Oceanologia, 67 (3)/2025, 67301
Polish Academy of Sciences
Institute of Oceanology
Open access article under the CC BY license
https://doi.org/10.5697/KSMY5385

Resilience of beach morphometric characteristics on decadal time scale: a case study from the Lithuanian Baltic Sea

Darius Jarmalavičius*, Gintautas Žilinskas, Donatas Pupienis, Rasa Janušaitė

Abstract
The sandy seashore is a highly dynamic environment where the beach experiences constant change. If the granulometric composition of beach sediment does not change substantially and the sediment circulation is undisturbed, as well as the prevailing hydrometeorological situation does not substantially change, the beach can maintain its morphology quasi-stably on a decadal time scale, even when coastal erosion or accretion processes prevail. In this study, beach width and volume characteristics of coastal segments with prevailing erosion or accretion were assessed based on interannual beach leveling surveys from the Lithuanian Baltic Sea coast in 2002–2023 (72 cross-shore profiles in total). Study results revealed that the beach on both coastal stretches with prevailing erosion processes and coastal stretches with prevailing accretion processes maintains its morphometric characteristics. On coastal stretches with prevailing erosion, the beach maintains its profile by supplementing its sediment budget with the sediment reserves in the foredune, while on coastal stretches with prevailing accretion and seaward shoreline migration, the indefinite increase in beach width is limited by the formation of the incipient dunes at the foredune toe.

Keywords
Coastal morphology; Coastal processes; Beach; Decadal beach measurements; Beach resilience; Baltic Sea

Laboratory of Geoenvironmental Research, Nature Research Centre, Vilnius, Lithuania
***Correspondence**: darius.jarmalavicius@gamtc.lt (D. Jarmalavičius)

Received: 14 August 2024; **revised:** 2 May 2025; **accepted**: 5 May 2025

1. Introduction

The sandy beach is in a constant state of change. It can experience significant sediment loss in a short period (during a single storm event) but, under favorable conditions, recover its profile during a period of shoreline regeneration (Thom and Hall, 1991; Morton et al., 1994; Choowong et al., 2009; Castelle et al., 2017). In accretion-dominated coasts, the beach can restore its former profile after storms with the sediment replenished from the nearshore. In erosion-dominated coasts, the beach can restore its former profile due to the presence of sand reserves in the foredunes (Psuty, 2004; Psuty and Silveira, 2010; Jarmalavičius et al., 2012a). The ability of a beach to restore its pre-storm profile is a characteristic of beach resilience (Brooks et al., 2017). For a beach profile to maintain its morphometric characteristics over a long period, the sediment supply in the coastal zone must be sufficient, and the sediment exchange across (between the nearshore, the beach, and the foredune) and along the coast must be undisturbed (Houser and Ellis, 2013; Masselink and Lazarus, 2019). Disrupting the free sediment exchange (e.g., by hard structures) between the beach and the nearshore in the case of erosion reduces the adaptive capacity of the beach due to coastal squeeze (Barnard et al., 2021). As the morphometric characteristics of the beach are constantly changing due to the intense hydrodynamic processes in the coastal zone, in this paper, resilience is understood as the ability of the beach profile to maintain its average morphometric characteristics as typical of a given coastal area under similar natural conditions on a decadal time scale. That is, if the shoreline retreats landward while the beach maintains its morphometric characteristics, the beach is considered stable in terms of ecological resilience (Flood and Schechtman, 2014; Kombiadau et al., 2019; Masselink, Lazarus, 2019; Malvarez et al., 2021). It should be noted that for the beach to sustain its characteristics, the prevailing hydrometeorological conditions should remain with no significant change. Otherwise, the morphometric characteristics of the beach would inevitably change as the coastal system adapts to the new conditions. In this case, long-term studies inevitably include time components (Dong et al., 2018).

This paper aims: 1) to determine how a beach profile can maintain its morphometric characteristics (particularly beach width and volume) with little variation in coastal environments with different dynamic conditions, including both landward shoreline retreat and seaward advance; and 2) to identify mechanisms that contribute to the maintenance of beach morphometric characteristics.

2. Study area

The study area covers Lithuania's Baltic Sea coast, which consists of two sections with different genesis and morphology: the mainland coast (38.5 km) and the Curonian Spit coast (51.0 km). They are separated by the Klaipėda Strait (1.1 km) (Figure 1).

As the tidal amplitude along the south-eastern Baltic Sea coast is not significant (up to 4 cm according to Medvedev et al., 2013), wind-generated waves and aeolian processes are the main beach-forming factors. Annual mean wave height at Klaipėda is 0.5–1.0 m (Kriaučiūnienė et al., 2006), but wave height might reach up to 4–6 m during extreme storms. The prevailing wave direction is SW-W (Figure 1C). Beaches are mainly formed by sediment of 0.2–0.3 mm. The beaches at the southern parts of Klaipėda and Šventoji ports consist of the finest sand (0.18–0.2 mm), while Juodkrante and Melnrage I beaches are composed of the coarsest sand (0.6–0.8 mm) (Figure 2B). In many places, the beach surface is covered with shingles, while pebbles or even boulders can be found at the cliffs of Šaipiai and Olando kepurė (the Dutch Cap). Beach slope ranges from

