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Beach-Foredune Sediment Budget Response to Sea Level Fluctuation. Curonian Spit, Lithuania

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Abstract: Beach-foredune sediment exchange maintains a coastal system's stability. Sea level fluctuation is one of the most important factors that modifies the beach and foredune sediment budget. This study aims to assess beach and foredune sand budget changes depending on sea level fluctuations. On the basis of annual measurements of cross-shore profiles on the Curonian Spit in Lithuania, the sediment volumes on the beach and foredune and their changes between 2002 and 2019 were calculated. The sea level fluctuations were examined in parallel. The obtained data revealed that in the case of a sand surplus, a relatively low sea level rise does not have a significant impact on the development of a foredune (and a minimal impact on a beach) on a decadal time-scale. Short-term sea level fluctuations are reflected in year-to-year variability in a beach sediment budget. However, no significant relationship between year-to-year variability in sea level fluctuation and the foredune sediment budget has yet been identified, nor is there a reliable year-to-year variability relationship between the foredune and beach sediment budget. The foredune sediment budget remained positive both through an increase and a reduction in the sediment volume on the beach.

Keywords: sea level; coastal erosion; coastal morphometry; Baltic Sea

1. Introduction

The global mean sea level has been rising during the past century [1]. Based on satellite data, the rate of sea level rising has peaked at 3.36 mm/yr since 1993 [2]. The sea level trend in the Baltic Sea is similar to the global mean sea level trend [3].

Global climate change and sea level rise are often related to increasing coastal erosion and associated socio-economic transformations in coastal regions [4,5]. One of the most important problems in predicting future coastal evolution is determining the impact of a potential rise in sea level on coastal systems. However, there are other significant factors that also influence coastal dynamics including the geologic framework [6,7] and sand availability [8–13]. It is worth noting that coastal changes on short-term and decadal time scales are relevant to coastal managers and planners [14]. Within a decadal time period, there are other factors besides sea level fluctuation and geologic framework: extreme events [15–19], vegetation cover [20–23], human activity [24–26], and river discharge [27]. Since there is a complex interrelationship between sea level change and other factors on a short-term time scale, it is difficult to separate the direct impact of sea level on coastal systems from other factors. Depending on the interaction between various factors, accumulation processes may predominate on the coast despite the rising sea level [9,13,17,28,29]. Due to different driving forces, there can be high uncertainties related to the prediction of sea level rise impact on coastal systems [30]. The sand spits with predominant alongshore sediment transport are good examples for illustrating erosion and accretion processes along the shore [31–33]. Similar shoreline dynamic processes can be observed at the Curonian Spit where at the base of the spit erosion dominates, whereas on the distal end of the spit accretion dominates [34,35]. Due to the reduction of sediment supply in the southern part of the spit and sea level rise, there is intensification of erosion [36]. Alongshore sediment transport directed northward creates favorable conditions for accumulation near the distal part of the spit. Thus, a huge sand mass is involved in the formation of coastal landforms [37]. The development of foredunes is closely linked to beach evolution and the formation of a beach-foredune system [38–40]. Despite close interaction between beach and foredune, these two components of the system do not necessarily evolve in one direction. For example, the foredune sand budget may be positive while the beach sand budget is in equilibrium or slightly negative [29,39,41–43].

Since 2002, annual changes in the beach and foredune sand volume have been monitored along the Lithuanian part of the Curonian Spit Baltic Sea coast. Between 2002 and 2019, the coastal dynamics in coastal systems with different geomorphologies were determined based on the obtained data. The aim of this paper is to evaluate the interrelationship between the beach and foredune sand budget, and the influence of annual mean sea level fluctuation on the Baltic Sea coast in the Lithuanian part of the Curonian Spit on a decadal time scale.

2. Study Area

Of the Lithuanian part of the Curonian Spit (51 km long), the foredune ridge occupies an area of about 262.3 ha (Figure 1). A continuous foredune ridge along the entire Curonian Spit was formed in the second half of the 19th century. The formation of the foredune was started along the shore in order to protect the coastal settlements from sand being blown and the coast from wave action. Semi-permeable sand fences were constructed along the shore between 1810–1892 [41].

