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Initial adjustment of underwater profiles after nourishment in a mild wave climate: a case study near Klaipėda, the Baltic Sea

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ABSTRACT

We analyze the spatio-temporal dynamics of sand relocation for beach nourishment in the low-energy coastal segment north of the Port of Klaipėda, eastern Baltic Sea, under mild wave conditions, with significant wave heights below 0.9 m and water level variations from −30 to 44 cm with respect to the long-term average. In summer 2022, about 180 000 m^3 of sand was added approximately 120 m from the shore at water depths of 2–3.5 m to form a 750 m long underwater bar. Sand relocation is evaluated based on repeated water depth measurements along 114 cross-shore coastal profiles. Some sand was rapidly transported to greater depths, down to about 6 m, even though wave conditions were particularly mild. The predominant sand motion was directed offshore, and characteristically for the area, wave-driven sediment transport was directed to the north. The analysis confirms that even very mild wave conditions can substantially relocate large volumes of deposited sand in shallow water, both offshore and onshore, from its original location during the initial adjustment phase following nourishment.

Introduction

Beach nourishment is one of the most effective yet complex ways to address coastal erosion (Regard et al. 2023). Success depends on many factors, including local conditions, such as grain size (Dean and Campbell 2016), weather patterns, existing coastal engineering structures, and human activity (Herrera et al. 2010; Brand et al. 2022). Sand can be deposited on the subaerial beach or in the nearshore (Johnson et al. 2021). Sediment placed on the nearshore profile can form sand bars or nearshore berms (Brutsché et al. 2014; Bain et al. 2021; Johnson et al. 2021) that resemble soft submerged breakwaters (Brutsché et al. 2014; Bain et al. 2021). On many occasions, nearshore nourishments can use sediments dredged from nearby navigation channels, subtidal bars, or offshore deposits, and sands can be deposited while the beach remains in use.

Beach nourishment offers numerous benefits to coastal areas, including increased recreational space, improved coastal protection, enhanced biodiversity, economic benefits, and long-term cost savings (Greene 2002; Pupienis et al. 2014). Adding sand to eroded beaches increases their width, providing more space for recreation and tourism (Luijendijk et al. 2018). Nourishment can protect coastal infrastructure and property from erosion and storm damage, acting as a buffer and reducing erosion rates (Mendes et al. 2021; McGill et al. 2022; Pinto et al. 2022), and careful placement offshore can operate as a “beach feeder” that releases sand during periods of higher wave energy (Colleter et al. 2019).

Cross-shore and alongshore sediment transport can redistribute sand after nearshore nourishment in various ways, depending on the specific conditions of the coastal system (Brutsché et al. 2014; McGill et al. 2022). The distribution of added sand can be influenced by the direction and intensity of waves and currents, as well as the topography and sediment characteristics of the beach and nearshore (Wang 2004; Work et al. 2004; George et al. 2020). The specific outcomes can vary, depending on many factors and local conditions (Chowdhury and Behera 2017; Kumar et al. 2017).

The type and quality of sand, the timing and frequency of nourishment events (Dean 2002), and the availability of funding for ongoing maintenance (Staniszewska and Boniecka 2017) can influence the success of nourishment projects. Environmental factors, such as storms, erosion, and rising sea levels, can also impact the long-term effectiveness of beach nourishment efforts (Hanslow 2007; Ferreira and Coelho 2021). This complexity calls for a comprehensive approach that includes regular monitoring and evaluation of project outcomes and ongoing stakeholder engagement to ensure that beach nourishment is aligned with broader coastal management goals (Hinkel et al. 2013; Hasan et al. 2020). Successful beach nourishment requires a commitment to adaptive management and a willingness to adjust strategies based on changing conditions (Kuang et al. 2019; Johnson et al. 2021). Therefore, proper planning and monitoring are essential to ensure that the added sand is distributed to maximize its effectiveness in protecting the coastal zone while maintaining the natural characteristics of the beach (Greene 2002; Armstrong et al. 2016). Effective beach nourishment requires a careful balance between human intervention, natural processes, and monitoring and maintenance to ensure long-term success (Armstrong et al. 2016; Mendes et al. 2021; Pinto et al. 2022).

Intrinsically, most beach nourishment actions take place on relatively high-energy beaches that lose sand owing to various hydrodynamic loads (Dean 2002). In these circumstances, wave activity, possibly combined with water level variations, rapidly relocates the added sand toward a new equilibrium (Guillén and Hoekstra 1997). However, even under relatively high energy conditions, relocation of sand over long distances can take significant time (Strauss et al. 2009). Conceptually, the establishment of a new equilibrium that accommodates the additional sand should take much longer on low-energy beaches and, in particular, on those with a small tidal range. We use a beach nourishment project undertaken in the summer of 2022 along a sandy Baltic Sea coastal section near the entrance to the Port of Klaipėda, Lithuania, to evaluate the time scale of sand relocation processes in a micro-tidal, low-energy environment driven by short and low energy waves of the Baltic Sea. This task is accomplished using repeated mapping of cross-shore beach profiles and an evaluation of sand relocation along and across such profiles based on short-term changes in the bottom surface height.

Materials and methods

Study site

The Lithuanian coastal zone (Fig. 1) is a narrow strip of land extending along the Baltic Sea's eastern coast for approximately 90 km. It contains a diverse landscape of sandy beaches, dunes, wetlands, lagoons, and forests. The shoreline is relatively straight and contains several wide, low-lying, almost flat segments, with the highest points reaching only a few meters above sea level (Bagdanavičiūtė et al. 2012). The sandy beaches are primarily located in the southern part along the Curonian Spit, while coarser sand, shores partially protected with boulders, and easily erodable cliffs are more common in the northern part along the mainland shore of Lithuania (Bagdanavičiūtė et al. 2012). The coastal zone of Lithuania is an important ecological and cultural landscape, supporting a rich diversity of plant and animal species and human communities that rely on the sea for their maintenance (Jurkus et al. 2021; Inácio et al. 2022). It is a unique and valuable resource that requires careful management to ensure its sustainability (Baltranaitė et al. 2021; Inácio et al. 2022).

The Klaipėda Strait divides the Lithuanian Baltic Sea coast into two geomorphologically different parts: the mainland and the Curonian Spit (Bitinas et al. 2005; Kondrat et al. 2021). The Curonian Spit coast is an accumulative environment consisting entirely of sandy sediments (Bitinas et al. 2005). In contrast, the mainland coast is geomorphologically diverse, with mostly erosive processes on the beach and nearshore (Bitinas et al. 2005).

