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ASSESSMENT OF SEDIMENT TRANSPORT ON LITHUANIAN SHORES OF THE BALTIC PROPER UNDER CHANGING NATURAL FACTORS AND ANTHROPOGENIC LOADS

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Ilona ŠAKUROVA

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Contents

Abstract

The cumulative doctoral dissertation is based on five peer-reviewed scientific publications and presents results of investigations of the evolution of coastal geomorphology and sediment transport on the Baltic proper shores of Lithuania, focusing on the effects of natural factors, anthropogenic pressures and single large-scale interventions to beach dynamics. From 2014 to 2018, the Port of Klaipėda performed beach nourishment to mitigate erosion, placing over 237,000 m³ of sand along the Melnragė and Giruliai beaches. Analysis of sediment transport dynamics revealed extensive variability in post-nourishment alongshore sediment movement, influenced by local hydrodynamic conditions and hydro-technical structures, particularly the port jetties. A shift in wind regime since 1992 has led to intensification of coastal erosion on both the Curonian Spit and mainland coasts, resulting in significant morphological changes. The results highlight the challenges of managing coastal erosion through sand nourishment, with observations of rapid sediment relocation and localised effects. To address knowledge gaps and improve coastal management practices, a new environmental alert system for timely maintenance solutions of the coastal zone is proposed to integrate long- and short-term data for stakeholders. This research underscores the need for a holistic approach and continuous monitoring to manage dynamic coastal environments adaptively.

Keywords

Sediment transport, coastal erosion; beach nourishment; coastal management; Baltic Sea; Port of Klaipėda; bathymetry change; cross-shore profile.

Reziumė

Disertacija parengta mokslinių straipsnių rinkinio pagrindu, remiantis penkiomis recenzuotomis mokslinėmis publikacijomis, kuriose nagrinėjama Lietuvos jūros kranto geomorfologijos ir nešmenų pernašos raida, daugiausia dėmesio skiriant gamtinių veiksnių ir antropogeninės veiklos poveikiui. 2014–2018 metais Klaipėdos uostas ėmėsi paplūdimių stiprinimo kampanijos erozijai švelninti – Melnragės ir Girulių paplūdimiuose išpilta daugiau kaip 237 000 m³ smėlio. Išanalizavus nešmenų pernašos dinamiką, paaiškėjo, kad išilgai kranto vyksta nepastovus nuosėdinės medžiagos judėjimas. Šiam procesui įtakos turi vietos hidrodinaminės sąlygos ir hidrotechniniai statiniai, ypač uosto molai. Nuo 1992 metų pasikeitęs vėjo režimas suintensyvino kranto eroziją tiek Kuršių nerijoje, tiek žemyninėje kranto dalyje. Pastaraisiais laikotarpiais pastebimi reikšmingi morfologiniai pokyčiai. Tyrime išryškėja kranto erozijos valdymo, naudojant smėlio papildymą, iššūkiai – pastebėtas greitas nuosėdinės medžiagos perskirstymas ir lokalus poveikis. Siekiant pašalinti žinių spragas ir pagerinti kranto valdymo praktiką, siūloma sukurti naują, į suinteresuotas šalis nukreiptą sistemą, kuri integruotų skirtus ilgalaikius ir trumpalaikius duomenis. Šis tyrimas pabrėžia holistinio požiūrio ir nuolatinės stebėsenos poreikį, siekiant adaptyviai valdyti dinamišką kranto aplinką.

Reikšmingi žodžiai

Baltijos jūra; Klaipėdos uostas; smėlio papildymas; batimetrijos pokyčiai; skersinis kranto profilis; nuosėdų pernašos greitis; kranto erozija.

List of original publications

The main results of this thesis are presented in five academic publications, referred to in the text as Papers I, II, III, IV, and V. All papers are indexed in the Clarivate Analytics Web of Science (CA WoS).

I. **Šakurova, I.**, Kondrat, V., Baltranaitė, E., Vasiliauskienė, E., Kelpšaitė-Rimkienė, L., 2023. Assessment of coastal morphology on the south-eastern Baltic Sea coast: The case of Lithuania. *Water (Switzerland)*, 15(1), 79. https://doi.org/10.3390/w15010079

II. Kondrat, V., **Šakurova, I.**, Baltranaitė, E., Kelpšaitė-Rimkienė, L., 2021. Natural and anthropogenic factors shaping the shoreline of Klaipėda, Lithuania. *Journal of Marine Science and Engineering*, 9(12), 1456. https://doi.org/10.3390/jmse9121456

III. **Šakurova, I.**, Kondrat, V., Baltranaitė, E., Gardauskė, V., Kelpšaitė-Rimkienė, L., Soomere, T., Parnell, K.E., 2025. Initial adjustment of underwater profiles after nourishment in a mild wave climate: a case study near Klaipėda, the Baltic Sea. *Estonian Journal of Earth Sciences*, 74(1), 22–33. https://doi.org/10.3176/earth.2025.02

IV. **Šakurova, I.**, Kondrat, V., Baltranaitė, E., Gardauskė, V., 2023. The need for an environmental notification system in the Lithuanian coastal area. *Journal of Marine Science and Engineering*, 11(8), 1561. https://doi.org/10.3390/jmse11081561

V. Kondrat, V., **Šakurova, I.**, Baltranaitė, E., Kelpšaitė-Rimkienė, L., 2023. EASTMOC: Environmental Alert System for Timely Maintenance of the Coastal Zone. *Oceanography,* 36(Suppl. 1), 78–79. https://doi.org/10.5670/oceanog.2023.s1.26

Author's contributions

Contribution to the papers in this thesis are:

Paper I	The candidate has led all study steps, including conceptualization, data curation, investigation, results analysis and writing.
Paper II	The candidate co-led most study design steps, performed meteorological data analysis, contributed to the formulation of results, and writing the manuscript.
Paper III	The candidate has led all study steps, including conceptualization, data curation, investigation, results analysis and writing.
Paper IV	The candidate has led all study steps, including conceptualization, data curation, investigation, results analysis and writing.
Paper V	The candidate co-led all steps of the development of the study and results analysis.

Abbreviations

Abbreviation	Explanation
EASTMOC	Environmental Alert System for Timely Maintenance sOlutions of the Coastal zone.
MEAD	Marine Environment Assessment Division
EPA	Environmental Protection Agency
LHS	Lithuanian Hydrometeorological Service under the Ministry of Environment

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Introduction

The favourite tale of every scientist or engineer working on sediment transport is believed to have originated from a discussion between Albert Einstein and his eldest son, Hans Albert Einstein, more than 70 years ago (Nelson, 1999). Hans informed his dad of his plans to study the mechanics of sediment transport. Albert advised his son not to seek a degree in this subject since, in his opinion, sediment transport is so challenging that it is unsolvable (Nelson, 1999). Albert had done some work in this area, particularly on impeded settling in sediment suspensions (Nelson, 1999). Like many good sons before him, Hans disregarded this advice and made his way into the group of prominent scientists who contributed to establishing modern sediment transport theory and practice (Nelson, 1999).

Sediment transport is a critical factor in understanding coastal environments, particularly sandy beaches, which may change extensively in time and space depending on sediment sources and sinks, the depositional morphology and hydrodynamic behaviour of the region in which they are located (Eelsalu et al., 2022; George et al., 2019; Quadrado and Goulart, 2020)being fundamental over sediment budget, and, so over the dynamic balance of coastlines. This study determined the most adequate methodology to estimate rates of non-cohesive sediments (from fine sand to gravel. A detailed understanding of nearshore physical processes is critical to the planning and implementation of coastal development programs (Bain et al., 2021; McGill et al., 2022). The reason is that coastal geomorphology can be significantly affected by alongshore and cross-shore sediment transport in the surf zone, resulting shoreline position changes, hydrometeorological conditions, and various human activities in the coastal area (Belibassakis and Karathanasi, 2017; Brutsché et al., 2014; Wang et al., 2002).

The Baltic Sea coast is a prime example of how natural and anthropogenic factors interact to shape coastal morphology. Its unique appearance is formed by the interaction of sea and wind, leading to the creation of various coastal forms (Bitinas et al., 2005, 2004; Jarmalavičius et al., 2017). The litho- and morphodynamic processes that drive shoreline formation are influenced by aeolian (wind-related) processes on land and hydrodynamic processes at sea (Burningham, 2006; Masselink et al., 2006; Valiente et al., 2019).

By the end of the 20th century, the anthropogenic impact became an important factor influencing various coastal formation processes (Brown et al., 2017). The primary factors influencing coastal evolution and requiring professional management include intensification of storms, increased sand discharge from coastal zones, rising global sea level, port development and dredging, and the expansion of recreational areas (IPCC, 2022; Meier et al., 2021; Weisse et al., 2021). Therefore, under persistent change and environmental pressure, management is the top priority in the coastal zone (Brand et al., 2022; Herrera et al., 2010; Johnson et al., 2021).

Understanding the functioning of cross-shore profiles is essential for understanding not only whether a beach is in equilibrium, but even more importantly for coastal structure design and construction, and coastal protection strategy planning (Bain et al., 2021; Bergillos et al., 2017; Gong et al., 2017). It is also needed in coastal models for predicting beach dynamics (Esteves et al., 2009). Shoreline relocation is the most commonly used indicator for assessing coastal erosion or accumulation. It could reflect various causes, such as storms, changes in wind or wave regime, and human activities (Almonacid-Caballer et al., 2016; Benkhattab et al., 2020; Hanslow, 2007). Monitoring its features could help predict changes in morphodynamics in the coastal area.

The features of coastal morphodynamic processes—the interaction between bathymetry (seafloor topography) and hydrodynamics (movement of water)—largely determine the volume distribution during sediment transport (Bain et al., 2021; Belibassakis and Karathanasi, 2017). Bathymetry data are the most crucial input for analysing seabed morphology and sedimentation patterns (Bezzi et al., 2021; Rosier et al., 2018; Sakhaee and Khalili, 2021; Yutsis et al., 2014). Variations in the bathymetry can reveal and characterise processes of seabed erosion or sedimentation (Guo et al., 2021).

The Baltic Sea is characterised by distinct geomorphic, hydrographic, and hydrodynamic features that influence the seafloor's morphology and coastal zone dynamics (Hoffmann and Lampe, 2007; Kaskela, 2017). Among the factors that impact the Baltic Sea's seabed, anthropogenic pressures are particularly significant. Key human activities, such as port construction, dredging, installation of cables and pipelines, or the development of nearshore and offshore renewable energy infrastructure, can induce coastal erosion or alter the direction of underwater sediment transport, thereby often adversely affecting specific regions of the Baltic Sea (Coelho et al., 2013). Therefore, these risk factors must be carefully evaluated before undertaking any construction activities (Aragonés et al., 2019; Coelho et al., 2013; Weisse et al., 2021).

Beach nourishment, which involves adding sediment to eroding beaches, is one of the most effective yet complex methods to address coastal erosion (Regard et al., 2023). Many factors, including local conditions, weather patterns, and human activity, can influence its success (Brand et al., 2022). Nourishment projects can be implemented on the subaerial beach or in the nearshore (Johnson et al., 2021). Dredged sediment is frequently used for beneficial purposes when placed in the nearshore, forming a sand bar or nearshore berm (Bain et al., 2021; Brutsché et al., 2014; Johnson et al., 2021) that resembles a soft, submerged breakwater (Bain et al., 2021; Brutsché et al., 2014). On many occasions, nearshore nourishment can use sediment dredged from nearby navigation channels, subtidal bars, or offshore deposits while the beach remains in use while the nourishment is taking place.

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 and the beach's and seafloor's topography and sediment characteristics (George et al., 2020; Wang, 2004; Work et al., 2004). Specific outcomes can vary depending on many factors and local conditions (Chowdhury and Behera, 2017; Kumar et al., 2017). Therefore, it is crucial for coastal managers and engineers to consider these factors when implementing nourishment projects to achieve the desired outcomes and avoid unintended consequences (Johnson et al., 2021; Kuang et al., 2019).

A comprehensive understanding of the variability of the behaviour of beaches over entire cross-shore profile, encompassing both terrestrial and underwater components, is essential for sustainable coastal management. This knowledge enables more precise implementation of various coastal engineering operations: (i) coastal nourishment (Cantasano et al., 2023; Jiménez and Sánchez-Arcilla, 1993; Kelpšaitė-Rimkienė et al., 2021); (ii) design of coastal protection structures (Aagaard et al., 2004; Aragonés et al., 2019; Hinton and Nicholls, 1998; Kelpšaitė-Rimkienė et al., 2021); (iii) coastal sediment budget calculations (Aragonés et al., 2019; Coelho et al., 2013). Single records of cross-shore profiles and calculations based on their changes are vital tools for assessing alongshore sediment transport rates and for developing and predicting erosion and accretion volumes (van Rijn et al., 2003). While detecting changes in the swash zone—the most dynamic part of the coastal profile—remains challenging, a deeper understanding of sediment transport processes in the nearshore zone is crucial (Héquette et al., 2001; Oo et al., 2022).