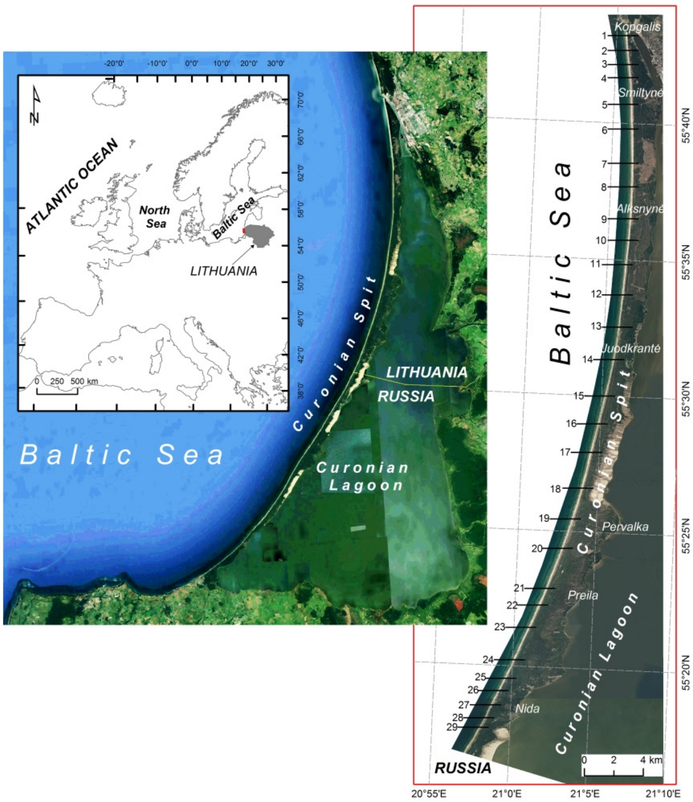
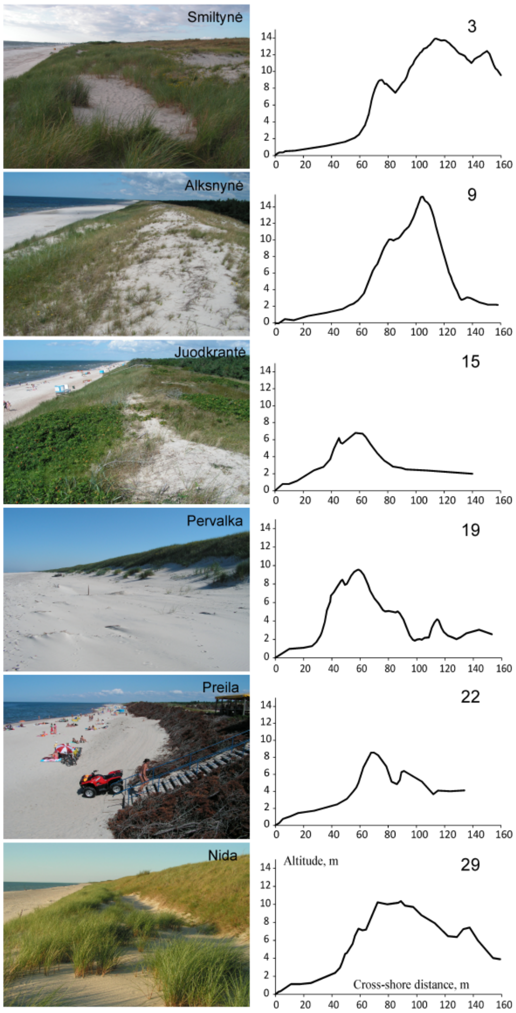


Figure 1. Location map. The black lines and numbers represent cross-shore profiles (Google Earth, earth.google.com/web/.).