The Lithuanian nearshore zone is fully open to hydrometeorological drivers from the Baltic Sea. It is a complex and dynamic environment affected by waves, currents, and weather conditions that evolve due to the Baltic Sea's relatively mild wave climate (Björkqvist et al. 2018) and two systems of moderate and strong winds in the northern Baltic proper. Southwestern winds are the most frequent, whereas (north-)northwestern winds are less frequent but may be even stronger (Soomere 2003). Waves approaching the study area from the western directions have the largest average significant wave heights (SWH), reaching approximately 0.9 m. The average SWH of waves approaching from the southern directions is about 0.6 m, and around 0.5 m for waves approaching from the northern directions. Waves propagating from the east to the west (to the offshore) can reach around 0.3 m at measurement locations 500–600 m from the shore (Kelpšaitė et al. 2008, 2011; Jakimavičius et al. 2018). These waves are short and evidently have negligible impact on sediment transport in the study area.

Sediment transport along the Lithuanian coast is predominantly from the south to the north, with a few temporary reversals (Viška and Soomere 2013). While the shores of the Curonian Spit south of Klaipėda are generally stable (Bitinas et al. 2005), erosion usually predominates along the mainland coast north of the Klaipėda Strait (Bitinas et al. 2005; Viška and Soomere 2013). To preserve the beaches in this coastal zone, beach nourishment has become a frequent and effective erosion mitigation method (Kondrat et al. 2021). For example, in the resort town of Palanga, beach nourishment has been used to widen the beach and provide additional recreational space (Pupienis et al. 2014; Kelpšaitė-Rimkienė et al. 2021).

Beach nourishment was recently utilized for the first time in the impact zone of the jetties protecting the fairway to the Port of Klaipėda. This port, located in the Klaipėda Strait on the eastern coast of the Baltic Sea, is the largest and busiest port in Lithuania (Žilinskas et al. 2020; Kondrat et al. 2021).

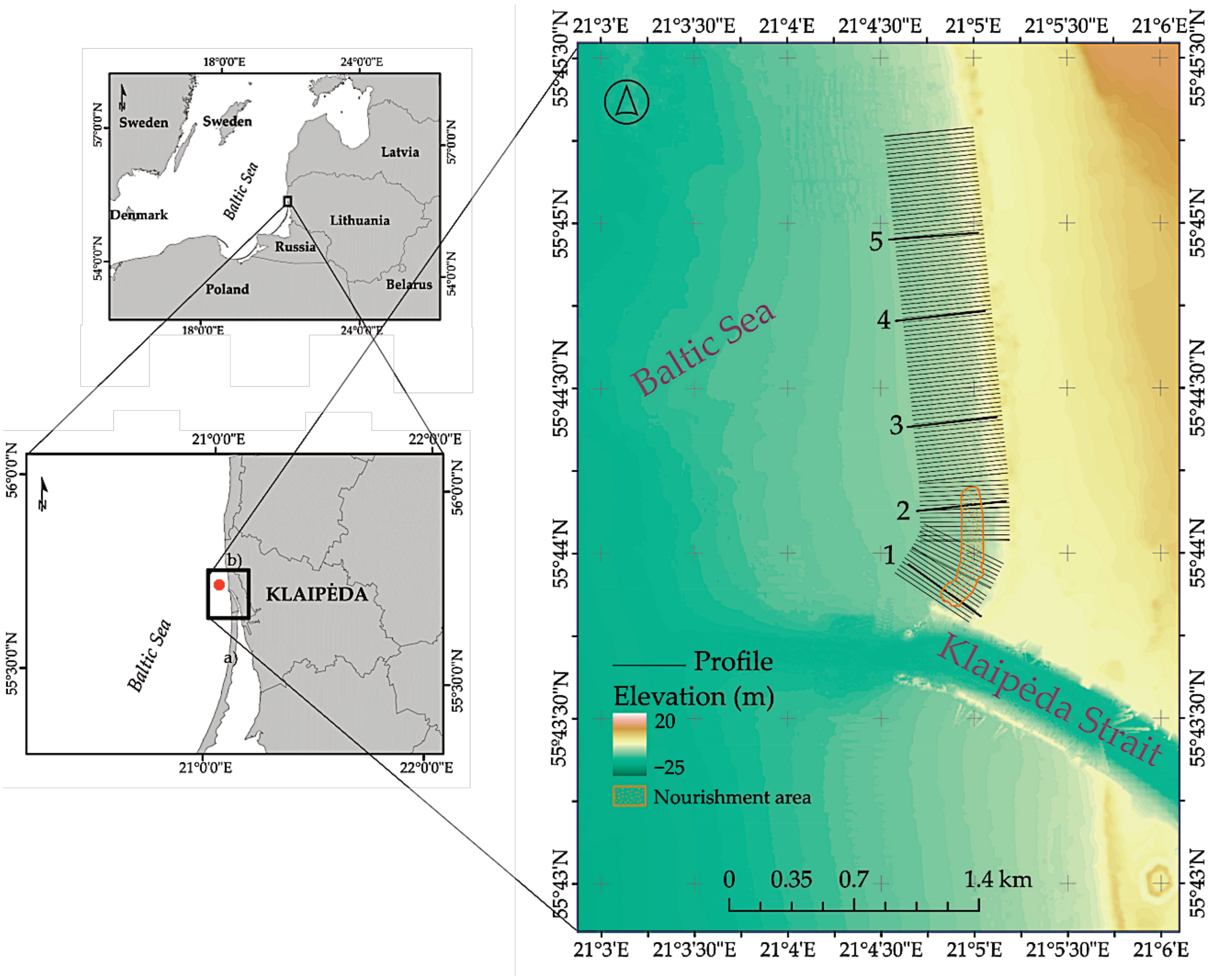

Fig. 1. Schematic map of the study site, the nourishment area, and the network of beach profiles. The red dot marks the location of the wave model grid cell centered at 55.75° N, 21.04° E: a) Curonian Spit, b) Giruliai Beach. The Port of Klaipėda is located about 2 km to the southeast along the Klaipėda Strait. Numbers 1–5 indicate cross-shore profiles that are discussed below in detail.