1.1. Aim and Objectives

The main aim of the thesis is twofold: (i) to comprehensively study sediment transport dynamics as the central factor in south-eastern Baltic coastal sustainability by examining its interactions with anthropogenic pressures, natural forces, and socio-economic factors, and (ii) to develop a knowledge-sharing platform that prioritises sediment transport knowledge to inform sustainable strategies and mitigate environmental impact.

The following single objectives were addressed to realise this aim:

1. To evaluate the impact of anthropogenic pressure and natural factors on cross-shore profile changes at sandy, high-energy coast on a country scale.
2. To analyse the impact of sediment transport on the shoreline dynamics in the context of changing weather patterns and increased anthropogenic pressure on a country scale.
3. To evaluate the core properties, spatial extent and time scale of local sand relocation processes in a specific, partially sheltered location of low-energy environment after nearshore nourishment using high-resolution data.
4. To use the collected data and results of their analysis to create architecture for a systemic knowledge sharing platform that enables addressing the knowledge gaps and determining thresholds that could limit activities or change the course of short- and long-term strategies from local to regional scales.

The core research object is the dynamics of the entire shoreline of Lithuania driven jointly by natural drivers and anthropogenic interventions. As the coast of Lithuania is almost straight, this dynamic is apparently well represented by processes in representative coastal segments in the vicinity of major man-made structures. Thus, **Paper I** and **Paper II** focus on coastal processes that occur within 10 km from the jetties of the Klaipėda Strait, the most significant man-made structures in the area. To understand the impact range and time scale of local anthropogenic interventions, the focus of **Paper III** is zoomed into an about 5 km long coastal stretch to the north of Klaipėda. The outcome of the analysis of these studies is consolidated and generalised for the use in knowledge sharing platforms at local, regional or country scale in **Paper IV** and **Paper V**.

1.2. Novelty

Coastal processes in the vicinity of the Lithuanian port city Klaipėda are analysed in detail with a focus on coastal sediment (re)distribution and associated nearshore changes. The findings about the impact of highly localised beach nourishment efforts, with significant sediment relocation even under mild wave conditions, offer new insights into the challenges of managing coastal erosion and studying sediment transport patterns. The observation that nourishment effects are limited in range and heavily influenced by specific local conditions, such as proximity to jetties and predominant wave directions, highlights the need for adaptive and site-specific management strategies. This nuanced understanding of post-nourishment dynamics is critical for refining future coastal protection measures and ensuring their effectiveness.

The research uniquely identifies and quantifies the impact of (wind regime) shifts in terms of wind direction on coastal erosion and sediment transport, linking these changes with broader climatic trends observed since the early 1990s. Focusing on the role of wind regime shifts, particularly the significant changes observed in 1992 and 2012, adds a novel dimension to understanding how climate change influences coastal dynamics. By correlating these shifts with varying erosion rates and changes in sediment distribution patterns, the study provides new evidence of direct impacts of climate variability on coastal environments.

Establishing a knowledge-sharing platform through the EASTMOC (Environmental Alert System for Timely Maintenance sOlutions of the Coastal zone) system introduces a novel mechanism for engaging stakeholders in the coastal management process. The platform facilitates real-time data exchange and observations and enhances collaboration among diverse stakeholders, including port authorities, safety administrations, and environmental agencies. This approach not only improves decision-making but also fosters a more integrated and responsive management framework tailored to the specific needs and challenges of the Lithuanian coastal zone.

1.3. Scientific and Applied Significance of the Results

The performed research of the evolution of coastal geomorphology and sediment transport in the nearshore of Lithuania provides significant scientific insights and practical applications that contribute to the broader understanding and management of coastal dynamics. The findings have several important implications:

- The detailed analysis of sediment transport patterns and shoreline changes offers critical insights into the complex interactions between natural drivers, such as wind and hydrometeorological conditions, and anthropogenic pressures like seaport activities. These findings contribute to the broader knowledge of coastal geomorphology, particularly in regions where human activities significantly impact natural processes.
- The study also explains the impact of wind direction changes and hydrodynamic conditions on sediment (re)distribution, highlighting the importance of

considering both short-term and long-term environmental changes in coastal studies.
- The observed shifts in wind regime and their subsequent impact on coastal erosion and sediment dynamics are crucial for understanding the implications of climate change on coastal environments. The data indicating changes in wind speed and direction provide valuable evidence for climate change studies, particularly in understanding how these shifts influence coastal erosion and accumulation patterns.
- The proposed implementation of the EASTMOC system represents a novel approach to integrating real-time monitoring with long-term observation data. This methodological advancement addresses existing knowledge gaps and creates a framework for more comprehensive and adaptive coastal management, potentially serving as a global model for similar coastal environments. The development of the EASTMOC system, which facilitates real-time data sharing and monitoring, will enable stakeholders to make more informed decisions regarding coastal management and operations. This system can be particularly beneficial for managing the complex interactions between natural coastal processes and human activities, reducing the risk of unforeseen consequences and enhancing coastal infrastructure resilience.
- The findings directly contribute to the efficacy of management of coastal erosion, particularly in the context of the Port of Klaipėda’s beach nourishment efforts. The research highlights the necessity for continuous monitoring and adaptive management strategies to ensure the long-term success of nourishment projects. These insights can be directly applied to optimise future nourishment campaigns and other coastal protection measures, enhancing their effectiveness.
- Identifying critical knowledge gaps, particularly regarding sediment transport in Baltic Sea, highlights areas where further research is needed. By pinpointing these gaps, the study sets the stage for future research initiatives that can build on the existing findings, leading to a more comprehensive understanding of coastal dynamics and more effective management strategies.

Overall, the results presented in this thesis have both scientific and practical significance, advancing the understanding of coastal processes in Lithuania while providing actionable insights for managing and protecting these vulnerable coastal environments. Integrating scientific research with practical applications highlights the importance of interdisciplinary methods in addressing complex environmental challenges.

1.4. Scientific Approvals

The author has presented the main results described in this thesis at the following national and international conferences:

Oral presentations:

Šakurova, I., Kondra, V., Baltranaitė, E., Kelpšaitė-Rimkienė, L., 2021. Sandy beach evolution under the climate change and increasing anthropogenic pressure: eastern Baltic Sea case. *Smart urban coastal sustainability days 2021: Interdisciplinary approaches to the understanding of coastal systems (8–9 April 2021, La Rochelle, France, online).*

Šakurova, I., Kondrat, V., Baltranaitė, E., Kelpšaitė-Rimkienė, L., 2022. Estimation of longshore sediment transport: the case of Lithuania. *European Geosciences Union General Assembly 2022 (23–27 May 2022, Vienna, Austria, online).*

Šakurova, I., Kondrat, V., Kelpšaitė-Rimkienė, L., 2022. Assessment of underwater slope change on the Lithuanian coast. *Lithuanian Academy of Sciences conference Biofuture: perspectives for nature and life sciences (24 November 2022, Vilnius, Lithuania).*

Šakurova, I., Kondrat, V., Baltranaitė, E., Vasiliauskienė, E., Kelpšaitė-Rimkienė, L., 2023. Jūros kranto kaitos vertinimas Lietuvos kranto zonoje. *VII National Conference "GEOGRAPHIA JUVENTA" (28 March 2023, Vilnius, Lithuania).*

Poster presentations:

Šakurova, I., Kondrat, V., Kelpšaitė-Rimkienė, L., Baltranaitė, E., Soomere, T., 2020. Changes in coastal lithodynamical processes of semi-enclosed seas under changing climate: the case of Lithuania. *Eurolag9 (20–24 January 2020, Venice, Italy).*

Šakurova, I., Kondrat, V., Kelpšaitė-Rimkienė, L., Baltranaitė, E., Dabulevičienė, T., Soomere, T., 2020. Fluctuations in coastal lithodynamical processes of semi-enclosed seas under changing climate: the case of Lithuania. *Ocean Science Meeting 2020 (16–21 February 2020, San Diego, USA).*

Šakurova, I., Kondrat, V., Gardauskė, V., Kelpšaitė-Rimkienė, L., 2023. The influence of artificial nourishment on underwater profile. *Baltic Sea Science Congress 2023 (21–25 August 2023, Helsinki, Finland).*

2

Materials and methods

This cumulative thesis is based on five peer–reviewed publications. The original publications were published during the Ph.D. research period and are provided in Annex I.

2.1. Study Area

The intention in the thesis is to improve understanding and better characterise core coastal processes in the entire shoreline of Lithuania (Figure 1). The analysis in **Paper I** and **Paper II** focuses on about 20 km long coastal stretch centred at the Klaipėda Strait and covering sections of the mainland coast and the Curonian Spit. This stretch that covers almost 1/4 of the Lithuanian Baltic proper shoreline is assumed to be representative of coastal dynamics under joint impact of natural drivers and anthropogenic activities. The analysis presented in **Paper III** focuses on the consequences of a beach nourishment on the nearshore and dry beach of the mainland coast of Lithuania part. The focus is on about 5 km long coastal stretch to the north of the Klaipėda Strait. **Paper IV** and **Paper V** formulate the ideas of a prospective knowledge sharing platform so that the outcome could be used at different spatial scales.

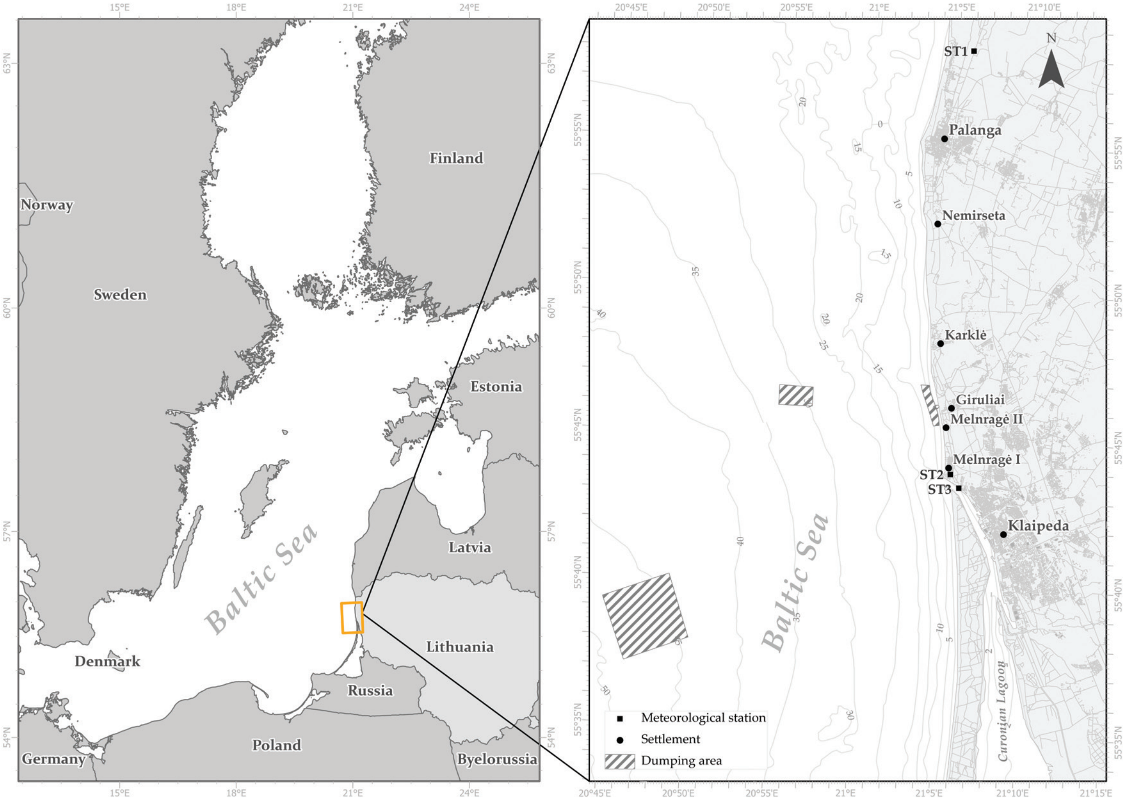

Figure 1. The overview of the study site. ST1—Palanga Aviation meteorological station, ST2—Klaipėda meteorological station, ST3—Port of Klaipėda station (Paper I).

1 pav. Tyrimo vietos apžvalga. ST1–Palangos aviacijos meteorologijos stotis, ST2–Klaipėdos meteorologijos stotis, ST3–Klaipėdos uosto stotis (I straipsnis).

