliningrad Oblast Administration). Shore protection structures protect the marine shores of the seaside resorts and towns (Baltiysk, Yantarniy,

Table 1. Emergency sites on the coastline of Kaliningrad Oblast (Burnashov 2011)

Location and features	Length, [km]	No in Fig. 1
Village of Kosa at the Vistula Spit (town of Baltiysk territory), flooding hazard	600	1
Village of Yantarnyy, hazard of destruction of waste water treatment facilities	1000	2
Town of Svetlogorsk, western part, hazard to residential properties and to the sanatorium Yantarnyy Bereg	400	3
Village of Zaostrov'ye, cape Gvardeysky, hazard to collectors of waste water treatment facilities	300	4
Village of Kulikovo, wind park area, hazard to residential properties	600	5
Town of Zelenogradsk, western part, destruction of shore protection structures, hazard to residential properties	700	6
Root of the Curonian Spit, flooding hazard to the only motorway/road leading to the checkpoint on the Lithuania-Russia state border, forest and lowland ("cutting" of the spit)	2500	7

Table 2. A list of shore protection structures built and restored in 2007–2017

No.	Type of the shore protection structure	Built/restored in	Length, [m]
1.	Retaining wall, waste water treatment facilities in Yantarniy	2012	115
2.	Landslide protection structures around the Svetlogorsk embankment (gabions)	2007–2009	1442
3.	Shore protection structures around a recreational facility for children in Pionerskiy	2007	913
4.	The connectionbetween the western and eastern parts of the Pionerskiy City promenade	2012	143
5.	Eastern part of the Pionerskiy City promenade	2010–2011	900
6.	Gabions in Zaostrov'ye at pine wood stairs	2016	30
7.	Gabions in Zaostrov'ye at the drain of OKOS (United Sewage Treatment Facilities)	2008	90
8.	Shore protection structures of LLC Lukoil-Kaliningradmorneft around the Aleika river	2012	50
9.	Embankment in Zelenogradsk	2009–2014	1218
10.	A set of groins in Zelenogradsk	2017	2000
11.	TOTAL	2007–2017	6901

Svetlogorsk area with the villages of Filino and Otradnoye, Pionerskiy, Zelenogradsk, the village of Lesnoy on the Curonian Spit).

The aim of this study was to estimate contemporary coastline dynamics of the Baltic shore within Kaliningrad Oblast, namely the rates of shore retreat and advance during a 10-year period of 200–2017, and to describe the alongshore and year-to-year variability of mean annual characteristics of this dynamics.

2. Methods

In order to evaluate the coastline dynamics of the Baltic Sea within Kaliningrad Oblast during the period of 2007–2017, we used data from monitoring observations at 285 locations of the Baltberegozashchita network. This network covers the entire sea shore of Kaliningrad Oblast, with an average distance of 500 m between the locations.

The data on rate of the coastline retreat and advance at every location of the monitoring network were obtained by repeated elevation profiling along cross-sections perpendicular to the shoreline or through analysis of satellite images of the Earth's surface.

The annual variation in the horizontal position of the conventional shore boundary was treated as a qualitative feature of shore dynamics: retreat or advance (in meters) which are the results of erosion and accumulation. The conventional shore boundary, in its turn, was defined as either the foot of the foredune (the boundary between the upper part of the beach and the slip face), for accumulative shores, or the cliff/foredune edge, for abrasion ones (Bobykina and Boldyrev 2007, Burnashov et al 2008).

Repeated elevation profiling was done on the accumulative shores along the shore cross-section profile from a permanent bench mark, located remotely enough from the water edge, perpendicular to the shoreline. The work was done mostly in summer, the calm season, when accumulative shores could recover partially or completely after the stormy winter season.

For each cross-section profile, the result was expressed as a measured distance from the benchmark to the main features and elements of the shore profile and their elevations (in order from dune crest towards the swash line): the edge of the main foredune (if it was present), its foot; the top or the edge of the incipient dune (if it was present); the upper and lower boundaries of eolian inflation; runnels, beach berm, swash line. The changes in horizontal positions of the foot of the foredune were determined by comparing two repeated elevation profiles.