It is an important hub for international trade and commerce, serving as a gateway to the Baltic States and the wider region (Baltranaitė et al. 2021). Its jetties extend to depths greater than closure depths in this region, at about 5.5 m (Soomere et al. 2017), stopping most wave-driven sediment transport. These massive structures thus create sediment deficit in the downdrift direction of alongshore sediment flux. A beach or nearshore nourishment is a natural way to restore sediment balance in the affected area north of the jetties.

The beach nourishment project

On 29 June 2022, dredging started in the Klaipėda Strait entrance channel. The dredged material was tested to meet the established physical and chemical requirements (Filipkowska et al. 2011; Staniszewska and Boniecka 2017), and was then deposited near the northern jetty (Fig. 1). About 180 000 m^3 of compliant sand was pumped there to form a 700–750 m long underwater bar about 120 m from the shore, where the depth before nourishment was 2–3.5 m. The project, funded by the European Union's Operational Investment Programme 2014–2020, was part of the Coastal Management Programme of Lithuania's Ministry of Environment. Previously, between 2001 and 2018, the Port of Klaipėda Authority had added 1 220 000 m^3 of sand to replenish the beaches, including a 2018 nourishment at Giruliai Beach (55.75° N, 21.08° E; Port of Klaipėda 2023).

Data sources

The analysis relies on the outcome of three surveys. The nearshore bathymetry data were collected using a 3-frequency Deeper Smart Sonar CHIRP+ 2 (Deepersonar 2024) twice: on 24 June 2022, before the nourishment, and on 1 October 2022, a few months after the nourishment campaign. Changes in seabed height were observed along cross-shore profiles extending from the shoreline to about 6-m depth. Measurements were made on the mainland segment of the study area, 5 km north of the northern jetty of the Port of Klaipėda (Fig. 1).

The Port of Klaipėda authorities provided the third set of bathymetry data sampled on 20 August 2022 (after the nourishment). This dataset was collected with a Kongsberg EM2040C multibeam echo sounder (Kongsberg Gruppen ASA, Norway), following International Hydrographic Organization Standards for Hydrographic Surveys (IHO

2020). The depth data were processed using Hypack Max (HYSWEEP) hydrographic data acquisition and processing software (Xylem Water Solutions 2023).

A triangular irregular network (TIN) was created in Global Mapper 2022 (Blue Marble Geographics 2019) using a point cloud dataset to represent the seabed surface morphology. This method joins 3D point features (*x, y, z*) into a network of triangles. The software then interpolated over the triangular faces, using the feature elevation and slope values to create an elevation grid layer. The digital elevation model (DEM) (Hell 2011; James et al. 2012) was extracted to create a bathymetric surface and calculate volume changes by comparing surface grids from different periods. The Path Profile tool (Blue Marble Geographics 2019) created a cross-section of the studied surface to more accurately assess seabed elevation changes and bathymetric features. Elevation changes were calculated for 114 profiles located every 25 m along the study area. The changes in the volume of sand along all cross-shore profiles (ΔV) were calculated by applying the following equation (Guillot et al. 2018):

$$\Delta V = \frac{1}{L}\sum_{j=1}^{n} SI, \tag{1}$$

where $n = 114$, j is the sequential number of the cross-shore profile (Fig. 1), S is the seabed surface height, I is an extrapolation between two profiles, and L is the distance between the subsequent profiles. The volume changes are estimated in cubic meters per shoreline unit length (m^3/m).

The total sediment transport rate per unit length of the coastline at a particular location x_n of a profile between any two time instants (Δt) is calculated as follows (Baldock et al. 2010, 2011):

$$Q(x_n) = Q(x_{n-1}) - \int_{x_{n-1}}^{x_n} (1-p)\frac{\Delta z_b}{\Delta t}\,dx, \tag{2}$$

where the positive values of $Q(x_n)$ (m^2/Δt) represent onshore sediment transport at position n along a profile, Δz_b (m) is the difference in bed elevation between measurement intervals, and $p = 0.4$ is the sand porosity.

The bulk cross-shore sediment transport $\hat{Q}$ (m^3/m) along the profile between two measurement instants was calculated by integrating the local transported volume across the profile from the seaward end x_{min} of the profile to its landward end x_{max}:

$$\hat{Q} = \Delta t \int_{x_{min}}^{x_{max}} Q(x)dx. \tag{3}$$

The quantity $\hat{Q}$ represents the amount of sediment moved either shoreward (positive values) or offshore (negative values) along a particular profile. This measure has been used to categorize the overall beach response as erosive ($\hat{Q} < 0$), accretionary ($\hat{Q} > 0$), or stable ($\hat{Q} \approx 0$). An alternative (normalized) parameter that considers the width of the beach or a beach segment in a particular location is $\hat{Q} / (x_{max} - x_{min})$, where $x_{max} - x_{min}$ is the width of the active beach profile. This quantity provides the mean volume of sediment moved per unit length of profile.

The hydrometeorological data for 2022, including wind speed (m/s) and direction (degrees), water level (cm), and wave height (m), were obtained from the Lithuanian Environmental Protection Agency's Marine Environment Assessment Division and the Lithuanian Hydrometeorological Service under the Ministry of Environment.

During the nourishment period (24 June to 20 August 2022), westerly winds prevailed with an average wind speed of 2–5 m/s (Fig. 2). The water level peaked at 544 cm on 15 July 2022 and gradually decreased after that (Fig. 3). Note that this value is given in the historic height system linked to the so-called Kronstadt zero, where the long-term average is 500 cm. In essence, the water level fluctuated around the long-term average in the range from –30 to 44 cm.

The predominant wind directions during the period after nourishment (20 August to 1 October 2022) were east and southeast, with an average wind speed of 1.5–5 m/s (Fig. 2). This wind pattern led to the lowest observed sea level during the study period, measuring 470 cm, 30 cm below the long-term average (Fig. 3).

The term "closure depth" is commonly used in coastal engineering and sediment transport studies to describe the offshore limit beyond which sediment movement is negligible (Dean and Dalrymple 2002; Li et al. 2022). It is often defined as the depth at which there is no systematic net sediment transport, meaning that waves and currents can move sediment beyond that depth but do not shape a profile with specific properties (Hallermeier 1978; Guillén and Hoekstra 1997). While the closure depth is more commonly associated with long-term average conditions rather than specific seasonal variations, it can still be relevant in the context of synchronization of seasonal wave and coastal processes (Cerkowniak et al. 2017; Soomere et al. 2017). Seasonal variations in wave climate, storm events, and sediment transport patterns can influence the effectiveness of sediment movement along the coast.