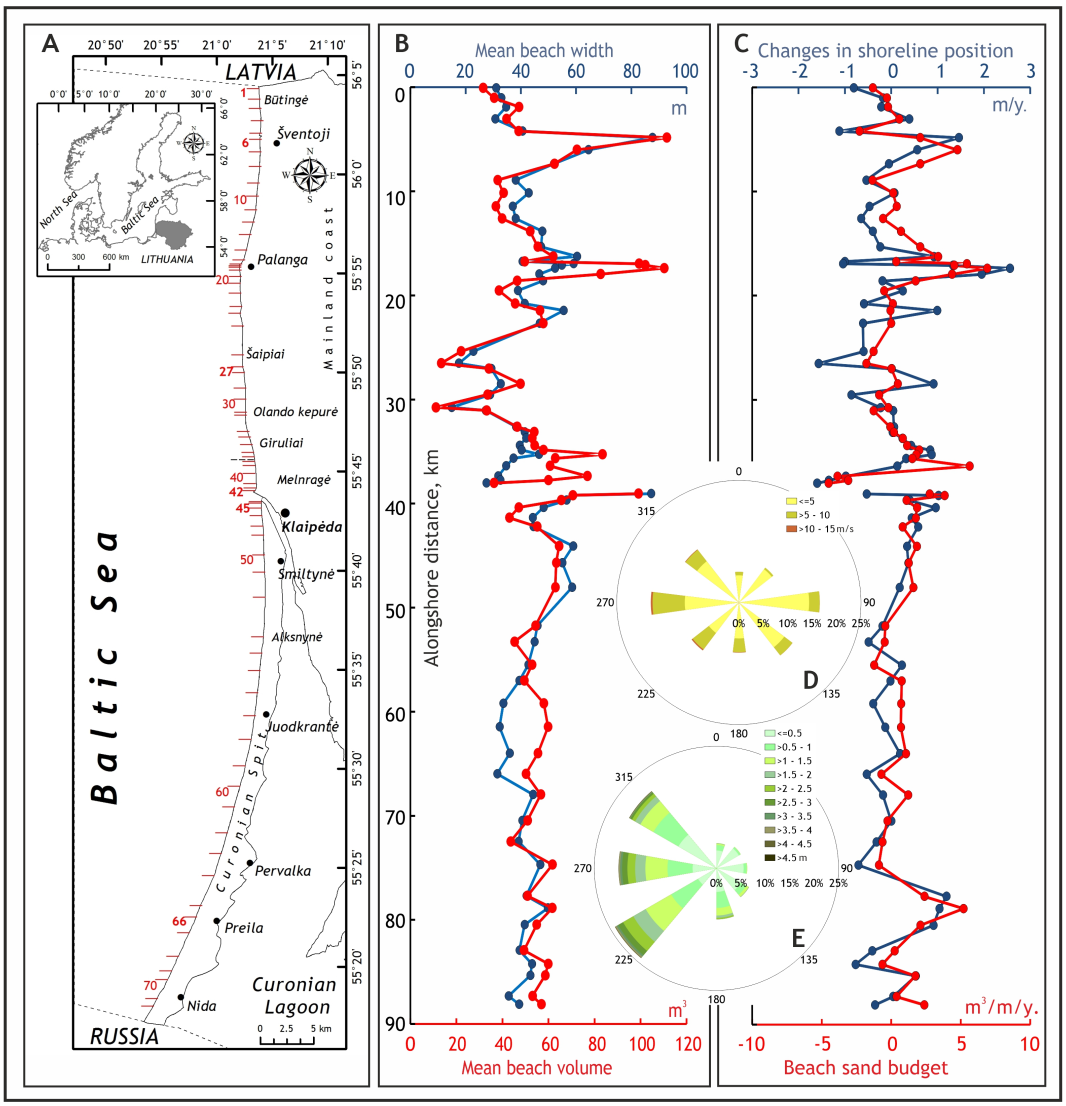

Figure 1. Study area configuration and the locations of beach leveling profiles (in red) (A); mean beach width (blue line) and mean beach volume (red) (B); changes in shoreline position (blue line) and beach sand budget (red line) (C); wind rose based on 2002–2023 data obtained from the Lithuanian Hydrometeorological Service under the Ministry of Environment (D); wave rose based on 2002–2023 data obtained from the Environmental Protection Agency (E).

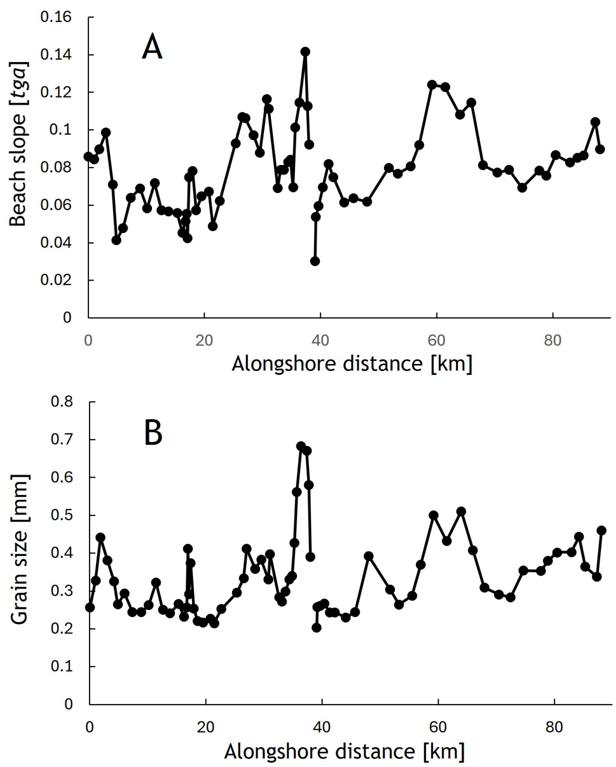

Figure 2. The beach slope (A) and average sand grain size (B) distribution alongshore.

0.03–0.04 at Šventoji and Smiltynė to 0.12–0.14 at Melnragė and Juodkrantė (Figure 2A). The sand volume is the highest on the mainland coast south of Šventoji (150–160 m^3 m^{-1}) and the Curonian Spit coast at Smiltynė (100–120 m^3 m^{-1}) (Figure 2B). The sand volume at the beaches near the moraine cliffs of Šaipiai and the Olando kepurė is the lowest, ranging from 10 to 30 m^3 m^{-1}. The beach width varies depending on the sand volume and the mean sediment particle size. The widest beaches can be found south of Šventoji (70–90 m) on the mainland coast and at Smiltynė (60–80 m) on the Curonian Spit coast. The narrowest beaches are at the moraine cliffs (15–20 m) on the mainland coast (Figure 2A).

The foredune stretches along most of the mainland coast and the entire Curonian Spit. The altitude of the foredune in the Curonian Spit reaches up to 15 meters. On the mainland coast, apart from the foredune, which reaches its highest point (12 m) south of Šventoji, there are moraine cliffs between Šaipiai and Giruliai. The cliff reaches its highest point at Olando Kepurė, which is about 20 meters high. The foredune surface is covered mainly by *Ammophila arenaria* and *Leymus arenarius*.

The main hydro-technical structures that have caused the largest shoreline changes in the coastal zone during the 20th century are the Klaipėda and Šventoji port jetties and the Palanga pier (Žilinskas et al., 2010; Jarmalavičius et al., 2012b; Kriaučiūnienė et al., 2013; Pupienis et al., 2013, 2014; Žilinskas et al., 2020).