The lack of funding prevents annual elevation profiling at all locations. In order to obtain data on shore dynamics for periods without land-based measurements, open-access satellite images of the sea shore for 2007–2017 were obtained from GoogleEarth services. In two consequence images, the shortest distance was measured from an inland object, clearly seen in both images and located not far from the monitoring location, to the foredune foot or cliff/forefune edge. The rate of retreat/advance was calculated as the difference between these distances (the earlier was subtracted from the later) divided by the number of years (Karmanov and Chubarenko 2016).

Both methods produced errors in determinig shoreline changes, and larger errors resulted from the processing of satellite images. That is why the following confidence limit was adopted for the analysis of shoreline dislocation: the shore was considered stable if the annual change in coastline position was within the limits from −0.25 to +0.25 m/year (Karmanov and Chubarenko 2016).

In cases where there were no results of repeated elevation profiling or satellite images for a certain monitoring point for a given year, the distance from the benchmark to the coastline was interpolated on the basis of the average rate of coastline retreat or advance obtained for a given period for morpholithodynamic segments (Fig. 1) to which the certain monitoring point belongs to. If later satellite images are obtained for the missing periods, the interpolation results can be improved.

We compiled a table of mean annual rates of coastline retreat and advance for 285 monitoring profiles for 10 years from 2007 to 2017 (in total, 2850 values of the rate of coastline movement for 145 km of sea shore). The rates of coastline retreat and advance were averaged for 10 years for every monitoring point, and then these rates of movement were averaged along with all four major morpholithodynamic segments: the Russian parts of the Vistula and Curonian spits and the northern and western shores of the Sambia Peninsula.

The data obtained were used to evaluate geo-ecological conditions of the sea shore according to the classification by (Burnashov 2011) (Table 3) and to update the database of the Automated Informational Forecasting System (AIFS) used by Baltberegozashchita.

Table 3. Classification of sea shores of Kaliningrad Oblast according to their geo-ecological conditions (Burnashov 2011)

Mean annual coastline movement averaged for the segment, [m/year]	Geo-ecological conditions of the shore segment
[−8; −2)	Extremely unsustainable
[−2; −1)	unsustainable
[−1; −0.5)	Marginally sustainable
[−0.5; −0.25)	Moderately sustainable
[−0.25, +2.8]	Stable

The data on wind speed and direction (mean averaged for 15 min for every 3-hour period of observation) from meteostations in Baltiysk (Russian Research Institute of Hydrometeorological Information – World Data Center in Obninsk, http://meteo.ru/data) were used in the analysis. The duration of wind which might cause deformations of the coastline was calculated as

$$\Delta T \left(Wa \geq 15 \text{ ms}^{-1} \right) = N_{\geq 15} \cdot 3 \text{ hour}, \tag{1}$$

where $N_{\geq 15}$ is the number of 3-hour periods when the wind speed was at least 15 ms^{-1} and it was not directed from the south-eastern quarter. Thus the analysis did not include wind directions from 90° to 180°, since south-eastern winds do not result in strong waves near the shores of the south-eastern coast of the Baltic Sea. One year (from 01 September of previous year to 31 August of the current year) was taken as time step, as annual values of coastline retreat and advance were determined from the results of monitoring conducted in summer.

3. Results and Discussion

3.1. Analyses of Shore Protection Measures Implemented in 2007–2017

According to Baltberegozashchita, out of the 145 km of sea shore in Kaliningrad Oblast, only 11.1 km was under permanent protection. Over the last 10 years, 10 shore protection structures, 6.9 km long in total, were built or reconstructed on the sea shores of Kaliningrad Oblast (Tabl. 2). Altogether, by the end of 2017, there were 14 680 m of shore protection structures. In the eastern part of Svetlogorsk, a 1 km long promenade is being built (since 2015). For its construction, a temporary shore protection structure was installed, which provided additional protection to 950 m of the sea shore. Thus, the overall length of protected shore by the end of 2017 was 15 630 m.