When the ridge of accumulated sand reached 3 m in height it was planted with marram grass. Later on, the ridge developed without human intervention, except for being reinforced with tree branches in some places. Therefore, human activity has no crucial effect on foredune development. The height of the foredune ranges from 6 m at Juodkrantė to 16 m at Alksnynė (Figure 2). Striking differences have also occurred in the foredune volume. The largest foredune is at Smiltynė (up to 2200 m^3/m) and the smallest is at Juodkrantė (110 m^3/m). The foredunes are densely covered with marram grass. The widths of the beaches vary from up to 65 m at Smiltynė to 30 m at Juodkrantė. The volume of beach sediment ranges between 124 m^3/m at the Smiltynė and 42 m^3/m at the Juodkrantė. The Curonian Spit is formed exclusively of Quaternary deposits. The upper part of the Quaternary deposits in the Curonian Spit is composed of sediments that have been formed in the basins of the various stages of the Baltic Sea's development—starting from the Baltic Ice Lake and ending with recent marine sediments [34]. The beach of the Curonian Spit is composed of fine and medium sand. Mean sand grain size ranged from 0.2 mm at Smiltynė to 0.5 mm at Juodkrantė.



Profile No.	Distance km	Mean beach width, m	Mean foredune altitude, m
1	0.05	86.1	8.9
2	0.20	58.7	10.6
3	0.67	57.9	13.2
4	1.38	48.3	14.0
5	2.36	44.9	13.4
6	3.22	44.1	14.0
7	5.08	59.6	13.5
8	6.69	54.4	15.8
9	9.04	59.8	13.6
10	12.74	48.3	11.9
11	14.27	47.2	11.9
12	16.50	43.7	9.9
13	18.02	39.9	10.2
14	20.19	34.9	7.5
15	22.45	32.7	6.4
16	24.99	37.0	8.2
17	26.97	31.2	9.5
18	28.96	49.3	9.2
19	31.46	39.8	9.9
20	33.47	39.7	8.6
21	35.69	48.6	7.9
22	38.70	39.9	7.9
23	39.87	51.8	8.5
24	41.47	42.0	10.6
25	43.93	41.6	8.4
26	45.23	45.1	10.6
27	46.33	43.4	9.6
28	48.31	33.3	10.0
29	49.12	40.5	9.8

Figure 2. Typical cross-shore profiles and mean values of beach width and foredune height.

As the tidal range of the South-Eastern Baltic coasts is not significant and barely reaches 3.5–4.0 cm [44,45], the wind-generated waves [46], the prevailing alongshore currents, and accordingly the sand transport from south to north [35,47–49] and the aeolian processes [42] are the main beach-forming factors on the Lithuanian Baltic Sea coast. The most significant short-term sea level fluctuations near the Lithuanian coast occur due to storm surges. The most extreme storm surges are observed between November and February. In extreme cases, the sea level can rise up to 185 cm above the mean sea level [50] and wave height can reach up to between 4 and 6 m [46]. The most frequent recurrences of the storm wind directions are south-westerly (35.6%) and westerly winds (24.3%) [51].

3. Materials and Methods

The sediment volume of the Curonian Spit beach and foredune (m^3/m—cubic meters per meter of beach length) was assessed based on cross-shore profiles. The cross-shore profile was measured at 29 sites in May of each year using Global Navigation Satellite System (GNSS) Topcon HiPer SR (Livermore, CA, USA) with a horizontal accuracy of ±1.0 cm and vertical accuracy of ±1.5 cm. The leveling of all 29 cross-profiles was done in calm weather over 16 hours, therefore the morphometric changes are insignificant. Cross-shore leveling has been conducted at fixed positions from benchmarks installed some distance inland from foredune to waterline. The placement of each cross-profile has been chosen to correspond with the best representation of the general geomorphological characteristics. Cross-shore profiles are denser where there is relatively high variability in morphometrical characteristics. The sediment budget (m^3/m) was established by comparing cross-shore profiles in two successive years. Beach and foredune volumes were calculated separately. Cross-shore beach volume is defined as the sand volume enclosed by beach surface and the horizontal line from the waterline to the foredune toe. Foredune volume is defined as the volume of enclosed sand vertically from the foredune toe to some distance inland where the vertical variability is negligible. The cross-shore profile area was calculated using ArcMap software.