3. Material and methods

To evaluate beach changes, the authors conducted multi-annual levelling of the subareal beach cross-section. Surveys were conducted along the stretch of the Baltic Sea coast between the Latvian and Russian borders (Figure 1). Cross-shore beach leveling was performed on 72 profiles, with 43 on the mainland coast and 29 on the Curonian Spit coast, using GNSS Topcon HiPer SR with a horizontal accuracy of ±1.0 cm and vertical accuracy ±1.5 cm. Spacing between individual profiles is on average 1.5 km. The measurements were conducted annually in April or May, when weather conditions were calm. The shoreline position was adjusted according to the Baltic Height System zero level (0 BS). The measurements covered the period from 2002 to 2023. The measurements were used to determine the beach width and beach volume. Beach width was defined as the horizontal distance between the shoreline and the dune toe. Beach volume was defined as the volume of sediment per m longshore constrained by the shoreline, dune toe, and horizontal line of the mean sea level (Figure 3). The foredune toe was recorded at the point where the angle of inclination of the ridge transitions to the beach. The beach face slope was defined as the angle between the beach face and the mean sea level. To compare two cross-shore profiles from adjacent years, the shoreline position change and sand budget were determined (Figure 2). Changes in shoreline position and sand budget were calculated relative to the reference year 2002. Since beach characteristics vary significantly from year to year, this study focuses on the long-term trends in parameter changes rather than on year-to-year fluctuations.

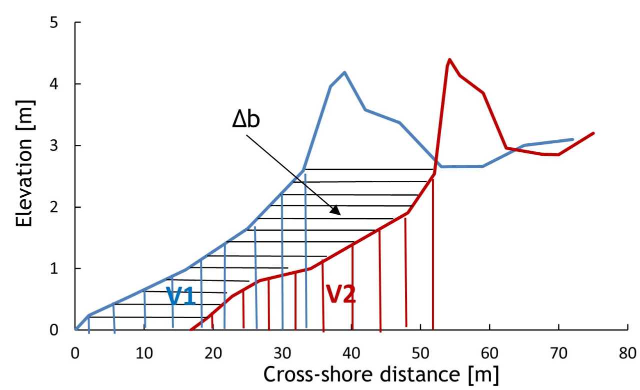

Figure 3. Morphometric indicators of the cross-shore profile: V1 (area covered with blue vertical lines) and V2 (area covered with red vertical lines) – beach volume in different years; Δb (area covered with black horizontal lines) – sand budget.

To analyze the composition of the beach-forming sand at the measurement sites, surface sand samples were collected from the lower part of the beach, the middle of the beach, and the foredune toe. Sand samples were used to evaluate the average sand particle size for the entire profile. Samples were collected in 2002, 2011, and 2014. In this study, the mean grain size was used. It was obtained through the logarithmic moment method (Blott and Pye, 2001) using the GRADISTAT software package.

4. Results

4.1 Alongshore variability in beach morphometrics

Beach width is one of the most sensitive morphometric characteristics of the coast. Because beach width can vary from several to more than ten or tens of meters over a year, the average beach width for the period 2002–2023 was used to compare beaches along different coastal sections. Figure 2A shows that the average width of beaches along the entire Lithuanian coastline is 42 m. The widest beaches, over 80 m wide, are found on the southern sides of the hydro-technical structures, south of the jetties of the ports of Šventoji and Klaipėda. The narrowest beaches are located north of the Šventoji and Klaipėda port jetties and at the moraine cliffs, where the average beach width is up to 20 m.

Observations of changes in shoreline position show that the average shoreline position trend for the entire Lithuanian coast in 2002–2023 was not significant but varied considerably in different coastal sectors alongshore. The greatest seaward migration was observed along the coastal stretches of the widest beaches, south of the Šventoji and Klaipėda port jetties (above 1 m y^{-1}). Shoreline seaward advance of 0.5–1.0 m y^{-1} was also observed at Giruliai (the mainland coast) and south of Pervalka (the Curonian Spit). Significant increases in beach width and shoreline seaward displacement were also recorded on the coast of the Palanga Recreation Area, but these changes are related to the artificial beach nourishment, so this section was excluded from the analysis. The greatest landward shoreline recession was recorded north of Šventoji and Klaipėda port jetties, as well as along the moraine cliff coast. In these areas, the shoreline was retreating at a rate of over 1 meter per year.

A similar pattern to beach width and shoreline changes was also observed in the sediment budget. The interannual variations in the sediment budget along the coast evidence that accretion processes with an average sand increase of 4–6 m^3 m^{-1} y^{-1} were predominant on the southern sides of the port jetties. Conversely, the northern sides of port jetties and the moraine cliff coast had the largest negative sediment budget, ranging from −1 to −5 m^3 m^{-1} y^{-1}.

4.2 The relationship between changes in beach width and shoreline position

The analysis of the interannual changes in shoreline position and beach width indicates that there was no significant correlation between these two indicators ($p > 0.05$). The data presented in Figure 4 show that the interannual variation in shoreline position varied over a much wider range (from −1.6 m y^{-1} to +1.5 m y^{-1}) compared to the interannual variation in beach width, which varied from −0.9 m y^{-1} to +0.9 m y^{-1}.

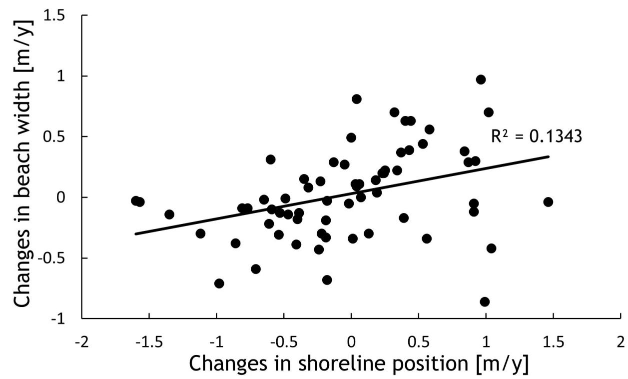

Figure 4. Correlation between trends in shoreline position and beach width in 2002–2023.