The Lithuanian coastal zone is a narrow strip of land extending along the Baltic Sea's eastern coast for approximately 90 km. It is characterised by a diverse landscape of sandy beaches, dunes, wetlands, lagoons, and forests. The shoreline is relatively straight and the nearshore land is gently sloping, with the highest points over many dozens of meters reaching only a few meters above sea level (Bagdanavičiute et al., 2012). Therefore, the properties of hydrometeorological drivers that impact the coast and shape the shoreline, and beaches vary slowly along the entire coastline of Lithuania. The sandy beaches are primarily located in the southern part of the coast along the Curonian Spit, while coarser sand, rocky shores and cliffs are typical in the northern part along the mainland of Lithuania (Bagdanavičiute et al., 2012). Thus, the reaction of the beaches and other elements of the coastal system may substantially vary even under spatially almost homogeneous forcing. This coastal zone 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 livelihoods (Inácio et al., 2022; Jurkus et al., 2021). It is a unique and valuable resource that requires careful management to ensure sustainability (Baltranaitė et al., 2021; Inácio et al., 2022).

The Lithuanian nearshore zone is fully open to the hydrometeorological drivers from the Baltic proper. It is a complex and dynamic environment affected by waves, currents, and weather conditions that evolves under the impact of relatively mild wave climate (Björkqvist et al., 2018) and two systems of moderate and strong winds (Soomere, 2003). South-western winds are the most frequent, whereas north-western or north-north-western winds are less frequent but could be even stronger.

The coastal system has been historically adjusted to waves approaching from the western directions having the greatest heights, reaching ~0.9 m on average, whereas mean wave heights for waves approaching from the southern directions are ~0.6 m, ~0.5 m for waves approaching from the northern direction, and ~0.3 m for waves approaching from the eastern direction. (Jakimavičius et al., 2018; Kelpšaite et al., 2008). The predominant sediment transport along the Lithuanian coast is from the south to the north, with a few temporary reversals on the annual scale (Viška and Soomere, 2013). Consistently with the above remarks, the segments of coasts at different sides of the the Klaipėda Strait respond differently to the drivers. While the shores of the Curonian Spit to the south of Klaipėda are generally stable (Bitinas et al., 2005), erosion usually predominates on the mainland coast north of the Klaipėda Strait (Bitinas et al., 2005; Viška and Soomere, 2013).

To preserve the beaches in this coastal area, beach nourishment has become a frequent and effective erosion mitigation method in Lithuania. For example, in the resort town of Palanga, beach nourishment has been used to widen the beach and provide additional recreational space (Kelpšaitė-Rimkienė et al., 2021; Pupienis et al., 2014). However, this coastal management tool was utilised for the first time in the impact zone of jetties of the Port of Klaipėda. A detailed analysis of this intervention is used to understand how hydrodynamic drivers relocate sediment immediately after nourishment in **Paper III**.

The Port of Klaipėda is the largest and busiest port in Lithuania (Žilinskas et al., 2020). It is an important hub for international trade and commerce, serving as a gateway to the Baltic States and the wider region (Inácio et al., 2022). Its jetties extend to depths that are clearly larger than closure depth (~6 m) in this region (Soomere et al., 2017) and thus almost entirely stop wave-driven sediment alongshore transport. The presence of these massive structures thus creates a 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 Klaipėda Strait divides the Lithuanian Baltic Sea coast into two geomorphologically different parts – coastal segments of the mainland and the Curonian Spit (Bitinas et al., 2005). The Curonian Spit coast represents an accumulative environment consisting entirely of sandy sediments (Bitinas et al., 2005). On the contrary, the mainland coast is geomorphologically diverse, representing mostly erosive processes on the beach and in the nearshore (Bitinas et al., 2005). The Lithuanian mainland coast's northern section is dominated by fine-grained sand (grain size 0.25–0.1 mm). The southern and central parts are dominated by medium-grained (0.5–0.25 mm) and coarse-grained (1–2.5 mm) sand (Bitinas et al., 2005).

2.2. Cross–Shore Profile and Shoreline Evolution (Paper I, II)

Cross-shore profiles within the study area in **Papers I** and **II** were measured from the shoreline to the dune crest, with a total of 40 profiles taken at 500 m intervals. Data collection in 2019–2022 was performed using an Emlid Reach RS+ RTK GNSS receiver, which provides centimetre–level precision, and a dual–band GPS receiver (Table 1). Additionally, cross-shore profile data from the Lithuanian Geological Survey, spanning the years 1993 to 2022, were utilised (Table 1). The collected profile data were used to calculate sediment volume changes by applying the following equation (Guillot et al., 2018):

$$v_1 = \frac{\sum_{p=1}^{n}(SI)}{L} \tag{1}$$

where p is the sequential number of the cross–shore profile, n is the total number of such profiles along the coastal segment in questions, S is (seabed or dry beach) surface height, I represents extrapolation between two neighbouring profiles, and L is the distance between the profiles, used here to normalise the estimates of changes to reach the output of Eq. (1) in terms of volume changes in m^3/m, equivalently, per unit of the shoreline.

Table 1. Variables used in this research.

1 lentelė. Šiame tyrime naudoti kintamieji.

Variables	Data source	Time scale	Details	Paper
Wind speed, m/s	Lithuanian Hydrometeorological Service under the Ministry of Environment; the Palanga Aviation Meteorological Station	1960–2019	The data were collected using meteorological instruments, in line with the State Environmental Monitoring Programme approved by the Government of the Republic of Lithuania (2024-06-27 Nr. 2024-11746).	II, IV, V
		1993–2022		I, IV, V
Wind direction, degrees		1960–2019		II, IV, V
		1993–2022		I, IV, V
Wave height, m	Marine Environment Assessment Division of the Environmental Protection Agency; the Port of Klaipėda administration	1993–2022	The data were collected using oceanographic instruments, in line with the State Environmental Monitoring Programme approved by the Government of the Republic of Lithuania (2024-06-27 Nr. 2024-11746).	I, IV, V
Wave direction, degrees		1993–2022		I, IV, V
Water level, cm	Marine Environment Assessment Division of the Environmental Protection Agency	2022		III
Sediment (grain size)	The Lithuanian Geological Survey	1993–2003	Data were collected in line with the Lithuanian Geological Survey methodology at 3 points in every cross-shore profile.	I, IV, V
	Sampling campaign	2003–2022		
Cross-shore profile	Geological atlas of the Lithuanian coast of the Baltic Sea (2004)	1993–2003	The data were used for validation and interpolation.	I
Depth, m	The Port of Klaipėda administration	1993–2022	Collected with a Kongsberg EM2040C multibeam echo sounder (Kongsberg Gruppen ASA, Norway), following International Hydrographic Organization Standards for Hydrographic Surveys (IHO, 2020).	I, III, IV, V
	Sampling campaign	June to October 2022	Collected using a 3-frequency Deeper Smart Sonar CHIRP+ 2 (Deepersonar, 2024).	I, III, IV, V

Variables	Data source	Time scale	Details	Paper
Aerial maps	Lithuanian National Land Service under the Ministry of Agriculture	1984, 1990	All shoreline position changes were determined using the available high accuracy (1:10,000) cartographic data.	II, IV, V
Orthophotos		1995, 2005		II, IV, V
Survey datasets from GPS determined shoreline positions		2010, 2015, 2019–2022	The shoreline position was established at the middle of the swash zone by an Emlid Reach RS+ RTK GNSS receiver with centimeter precision and a dual-band GPS receiver, Leica 900.	II, IV, V

Time series of shoreline positions from 1993 to 2022 were determined using aerial maps, orthophotos, and GPS-based survey datasets (Table 1). A dual-band "Leica 900" GPS receiver was used to measure the shoreline location in the middle of the swash zone. Historical shoreline positions were recorded at 25 m intervals along 800 transects. The changes in shoreline positions were analysed using the Digital Shoreline Analysis System (DSAS) v. 5.0 (Himmelstoss et al., 2018), an ArcGIS (Esri, 2023) extension developed by the United States Geological Survey (USGS). Analysis of long–term shoreline changes revealed that the long–lasting processes responsible for shaping and balancing the shoreline have intensified due to the human impact of port reconstruction.

Three types of errors related to shoreline positioning and detection were calculated (Crowell et al., 1993) to evaluate shoreline changes using data from different sources and time periods (Table 1):

1) for the aerial photo charts

$$U_t = \sqrt{E_s^2 + E_d^2 + E_p^2 + E_{tc}^2 + E_c^2}\ , \tag{2}$$

2) for the orthophotos

$$U_t = \sqrt{E_s^2 + E_d^2 + E_p^2 + E_r^2 + E_c^2}\ , \tag{3}$$

3) for the GPS survey data

$$U_t = \sqrt{E_s^2 + E_c^2} \ , \tag{4}$$

where E_s stands for the inaccuracy of representation of sea level fluctuations, E_d expresses digitisation inaccuracy (often called digitisation error), E_p is a similar inaccuracy of pixelisation of data (often called pixel error), E_c represents shoreline line detection or resolution errors, E_{tc} are T-sheets plotting errors, and is rectification error.

2.3. Beach Sediment Sampling and Processing (Paper I)

Historical sediment data from 1993 to 2003 (Table 1) were sourced from the Lithuanian Geological Survey (Bitinas et al., 2004). For the period from 2003 to 2019 (Table 1), sediment samples were collected by team of Physical Geography and Oceanography Department at Klaipėda University, and from 2019 to 2022 by the authors of **Paper I**, following the Lithuanian Geological Survey's methodology at three specific locations within each cross-shore profile: the dynamic shoreline, the mid-beach, and the foredune. These samples were then processed in the laboratory using a series of 19 sieves with the following size fractions: >2500 µm; 2500–2000 µm; 2000–1600 µm; 1600–1250 µm; 1250–1000 µm; 1000–800 µm; 800–630 µm; 630–500 µm; 500–400 µm; 400–315 µm; 315–250 µm; 250–200 µm; 200–160 µm; 160–125 µm; 125–100 µm; 100–80 µm; 80–63 µm; 63–50 µm; <50 µm. This large set of sieves makes it possibly to quantify a large range of sediment fractions, from silt (<50 µm) to very fine gravel (2500–2000 µm) while all fractions with >2500 µm are considered as gravel. The resulting data were analysed using the GRADISTAT add-in for Excel (Blott and Pye, 2001)however, be a laborious process. A computer program called GRADISTAT has been written for the rapid analysis of grain size statistics from any of the standard measuring techniques, such as sieving and laser granulometry. Mean, mode, sorting, skewness and other statistics are calculated arithmetically and geometrically (in metric units, which employs the Udden (Udden, 1914) and Wentworth (Wentworth, 1922) sediment size classification scales to determine the grain size distribution and sediment characteristics.

This thesis used the historical grain size data until 2003 alongside the classification provided by the Lithuanian Geological Survey while the classification based on Udden (1914) and Wentworth (1922) was used starting from 2004. In order to ensure data integrity and comparability between the two classifications, adjustment was made to align with the following grain size categories: 2500–2000 µm: very fine gravel; 2000–1000 µm: very coarse sand; 1000–500 µm: coarse sand; 500–250 µm: medium sand; 250–100 µm: fine sand; 100–50 µm: very fine sand; <50 µm: silt.

2.4. Bathymetric Survey Data

Bathymetric data for the period 1993–2022 (Table 1) were obtained from three sources: (1) The data set from the Port of Klaipėda administration covers the nearshore of the Port of Klaipėda access area with a 0.5 m resolution and extends to the north and south from the jetties ~5 km. (2) The data set from the Lithuanian Geological Survey covers the entire coast of Lithuania with a 1.5 m resolution. These data sets were collected using a Kongsberg EM2040C multibeam echo sounder in accordance with the International Hydrographic Organization›s Standards for Hydrographic Surveys (S-44) (**Paper I, III**). Depth data were processed with Hypack Max (HYSWEEP), a specialised hydrographic data recording and processing software. (3) Nearshore bathymetry data for a coastal segment to the north of the Klaipėda Strait were collected on 24 June 2022, prior to the beach nourishment at Klaipėda, and on 01 October 2022, several months after the nourishment campaign (**Paper III**), using a 3-frequency Deeper Sonar. Seabed elevation measurements were conducted along 10 cross-shore transects every 500 m. These transects extended from the shoreline to approximately 6 m deep water and covered about 5 km long coastal segment to the north of the northern jetty. All these data have inaccuracies of a few centimetres, which is much smaller than the typical amplitudes of fluctuations of seabed height over a few days.