The closure depth (h_c) refers to the seaward limit of profile variability over long-term (seasonal or multi-year) time scales. Hallermeier (1978, 1981) devised the first rational method for its evaluation based on evidence from the field and laboratory (Soomere et al. 2017). Hallermeier (1981) also established a requirement for sediment motion coming from very unusual wave situations based on correlations with the Shields parameter. The effective wave period (T_e) and effective maximum significant wave height (H_e) that govern the closure depth were calculated, using H_e that was exceeded for only 12 hours annually, or 0.14% of the time, and the associated periods (T_e). The closure depth is approximated by the following equation:

$$h_c = 2.28H_e - 68.5\left(\frac{H_e^2}{gT_e^2}\right). \tag{4}$$

We apply the following approximations:

$$H_e = \overline{H} + 5.6\sigma_H, \tag{5}$$

$$h_c = 2\overline{H} + 11\sigma_H, \tag{6}$$

where $g \approx 9.81$ m/s² is the acceleration due to gravity, $\bar{H}$ is the annual mean significant height, and σ_H is the annual wave height standard deviation. Furthermore, $h_c = 1.57\ H_e$ provides a first approximation of the closure depth (Soomere et al. 2017).

The predominant approach direction of wave energy flux (the quantity that governs coastal processes) in the Lithuanian Baltic Sea nearshore varies from west-south-west (WSW) in the north to west-north-west (WNW) in the south (Soomere et al. 2024). The second most important direction varies from north-west in the north to north-north-west (NNW) in the south. Waves approaching from WSW–WNW are the most significant in terms of height, and SWH reaches 0.9 m on average (Jakimavičius et al. 2018). The wave parameters for

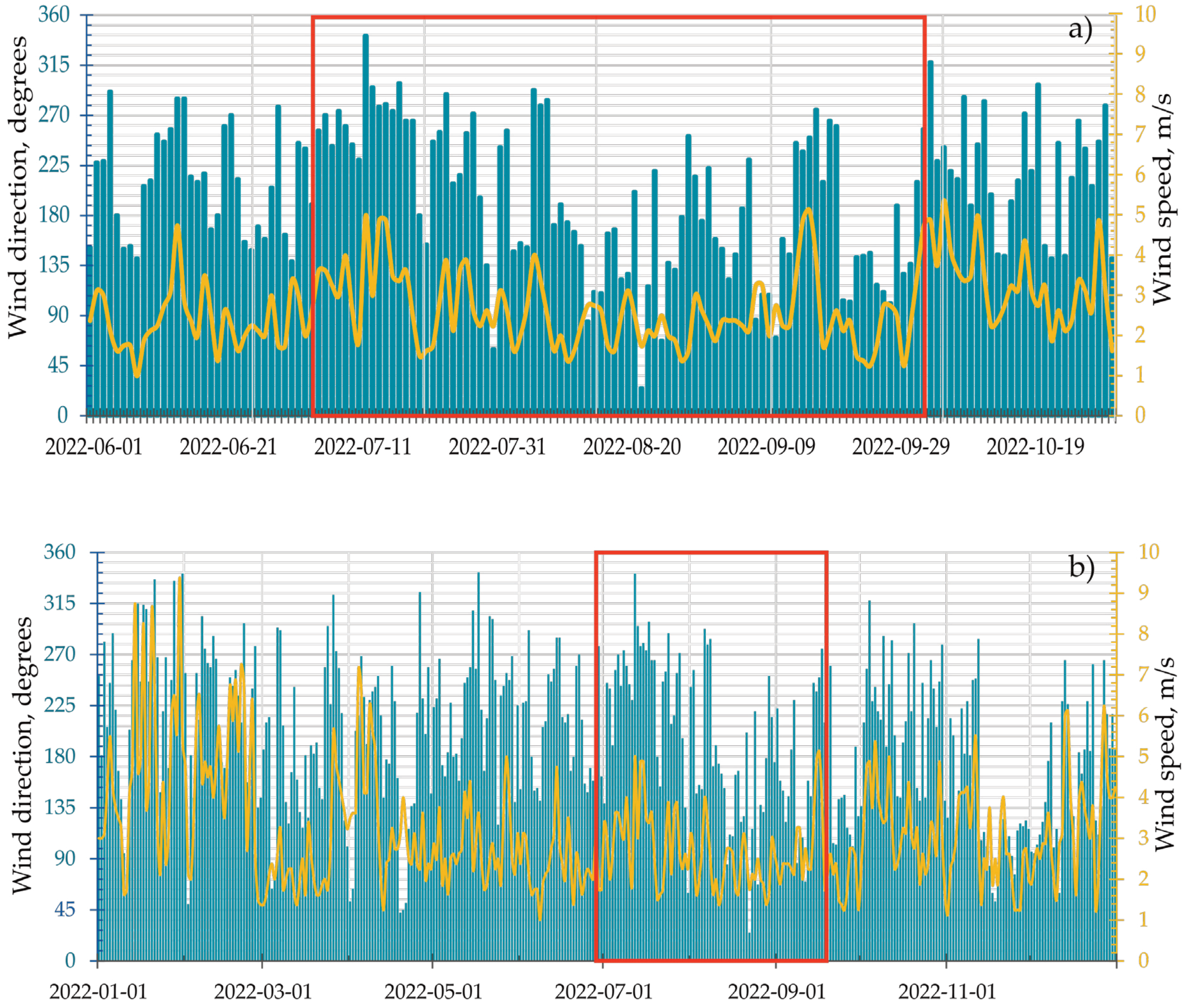

Fig. 2. Wind direction (blue bars) and speed (yellow bars) during **a**) the study period (highlighted in a red box) and **b**) the year 2022.