The differences in variations of the beach width and shoreline position were particularly noticeable in areas where erosion or accretion processes dominate. Figure 4 shows the coastal stretches with the highest rates of shoreline retreat (profiles 1, 27, 42) and the highest rates of shoreline accretion (profiles 6, 45, 66) over the period 2002–2023 (profile locations are shown in Figure 1). In all analyzed cases, changes in shoreline position had clearly defined significant trends ($p < 0.05$). However, the trends in beach width changes were minor and insignificant ($p > 0.05$). In the coastal sectors where the average shoreline retreat in the last 21 years was between 15 m (profile 1) and 36 m (profile 42), the average decrease in beach width was only about 3 m (profiles 1, 42). Meanwhile, in profiles, where the average shoreline seaward displacement over the 21 years was from 20 m (profile 45) to 35 m (profile 6), the beach width increased by up to 14 m (profile 45), or remained practically unchanged (profiles 6, 66) (Figure 5). In other words, shoreline position changes (both seaward and landward) did not have a significant effect on the beach width. It should be noted that this is a case of long-term trends. In particular years, these changes may not reflect this pattern. For example, a beach that narrowed after a period of stormy weather (autumn–winter) has recovered during a period of relatively calm weather (spring–summer), and these changes have not had a significant impact on the long-term trend in beach width.

4.3 The relationship between beach sand budget and beach sand volume

The assessment of the relationship between beach sand budget (annual change in sand amount between adjacent year profiles) and beach volume (amount of sand in the beach profile) (for explanations of the indicators, see Figure 3) in 2002–2023, showed that there is no reliable re-

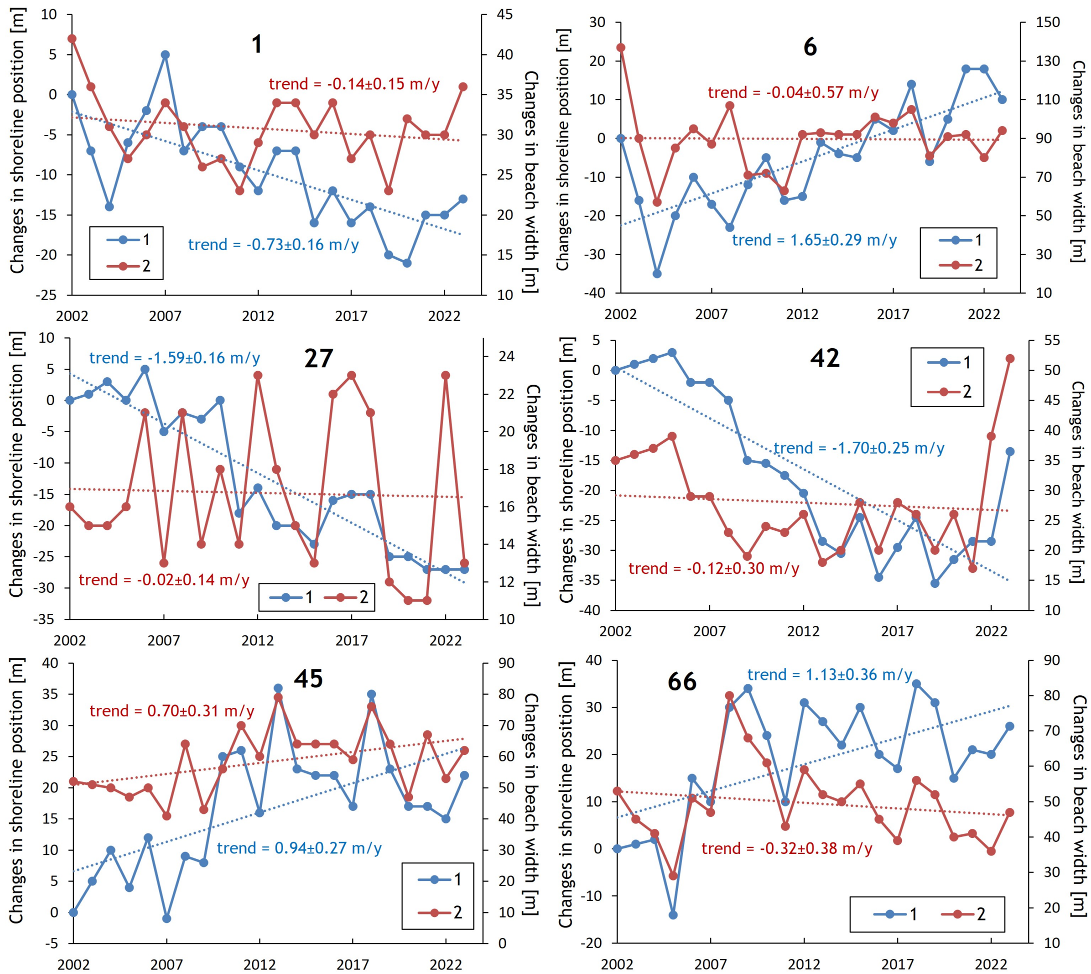

Figure 5. Changes in shoreline position (1) and beach width (2) in 2002–2023 with their linear trends at the cross-shore profiles with the greatest shoreline retreat and advance. Numbers in bold indicate profile numbers. The locations of the profiles are indicated in Figure 1. The 0 m shoreline position corresponds to the initial observation year.

lationship between these indicators ($p < 0.05$) (Figure 6). The amount of sand accumulated or eroded from the beach per year varied over a much wider range (from −4.5 m^3 m^{-1} y^{-1} to +5.6 m^3 m^{-1} y^{-1}) than the amount of sand in the beach profile (from −3.9 m^3 m^{-1} y^{-1} to +2.5 m^3 m^{-1} y^{-1}). As can be seen, regardless of the change in the beach sand budget, the amount of sand in the beach profile varies in smaller intervals, regardless of whether the coast is eroding or accreting.