To represent the surface morphology, a triangular irregular network (TIN) was created in Global Mapper 2022 (Marbel, 2019) using data from a point cloud dataset. This method joins three-dimensional (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 then developed and used to create a bathymetric surface to calculate volume by comparing surface grids from different periods. The Path Profile tool in Global Mapper 2022 (Marbel, 2019) generated a cross-section of the analysed surface to more accurately assess bathymetric features and seabed elevation changes. Elevation changes were calculated in 114 approximated profiles every 25 m along the studied coast. 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., 2011, 2010):

$$Q(x_n) = Q(x_{n-1}) - \int_{x_{n-1}}^{x_n} (1-p)\frac{\Delta z_b}{\Delta t}\,dx, \tag{5}$$

where $Q(x_n)$ is the integral volume of sediment transport (m^2/s) at position n, z_b is the difference in the bed elevation between measurement intervals (mm).

The bulk cross-shore sediment transport $\hat{Q}$ across the profile between two time instants was calculated by integrating the local transported volume across the profile as follows:

$$\hat{Q} = \Delta t \int_{x_{min}}^{x_{max}} Q(x)dx \,. \tag{6}$$

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 categorise the overall beach response as erosive ($\hat{Q} < 0$), accretionary $(\hat{Q} > 0)$ or stable $(\hat{Q} \approx 0)$. An alternative (normalised) 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 profile length.

The depth of closure h_c refers to the seaward limit of profile variability over long-term (seasonal or multi-year) time scales. Hallermeier (1981, 1978) devised the first rational method for evaluating closure depth based on evidence from the field and laboratory. Hallermeier (1981) established this depth as a threshold, deeper to which waves do not systematically shape the seabed and usually do not excite systematic sediment motion. His estimate is based on properties of the most intense waves. The effective wave period T_e and effective significant wave height H_e that govern the closure depth were calculated using H_e that was exceeded only 12 hours annually, or 0.14 percent of the time, and the associated periods T_e. The following equation approximates the depth of closure:

$$h_c = 2.28H_e - 68.5\left(\frac{H_e^2}{gT_e^2}\right). \tag{7}$$

We applied the following approximations:

$$H_e = \overline{H} + 5.6\sigma_H \,, \tag{8}$$

$$h_c = 2\overline{H} + 11\sigma_H \,, \tag{9}$$

where $g \approx 9.81$ m/s^2 is acceleration due to gravity, $\overline{H}$ is the annual mean significant height and σ_H is the annual wave height standard deviation. Also, $h_c = 1.57\,H_e$ provides a first approximation of the closure depth (Soomere et al., 2017).

2.5. Hydrometeorological Data

The hydrometeorological data, including 10-minute mean wind speed (m/s) and direction (degrees) from 1993 to 2021, as well as mean wave height (m) and wave propagation direction (degrees) from 1993 to 2019, were utilised in **Paper I** and processed using Origin Pro 2021 software (OriginLab, 2021) for statistical analysis and visualisation. These datasets were sourced from several institutions, including the Marine Environment Assessment Division of the Environmental Protection Agency (MEAD EPA), the Lithuanian Hydrometeorological Service under the Ministry of Environment (LHS), Palanga Aviation Meteorological Station, and the Port of Klaipėda administration.

The data were collected at various stations in the city of Klaipėda, Palanga, and the Port of Klaipėda area. The wind speed data were generally recorded with an accuracy of ±0.5 m/s or better. Wind direction was recorded in the 16-rhumb system (that is, with a step of 22.5°) until about 1992 and with a step of 10° or better since then. The Klaipėda meteorological station, situated near the jetties of the Port of Klaipėda, is located at an elevation of 6.2 m above sea level. It is surrounded by constructions, lacking direct access to the Baltic Sea, and thus only partially reflect offshore meteorological conditions. However, the timing and nature (e.g., increase or decrease) of regime shifts in time series of meteorological parameters are adequately reflected in such data sets.

The meteorological data (annual mean wind speed and direction) in 1960–2019 (Table 1) was analysed to detect the regime shifts in wind properties, with focus on wind directions in **Paper II**. The meteorological data were acquired from EPA and derived from the Klaipėda coastal meteorological station under the Lithuanian Ministry of Environment›s environmental monitoring program. The program has been prepared in accordance with EU legislation, primarily the Water Framework Directive (2000/60/EC), the Ambient Air Quality Directive (2008/50/EC), and other relevant directives and regulations.

A STAR (Sequential *t*-test Analysis of Regime Shifts) algorithm was applied to determine regime shifts in the analysed time series (https://www.beringclimate.noaa.gov/, accessed 10 October 2021). The algorithm was built upon a sequential *t*-test that can signal the possibility of a real-time regime shift (Rodionov, 2004). The algorithm can process the data regardless of whether it is presented in terms of anomalies (deviations from the mean) or as raw time series. It can automatically calculate regime shifts in large sets of variables (Rodionov and Overland, 2005; Rodionov, 2004). For this study, the following set of input parameters were used: cutoff length (l) was set to 10 years and Hubert's weight parameter was set to 1. This parameter is used to determine the weight of outliers by calculating the average values of the regime shift. The confidence level was set to 0.1.

The hydrometeorological data (wind speed (m/s) and direction (º), water level (cm), and wave height (m)) for 2022 were obtained from the MEAD EPA and the LHS (**Paper III**). According to the LHS, measurements of wind properties are conducted at three-hour intervals and presented as averaged values in observation stations. Automated measurement stations provide hourly average values of wind data. Wind speed data provided by the LHS is measured with accuracy of ±0.5 m/s. The MEAD EPA records hydrometeorological data using automated measurement stations. The results of all measured parameters including wave height and period, as well as sea level are recorded every 10 minutes and presented as average values over this interval. The accuracy of measured wave height and sea level is ±0.1 m and ±1–4 cm.

3

Results and discussion

The information presented comprises the most relevant fragments of results and discussion to support the conclusions. It is covered by five publications included in the thesis.

Paper I presents and analyses data on the evolution of coastal geomorphology of the Baltic Proper shores of Lithuania under joint influence by anthropogenic pressures, such as tourism and seaport activities, and natural factors like (changes in) hydrometeorological conditions. Coastal erosion on the coast of the mainland of Lithuania is associated with local hydrodynamic conditions and hydro-technical constructions, mostly seaport jetties. Sediment flow patterns along the Curonian Spit and the Lithuanian mainland coast are governed by the prevailing wave directions. These in turn largely follow the predominant wind directions.

The orientation of the shoreline is from the south to the north along the Curonian Spit and the Lithuanian mainland coast. The sediment flow is predominantly to the north. This pattern substantially affects sediment budget northwards of Klaipėda (Figure 2). The jetties of the port almost entirely stop alongshore sediment transport and thus erosion is expected at some distance to the north of these jetties. Accumulation is the predominant coastal process on the Curonian Spit coast, while erosion prevails on the mainland coast (Figure 2).

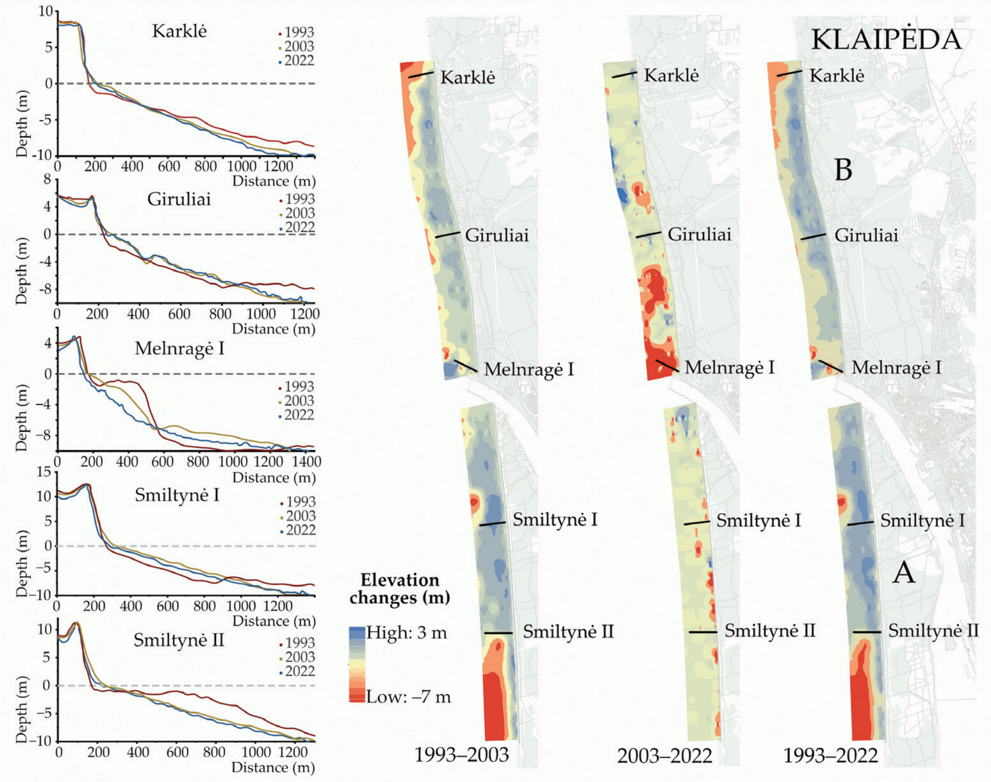

Figure 2. Elevation changes of the coastal zone on the Curonian Spit (A) and the mainland (B) coasts (Paper I).

2 pav. Aukščių pokyčiai Kuršių nerijos (A) ir žemyninės (B) karnto zonų dalyje (I straipsnis).

To manage and restore coastal segments affected by erosion, the Port of Klaipėda initiated a beach nourishment campaign from 2014 to 2018. During this initiative, 237.78 × 10^3 m^3 of sand was placed in the nearshore of Melnragė and Giruliai beaches. The grain size distribution is a natural result of sediment transport processes, mainly related to the effects of erosion and accumulation. During the study period from 2003–2022, the grain size of sediment on the mainland coast became slightly finer and more evenly distributed (Figure 3), possibly due to the beach replenishment. In contrast, sediment became coarser on the Curonian Spit coast during this time.

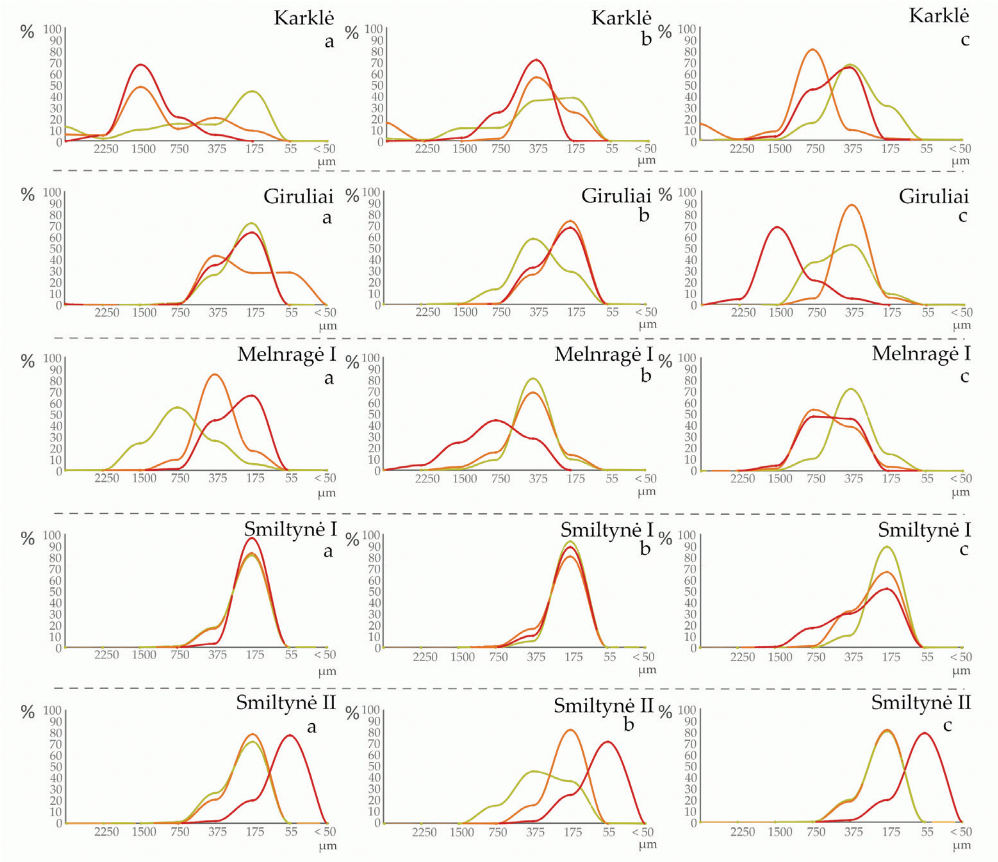

Figure 3. Grain size composition of surface sediment (%) at profiles from Karklė, Giruliai, Melnragė I, Smiltynė I, and Smiltynė II. The columns indicate the situation at a) the dynamic shoreline, b) mid-beach, and c) foredune. The data reflect samples in 2003 (red line), 2012 (orange line), and 2022 (yellow line) years (Paper I).