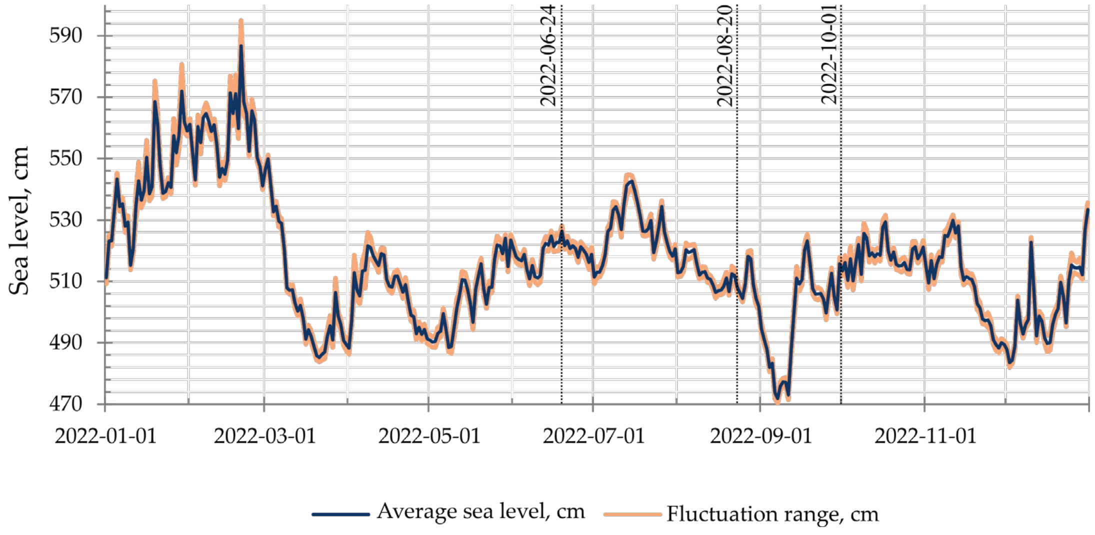

Fig. 3. Sea level during the year 2022 with the highlighted survey dates.

2022 near the study site were calculated using the SWAN wave model cycle III, version 41.31A (Giudici et al. 2023) that covers the entire Baltic Sea with a regular grid with a spatial resolution of 3 × 3 nautical miles. During the study period, the simulated SWH reached up to 2.3 m (Fig. 4). With the mean SWH of 0.9 m and standard deviation of 0.6 m, H_e for the year 2022 was 4 m. The corresponding short-term closure depth for Klaipėda reached 8.6 ± 0.5 m.

Results and interpretation

As described above, about 180 000 m^3 of dredged material was placed approximately 120 m from the shore, at an original still water depth of 2–3.5 m, to form a 700–750 m long underwater sand bar. This operation led to apparent changes in the seabed height. We chose five cross-shore profiles (Fig. 1) to characterize sediment relocation processes in different segments of the study area.

The estimated net sediment transport along all profiles (right column of Fig. 5) shows extensive spatio-temporal variations, indicating active changes across the entire study area, even under relatively mild wave conditions. While negative (offshore-directed) net transport prevailed in most profiles between 24 June and 20 August 2022, this direction reversed during the period from 20 August to 1 October 2022. Total net transport was positive during the entire study period along profiles 3–5, while it was sign-variable along profiles 1 and 2. The changes represented on profiles 1 and 2 in the nourishment area (Figs 5, 6) were directly shaped by the added sand. The cross-section of the formed sand bar in the nourishment area gradually decreased to the north from the jetties.

The seabed height along profile 1 (Fig. 5) increased by 0.5 m on average between 24 June and 20 August 2022, at depths from –1.6 to –5.4 m. At greater depths, from –5 to –6 m, the seabed height decreased by 0.2 m on average. The most significant decrease reached 0.4 m. The reasons for this process are unclear and probably unrelated to the nourishment. The sand volume along the entire profile increased by ΔV = 68.6 m^3/m (sand volume per meter of the coastline). The net sediment transport rate Q = –33.4 m$^2/\Delta t$ was negative (Fig. 5), indicating offshore-directed net sediment transport. The sea level was slightly (about 10 cm) above the long-term average (MSL) during most of this time and increased to 44 cm above MSL for a short time (Fig. 3), while wave heights remained well below 1 m (Fig. 4). This early relaxation phase of the nourishment thus occurred under a basically constant sea level and mild wave conditions.

During the six subsequent weeks from 20 August to 1 October 2022, sediment moved landward along profile 1 (Fig. 5). The profile's sand volume increased by 27.2 m^3/m (Fig. 6). This continuing increase most likely indicates substantial alongshore sediment relocation. Cross-shore transport moved most of the sediment from depths of –2.5 to –4 m closer to the shore (to depths from –1.5 to –2 m), raising the seabed height by 0.8 m on average. The seabed height increased rapidly (up to 1.5 m) at depths from –1 to –2.5 m. Part of the nourished material was distributed into the deeper segments of the profile. The average seabed height at depths from –5 to –6.5 m increased by 0.5 m. This increase may reflect a reversal of the earlier decrease in the seabed height, or may be the result of alongshore sediment transport (most likely from the north) and its further relocation to deeper water.

During the whole study period from 24 June to 1 October 2022, the sediment volume along the entire profile 1 increased by 95.9 m^3/m. This increase demonstrates that the nourishment significantly impacted the system (Figs 5, 6). The negative net sediment transport rate Q = –46.7 m$^2/\Delta t$ again indicates that sediment, on average, was transported offshore. The average height of the seabed along this profile increased by 0.2 m. At depths from –1.5 to –5.5 m, the average height increased by 0.7 m. The maximum increase was 1.5 m.

The seabed height along profile 2 during the nourishment and initial relaxation period from 24 June to 20 August 2022 was also clearly impacted by the added sand (Fig. 5) at depths from –3 to –4 m. The seabed height increased by 0.8 m on average, and the volume along this profile increased by

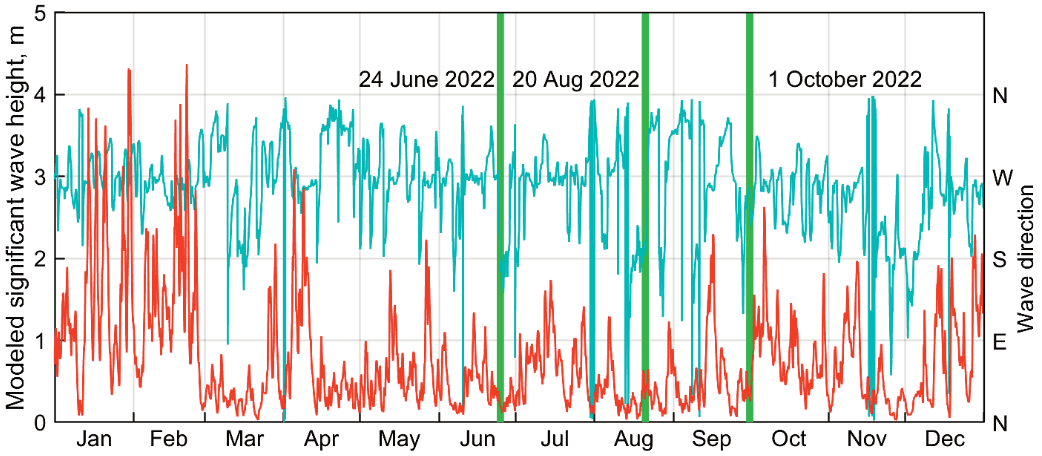

Fig. 4. Modeled significant wave height (red line) and wave direction (cyan line) during the year 2022, with the highlighted survey dates in the wave model grid cell at 55.75° N, 21.04° E (red dot in Fig. 1). Waves approaching from the east are generated by easterly winds. These short waves propagate offshore and have a negligible impact on sediment transport in the study area.