In the 10-years study period, six shore protection structures (175 m in total) were partially damaged during severe and lengthy storms.In general, taking into account all changes during those 10 years (all shore protection structures present and destroyed), the total length of the protected shoreline grew by 3419 m. Such a considerable increase in the protected area (30% in 10 years) should reduce the average rate of coastline retreat for the entire Kaliningrad Oblast. Undoubtedly, it also changes the sand drift budget in the coastal zone, intensifying the deficiency of free sand drift on the northern coastal slope of the Sambia Peninsula, where all shore protection complexes are located.

3.2. Analysis of Shore Dynamics from 2007 to 2017

3.2.1. The Baltiysk Spit (the Russian Part of the Vistula Spit)

The rate of retreat/advance for the Baltiysk Spit (25 km) were determined earlier from measurements at 10 monitoring points, and additionally a 5 km segment adjacent to the Strait of Baltiysk was monitored in more detail (Bobykina et al 2016). The results of the present study, conducted for 52 monitoring points (Fig. 2), confirmed the conclusions of (Bobykina et al 2016) that the sea shore of the Baltic Spit is generally characterized by the alternation of eroding, stable, and accumulative shore segments.

The analysis demonstrated that, in general, eroding shores are prevalent (44%) on the Baltiysk Spit. Shores characterized by forced accumulation represent 15% of the coastline. Relatively stable shores, where the rate of erosion and accumulation is within the limits of −0.25 to +0.25 m/year, make up 41% of the total length of the sea shore on the spit.

3.2.2. The Western Shore of the Sambia Peninsula

The western shore of the Sambia Peninsula (37 km) starts from the Strait of Baltiysk and stretches north to Cape Taran. The height of the foredune and abrasion edge grows from the south to north, from 6–7 m at Baltiysk to 50 m in the village of Donskoye. Its

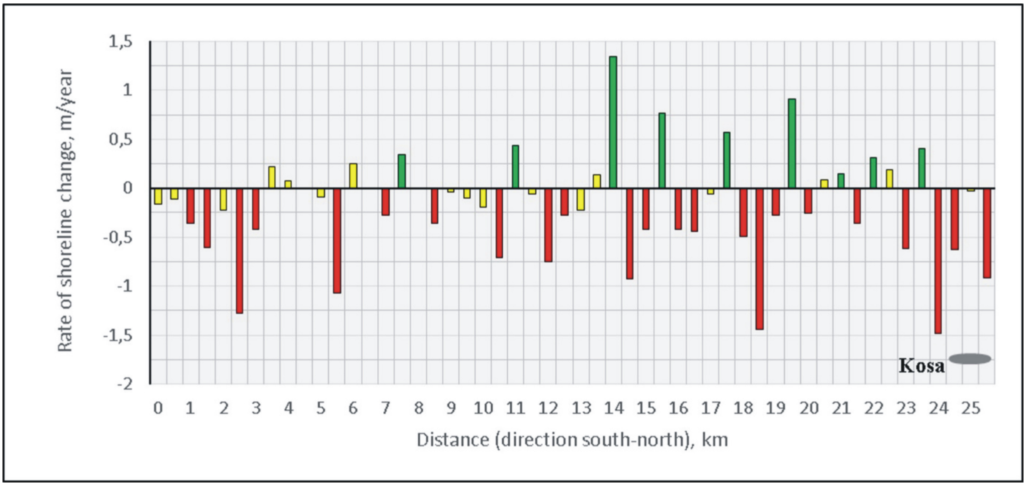

Fig. 2. Rates of coastline movement in the Russian part of the Vistula Spit in 2007–2017: mean annual rates of retreat (red) and advance (green), values within confidence limits are yellow

peculiar feature are foredunes in its southern and central parts (Baltiysk – Bakalino). These foredunes were formed in the second part of the 20th century as a result of the operation of the Amber Mining Plant. Before 2000, from 1.5 to 4.5 mln m^3 of sediments were dumped into the coastal zone (Bass and Zhindarev 2007). From 2000 to 2006, the dumping of sand pulp stopped completely, which led to intensive erosion of the previously accumulative shore (Burnashov et al 2010). From 2007 until 2017, the Amber Mining Plant resumed the dumping of sand on the beach. From 0.5 to 1.2 mln m^3 was dumped every year during that period, which slowed down erosion and ultimately stopped it completely south of the village of Okunevo. In some parts of the shore, accumulation processes started again (Fig. 3).