3 pav. Granulometrinė nuosėdinės medžiagos sudėtis Karklėje, Giruliuose, Melnragėje I, Smiltynėje I ir Smiltynėje II, kur a) dinaminė kranto linija, b) paplūdimio vidurys ir c) apsauginio kopagūbrio papėdė, 2003 (raudona), 2012 (oranžinė), ir 2022 (geltona) metais (I straipsnis).

The regime shift in wind direction (Figure 4; **Paper II**) naturally translates into morphological changes in the coastal zone, with winter erosion and summer accretion occurring in the Lithuanian coastal zone. The shift in hydrometeorological conditions could change the predominant sediment transport intensity and even direction, possibly leading to major changes in the location of erosion and accumulation processes. An increase in the frequency of wind speeds in the range of 2–4 m/s and 4–6 m/s occurred during the study period (**Paper I**). These wind conditions have significant impact on the hydrodynamic processes that determine coastal development and geomorphology. Waves excited by lower wind speeds continuously affect the shore, leading to a slow shore regeneration process as described in (Eelsalu et al., 2022).

The findings of this study align with previous research on shoreline changes and sediment dynamics (**Paper II**). Morphological changes to a sandy beach often occur rapidly as a response to changes in the properties of the forcing, such as wind direction or speed, wave climate, or sea level regime. In the Baltic Sea, climate change becomes evident *inter alia* in changes in several properties of the wind (and associated wave) climate, which can alter the magnitude and predominant direction of alongshore sediment transport (Soomere et al., 2015).

Average wind direction is the simplest property that can be used to detect variations in the directional structure of wind properties. It is commonly understood as the direction of the vector sum of all recorded wind properties expressed as vectors (speed and direction). In essence, this direction and speed express so-called average air flow direction and speed used, e.g., in (Soomere et al., 2015) to detect regime shifts in geostrophic air flow in the entire Baltic Sea and in (Keevallik and Soomere, 2014) to detect similar shifts in surface-level wind properties in the Gulf of Finland region. As the Baltic Sea wind climate is substantially anisotropic, with most winds blowing from the western directions, this concept (that is meaningless in isotropic wind climates) is applicable in this region.

A major change in the directional structure of winds occurred in 1992. As its magnitude is about 30°, it is unlikely that it stems from a change in the measurement routine and/or directional resolution from the 16 rhumb system (22.5°) to a higher resolution. Another, less obvious and apparently temporary shift is evident in the average wind direction in 2012. These shifts have eventually caused significant changes in coastal processes and evolution. Shifts in wind direction (Figure 4) coincide with changes in properties of coastal erosion on both the Curonian Spit and mainland coasts. The shoreline predominantly experienced a shift towards the sea in the 19th century on both the Curonian Spit and the mainland coast of Lithuania. The rate of erosion on this coast was 4.57 ± 0.09 m/year in 1990–1995 and 4.24 ± 0.12 m/year in 2015–2019 (**Paper II**).

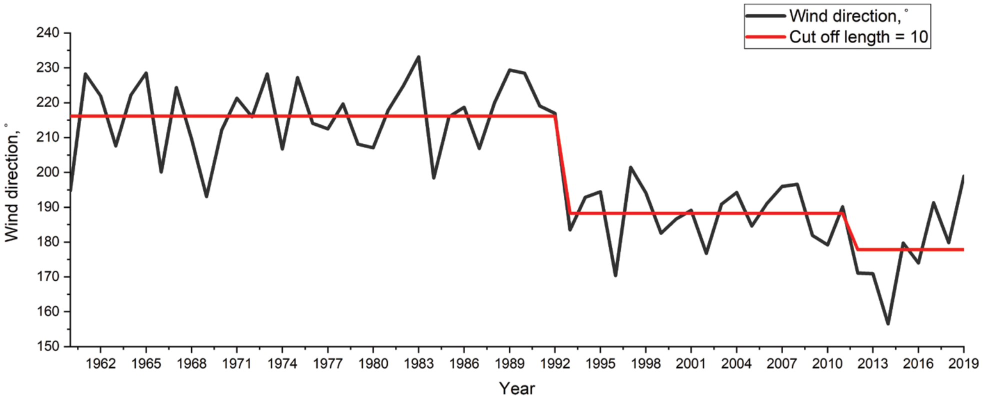

Figure 4. A shift in the annual average wind direction in Klaipėda in 1960–2019 (Paper II).

4 pav. Vėjo krypties režimo pokytis (vidutinė metinė reikšmė) Klaipėdoje 1960–2019 metais (II straipsnis).

These tendencies and patterns are crucial for sustainable coastal management. One of the coastal management methods actively used in Lithuanian coastal areas is nourishment. The effectiveness of nourishment, properties of post-nourishment processes and potential implications on coastal erosion management of one of such campaigns are addressed in **Paper III**. On 29 June 2022, a dredging campaign in the Klaipėda Strait entrance channel started. The dredged material was first tested to see if it met the required physical and chemical properties (Filipkowska et al., 2011; Staniszewska and Boniecka, 2017) and then placed in the proximity of the northern jetty (Figure 5). 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 in the area where the depth before nourishment was 2–3.5 m (Port of Klaipėda, 2024).

The findings highlight several critical aspects of post-nourishment sediment dynamics. The added sand exhibited significant relocation, even under mild wave conditions. Specifically, around Profile 1, approximately 10,000 m^3 of sediment was relocated, and around Profile 2, about 5,000 m^3 (Figure 5). Interestingly, notable rapid reshaping occurred within just six weeks under wave conditions that were much milder than average. This unexpected finding underscores the dynamic nature of sediment transport in the study area and its challenges for coastal management.

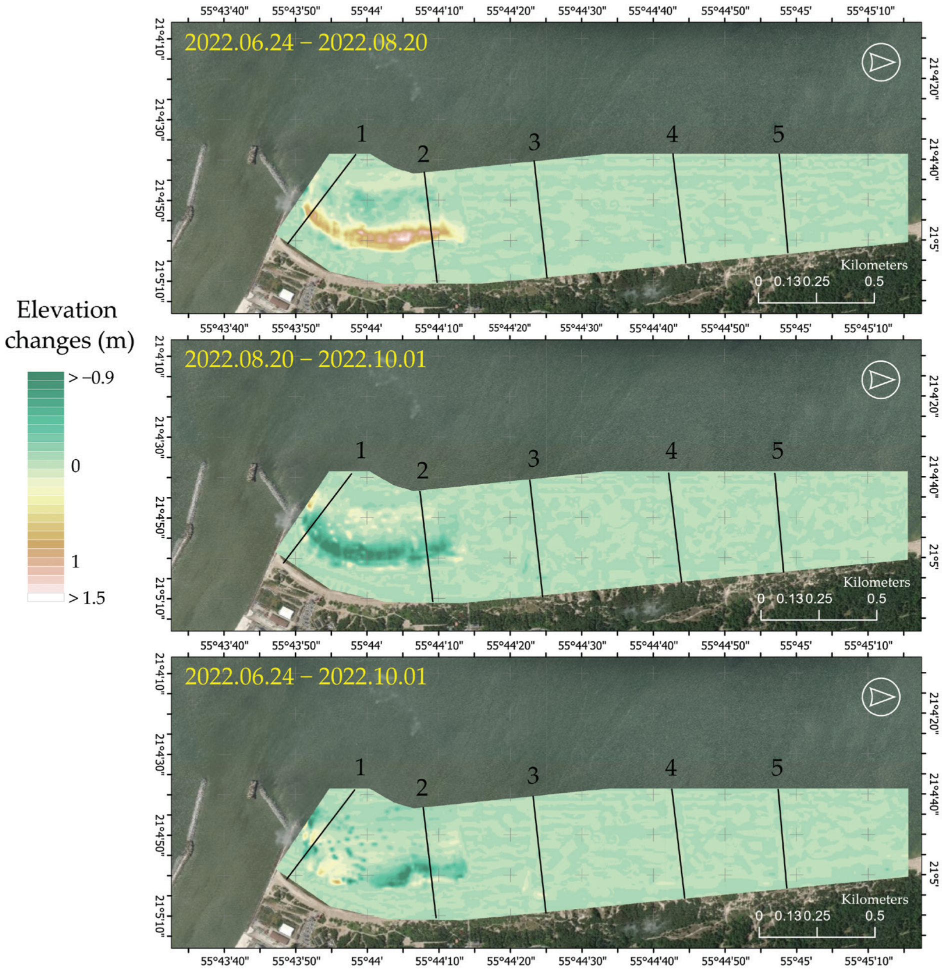

Figure 5. Changes in seabed elevation at the study site nearshore during the study period from 24 June 2024 to 01 October 2024 (Paper III).

5 pav. Kranto povandeninio šlaito pokyčiai tiriamosios vietos priekrantėje tiriamuoju laikotarpiu nuo 2024–06–24 iki 2024–10–01 (III straipsnis).

The direction of alongshore sediment transport was highly variable. The observed transport was mainly to the south near Profile 1 and to the north near Profile 2 (Figure 5 and 6). This variability is likely governed by the proximity to the jetties of the Port of Klaipėda, which affect local hydrodynamic loads by sheltering the southernmost part of the nourished beach against waves from the south-west. Such extensive variability complicates predictions and requires adaptive management strategies to account for specific local conditions.

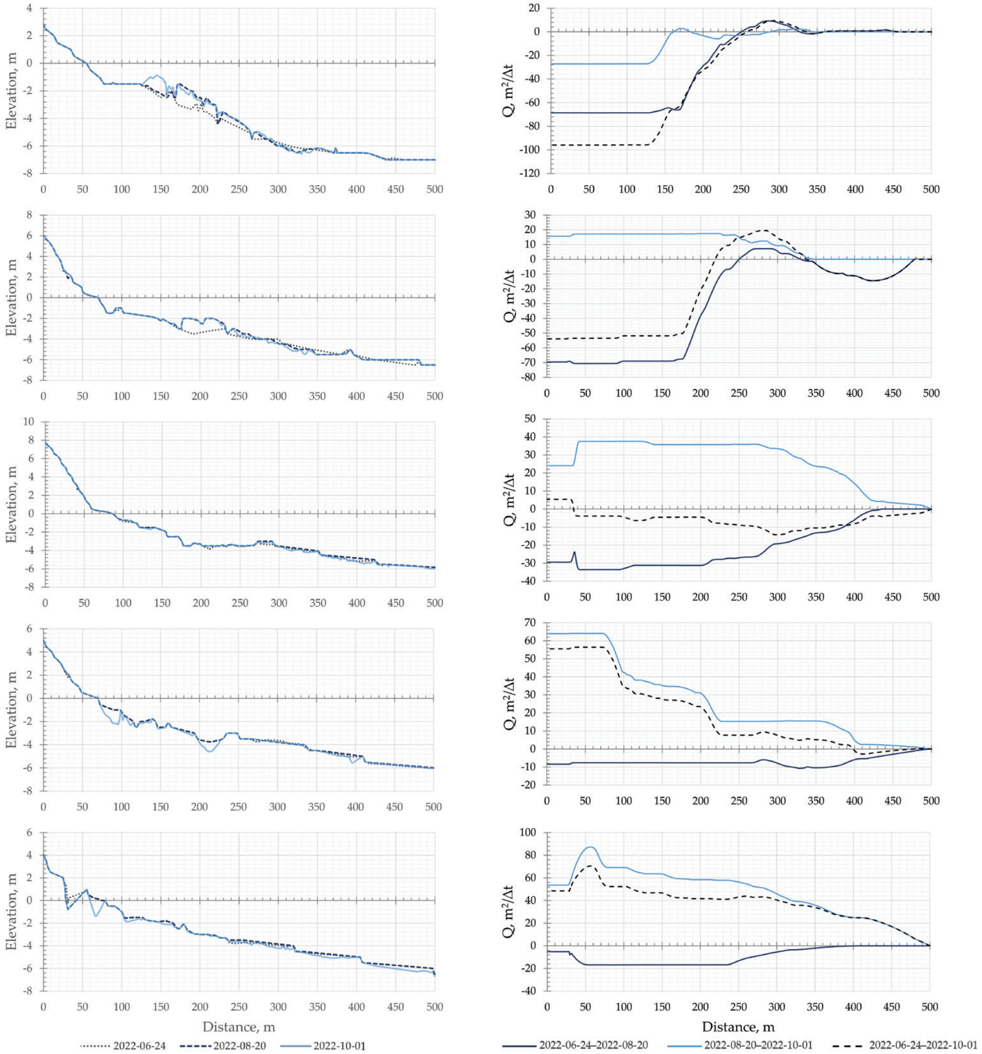

Figure 6. Comparison of seabed elevation along nearshore profiles (left column) and net sediment transport rate (right column) at profiles 1 to 5 (see Figure 5 for locations) (Paper III).