Spacing between individual profiles is on average 1.5 km. The observation periods were from 2002 to 2019. Changes in the sediment volume were calculated over time from the first observation in 2002. The trend of beach and foredune volume (m^3/m per year) was determined from the linear regression of each individual profile. A 95% confidence interval was chosen (p-value < 0.05). The height of the foredune in different years was also determined. The sea level and frequency of the westerly wind (SW-NW direction) data from the Klaipėda station between 2002 and 2019 were collected from the Department of Marine Research of the Environmental Protection Agency. Annual mean values of sea level and frequency of the westerly wind were calculated from daily data. This way, seasonal variation was eliminated.

4. Results

During the research period (2002–2019), the recorded sea level rise was 0.12 cm/yr (Figure 3). The obtained trend is not statistically significant ($p > 0.05$). A reason for this is the large interannual variability. However, it was determined that the sea level has been rising at a similar rate (0.16 ± 0.02 cm/yr) since the beginning of the 20th century.

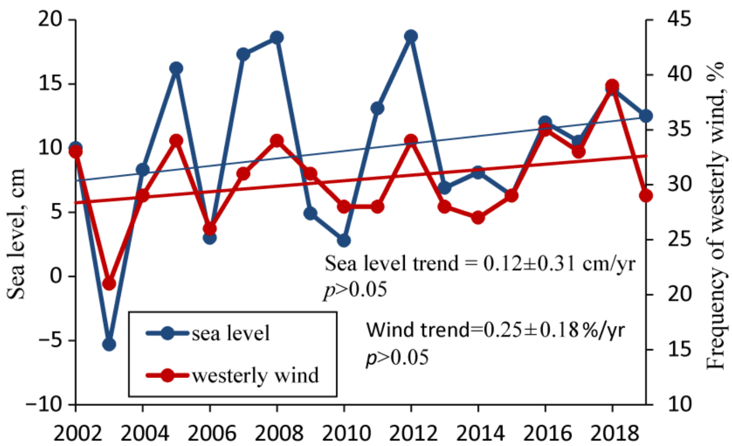


Figure 3. Sea level changes between 2002 and 2019 and their linear trends.

The marked sea level fluctuations in different years could have been the result of meteorological factors, in particular, cyclonic activity. This is proven by the frequency of westerly winds in 2002–2019, as shown in Figure 3. The relation between these characteristics (r = 0.77) is statistically significant ($p < 0.05$).

During the research period (2002–2019), no extreme storms occurred. The strongest storm, Ervin, was recorded on 9 January 2005, when gusts of W-SW winds reached 28 m/s and the storm surge rose up to 153 cm [50]; on 5 December 2013 the storm surge resulting from southwesterly winds (up to 21 m/s) generated by storm Xaver reached up to 120 cm, and on 11 January, 2015 (storm Felix) SW winds of 28 m/s elevated storm surge by up to 137 cm. However, due to a rapid beach recovery, the erosion had no determinant influence on the long-term trend of the shoreline displacement and beach and foredune sand volume variations.

Despite sea level rise, a high alongshore variation of shoreline displacement was determined (Figure 3). In the northern part, Klaipėda port jetties caused a seaward shoreline displacement up to 1.5 m per year, whereas in the central and southern parts the shoreline displacement rate ranges from −1.0 m/yr to 2.0 m/yr (Figure 4). It was noticed that shoreline fluctuations vary over a wide range in individual years. Annual changes in individual cases may reach 20 m or more. This is also reflected in the *p*-value (red line in Figure 4). Of 29 cases, nine trends are reliable ($p < 0.05$). This indicates that changes in shoreline position did not have a clear trend.

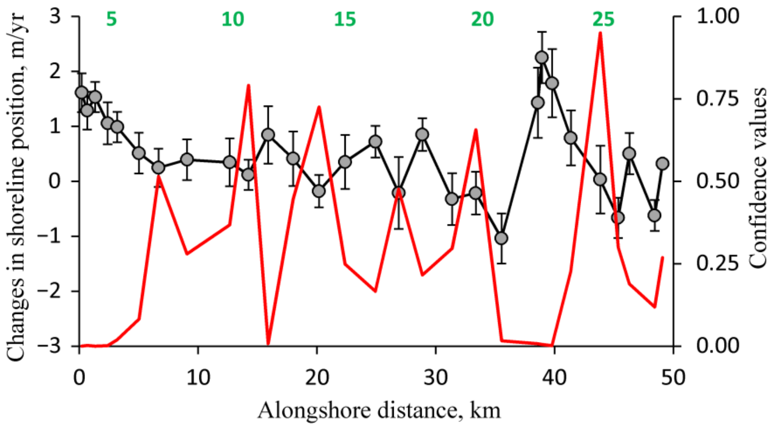


Figure 4. Linear trends (m/yr) in the shoreline position between 2002 and 2019. Red line—significance level (*p*-value). Green labels indicate cross-shore profile numbers.