Figure 7 shows that coastal sections with the highest erosion (profiles 1, 27, 42) and the highest accumulation (profiles 6, 45, 66) had a significant ($p < 0.05$) long-term trend in the beach sand budget. However, there was no clear trend ($p > 0.05$) in the beach volume. Over the analyzed 21-year period, on average, the sediment volume in the beach profile was reduced by only 3 m^3 m^{-1}; nevertheless, the beach has lost from 26 m^3 m^{-1} (profile 1) to 96 m^3 m^{-1} (profile 42) of sediment. Similar patterns were observed in coastal sectors, with a predominant accretion trend. Over the analyzed 21-year period, the sediment amount deposited on the beach varied from 50 m^3 m^{-1} (profile 6) to 112 m^3 m^{-1} (profile 66), while the beach volume only increased by up to 18 m^3 m^{-1} (profile 6) and even decreased by up to 12 m^3 m^{-1} (profile 66) on other coastal

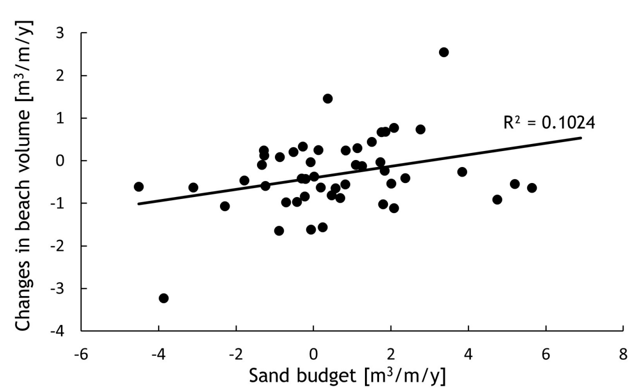

Figure 6. Correlation between trends in beach volume change and beach sand budget.

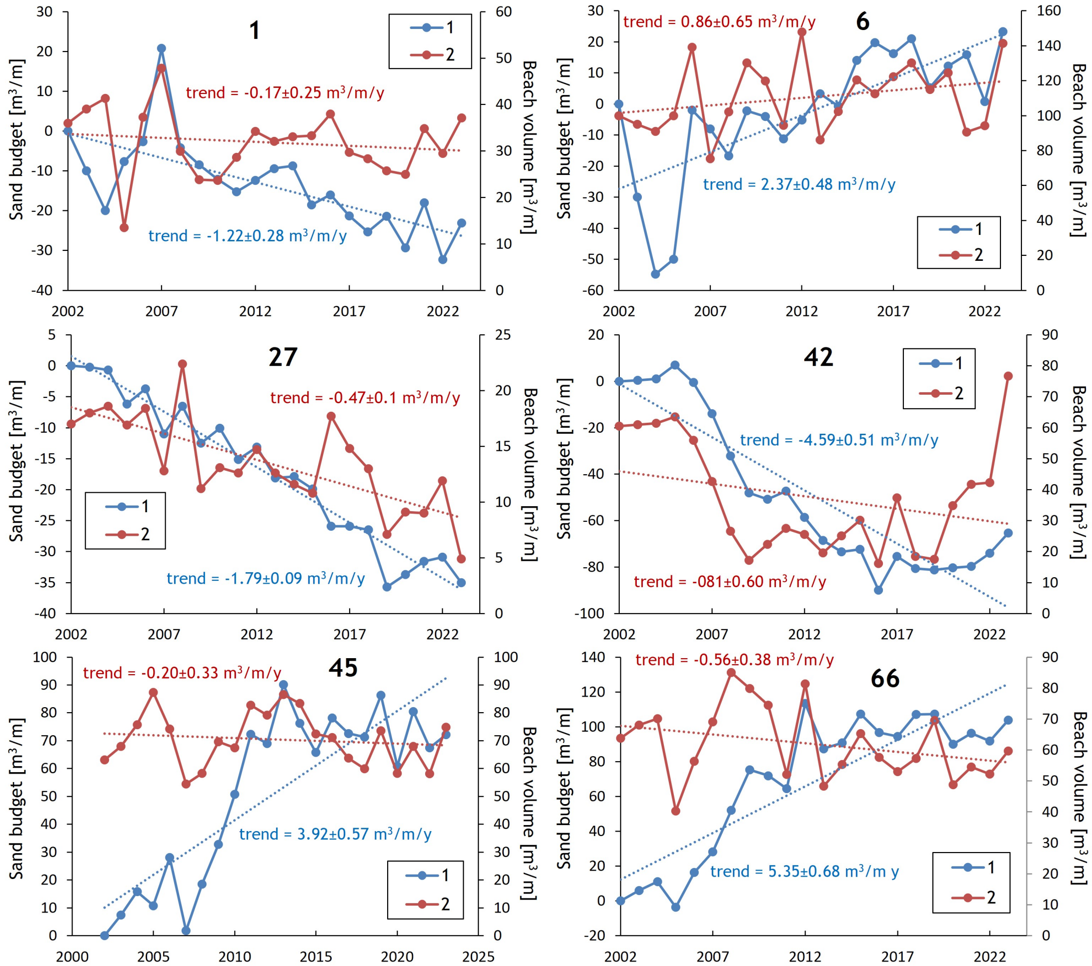

Figure 7. Beach sand budget (1) and beach volume changes (2) in 2002–2023 with their linear trends. Numbers in bold indicate profile numbers. The locations of the profiles are indicated in Figure 1.0 m^3 m^{-1} of sand budget corresponds to the initial observation year.

stretches (Figure 7). It is important to note that changes in both beach width and volume occur more gradually than changes in shoreline position and sand budget. As a result, the patterns discussed above may not be evident in the short term. This is particularly noticeable after extreme storms, when narrow beaches may retain their shape due to replenishment by sand from the foredune, while wider beaches can protect the foredunes at the cost of their own sand budget. In the first case, the shoreline position will change only slightly, while the beach width will increase. In the second case, changes in beach width and shoreline position may coincide. However, these differences tend to diminish in the long-term trend.

5. Discussion

A beach can maintain its parameters in a quasi-steady state only if the following conditions are fulfilled: 1) the coastal zone contains a sufficient amount of sediment; and 2) a free sediment exchange without anthropogenic disruption of the sediment supply between the nearshore, the beach, and the foredune exists (Kocurek and Lancaster, 1999; Masselink et al., 2020). It is important to note that when assessing beach stability, the emphasis is placed on long-term trends in the evolution of beach parameters rather than on annual variations, which can be substantial. As the beach is in a transitional position between the nearshore and the foredune, both erosion and accretion can lead to sediment supply to the beach from both the foredune and the nearshore (Jarmalavičius et al., 2012b). In the case of coastal regression, the sediment from the eroding foredune serves as the nourishment source for the beach, maintaining its morphometric characteristics (Figure 8). In the case of coastal transgression, as the beach widens and the fetch distance increases, the transported sand amount increases and its deposition at the foredune toe increases. This results in the incipient dune formation (Thom and Hall, 1991) or the seaward growth of the foredune (Figure 9). That prevents the beach from endlessly widening. The fact that the foredune toe moves proportionally to the