6 pav. Aukščių pokyčiai (kairėje) ir nuosėdinės medžiagos transporto greitis (dešinėje) profiliuose nuo 1 iki 5 (žr. 5 pav.) (III straipsnis).

The range of sediment relocation was relatively limited, with little to no impact observed at longer distances from the nourished beach on Profiles 3, 4, and 5 (Figure 5 and 6). This feature suggests that the nourishment effects are highly localised and possibly influenced by specific wave directions, which, in this case, were dominated by western winds and the presence of the jetties. This localised impact indicates that while nourishment can be effective in targeted areas, its broader influence may be restricted.

The analysis in **Paper III** observed typical sediment transport patterns, including offshore transport along profiles where sand was added and a combination of offshore erosion with onshore transport in other areas. These patterns indicate that it will take longer time than a few weeks for the nourished profiles to achieve equilibrium. This feature demonstrates the need for continuous monitoring and adjustment.

During the study period, a notably low sea level event occurred, particularly from 06 to 11 September 2022 (Figure 7). This sea level drop and prevailing wind patterns from the south-east to the south-west significantly influenced sediment dispersion as even small waves reached dumped sands in locations that are impacted only by higher or longer waves under average water level (Eelsalu et al., 2022). Most of sediment transport under the wind and sea level conditions during the survey occurred in the cross-shore direction while the nourishment's alongshore effects were quite limited.

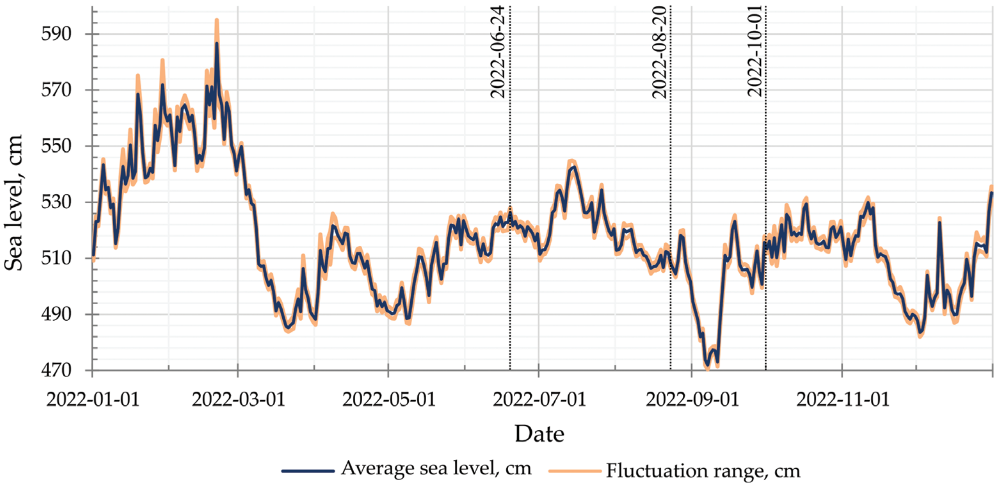

Figure 7. Sea level (cm, 500 cm corresponds to the long-term average) during the year 2022 with the highlighted survey dates (Paper III).

7 pav. Jūros lygis (cm, atitinka daugiametį 500 cm vidurkį) 2022 m. su pažymėtomis tyrimų datomis (III straipsnis).

The results indicate that comprehensive measurements are essential to understand the broader impacts of nourishment on more distant coastal segments and to refine management strategies accordingly. Such research would provide a more holistic understanding of the effects of nourishment and improve coastal management practices. Overall, the study emphasises that while beach nourishment can be a valuable tool in 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.

The gathered data and implemented research led to the idea of developing a system that addresses the knowledge gaps, creates a knowledge-sharing platform and determines thresholds that could limit activities or change the course of short- and long-term strategies (**Paper IV** and **Paper V**). As hydrometeorological data alone cannot explain current changes, a holistic approach and modelling are needed to ensure that decision-makers operating in the Klaipėda coastal zone are well-informed about the causation of coastal dynamics. The development of the EASTMOC system (Figure 8) results from this collaboration, where stakeholders are the initiators.

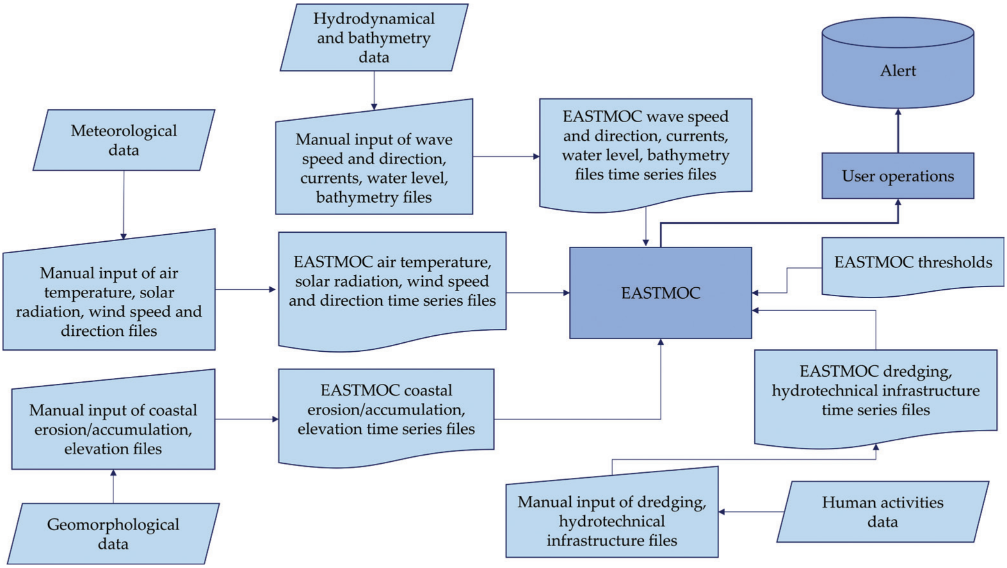

Figure 8. Conceptual diagram of the EASTMOC system (Paper IV).

8 pav. EASTMOC sistemos koncepcinė schema (IV straipsnis).

A knowledge gap exists regarding alongshore and cross-shore sediment transport in the Baltic Sea. This area requires funding and technical solutions for research. A pilot study was conducted with ten selected stakeholders, including the Port of Klaipėda

Authority, SC “Smiltynės perkėla”, and the Lithuanian Transport Safety Administration. The most relevant data on natural factors used for day-to-day operations and future plans included beach width, underwater slope, shoreline position, significant wave height and direction, wind speed and direction, current speed and direction, ice cover, and visibility.

Critical gaps were identified as nearshore bathymetry, hydrological data of rivers and the Curonian lagoon, and easy access to real-time hydrometeorological data. Stakeholders’ activities depend on different variables and the nature and scale of their operations. For example, monitoring operations and shipping of small vessels in the nearshore area can be limited at a wind speed of 7 m/s and a wave height of above 1.5 m. Shoreline position is the most commonly used indicator for assessing coastal erosion or accumulation processes (Bagdanavičiute et al., 2012) and is important for long-term planning.

The net shoreline movement analysis from 1993 to 2022 revealed that 39% of the shoreline was experiencing erosion, 34% showed accumulation, and 26.5% remained stable within an uncertainty range of ±5.02 m (Figure 9). A comparison of shoreline changes in time periods of 1993–2003 and 2003–2022 indicated that the length of the eroded coastal area increased by 4.4 times, from 2.73 km to 11.90 km. Notably, significant coastal erosion, up to 51.95 m, was observed in a coastal segment to the north of the jetties of the Port of Klaipėda (Figure 9). Such analysis could reach broad society of stakeholders and locals once put in the proposed system.

The gathered data supports the need for timely knowledge sharing. It was concluded that while catering to select stakeholders and providing monitoring data and personalised alerts is possible, the datasets need to be continuously updated.

In order to support the idea of the study, an automated system and timely data input are needed. The EASTMOC system, a short insight into which is provided in **Paper V**, aims to create a link between long- and short-term observation and monitoring data to stakeholders (wind speed and direction, wave direction and significant height, water and air temperature, atmospheric pressure, sediment size and distribution, cross–shore elevation, shoreline position, beach width, change in beach protection measures, beach wreck, and marine debris management). In general, applying systems thinking and integrated modelling methods can significantly improve our understanding of complex systems and support the development of more effective and sustainable management strategies.

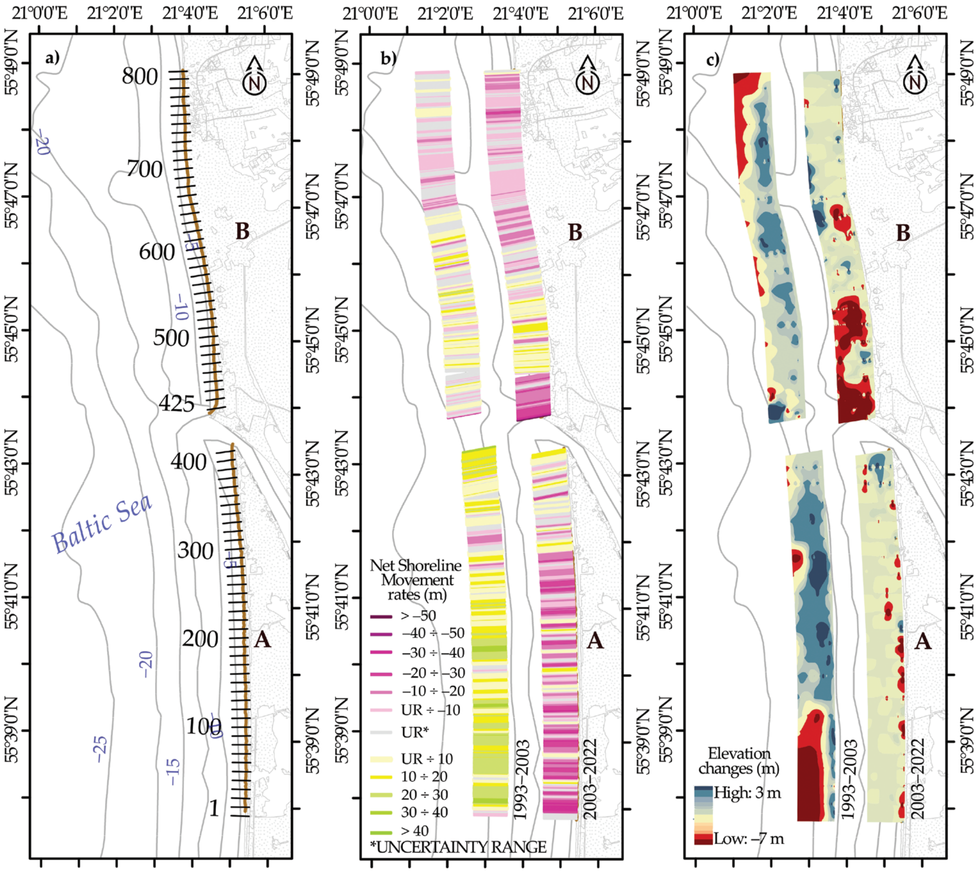

Figure 9. **a)** Transect positions along the study area, **b)** net shoreline movement (m) during 1993–2003 and 2003–2022 along the study area, and **c)** elevation change for 1993–2003 and 2003–2022, including underwater and onshore parts on both the Curonian Spit (A) and mainland (B) coasts (Adapted from Kondrat et al., 2023 and Šakurova et al., 2023) (Paper IV).

9 pav. **a)** transektų padėtis išilgai tiriamos teritorijos, **b)** kranto linijos kismas (m) 1993–2003 m. ir 2003–2022 m. išilgai tiriamos teritorijos ir **c)** aukščio pokytis 1993–2003 m. ir 2003–2022 m., įskaitant povandeninę ir sausumos dalis tiek Kuršių nerijos (A), tiek žemyninėje (B) dalyse (adaptuota pagal Kondrat et al., 2023 ir Šakurova et al., 2023) (IV straipsnis).

4

Conclusions and recommendations

1. The bathymetric data and cross-shore profiles were used to calculate seabed height changes and variations in the underwater and dry beach sediment volume. The sediment loss on the shores of the Curonian Spit and mainland coasts of Lithuania increased after the Port of Klaipėda reconstruction. The estimated net sediment loss was about 1,5 million m^3. The rate of sediment loss decreased on the Curonian Spit coast, indicating that hydro-technical structures influence sediment flow along the coast. This process was accompanied with steepening of underwater parts of beach profiles near jetties at the entrance of the Klaipėda Strait. This feature signals that more wave energy reached the shore under the existing climate conditions. Recreational activities in the coastal zone are not directly affected by these changes until the sandy beach persists but are highly dependent on planners' decisions. The study emphasises the need to monitor sediment dynamics to provide customised coastal management methods.
2. The northern part of the coast exhibits more intense erosion, and the eroding coast length increased three times. Short-term shoreline changes are associated with wind direction and the effect of dredging works. The research also identified the part of the mainland coast that exhibits other properties, such as accumulation.