The analysis performed for the western shore of the peninsula showed the predominance of erosion (39%, mostly in the northern part of the segment) over accumulation (27%, mostly the southern part of the segment). A relatively stable shore, where the rate of erosion or accumulation is within the confidence limits of −0.25 to +0.25 m/year, makes up 34% of the shore.

On average, the entire western shore of the Sambia Peninsula was eroded at a rate of less than 0.4 m/year during those 10 years, so it can be regarded as moderately sustainable (Table 3). On the other hand, north and south of the central part of the village of Yantarniy there are some unstable morphodynamic parts of the shore where the rate of erosion may reach 8 m/year.

3.2.3. The Northern Shore of the Sambia Peninsula

The northern shore of the Sambia Peninsula (36 km) starts at Cape Taran and stretches eastwards to Zelenogradsk. From west to the east, the shore height decreases from 55

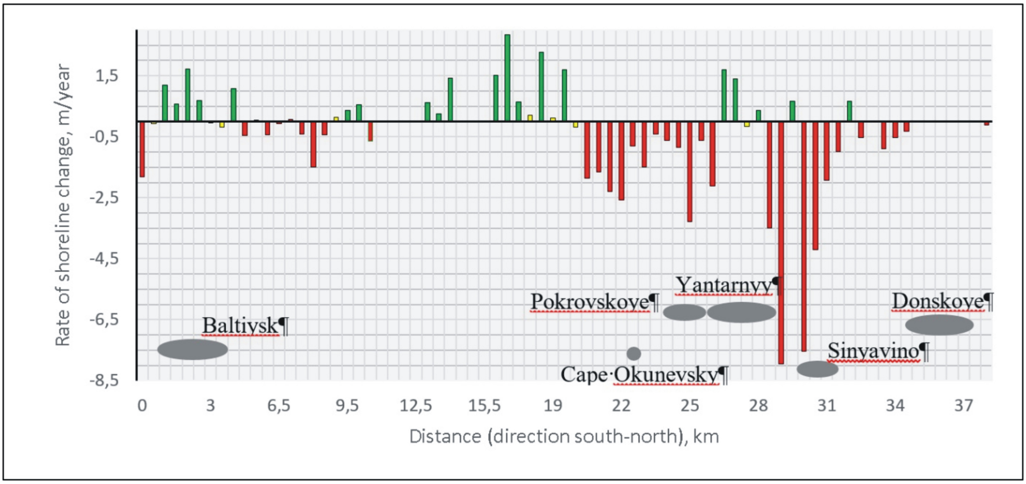

Fig. 3. Shore dynamics of the western shore of the Sambia Peninsula in 2007–2017: mean annual rates of retreat (red) and advance (green), values within confidence limits are yellow. The shore opposite Donskoe is under permanent erosion, but it is excluded from the analysis for lack of data

m around Filino to 5–7 m in Zelenogradsk. Along the valley side, where resort towns are located, there are shore protection and beach-holding structures 10.7 km long in total, which makes this segment special. The shore protection structures prevented shore degradation in resort areas, but at the same time provoked an even greater deficit of sand drifts, which resulted in severe narrowing of beaches and stronger leeward erosion of the neighboring shore areas.