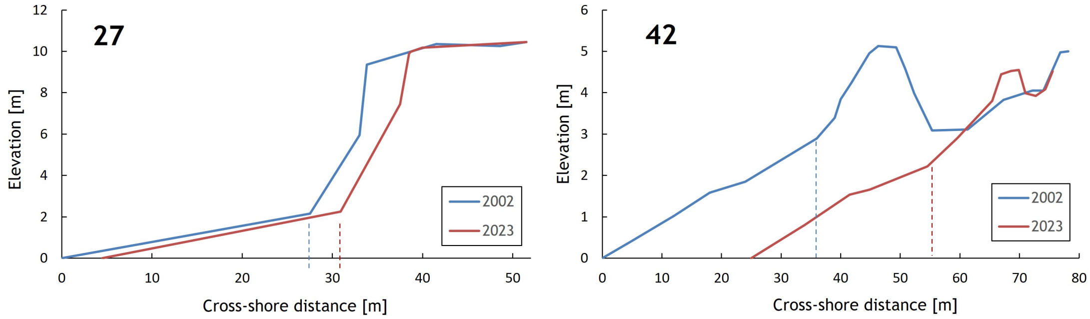

Figure 8. The cross-shore profile change between 2002 and 2023 at profiles where coastal erosion was observed (profiles 27 and 42). The dashed lines indicate the position of the foredune toe. The locations of the profiles are indicated in Figure 1.

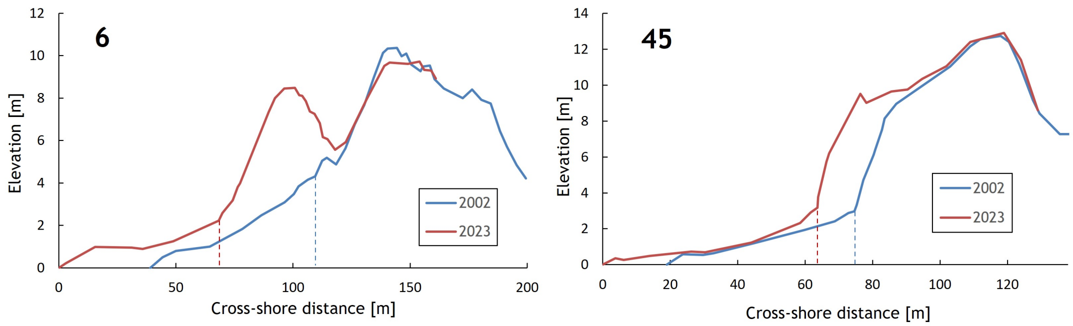

Figure 9. The cross-shore profile change between 2002 and 2023 at profiles where coastal accretion was observed (profiles 6 and 45). The dashed lines indicate the position of the foredune toe. The locations of the profiles are indicated in Figure 1.

shoreline has been observed by other researchers (Bristow et al., 2000; Ruessink and Jeuken, 2002; Saye et al., 2005).

However, the question remains, why does the beach maintain a certain beach profile on different coastal stretches? In this case, attention should be focused on the beach-forming factors. On the non-tidal Baltic Sea coast, wave activity and sea level fluctuations are the dominant beach-forming factors. Meanwhile, the main passive factors are the granulometric composition and the amount of unconsolidated sediment. The relationship between the mean grain size and the beach slope was established by Bascom (1951) and subsequently confirmed by several authors around the world (Firoozfar et al., 2014; Gallagher et al., 2016; McFall, 2019). Depending on the wave energy and the sediment grain size, different beach slopes are formed (Reis and Gama, 2010). This dependency is also evident on the sandy beaches of the Baltic Sea in Lithuania (Figure 10), where a positive ($r = 0.75$) and significant ($p < 0.05$) correlation between the average beach sediment particle size and the beach slope is observed. Beach slope formation is governed by swash hydrodynamics and associated sediment transport (Elfrink and Baldock, 2002). Infiltration/exfiltration processes are the main drivers of sediment redistribution in a swash flow (Butt et al., 2001; Karambas, 2003; Reis and Gama, 2010; Bujan et al., 2019). With the present average particle size, these processes result in the beach surface reaching a slope, which allows maximizing swash flows over and inside the sand layer of the beach (Butt et al., 2001; Reis and Gama, 2010). As sand particle size changes due to non-uniform flow in the swash zone, a differentiation of sand particles in the cross-shore profile begins: finer particles start to move seaward, thus decreasing the beach slope, and conversely, coarser particles start to move shoreward, increasing the beach slope (Butt et al., 2001). This process continues until an

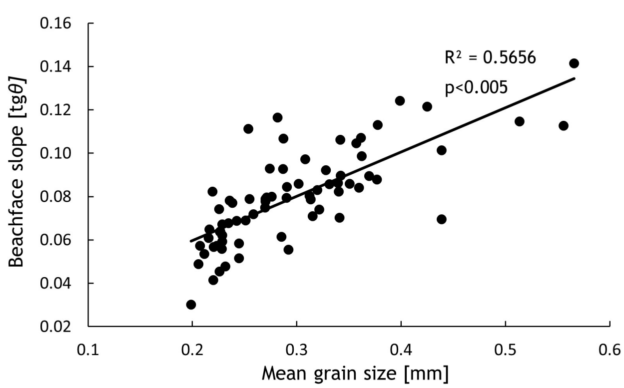

Figure 10. The correlation between the mean sand grain size composition of the beach and the beach slope.

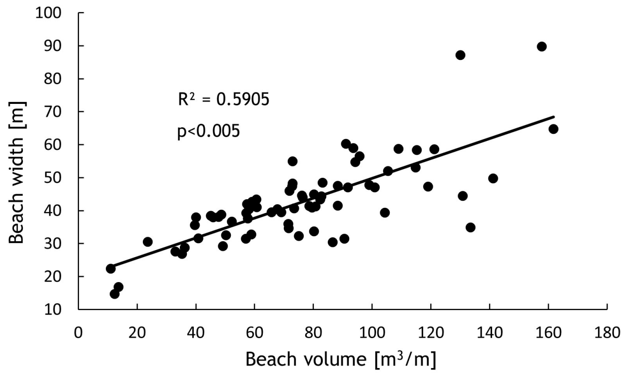

Figure 11. The correlation between the beach volume in cubic meters per meter of beach length and the beach width.

equilibrium between the sand particle size and the beach slope is reached.