3. The results indicate that comprehensive measurements are essential to understand the broader impacts of nourishment on more distant coastal segment and to refine management strategies accordingly. Such research would provide a more holistic understanding of the effects of nourishment and improve coastal management practices. Overall, the study emphasises that while beach nourishment can be a valuable tool in 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.
4. The pilot research and the determined thresholds demonstrated the necessity of an environmental notification system. The stakeholder effort has also highlighted the coastal region's traits and characteristics that require closer monitoring. Their involvement ensures that a working system is feasible. The development of an environmental notification system highlighted important differences between the two segments of the study region – the mainland coast and the Curonian Spit coast. Along with different geomorphologies, the two regions also have different access points, social and economic values, and uses. A natural conjecture is that each assessment of them in the system should use a different data set.

5

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Curriculum Vitae

The author of the dissertation, Ilona Šakurova, was born on February 24, 1994. After graduating from Visaginas Technology and Business Training Centre (now Visaginas TECH) in 2012, she obtained the qualification of Computer Tuner in 2013. In the same year, she entered the bachelor's study programme in Hydrology and Oceanography (now Physical Geography and Oceanography) at the Faculty of Natural and Mathematical Sciences of Klaipėda University (now the Faculty of Marine Technologies and Natural Sciences). She completed her bachelor's studies in 2017 with a thesis titled "Modelling of isostatic sea level fluctuations in the southeastern Baltic Sea." She continued her studies at Klaipėda University in the master's study programme in Ecology and Environmental Science. In 2019, she defended her master's thesis, "Modeling of eutrophication processes in the Curonian lagoon." That same year, she enrolled in doctoral studies in the field of physical geography at Klaipėda University.

7

Santrauka

ĮVADAS

Manoma, kad žymiausia istorija cituojama tarp, nešmenų pernašos tema dirbančių, mokslininkų ar inžinierių kilo iš Alberto Einšteino ir jo vyresniojo sūnaus Hanso Alberto Einšteino diskusijos, vykusios daugiau nei prieš 70 metų (Nelson, 1999). H. A. Einšteinas informavo tėvą apie savo planus tirti nešmenų pernašos dinamiką. A. Einšteinas patarė sūnui nesiekti akademinio laipsnio šia tema, nes, jo nuomone, nešmenų pernaša tokia sudėtinga, kad jos neįmanoma išspręsti (Nelson, 1999). A. Einšteinas tai pat dirbo šioje srityje, jis domėjosi suspenduotos medžiagos nusėdimo greičiais (Nelson, 1999). Kaip ir daugelis sūnų prieš jį, Hansas nepaisė tėvo patarimo ir pateko į žymių mokslininkų, prisidėjusių prie šiuolaikinės nešmenų pernašos teorijos ir praktikos sukūrimo, būrį (Nelson, 1999).

Nešmenų pernaša yra labai svarbus veiksnys, padedantis suprasti jūros kranto aplinką, ypač smėlėtus paplūdimius. Paplūdimiai kinta laike ir erdvėje priklausomai nuo nešmenų morfologijos ir hidrodinaminių sąlygų regione, kuriame jie yra (Eelsalu et al., 2022; George et al., 2019; Quadrado ir Goulart, 2020). Išilgai ir skersai kranto pernešami nešmenys bangų gožos zonoje, hidrometeorologinės sąlygos ir įvairi žmogaus veikla pakrantės zonoje gali labai paveikti kranto zonos geomorfologiją, kas pirmiausia atsispindi kranto linijos padėties pokyčiuose (Belibassakis ir Karathanasi, 2017; Brutsché ir kt., 2014; Wang ir kt., 2002). Todėl išsamus priekrantės fizinių procesų supratimas ir vertinimas yra labai svarbus planuojant ir įgyvendinant kranto zonos plėtros programas (Bain et al., 2021; McGill et al., 2022).

Baltijos jūros pakrantė yra puikus pavyzdys, kaip gamtiniai ir antropogeniniai veiksniai sąveikauja formuodami jūros kranto morfologiją. Lito- ir morfodinaminius procesus, sąlygojančius kranto linijos formavimąsi, veikia eoliniai procesai sausumoje ir hidrodinaminiai procesai jūroje (Burningham, 2006; Masselink et al., 2006; Valiente et al., 2019). Tad savitą Baltijos jūros kraštovaizdį formuoja jūros ir vėjo sąveika, sukurianti įvairias pakrantės formas (Bitinas ir kt., 2005, 2004; Jarmalavičius ir kt., 2017).

XX a. pabaigoje antropogeninis poveikis tapo įvairius pakrantės formavimosi procesus veikiančiu veiksniu (Brown ir kt., 2017). Pagrindiniai kranto zonos raidą lemiantys ir profesionalaus valdymo reikalaujantys veiksniai šalia gamtinių tokių, kaip audrų intensyvėjimas, didėjantis smėlio praradimas paplūdimiuose, kylantis pasaulinio vandenyno lygis yra ir žmogaus ūkinės veiklos nulemti tokie, kaip uostų ir kitų hidrotechninių statinių įrengimas, uostų gilinimas, rekreacinių zonų plėtra (IPCC, 2022; Meier et al., 2021; Weisse et al., 2021). Todėl, vykstant nuolatiniams pokyčiams, kranto zonos valdymas tampa svarbiu prioritetu šiuolaikinėje visuomenėje (Brand et al., 2022; Herrera et al., 2010; Johnson et al., 2021).

Vertinant paplūdimių stabilumą, projektuojant, statant ir vystant visuomeninę ir rekreacinę kranto zonos infrastruktūrą, planuojant kranto zonos apsaugos strategiją, labai svarbus tampa gebėjimas suprasti skersinių kranto profilių formavimosi ypatumus (Bain et al., 2021; Bergillos et al., 2017; Gong et al., 2017). Šios žinios reikalingos, tiksliau prognozuojant paplūdimių dinamiką jūros kranto raidos modeliuose (Esteves et al., 2009), o kranto linijos poslinkis yra dažniausiai naudojamas rodiklis, vertinant kranto erozijos ar akumuliacijos procesus. Pastarasis gali atspindėti įvairių veiksnių poveikį – audrų sukeliamas pasekmes, vėjo ar bangų režimo kitimus, taip pat žmogaus veiklą (Almonacid-Caballer ir kt., 2016; Benkhattab ir kt., 2020; Hanslow, 2007). Nuosekli šio rodiklio kitimo stebėseną leidžia geriau suprasti pakrantės zonos morfodinaminius procesus ir sudaro prielaidas jų raidos prognozėms.

Jūros kranto morfodinaminių procesų (dugno reljefo ir hidrodinamikos sąveikos) ypatumai daugiausia lemia smėlio tūrio perskirstymą pernešant nuosėdinę medžiagą (Bain et al., 2021; Belibassakis ir Karathanasi, 2017). Batimetriniai duomenys yra svarbūs analizuojant jūros dugno sedimentacijos ir morfologijos kaitos dėsningumus (Bezzi ir kt., 2021; Rosier ir kt., 2018; Sakhaee ir Khalili, 2021; Yutsis ir kt., 2014). Baltijos jūrai būdingi saviti geomorfologiniai, hidrografiniai ir hidrodinaminiai režimai, lemiantys jūros dugno morfologiją ir kranto zonos dinamiką (Hoffmann ir Lampe, 2007; Kaskela, 2017). Tarp Baltijos jūros dugną veikiančių veiksnių ypač reikšmingos yra antropogeninės apkrovos. Pagrindinės žmogaus veiklos formos tokios kaip uostų statyba, gilinimo darbai, kabelių ir vamzdynų tiesimas bei priekrantės ir jūrinės atsinaujinančios energetikos infrastruktūros plėtra, gali skatinti pakrantės eroziją arba keisti povandeninės nešmenų pernašos kryptį, taip neretai neigiamai paveikdamos atskiras Baltijos jūros akvatorijos dalis (Coelho et al., 2013). Todėl šiuos rizikos veiksnius būtina kruopščiai įvertinti, prieš imantis bet kokios vystymo veiklos (Aragonés et al., 2019; Coelho et al., 2013; Weisse et al., 2021).

Paplūdimių papildymas (maitinimas) nuosėdine medžiaga, t. y. smėlio įterpimas į eroduojančius paplūdimius, yra vienas veiksmingiausių ir sudėtingiausių krantosaugos priemonių (Regard et al., 2023). Jo efektyvumą lemia daugybė veiksnių, įskaitant vietos sąlygas, orų režimą ir žmogaus veiklą (Brand et al., 2022). Smėlio papildymas gali būti vykdomas tiek paplūdimyje tiek priekrantėje (Johnson ir kt., 2021). Priekrantėje neretai tikslingai panaudojamos uostų gilinimo metu iškasta nuosėdinė medžiaga, suformuojant bermą arba smėlio seklumą (Bain et al., 2021; Brutsché et al., 2014; Johnson et al., 2021), kuri funkciškai veikia kaip „minkštas“, panardintas bangolaužis (Bain ir kt., 2021; Brutsché ir kt., 2014). Dažnais atvejais priekrantės papildymui galima naudoti netoliese esančių laivybos farvaterių, sėklių ar atviros jūros telkinių nuosėdinę medžiagą, o paplūdimys papildymo metu lieka naudojamas.

Išilginė nešmenų pernaša gali įvairiai perskirstyti smėlį po paplūdimių papildymo, priklausomai nuo konkrečių pakrantės sistemos sąlygų (Brutsché et al., 2014; McGill et al., 2022). Papildyto smėlio sklaidą lemia bangų ir srovių kryptis bei intensyvumas, paplūdimio ir jūros dugno topografija, taip pat nešmenų granuliometrinės charakteristikos (George et al., 2020; Wang, 2004; Work et al., 2004). Todėl siekiant pasiekti maksimaliai geriausią rezultatą ir išvengti nenumatytų pasekmių, kranto zonos valdytojams ir inžinieriams planuojant paplūdimių papildymą smėlių, būtina įvertinti minėtus veiksnius (Johnson ir kt., 2021; Kuang ir kt., 2019).

Tvariam kranto zonos valdymui labai svarbu visapusiškai suprasti viso skersinio kranto profilio kintamumą, apimantį tiek sausumą, tiek povandeninį šlaitą. Šios žinios leidžia tiksliau ir efektyviau taikyti įvairias pakrančių inžinerines priemones: i) kranto zonos maitinimą smėliu (Cantasano ir kt., 2023; Jiménez ir Sánchez-Arcilla, 1993; Kelpšaitė-Rimkienė ir kt, 2021); ii) krantosauginių statinių (pvz.: bangolaužių) projektavimą (Aagaard et al., 2004; Aragonés et al., 2019; Hinton ir Nicholls, 1998; Kelpšaitė-Rimkienė et al., 2021); iii) nešmenų pernašos balanso skaičiavimą (Aragonés et al., 2019; Coelho et al., 2013). Skersinių kranto profilių matavimai ir jų pokyčiais pagrįsti skaičiavimai yra svarbūs įrankiai, vertinant išilgai kranto pernešamų nešmenų greitį bei prognozuojant kranto erozijos ir akumuliacijos mąstą (van Rijn et al., 2003). Nors aptikti pokyčius bangų gožos zonoje – dinamiškiausioje jūros kranto profilio dalyje – tebėra sudėtinga, labai svarbu geriau suprasti nešmenų pernašos procesus visoje kranto zonoje, tad nuolatinė stebėsena bei monitoringas yra neatsiejama šio proceso dalis (Héquette et al., 2001; Oo et al., 2022).

Tyrimo tikslas ir uždaviniai

Pagrindinis disertacijos tikslas yra dvejopas: i) visapusiškai ištirti nešmenų pernašos dinamiką kaip pagrindinį pietryčių Baltijos jūros pakrančių tvarumo veiksnį, nagrinėjant jos sąveiką su antropogeniniu poveikiu, gamtinėmis jėgomis ir socialiniais bei ekonominiais veiksniais, ir ii) išvystyti žinių dalijimosi platformą, kurioje būtų teikiami duomenys apie kranto zonoje vykstančius, nešmenų pernašą lemiančius procesus, siekiant suteikti tikslingą informaciją tvarių krantosauginių strategijų kūrimui ir sušvelninti poveikį aplinkai.