Similarly, high variations of beach volume were determined in different coastal sectors (Figure 5A). In the northern part, the amount of beach sand has tended to increase (on average by 1–5 m^3/m per year), whereas in the southern part it has been decreasing (Figure 5A). It should be pointed out that these changes in beach sand volume in different coastal sectors are asynchronous. For example, until 2007, sand accretion had been the dominant trend in the southern part of the investigated sector. In 2008, this trend changed to erosion. Meanwhile, in the northern part of the Curonian Spit, this pattern was not observed. In general, permanent sand accretion on the beach in 2002–2019 only took place in the northern part of the spit (the Smiltynė–Alksnynė coastal sector), predetermined by a blockage of the alongshore sediment transport by the Klaipėda port jetties [35,49]. In the southern part (Pervalka–Nida), the variations in beach sand volume followed no definite pattern.

During the investigation period, the volume of foredune sand increased along the entire spit coast except for short stretches near Pervalka and Preila (Figure 5B). The foredune sand volume increased from 0.3 m^3/m per year in the southern part to 3.9 m^3/m/yr in the northern part. It should be noted that in the long term, no considerable variations in foredune sand volume were observed. Similar to the beach sand volume budget, the foredune sand volume variations in different coastal sectors were also asynchronous. Until 2007, sand volume variations in the northern part had been negligible, whereas after 2007 the accretion rates have been increasing. In the southern part, this pattern has not been observed.

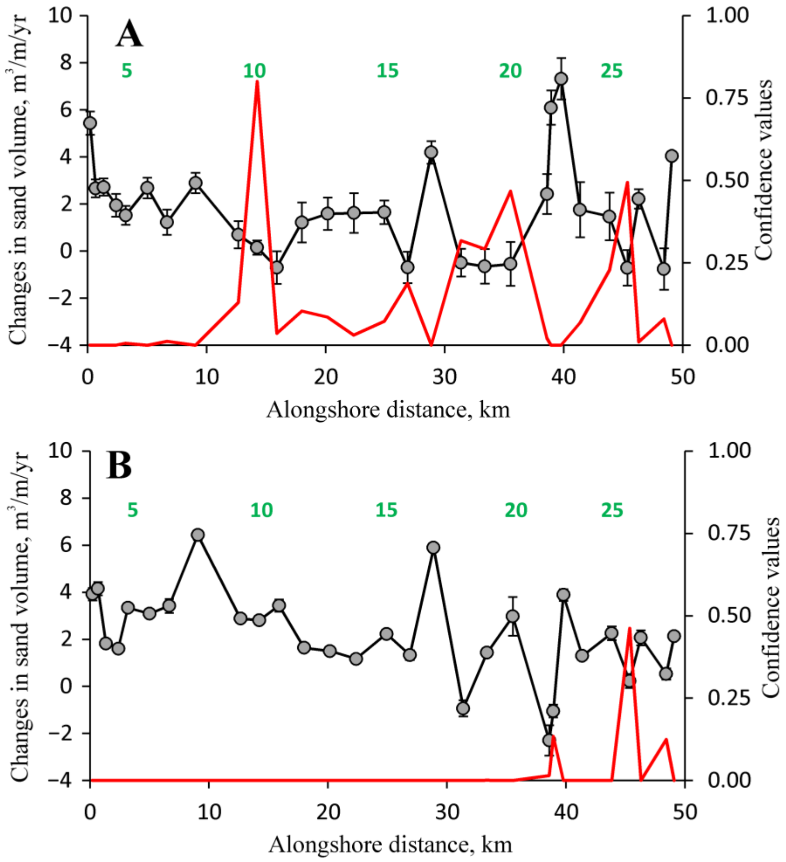


Figure 5. Linear trends (m^3/m per year) in the (**A**) beach and (**B**) foredune volume alongshore. Distance from Klaipėda port jetties. Red line—significance level (*p*-value). Green labels indicate cross-shore profile numbers.