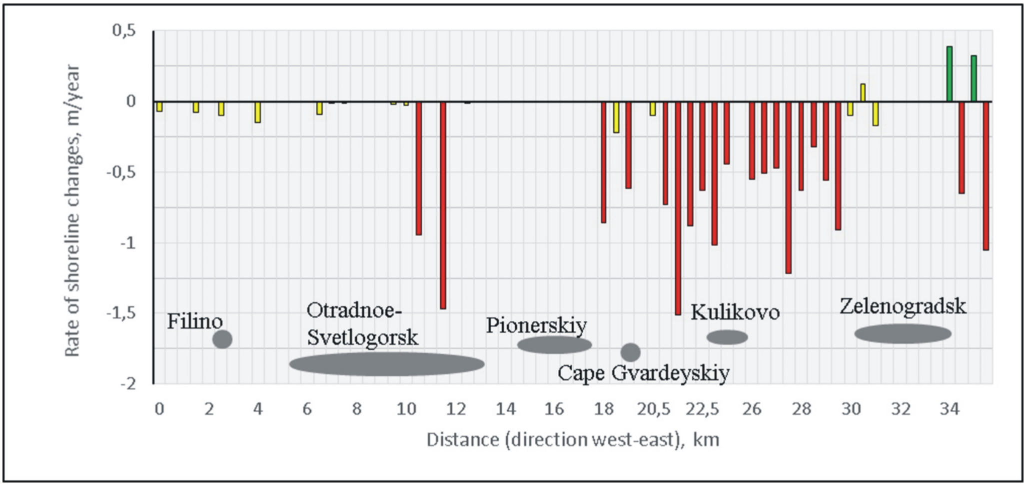

Fig. 4. Shore dynamics on the northern shore of the Sambia Peninsula in 2007–2017: mean annual rates of retreat (red) and advance (green), values within the confidence limits are yellow

The analysis demonstrated the predominance of relatively sustainable shores (68%) over accumulation shores (3%) and eroded shores, where the mean annual erosion rates are above 0.25 m/year (29% of the total length of the northern shore).

On average, the entire northern shore of the Sambia Peninsula was eroded at a rate of less than 0.25 m/year in 10 years, so it can be regarded as moderately sustainable. However, there are some unprotected shores east of Cape Gvardeyskiy where the average rate of erosion may reach −1.5 m/year as well as active landslide parts of the coastal slope at an emergency site in the town of Svetlogorsk.

3.2.4. The Curonian Spit

The sea shore of the Curonian Spit in Kaliningrad Oblast (47 km) stretches north as a curved line from the eastern part of Zelenogradsk to the Lithuanian-Russian border. The shore of the Curonian Spit has the form of a beach and a foredune, and at some locations at the root of the spit, it takes the form of a low terrace, 5 m high. The entire shore of the spit consists of alternating local dynamic fragments along the shoreline (Fig. 5). In total, more than a half (58%) of the Russian part of the Curonian Spit is subject to erosion. Accumulative processes take place on the least proportion of the shore (20%). A relatively stable shore, where the processes of accumulation and erosion are within the range from −0.25 to +0.25 m/year, makes up 22% of the total length of the sea shore there.

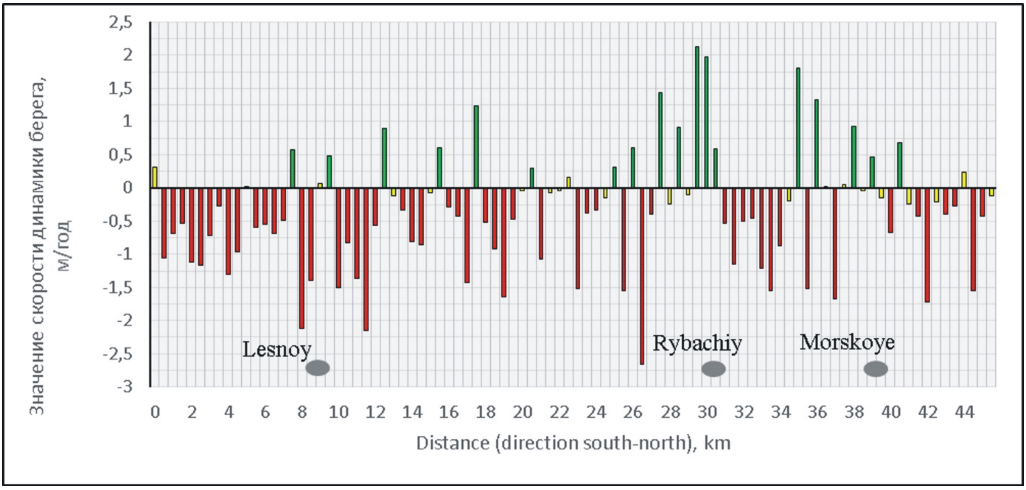

Fig. 5. Shore dynamics of the Russian part of the Curonian Spit in 2007–2017: mean annual rates of retreat (red) and advance (green), values within the confidence limits are yellow