Another important factor influencing beach width, and thus partly beach slope, is the unconsolidated sediment volume. The analysis showed a significant ($p < 0.05$) positive correlation ($r = 0.77$) between the beach volume and beach width (Figure 11). However, based on the observations (Figure 8), the beach width does not increase endlessly. As fetch distance increases, the energy of swash flow dissipates before reaching the foredune toe, leading to the formation of incipient dunes and a reduced increase in beach width. Conversely, as the beach narrows, its width becomes insufficient to dissipate the full energy of swash flow, resulting in erosion at the foredune toe. Figure 10 shows that only two cross-shore profiles reach a multiannual average beach width of 90 m. It is important to note that they are situated on the southern side of the Šventoji and Klaipėda port jetties. This is where the alongshore sediment transport is interrupted, leading to a high accumulation of sand. Meanwhile, on a naturally developing coast, there is little change in the beach width once the beach reaches an average width of 60–70 meters.

The fact that the beach maintains its morphometric characteristics, quasi-stable even in the most dynamic (erosion/accretion) coastal stretches on a decadal time scale, and can rebuild its cross-shore profile during the regeneration period after severe storms indicates that the coastal system is ecologically stable under the prevailing hydrometeorological conditions (Kombiadou et al., 2019; Masselink and Lazarus, 2019; Malvarez et al., 2021).

6. Conclusions

Due to infiltration and exfiltration, a non-uniform flow occurs in the swash zone. This process involves the differentiation of sand particles to form a beach profile that reduces the mobility of sand particles. In other words, it creates a quasi-stable beach profile that adapts to the existing external conditions. In this way, the beach morphometry remains relatively constant despite the fluctuations in the shoreline position. Even after extreme storms, the beach is restored to its initial state during the regeneration period. The main condition to maintain the beach profile stable is a sufficient sand supply to the beach and a free movement of sand within the cross-shore profile. On the eroding coast, sand supply from the foredune rebuilds the beach, while on the accreting coast, shoreline seaward migration and sand deposition on the backshore, where the incipient dunes form and occupy the beach space, allow the beach to maintain its profile. If external factors (such as the prevailing wave energy or the sediment composition and quantity) change, the beach profile will change to adapt to the new conditions. If the sediment transport is disrupted (e.g., by the hard construction), the beach will be unable to replenish the sand supply from the nearshore, which is necessary to maintain its profile, potentially leading to its degradation.

Conflict of interest

None declared.

References

.25in1

Barnard, P.L., Dugan, J.E., Page, H.M., Wood, N.J., Hart, J.A.F., Daniel R. Cayan, D.R., Erikson, L.H., Hubbard, D.M., Myers, M.R., Melack, J.M., Iacobellis, S.F., 2021. *Multiple climate change-driven tipping points for coastal systems*. Sci. Rep. 11 (1), 15560.
https://doi.org/10.1038/s41598-021-94942-7

Bascom, W.N., 1951. *The relationship between sand size and beach face slope*. Trans. Am. Geophys. Union 32, 866–874.
https://doi.org/10.1029/TR032i006p00866

Bujan, N., Cox, R., Masselink, G., 2019. *From fine sand to boulders: Examining the relationship between beach-face slope and sediment size*. Mar. Geol. 417, 106012.
https://doi.org/10.1016/j.margeo.2019.106012

Blott, S.J., Pye, K., 2001. *Gradistat: a grain size distribution and statistics package for the analysis of uncollected sediments*. Earth Surf. Proc. Land. 26, 1237–1248.
https://doi.org/10.1002/esp.261

Bristow, C.S., Chroston, P.N., Bailey, S.D., 2000. *The structure and development of foredunes on a locally prograding coast: insights from ground-penetrating radar surveys, Norfolk, UK*. Sedimentology 47, 923–944.
https://doi.org/10.1046/j.1365-3091.2000.00330.x

Brooks, S.M., Spencer, T., Christie, E.K., 2017. *Storm impacts and shoreline recovery: Mechanisms and controls in the southern North Sea*. Geomorphology 283, 48–60.
https://doi.org/10.1016/j.geomorph.2017.01.007

Butt, T., Russell, P., Turner, I., 2001. *The influence of swash infiltration-exfiltration on beach face sediment trans-*

port: onshore or offshore?. Coastal Eng. 42, 35–52.
https://doi.org/10.1016/S0378-3839(00)00046-6

Castelle, B., Stéphane Bujan, S., Ferreira, S., Dodet, G., 2017. *Foredune morphological changes and beach recovery from the extreme 2013/2014 winter at a high-energy sandy coast*. Mar. Geol. 387, 41–55.
https://doi.org/10.1016/j.margeo.2016.12.006

Choowong, M., Phantuwongraj, S., Charoentitirat, T., Chutakositkanon, V., Yumuang, S., Charusiri, P., 2009. *Beach recovery after the 2004 Indian Ocean tsunami from Phang-nga, Thailand*. Geomorphology 104, 134–142.
https://doi.org/10.1016/j.geomorph.2008.08.007

Dong, Z., Elko, N., Robertson, Q., Rosati, J., 2018. *Quantifying beach and dune resilience using the coastal resilience index*. Coast. Eng. Proc. 36, 30–30.

Elfrink, B., Baldock, T., 2002. *Hydrodynamics and sediment transport in the swash zone: a review and perspectives*. Coastal Eng. 45, 149–167.
https://doi.org/10.1016/S0378-3839(02)00032-7

Firoozfar, A., Neshaei, M.A.L., Dykes, A.P., 2014. *Beach profiles and sediments, a case of the Caspian Sea*. Int. J. Mar. Sci. 4 (43), 1–9.
https://doi.org/10.5376/ijms.2014.04.0043

Flood, S., Schechtman, J. 2014. *The rise of resilience: Evolution of a new concept in coastal planning in Ireland and the US*. Ocean Coast. Manage. 102, 19–31.
https://doi.org/10.1016/j.ocecoaman.2014.08.015

Gallagher, E., Wadman, H., McNinch, J., Reniers, A., Koktas, M., 2016. *A conceptual model for spatial grain size variability on the surface of and within beaches*. J. Mar. Sci. Eng. 4, 38.
https://doi.org/10.3390/jmse4020038