It is worth noting that the foredune in the Lithuanian part of the Curonian Spit has grown since the end of the 19th century [52]. Between 1859 and 1910 (from the beginning of foredune formation) its height increased from 2.3 m (Juodkrantė) to 8.9 m (Smiltynė) (Figure 6). During the investigation period (2002–2019) the rate of foredune growth slowed but remained positive. Averaged foredune height increases at a rate of 1.4 cm/yr. It was observed that despite the high variability of beach sand volume, almost all (26 of 27 cases (Figure 5B)) trends are statistically significant ($p < 0.05$). The reason for the slowing down of foredune growth is the high elevation reached in the middle of the 20th century. Due to high elevation and dense coverage with marram grass on the western slope, sand particles hardly reach the top of the foredune. Therefore, the most accretion takes place at the foredune toe and western slope. Often, especially in the northern part, incipient dunes are formed. In recreational zones, due to high pedestrian pressure, foredunes are reinforced with tree branches, which is the second reason for accretion at the foredune toe and western slope. The height of the foredune has increased more in the southern part where the foredune is lower, while in the northern part where the foredune height reaches up to 16 m, the height of the foredune has remained practically unchanged for the last 20 years. Thus, the foredune grew rapidly upwards in the early 20th century, and currently, with similar accumulation rates, it has been widening. It should also be noted that between 2002 and 2019 there was not an appreciable shoreline and foredune migration.

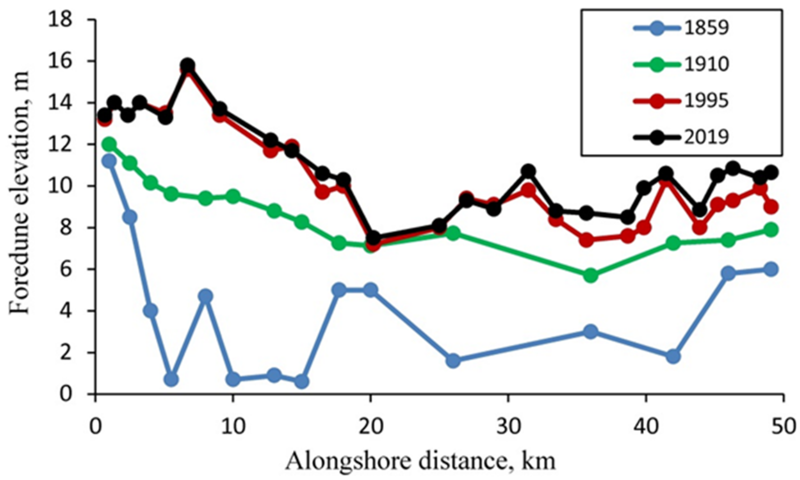


Figure 6. Changes in foredune elevation since 1859. Distance from Klaipėda port jetties.

5. Discussion

It can be seen in Figure 4 that over the last 17 years both the beach and foredune accretion processes have prevailed despite a rise in sea level of up to 0.12 cm/yr. The alongshore sediment transport from the southern part of the Curonian Spit (Kaliningrad district) is the main cause of this sand accretion. Due to the sand transport being blocked by the Klaipėda port jetties, the most intense accretion takes place in the northern part of the spit [35,49]. The observed rate of sea level rise does not stop the dominant trend of sand accumulation and coastal accretion [43]. Even during storms, the sand washed away from the coast is returned during the recovery phase and is not reflected in the long-term sand budget [41,53].