During the 10 years, the entire sea shore of the Russian part of the Curonian Spit was eroded at an average rate of 0.4 m/year, so it can be regarded as moderately sustainable (Table 3). Nonetheless, in the southernmost root part of the spit, there is an unstable fragment, which is an emergency site due to the absence of a foredune on a 1–2 km fragment of the spit. As a result, the forest adjacent to the shore is flooded during storms. Moreover, unstable fragments with foredunes eroding at a rate of up to 1 m/year are found regularly all along the Russian part of the Curonian Spit.

3.3. Long-term Mean Annual Dynamics of the Coastline of Kaliningrad Oblast

Taking into account modern conditions and changes of the last decade on the coastline of Kaliningrad Oblast, the morphodynamic zoning conducted in the 1990s and supplemented in 2010 has undergone a series of changes. The impact of anthropogenic factors on the shore in the last decade has led to morphodynamic changes of some fragments and of the coastal area as a whole. The expansion of the monitoring network from 70 to 285 points made it possible to obtain quantitative data on previously ignored parts of the sea shore.

In general, the average rate of sea shore changes in Kaliningrad Oblast is −0.3 m/year. Thus, according to geoecological classification, the entire shore is moderately sustainable (Table 3) with respect to the impact of natural and anthropogenic factors (Burnashov 2011). Still, the analysis showed that the sea shore of Kaliningrad Oblast is eroded unevenly: in some locations the shore is stable, and certain parts are even accumulative. Nevertheless, most of the shore of Kaliningrad Oblast (44%) suffers from erosion, which is consistent with earlier monitoring studies (Boldyrev and Ryabkova 2001, Bobykinaand Boldyrev 2008).

Accumulation (on 17% of the shore length of Kaliningrad Oblast) is observed in small isolated parts of the Baltic and the Curonian Spits, which many authors regard as a consequence of the erosion of the Sambia Peninsula and predominant sand drift migrations towards the spits (Boldyrev et al 1979, Ryabkova 1982, Zharomskis 2000, Zhindarev et al 2004, Babakov 1999, 2003, 2009). Accumulative processes on the western shore of the Sambia Peninsula are related to the resumption of pulp dumping from the Amber Mining Plant in 2007 (about 1 mln m^3 of sand material delivered to the beach area). And the fact that the sediments are accumulated south of Cape Obzorniy confirms the wide-spread opinion that the dominant sediment drift from Yantarniy to Okunevo occurs from north to south (N-S direction) (Babakov 2009, Ostrowski et al 2010). A relatively stable shore, where the processes of accumulation and erosion are within the limits from −0.25 to +0.25 m/year, makes up 39% of the entire coastline of Kaliningrad Oblast. Stable shore segments are found mostly along the northern shore of the Sambia Peninsula, which is a result of a large number of shore protection and beach holding structures there.

A scheme of long-term mean annual dynamics of the coastline of Kaliningrad Oblast based on estimates of the rates of coastline changes was created for the period 2007–2017 (Fig. 6). The most vulnerable are segments where the mean annual rate of retreat exceeds 2 m/year which is related to the presence of relatively unstable beach forms, such as cliff, foredune, beach terrace: Pokrovskaya Bay, southern part of Yantarniy, shore around Sinyavino, and some shore fragments on the Curonian Spit.

Fig. 6. A scheme of the geo-ecological state of the shore based on the mean annual rates of coastline retreat/advance for Kaliningrad Oblast in 2007–2017

3.4. Changes in Mean Annual Rates of Retreat and Advance for Major Morpholithodynamic Segments in 2007–2017

In the 10-year period, the erosion process was dominant in all four morpholithodynamic shore segments, except for the periods of 2008–2009 and 2009–2010, when the entire shore was generally stable, and 2015–2016, when intensive accumulation was detected in three coastline segments of Kaliningrad Oblast (but not on the northern shore of the Sambia Peninsula).