Houser, C., Ellis, J., 2013. *Beach and Dune Interaction*. [In:] Shroder, J.F. (Ed.), *Treatise on Geomorphology*, Vol. 10, Acad. Press, San Diego, 267–288.
https://doi.org/10.1016/B978-0-12-374739-6.00283-9

Jarmalavičius, D., Satkūnas, J., Žilinskas, G., Pupienis, D., 2012a. *Dynamics of beaches of the Lithuanian coast (the Baltic Sea) for the period 1993–2008 based on morphometric indicators*. Environ. Earth Sci. 65 (6), 1727–1736.
https://doi.org/10.1007/s12665-011-1152-3

Jarmalavičius, D., Žilinskas, G., Pupienis, D., 2012b. *Impact of Klaipėda port jetties reconstruction on adjacent sea coast dynamics*. J. Environ. Eng. Landsc. 20 (3), 240–247.
https://doi.org/10.3846/16486897.2012.660884

Karambas, T.V., 2003. *Modelling of infiltration-exfiltration effects of cross-shore sediment transport in the swash zone*. Coast. Eng. J. 45 (1), 63–82.
https://doi.org/10.1142/S057856340300066X

Kocurek, G., Lancaster, N., 1999. *Aeolian system sediment state: theory and Mojave Desert Kelso dune field example*. Sedimentology 46, 505–515.
https://doi.org/10.1046/j.1365-3091.1999.00227.x

Kombiadou, K., Costas, S., Carrasco A.R., Plomaritis, T.A., Ferreira, Ó, Matias, A., 2019. *Bridging the gap between resilience and geomorphology of complex coastal systems*. Earth-Sci. Rev. 198, 102934.
https://doi.org/10.1016/j.earscirev.2019.102934

Kriaučiūnienė, J., Gailiušis, B., Kovalenkovienė, M., 2006. *Peculiarities of sea wave propagation in the Klaipėda Strait, Lithuanica*. Baltica, 19 (1), 20–29.

Kriaučiūnienė, J., Žilinskas, G., Pupienis, D., Jarmalavičius, D., Gailiušis, B., 2013. *Impact of Šventoji port jetties on coastal dynamics of the Baltic Sea*. J. Environ. Eng. Landsc. 21 (2), 114–122.
https://doi.org/10.3846/16486897.2012.695736

Malvarez, G., Ferreira, O., Navas, F., Cooper, J.A.G., Gracia-Prieto, F.J., Talavera, L., 2021. *Storm impacts on a coupled human-natural coastal system: Resilience of developed coasts*. Sci. Total Environ. 768, 144987.
https://doi.org/10.1016/j.scitotenv.2021.144987

Masselink, G., Lazarus, E., 2019. *Defining coastal resilience*. Water 11, 2587.
https://doi.org/10.3390/w11122587

Masselink, G., Russell, P., Rennie, A., Brooks, S., Spencer, T., 2020. *Impacts of climate change on coastal geomorphology and coastal erosion relevant to the coastal and marine environment around the UK*. MCCIP Sci. Rev. 2020, 158–189.
https://doi.org/10.14465/2020.arc08.cgm

McFall, B.C., 2019. *The relationship between beach grain size and intertidal beach face slope*. J. Coastal Res. 35 (5), 1080–1086.
https://doi.org/10.2112/JCOASTRES-D-19-00004.1

Medvedev, I.P., Rabinovich, A.B., Kulikov, E.A., 2013. *Tidal oscillations in the Baltic Sea*. Oceanology 53 (5), 596–609.
https://doi.org/10.1134/S0001437013050123

Morton, R.A., Paine, J.G., Gibeaut, J.C., 1994. *Stages and Durations of Post-Storm Beach Recovery, Southeastern Texas Coast, U.S.A.* J. Coastal Res. 10 (4), 884–908.

Psuty, N.P., 2004. *The coastal foredune: a morphological basis for regional coastal dune development*. [In:] Martínez, M.L., Psuty, N.P. (eds.), *Coastal dunes: ecology and conservation*, Springer, Berlin, Heidelberg, 11–27.
https://doi.org/10.1007/978-3-540-74002-5_2

Psuty, N.P., Silveira, T.M., 2010. *Global climate change: an opportunity for coastal dunes?* J. Coast. Conserv. 14, 153–160.

Pupienis, D., Jonuškaitė, S., Jarmalavičius, D., Žilinskas, G., 2013. *Klaipėda port jetties' impact on the Baltic Sea shoreline dynamics, Lithuania*. J. Coast. Res. 65, 2167–2172.
https://doi.org/10.2112/SI65-366.1

Pupienis, D., Jarmalavičius, D., Žilinskas, G., Fedorovič, J., 2014. *Beach nourishment experiment in Palanga, Lithuania*. J. Coast. Res. 70, 490–495.
https://doi.org/10.2112/SI70-083

Reis, A.H., Gama, C., 2010. *Sand size versus beachface slope – An explanation based on the Constructal Law*. Geomorphology 114, 276–283.
https://doi.org/10.1016/j.geomorph.2009.07.008

Ruessink, B.G., Jeuken, M.C.J.L., 2002. *Dunefoot dynamics along the Dutch coast*. Earth Surf. Process. Landforms 27, 1043–1056.
https://doi.org/10.1002/esp.391

Saye, S.E., van der Wal, D., Pye, K., Blott, S.J., 2005. *Beach-dune morphological relationships and erosion/accretion: An investigation at five sites in England and Wales using LIDAR data*. Geomorphology 72, 128–155.
https://doi.org/10.1016/j.geomorph.2005.05.007

Thom, B.G., Hall, W., 1991. *Behavior of beach profiles during accretion and erosion-dominated periods*. Earth Surf. Processes 16, 113–127.

Žilinskas, G., Pupienis, D., Jarmalavičius, D., 2010. *Possibilities of regeneration of the Palanga coastal zone*. J. Environ. Eng. Landsc. 18 (2), 95–101.
https://doi.org/10.3846/jeelm.2010.11

Žilinskas, G., Janušaitė, R., Jarmalavičius, D., Pupienis, D., 2020. *The impact of Klaipėda Port entrance channel dredging on the dynamics of the coastal zone, Lithuania*. Oceanologia 62 (4), 489–500.
https://doi.org/10.1016/j.oceano.2020.08.002