The influence of the sea level rise taking place during decadal time span on coastal sand volume changes is inconspicuous. Due to erosion at the Curonian Spit base (Kaliningrad district, Russia) where coastal regression occurred already in the 19th century [52] large amounts of sand transported northward helped to maintain a stable shoreline position in the central part of the spit (between Nida and Juodkrantė), while in the northern part (Alksnynė–Smiltynė) shoreline displacement seaward took place [52]. The same process takes place in the early 21st century. A comparison has shown that the shoreline displacement coincides with sand volume variations on the beach (Figure 7) (the correlation is significant at $p < 0.05$). Short erosion periods do not reverse the general accretion trend over a long-term period.

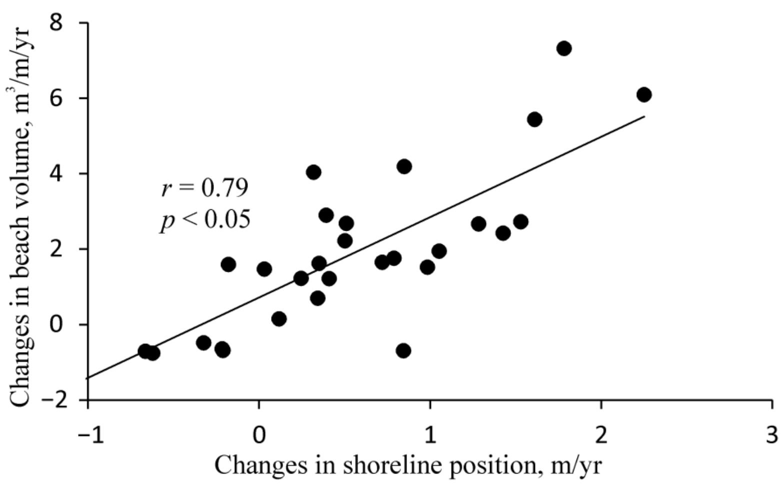


Figure 7. Correlation between mean changes in the shoreline position and beach sand volume.

An analysis of the interdependence of changes in shoreline position and foredune sand volume variations has shown no significant correlation ($p > 0.05$) (Figure 8). Even during years with predominated storm activity, the foredune sand budget has remained positive. The dominant sand accretion in the foredune takes place despite sea level oscillations or the beach sand budget.

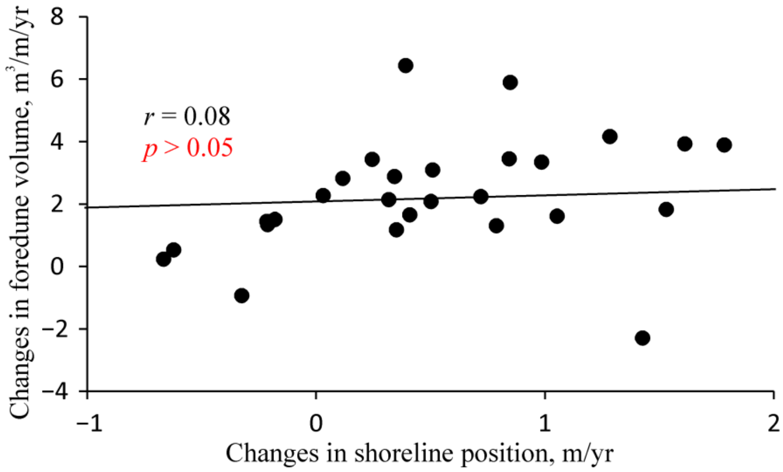


Figure 8. Correlation between changes in the shoreline position and foredune sand volume.