The average rate of coastline retreat for the Baltic Spit in the entire study period (2007–2017) was −0.2 m/year, which shows a relative sustainability of this segment as a whole. The most intensive erosion, at an average rate of 1.4 m/year, was recorded in 2010–2011. In 2015–2016, accumulation proceeded at an average rate of 0.6 m/year for the entire segment.

The western shore of the Sambia Peninsula was eroded at an average rate of 0.5 m/year. The maximum average rate of erosion (2 m/year) for the entire segment was noted in 2010–2011, and the peak of accumulation (1.1 m/year on average) was observed in 2015–2016.

The northern shore of the Sambia Peninsula in the study period was generally relatively stable: the average rate of retreat was −0.2 m/year, and the most intensive erosion in this segment occurred in 2012–2013 at an average rate of −0.6 m/year.

The sea shore of the Curonian Spit, in contrast, was eroded at an average] rate of 0.4 m/year in the study period. The most intensive erosion of 1.5 m/year (on average) occurred in 2014–2015. Accumulation was observed in 2015–2016, reaching a maximum average rate of 1.2 m/year. This predominance of accumulation after a long period of considerable erosion was most probably connected with the formation of accumulative beach forms by material previously eroded but returning to the shore in calm periods.

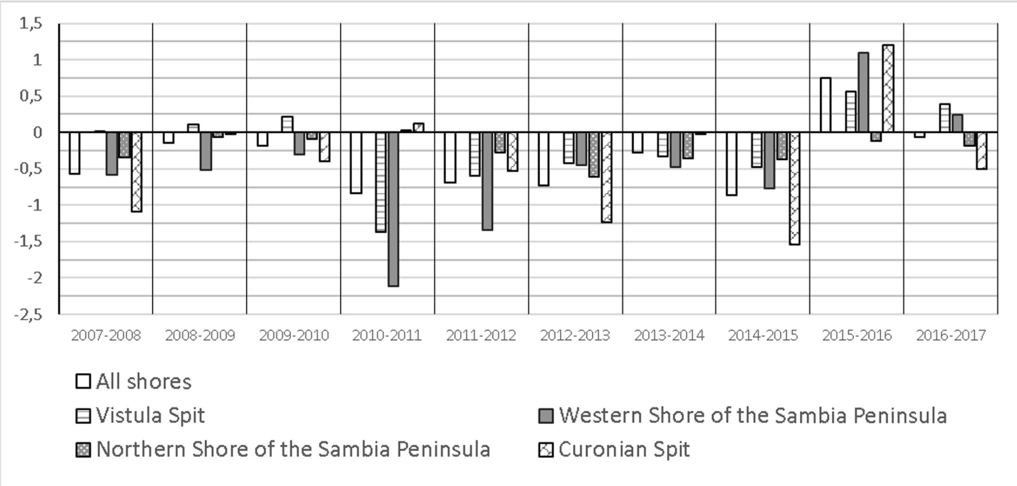

Fig. 7. Mean annual rates of coastline retreat/advance for Kaliningrad Oblast and its four major morpholithodynamic segments in 2007–2017

3.5. Correlation Between the Annual Duration of Winds and Shore Dynamics in Kaliningrad Oblast during 2007–2017

In order to evaluate the relationship between coastline retreat/advance and wind conditions at a time scale of one year, an analysis was conducted to see if there was a correlation between the mean annual retreat/advance for every coastal segment of Kaliningrad Oblast and the duration of winds of 15 m/sec or stronger for given year in 2007–2017. The winds were taken into account only if their direction could contribute to the reformation of the coast (SW, W, NW, N, NE).

It turned out that the correlation coefficient between mean annual rates of retreat/advance and the duration of winds posing a threat for coastal reformation was only −0.2 for the entire coastline of Kaliningrad Oblast and was within the limits of −0.05 and −0.22 for its particular segments (Table 4). Such low values of the correlation coefficient indicated the absence of any clear connection between the rate of coastal retreat and annual characteristics of wind conditions.