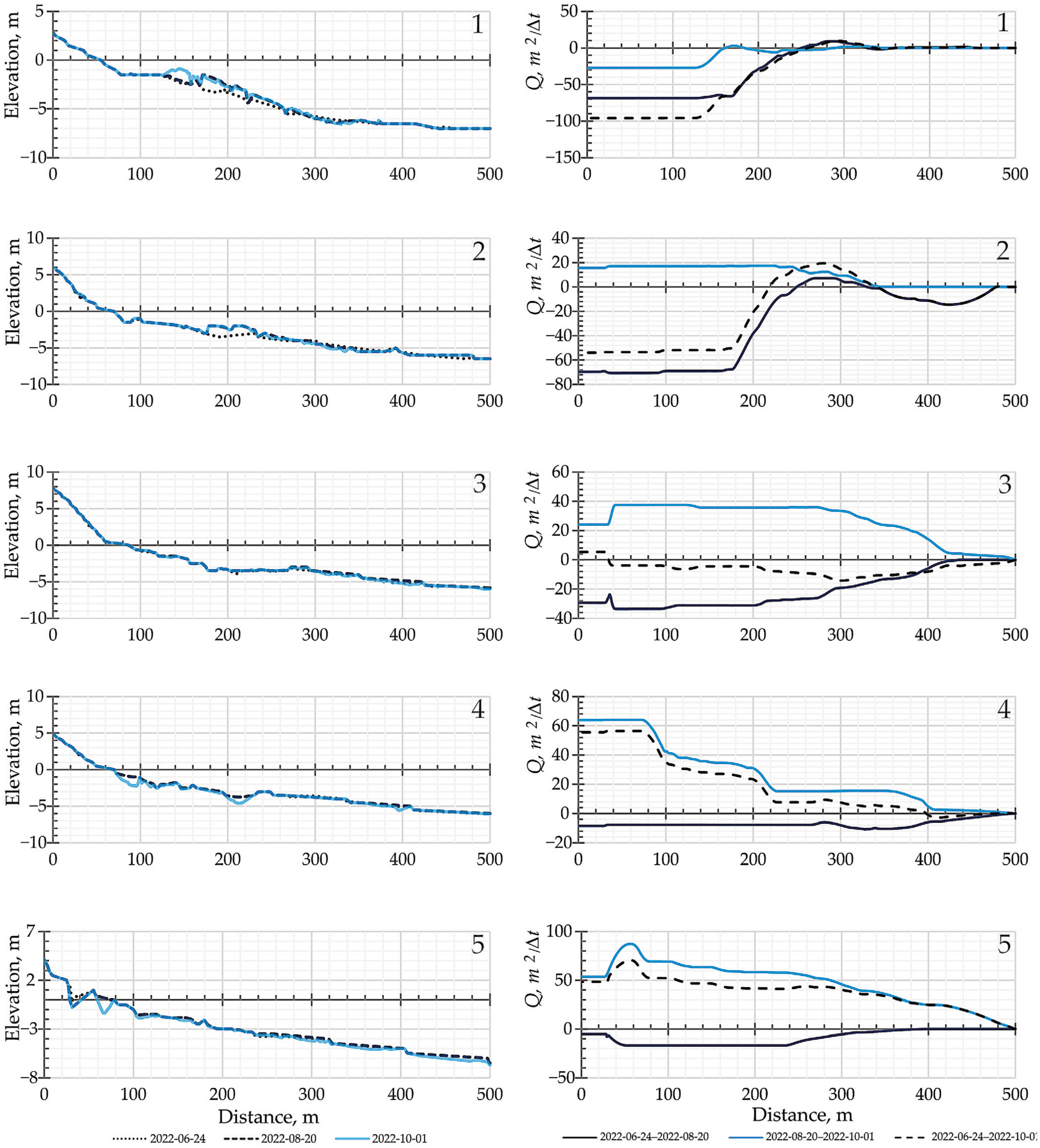

Fig. 5. Comparison of dry beach and seabed elevations along nearshore profiles (left column) and net sediment transport rates for three different periods (right column) on profiles 1 to 5 (numbers on panels; see Figs 1 and 6 for locations). The left-hand side of each panel represents the shore, while the right-hand side corresponds to the offshore.

70.6 m^3/m. This is a natural outcome of nourishment for the entire profile. The net sediment transport rate $Q = –33.9\ m^2/\Delta t$ was negative and signals that sediment was, on average, transported offshore (Fig. 5).

Relatively intense sediment relocation was observed in a deeper part of profile 2 between 20 August and 1 October 2022 (Fig. 5). The seabed height decreased by an average of 0.1 m at depths from –2.5 to –5.5 m, with a maximum change of –0.5 m. During the analyzed period, this profile lost 17.1 m^3/m of sediment. Differently from the above, the net sediment transport rate $Q = 7.6\ m^2/\Delta t$ was positive, indicating onshore sediment transport. This situation may reflect the restorative role of mild swell waves.