Despite a certain link between the beach and foredune sand budgets [39–41,54,55], as shown in Figure 9, no significant correlations between the changes in the beach and foredune sand budgets have been determined. Yet, the weak correlation between the beach and foredune sand budgets does not imply an absence of interdependence. The interdependence is presumably complicated by a few circumstances. One is the morphological properties of the beach [56]. During storms, narrow beaches can be replenished by foredune sand, in this way retaining their shape, whereas wider beaches can protect the foredunes at the expense of their sand budget. In the first case, when the foredune sand budget is negative, the beach sand volume will change insignificantly. In the second case, the beach sand budget will be negative, whereas in the foredune it will remain unchanged or even become positive [57]. It is also important that the beach and foredune budget are not synchronized in time [58]. Sand accretion on a beach takes place during calm meteorological conditions when a sandbar welds to the beach. Meanwhile, foredune accretion occurs during a storm season [58,59]. This process may also be influenced by interrelations with adjacent coastal sectors due to alongshore sediment transport [60]. The obtained results showed that if there is a sufficient amount of sand, even a slow sea level rise has a positive effect on the foredune sand budget. This is related not only to the alongshore transport of huge amounts of sediments from the southern part of the spit [35,47–49], but also to small nearshore inclines, which create favorable conditions for sandbar welding to the beach during fair weather conditions [61]. In these circumstances, foredunes that are built up at distal ends of some spits can build upwards despite a sea level rise [62]. Accretion was dominant in foredunes, even in coastal sectors where a low trend for sand decrease was observed on the beach. Such a situation is observed at 16, 27, 35, and 48 km from Klaipėda port jetties (Figure 5). This has also been supported by investigations carried out on other coasts [29,39,56,60].

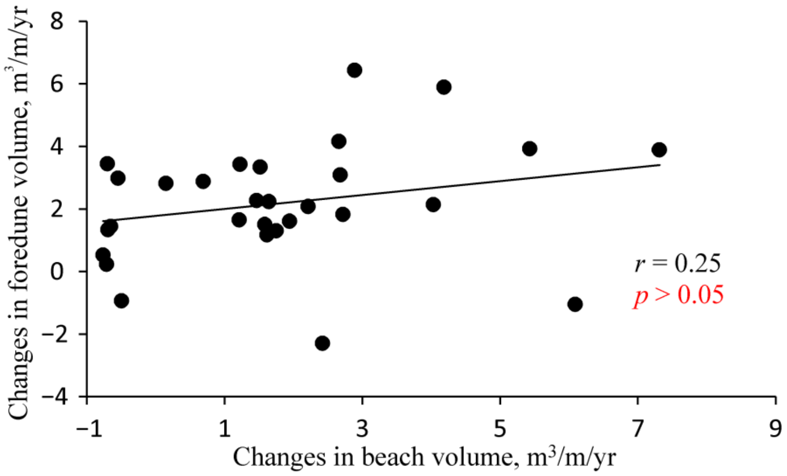


Figure 9. Correlation between changes in the beach and foredune sand volume.

It is worth noting that prevailing accretion in the Lithuanian part of the Curonian Spit has taken place since the end of the 19th century [52]. During the 20th century, there was not an appreciable shoreline or foredune migration. Due to alongshore sediment transport directed northward, rising sea level may increase coastal erosion in the southern part of the spit (Kaliningrad district) and the amount of sand transported, which may enhance sediment accumulation in the northern part of the spit) and herewith raise the transported sand amount, which may lead to the accumulation of sediments in the northern part of the spit.

It is assumed that coastal erosion processes start only when the sea level rise reaches a threshold value higher than the present rate on the Lithuanian coast of the Baltic Sea. According to Pye and Blott [63], the effects of these changes might not be significant for at least 30–50 years. However, it is worth noting that it is impossible to strictly predict threshold value determining erosional processes to be started because the aforementioned changes happen very slowly, so the coastal system can adapt to these alterations. It is also unclear what variations may happen to the sand supply, etc.

6. Conclusions

The present research showed that due to alongshore sand transport, the analyzed coastal sector is distinguished by a sand surplus. Therefore, a slow sea level rise (up to 0.12 cm/yr) has no negative effect on the foredune and only a minimal effect on beach development on a decadal time scale. No significant correlation was determined between the changes in foredune sand budget and sea level fluctuations. Also, no significant correlation between the changes in foredune and beach sand budgets was determined. Despite the rise in sea level and changes in beach sand volume, the foredune sand budget remained positive almost in the whole area of investigation. However, the absence of an interrelation between the beach and foredune budgets does not mean an absence of interdependence. The interrelation may have been complicated by a few circumstances: a time lag in different links (the beach in close contact with the sea tends to more readily adjust to changing sea levels, whereas in the foredune these processes lag behind). Moreover, the foredune sand washed away during more powerful storms may compensate for beach sand losses, thus preserving the unchanged beach sand budget.

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