Such a connection should probably be further investigated based on the idea that coastal reformation occurs during specific events (Kirlis 1990). And these events for each coastal segment result from a combination of wind action and sea elevation levels as well as anthropogenic impact.

Table 4. Mean annual rate of retreat (−) or advance (+) for the main segments of the coastline in Kaliningrad Oblast and the duration of wind impact (from SW, W, NW, N, NE, not less than 15 m s^{-1}) during the corresponded year (from 01 September of previous year to 31 August of the current year)

Yearly interval	Wind duration, hours for SW, W, NW, N, NE winds, $W_a \geq 15$ m s^{-1}	Mean annual movement, m y^{-1}				
		Russian part of the Vistula Spit	Western shore of the Sambia Peninsula	Northern shore of the Sambia Peninsula	Russian part of the Curonian Spit	Kaliningrad shore as a whole
2007–2008	72	0.0	−0.6	−0.3	−1.1	−0.6
2008–2009	12	0.1	−0.5	−0.1	0.0	−0.1
2009–2010	48	0.2	−0.3	−0.1	−0.4	−0.2
2010–2011	30	−1.4	−2.1	0.0	0.1	−0.8
2011–2012	42	−0.6	−1.3	−0.3	−0.5	−0.7
2012–2013	18	−0.4	−0.4	−0.6	−1.2	−0.7
2013–2014	39	−0.3	−0.5	−0.4	0.0	−0.3
2014–2015	45	−0.5	−0.8	−0.4	−1.5	−0.0
2015–2016	36	0.6	1.1	−0.1	1.2	0.7
2016–2017	9	0.4	0.2	−0.2	−0.5	−0.1
Correlation coefficient	–	−0.05	−0.13	−0.13	−0.22	−0.2

4. Conclusions

On the basis of direct observations and satellite image analysis, the coastline retreat and advance in Kaliningrad Oblast was evaluated at 285 monitoring points (2850 values of shore movement rates in total) for ten years from 2007 to 2017. This enabled us to estimate the mean annual rate of shore movement for each of the four major morpholithodynamic coastal segments: the Vistula (−0.2 m/year) and Curonian (−0.4 m/year) spits and the western (−0.5 m/year) and northern (−0.2 m/year) shores of the Sambia Peninsula.

The analysis of shore protection measures implemented from 2007 to 2017 showed that the length of protected shore increased by 30% to 14.5 km, which is 10% of the total coastline of Kaliningrad Oblast.

The scheme and diagram of the long-term mean annual shore retreat/advance obtained as a result of our anlysis clearly demonstrate an uneven distribution of eroded shore segments. It can be concluded, however, that the sea shore of Kaliningrad Oblast is mainly susceptible to erosion (44%). Accumulative segments of the shore make up only 17% of the total coastline, and the remaining 39% of the shore is relatively stable.

The most vulnerable parts of the coastline of Kaliningrad Oblast in the study period were Pokrovskaya Bay, the southern part of the Yantarniy village, the shore around the village of Sinyavino, and some fragments of the sea shore on the Curonian Spit.

The analysis of correlation between the mean annual shore movement in Kaliningrad Oblast and the total annual duration of winds stronger than 15 m/sec did not reveal any significant connection for any of the main coastal segments, since the correlation coefficients range from −0.05 to −0.22. The absence of a clear relationship between coastal degradation and the annul characteristics of wind impact suggests that this relationship should be investigated on the assumption that coastal reformation occurs during specific events and that these events result from a combination of wind action, sea elevation levels and anthropogenic impact on a given coastal segment.

The geomorphological condition of the coastline of Kaliningrad Oblast has generally improved. The results obtained show that the long-term mean annual value ofshore retreat decreased to −0.3 m/year from −1 m/year in the previous period (2000–2010). The general condition of the coastline of Kaliningrad Oblast can therefore be described as moderately sustainable. The changes are related to several factors: an increase in the length of the protected shore, the resumption of sand pulp dumping in the beach area by the Amber Mining Plant, changes in weather conditions and an increase in the amount of analytical data from the expanded monitoring network of Baltberegozashchita.

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