As a whole, profile 2 (Fig. 5) gained sediment throughout the study period. The sand volume along the profile increased by 53.5 m^3/m, as very little material was placed north of profile 2 (Figs 5, 6). This result indicates that the nourished material was transported from the south (the area between profiles 1 and 2) to profile 2. The overall net sediment transport rate $Q = –26.3\ m^2/\Delta t$ was negative, indicating offshore sediment transport also at this location. This feature signals that offshore parts of both profiles 1 and 2 had a severe sand

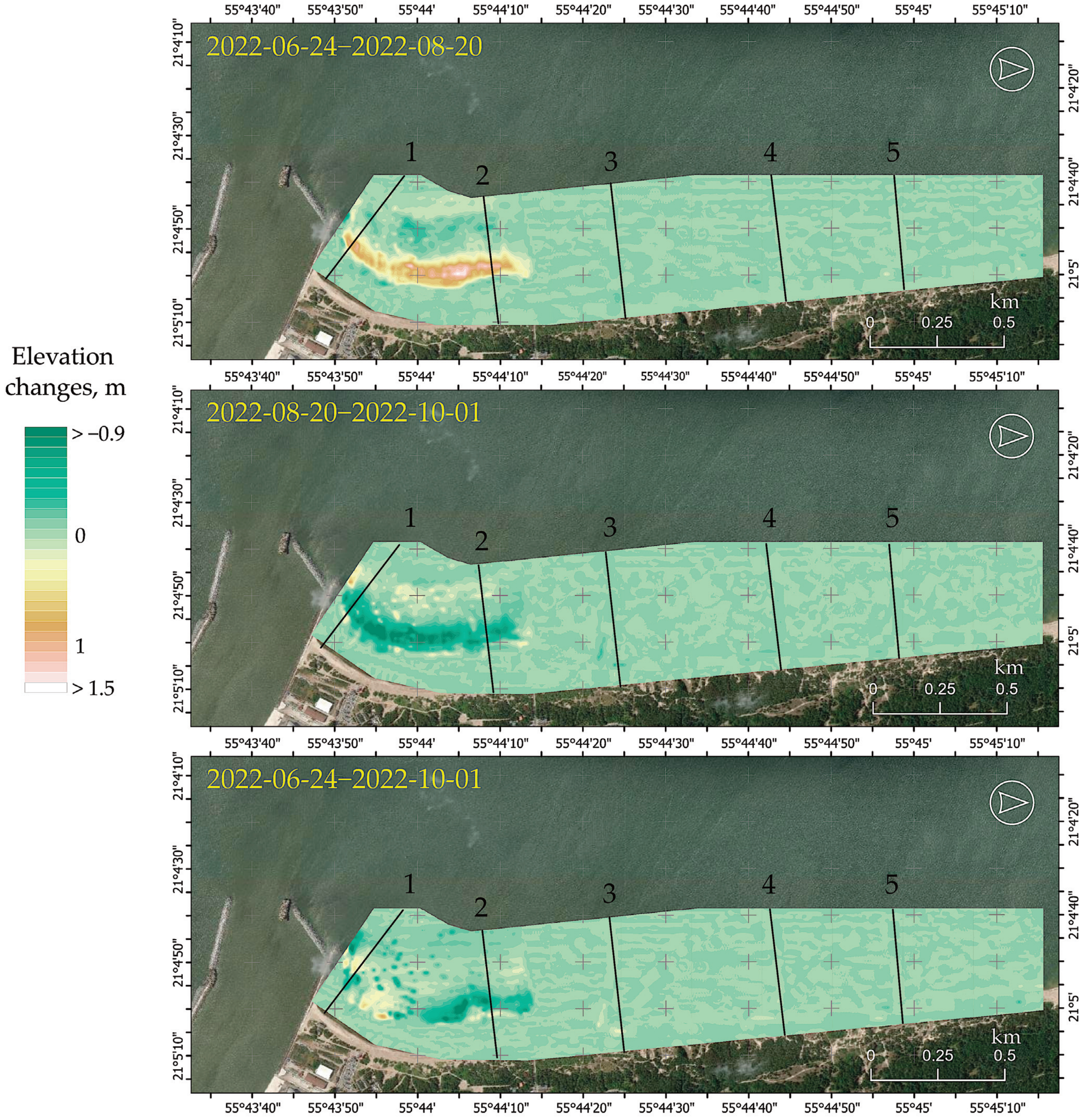

Fig. 6. Changes in seabed elevation in the nearshore area of the study site during the study period.

deficit and were at least partially filled by the added sand. In this context, nourishment likely impacted the system toward a more balanced status.

Even though no sand was added to the vicinity of profile 3, this profile showed accumulation during and after the nourishment from 24 June to 20 August 2022 (Fig. 5). The seabed height increased by 0.1 m on average, with a maximum increase of 0.4 m at depths from –3.5 to –5.5 m (Fig. 6). The sand volume along this profile increased by 33.6 m^3/m. Similar to the above, the negative sediment transport rate Q = –14.4 $m^2/\Delta t$ indicates that sediment was transported offshore.

During the following six weeks (20 August–1 October 2022), erosion prevailed along profile 3 (Fig. 5). The seabed height decreased by 0.1 m on average. At depths from –3 to –5.5 m, the seabed surface sank by 0.2 m on average, with a maximum decrease of 0.5 m. The sediment loss during this period reached 37.3 m^3/m. Therefore, all sand possibly transported from the nourishment area was relocated to other areas. Unlike with other profiles, the net sediment transport was directed onshore, as the net sediment transport rate was positive, Q = 11.7 $m^2/\Delta t$. Consistent with this estimate, during the entire study period, accumulation was observed in the nearshore part of the profile down to a depth of –3.5 m, while erosion prevailed on the deeper part of the profile (Fig. 5). At depths from the shoreline to –4 m, changes in the profile averaged 0.03 m, while in the dredged area, the profile's elevation decreased by 0.1 m on average. Throughout the studied period, the sediment loss along the profile reached 3.7 m^3/m, while sediment transport was directed onshore, as the net sediment transport rate was positive, $Q = 2.6$ m^2/Δt.

Changes along other profiles were much smaller and apparently almost unaffected by the nourishment. Profile 4 was the most dynamic in its deeper part (Fig. 5) from 24 June to 20 August 2022. Changes in the seabed height at depths from –3.5 to –6 m averaged 0.03 m. The range of seabed height changes was from –0.2 to 0.2 m. During this period, sediment was added, and the volume along this profile increased by 7.6 m^3/m. The net sediment transport rate $Q = –4.1$ m^2/Δt was negative, indicating that sediment was transported offshore.

Profile 4 suffered from erosion throughout the entire relaxation phase (20 August–1 October 2022). While some locations along this profile remained unchanged, the most significant decrease in the seabed height was 1.2 m. The most dynamic part of the profile was from the shoreline to a depth of –3.5 m (Fig. 5). The positive net sediment transport rate $Q = 31.2$ m^2/Δt during this period indicates overall onshore sediment transport, whereas this profile rapidly lost 64.1 m^3/m of sediment. This process continued from 24 August to 1 October 2022, during which the profile lost an additional 56.5 m^3/m of sediment (Fig. 5). The net sediment transport rate $Q = 27.1$ m^2/Δt remained positive, further confirming the onshore transport direction. The loss of sediment could mean increased erosion along the analyzed profile. However, additional measurements are required to fully explain the impact of nourishment on further areas.

Similar to the above, profile 5 represents the dynamics of an eroding beach (Fig. 5). During the entire study period from 24 June to 1 October 2022, the average seabed height decreased by 0.17 m. At depths from the shoreline to –2 m, the seabed height changed by –0.5 m on average, with a maximum change of –1.5 m. The most active part of the profile was located at depths from –3.20 to –7 m, where seabed height changes ranged from 0.3 (24 June–20 August 2022) to –0.4 m (20 August–1 October 2022).

Between the first two surveys (24 June–20 August), profile 5 gained 16.8 m^3/m of sand, even though sediment transport was directed offshore ($Q = –2.5$ m^2/Δt). However, a much more rapid sediment loss of 86.4 m^3/m was observed between 20 August and 1 October. The positive net sediment transport rate $Q = 26.2$ m^2/Δt during this period indicates the onshore transport direction. Over the entire study period, the profile lost 69.6 m^3/m of sediment, indicating fast erosion of the underwater profile. However, the positive net sediment transport rate $Q = 23.6$ m^2/Δt signals that a large part of sediment transport was directed onshore. Consequently, the erosion of the profile's underwater parts is masked for the observer on the dry beach by an increase in the sand volume in the immediate nearshore.

Discussion and conclusions

The study evaluated the effectiveness of sand nourishment for coastal erosion management in the Lithuanian Baltic Sea area, focusing on sand redistribution processes after the nourishment. The findings highlight several critical aspects of post-nourishment sediment dynamics. The added sand exhibited significant relocation, even under mild wave conditions. Specifically, approximately 10 000 m³ of sediment was relocated along profile 1, and about 5000 m³ along profile 2. This rapid reshaping is notable, as it occurred within just six weeks under wave conditions much milder than average. This unexpected finding underscores the dynamic nature of sediment transport in the study area and its challenges for coastal management.

The direction of alongshore sediment transport was highly variable, mostly to the south near profile 1 and to the north near profile 2. This variability is likely influenced by the proximity of the jetties at the Port of Klaipėda, which affect local hydrodynamics. Such variability complicates predictions and requires adaptive management strategies to account for specific local conditions.

The range of sediment relocation was relatively limited, with profile changes almost certainly related to the nourishment seen only on profiles 1 and 2, and with little or no impact observed on profiles 3–5, which were farther from the nourishment site. This limited range suggests that the nourishment effects are highly localized and possibly influenced by specific wave directions, which, in this case, were dominated by western directions, and the presence of the jetties. This localized impact indicates that while nourishment can be effective in targeted areas, its broader influence may be restricted, at least over the time scale of this study.

The study observed typical sediment transport patterns, including offshore transport in profiles where sand was added, and a combination of offshore erosion with onshore transport in other areas. These patterns indicate that nourished profiles may not achieve equilibrium quickly, necessitating continuous monitoring and adjustment.

During the study period, a notable decrease in sea level was observed, particularly from 6 to 11 September 2022. This sea-level drop and prevailing southeastern to south-southwestern wind patterns significantly influenced sediment dispersion. These conditions led to sediment being transported primarily in the cross-shore direction, thereby limiting the nourishment's alongshore effects.

Importantly, the presented pattern and magnitudes of changes essentially characterize the relatively mild conditions encountered during the study period. The strong seasonal variation in the Baltic Sea wave intensity suggests that this period mostly falls within the relatively mild season. Therefore, the natural beach profiles apparently reflect "summer" profiles (see, e.g., Ruessink et al. 2016). As the study period also includes one stronger wave event in September, it is likely that the observed changes on profiles 3–5 reflect a transition between the "summer" and "winter" profiles rather than a direct or indirect impact of nourishment. It remains unclear whether the described patterns and/or sediment transport directions are at least qualitatively the same under more energetic ("winter") conditions and/or clearly elevated water levels that are characteristic of the region's autumn and winter seasons.

The results indicate inter alia that comprehensive measurements are essential to understanding the broader impacts of nourishment on more distant profiles and refining management strategies accordingly. Such research would provide a more holistic understanding of nourishment effects and improve coastal management practices. Overall, the study emphasizes that while beach nourishment can be a valuable tool for managing coastal erosion, its success depends on careful consideration of local conditions, continuous monitoring, and adaptive management to address the dynamic nature of coastal environments.

Data availability statement

The data used in this study will be made available on request.

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Rannaprofiilide veealuse osa kiire kohanemine pärast ranna täitmist liivaga vaikses lainekliimas Klaipėda lähistel

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Enamasti tuleb lisada liiva randadele, mida kujundab tugev lainetus, kuid vahel vajavad täitmist ka vaiksemates kohtades asuvad liivarannad. Käesolevas uurimuses näitame, et ka selliste randade taastamiseks kasutatud liiv võib kiiresti ümber paikneda. Analüüsime, mis suunas ja kui kiiresti liigutas suhteliselt tagasihoidlik lainetus Läänemere idarannikul Klaipėda väina põhjamuuli lähistele lainete eest osaliselt varjatud madalmerre paigaldatud liiva esimese kolme kuu jooksul. Ligikaudu 180 000 m^3 liiva paigaldati 2022. aasta suvel umbes 120 m kaugusele rannajoonest, moodustades piirkonnas, kus vee sügavus oli algselt 2–3,5 m, ligi 750 m pikkuse veealuse liivavalli. Liiva ümberpaiknemise kiirust ja suunda hinnati 114 rannaprofiili muutuste põhjal. Oluline lainekõrgus oli uuringute perioodil alla 0,9 m ning veetase kõikus –30 ja 44 cm vahel võrreldes pikaajalise keskmisega. Sellest hoolimata hakkas osa paigaldatud liivast kiiresti liikuma. Üldiselt paiknes liiv ümber madalamalt sügavamale ning lõuna poolt põhja poole ehk selles piirkonnas tavapärases lainetuse põhjustatud rannasetete liikumise suunas. Osa liivast liikus kiiresti kuni 6 m sügavusele. Keskne järeldus on, et isegi Läänemere kontekstis tagasihoidliku kõrgusega lained võivad liigutada suure koguse madalmerre paigutatud täiteliiva nii sügavamale merre kui ka madalamasse vette, eriti esimeste kuude jooksul pärast liiva lisamist.