Siekiant įgyvendinti šį tikslą, buvo keliami šie uždaviniai:

1. Įvertinti antropogeninių ir gamtinių veiksnių poveikį skersinio kranto profilio pokyčiams smėlingoje, atviroje bangų energijos veikiamoje kranto zonos dalyje.
2. Išanalizuoti nešmenų pernašos poveikį kranto linijos dinamikai klimato kaitos ir padidėjusio antropogeninio poveikio kontekste.
3. Įvertinti smėlio perskirstymo procesų pagrindines savybes, erdvinę aprėptį ir laiko mastelį iš dalies užuovėjinėje, mažos energijos aplinkoje po priekrantės papildymo smėliu, naudojant didelės raiškos duomenis.
4. Remiantis surinktais duomenimis ir jų analizės rezultatais, sukurti sisteminės žinių dalijimosi platformos architektūrą, kuri leistų spręsti žinių spragas ir nustatyti ribines vertes, kurios galėtų apriboti veiklą arba pakeisti trumpalaikių ir ilgalaikių strategijų kryptį.

Pagrindinis tyrimo objektas – visos Lietuvos kranto dinamika, kurią lemia gamtiniai veiksniai ir antropogeninė veikla. Kadangi Lietuvos jūros kranto linija beveik tiesi, ši dinamika gerai atsispindi reprezentatyviuose kranto ruožuose, esančiuose prie stambių hidrotechninių įrenginių. Todėl I ir II straipsniuose dėmesys sutelkiamas į kranto raidą lemiančius procesus, vykstančius iki 10 km nuo Klaipėdos sąsiaurio molų – reikšmingiausių šio regiono hidrotechninių statinių. Siekiant suprasti vietinių antropogeninių intervencijų poveikio mastą ir trukmę, III straipsnyje analizė sukoncentruota į maždaug 5 km ilgio kranto ruožą į šiaurę nuo Klaipėdos. IV ir V straipsniuose šių tyrimų analizės rezultatai konsoliduojami ir apibendrinami, kad būtų pritaikomi vystant žinių dalijimosi platformą.

Darbo naujumas

Šiame darbe išanalizuota Lietuvos uostamiesčio Klaipėdos jūros kranto raida ir jos priežastingumas, daugiausia dėmesio skiriant kranto nešmenų perskirstymui ir su tuo susijusiems kranto zonos pokyčiams. Pateiktos išvados, apie taškinio paplūdimio maitinimo darbų poveikį, kai net esant nedidelėms bangoms vyksta didelis nešmenų perklostymas, suteikia naujų įžvalgų apie nešmenų pernašos dėsningumus ir kranto erozijos valdymo iššūkius. Pastebėta, kad paplūdimių papildymo poveikis yra ribotas ir labai priklauso nuo konkrečių vietos sąlygų, pavyzdžiui, atstumo iki molų ir dominuojančių bangų krypčių. Tai parodo būtinybę kurti ir taikyti konkrečiai vietovei skirtas krantosaugines strategijas. Toks nuoseklus po papildymo dinamikos supratimas yra itin svarbus siekiant tobulinti ateities krantosaugos priemones ir užtikrinti jų veiksmingumą.

Be to, tyrime nustatytas ir kiekybiškai įvertintas vyraujančių vėjo krypčių pokyčių poveikis pakrančių erozijai ir nešmenų pernašai, susiejant šiuos pokyčius su platesnėmis klimato tendencijomis, stebėtomis nuo XX a. dešimtojo dešimtmečio pradžios. Dėmesio sutelkimas į reikšmingus vėjo režimo pokyčius, užfiksuotus 1992 ir 2012 metais, atveria naują dimensiją aiškinantis, kaip klimato kaita lemia kranto zonos dinamiką. Šiuos pokyčius gretinant su erozijos intensyvumo svyravimais ir nešmenų persiskirstymo dėsningumais, pateikiami nauji įrodymai apie tiesioginį klimato kintamumo poveikį kranto zonai. Sukūrus dalijimosi žiniomis platformą – aplinkos perspėjimo sistemą, skirtą savalaikiams kranto zonos priežiūros sprendimams, būtų įdiegiamas naujas mechanizmas, kaip įtraukti suinteresuotąsias šalis į kranto zonos valdymo procesą. Ši platforma palengvintų keitimąsi duomenimis ir aplinkos stebėjimais realiuoju laiku ir stiprintų įvairių suinteresuotųjų šalių, įskaitant Klaipėdos uosto ir mažųjų uostelių administracijų, transporto administracijos ir aplinkosaugos agentūros, bendradarbiavimą. Ši sistema ne tik prisidėtų prie sprendimų priėmimo gerinimo, bet ir skatintų labiau integruotą ir operatyvesnę valdymo sistemą, pritaikytą konkretiems Lietuvos kranto zonos poreikiams ir iššūkiams.

Rezultatų mokslinė ir praktinė reikšmė

Lietuvos kranto geomorfologijos ir nešmenų pernašos priekrantėje tyrimai suteikia reikšmingų mokslinių įžvalgų ir praktinio pritaikymo galimybių, kurios prisideda prie platesnio jūros kranto dinamikos supratimo ir valdymo. Tyrimo rezultatai yra reikšmingi keliais aspektais:

- Išsami nešmenų pernašos dėsningumų ir kranto linijos pokyčių analizė suteikia svarbių įžvalgų apie sudėtingą gamtinių jėgų ir antropogeninio poveikio sąveiką. Šie rezultatai prisideda prie jūros kranto geomorfologijos žinių plėtimo, ypač tuose regionuose, kuriuose žmogaus ūkinė veikla daro didelį poveikį gamtiniams procesams.
- Tyrime taip pat aiškinamas vėjo krypties kaitos ir hidrodinaminių sąlygų poveikis nešmenų pasiskirstymui, pabrėžiant būtinybę į kranto zonos tyrimus įtraukti tiek trumpalaikių, tiek ilgalaikių aplinkos pokyčių analizę.

- Pastebėti vėjo režimo pokyčiai ir jų poveikis kranto erozijai ir nešmenų dinamikai yra labai svarbūs siekiant suprasti klimato kaitos poveikį jūros kranto aplinkai. Duomenys apie vėjo greičio ir krypčių pokyčius tampa vertingu įrodymu klimato kaitos tyrimams, ypač siekiant suprasti, kaip šie pokyčiai lemia erozijos procesų intensyvumą ir nešmenų kaupimosi dėsningumus.
- Siūlomas EASTMOC sistemos įgyvendinimas yra naujas požiūris į realaus laiko stebėsenos ir ilgalaikių stebėjimų duomenų integravimą. Ši metodologinė pažanga užpildo esamas žinių spragas ir sudaro pagrindą išsamesniam bei adaptyvesniam kranto zonos valdymui, galinčiam tapti pavyzdžiu ir kitoms panašioms smėlėtoms pakrantėms pasaulyje. EASTMOC sistema, palengvinanti realaus laiko duomenų mainus ir stebėseną, leis suinteresuotosioms šalims priimti labiau pagrįstus sprendimus dėl kranto zonos priežiūros ir naudojimo. Ši sistema gali būti ypač naudinga valdant sudėtingą natūralių procesų ir žmogaus veiklos sąveiką, mažinant nenumatytų pasekmių riziką ir didinant kranto ir pakrančių infrastruktūros atsparumą.
- Gauti rezultatai tiesiogiai prisideda prie kranto erozijos valdymo, ypač Klaipėdos uosto vykdomų paplūdimių papildymo darbų kontekste. Tyrime pabrėžiama nuolatinės stebėsenos ir adaptyvaus valdymo strategijų būtinybė, siekiant užtikrinti ilgalaikę sėkmingą paplūdimių papildymo projektų įgyvendinimą. Šios įžvalgos gali būti tiesiogiai pritaikytos optimizuojant būsimas paplūdimių maitinimo kampanijas ir planuojant taikyti kitas krantosaugos priemones bei didinant jų efektyvumą.
- Nustačius esmines žinių spragas, ypač susijusias su nešmenų pernaša Baltijos jūroje, išryškėja sritys, kuriose reikalingi tolimesni tyrimai. Nustačius šias spragas, tyrimu sudaromos prielaidos būsimoms mokslinių tyrimų iniciatyvoms, kurios gali būti grindžiamos esamais rezultatais, padedančiais geriau suprasti kranto dinamiką ir kurti veiksmingesnes kranto zonos valdymo strategijas.

Apskritai šiame darbe pateikti rezultatai turi tiek mokslinę, tiek praktinę reikšmę, nes padeda geriau pažinti Lietuvoje vykstančius krantodaros procesus ir kartu pateikia praktinių įžvalgų, kaip valdyti ir saugoti šią pažeidžiamą aplinką. Mokslinių tyrimų ir praktinio taikymo integracija pabrėžia tarpdisciplininių metodų svarbą sprendžiant sudėtingus aplinkosauginius iššūkius.

Rezultatų aprobavimas

Autorius pagrindinius šiame darbe aprašytus tyrimų rezultatus pristatė šiose nacionalinėse ir tarptautinėse konferencijose:

Žodiniai pranešimai:

Šakurova I., Kondrat V., Baltranaitė E., Kelpšaitė-Rimkienė L. 2021. Sandy beach evolution under the climate change and increasing anthropogenic pressure: eastern Baltic sea case. Smart urban coastal sustainability days 2021: Interdisciplinary approaches to the understanding of coastal systems. Online conference, 2021.

Šakurova I., Kondrat V., Baltranaitė E., Kelpšaitė-Rimkienė L. 2022. Estimation of longshore sediment transport: the case of Lithuania. EGU General Assembly 2022 (23–27 May 2022, Vienna, Austria, online).

Šakurova I., Kondrat V., Kelpšaitė–Rimkienė L. 2022. Assessment of underwater slope change on the Lithuanian coast. Lithuanian Academy of Sciences conference Biofuture: perspectives for nature and life sciences (24 November 2022, Vilnius, Lithuania).

Šakurova I., Kondrat V., Baltranaitė E., Vasiliauskienė E., Kelpšaitė–Rimkienė L. 2023. Jūros kranto kaitos vertinimas Lietuvos kranto zonoje. VII National Conference "GEOGRAPHIA JUVENTA" (28 March 2023, Vilnius, Lithuania).

Stendiniai pranešimai:

Šakurova I., Kondrat V., Kelpšaitė–Rimkienė L., Baltranaitė E., Soomere T. 2020. Changes in coastal lithodynamical processes of semi–enclosed seas under changing climate: the case of Lithuania. Eurolag9 (20–24 January 2020, Venice, Italy).

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TYRIMŲ MEDŽIAGA IR METODAI

Ši kaupiamoji disertacija parengta penkių mokslinių straipsnių, paskelbtų recenzuojamuose leidiniuose, pagrindu. Originalios publikacijos buvo paskelbtos doktorantūros tyrimų laikotarpiu ir pateikiamos disertacijos pabaigoje.

Tyrimų objektas

Šiame darbe siekiama pagerinti supratimą ir tiksliau apibūdinti pagrindinius Lietuvos Baltijos jūros (1 pav.) krantodaros procesus. I ir II straipsniuose yra analizuojamas maždaug 20 km ilgio kranto ruožas – 10 km į šiaurę ir pietus nuo Klaipėdos sąsiaurio, apimantis tiek Kuršių nerijos tiek žemyninio kranto ruožus. Ši atkarpa, apimanti beveik 1/4 Lietuvos Baltijos jūros kranto linijos, laikoma reprezentatyvia kranto raidos dinamikai, kurią lemia gamtinių veiksnių ir antropogeninės veiklos sąveika. III straipsnyje nagrinėjama nešmenų dinamika po taškinio paplūdimio papildymo smėliu. Tyrimas sufokusuotas į 5 km ilgio kranto atkarpą šiauriau Klaipėdos sąsiaurio, kur ir buvo vykdomas paplūdimio papildymas. IV ir V straipsniuose formuluojamos būsimos žinių dalijimosi platformos idėjos, kad anksčiau gauti tyrimų rezultatai būtų pritaikomi praktikoje skirtingais erdviniais masteliais.

Lietuvos kranto zona – tai siaura maždaug 90 km ilgio sausumos juosta besitiesianti palei rytinę Baltijos jūros pakrantę, kuriai būdingas įvairus smėlio paplūdimių, kopų, marių ir miškų kraštovaizdis. Kranto linija gana tiesi, o priekrantės sausuma nuolaidi – per keliasdešimt metrų į sausumą reljefo altitudės tesiekia tik kelis metrus virš jūros lygio (Bagdanavičiutė ir kt., 2012). Dėl to hidrometeorologinių veiksnių, formuojančių kranto liniją ir paplūdimius išilgai Lietuvos pakrantės, poveikis kinta lėtai.

Klaipėdos sąsiauris lietuviškąjį Baltijos jūros krantą skiria į dvi geomorfologiškai skirtingas dalis – žemyninį ir Kuršių nerijos (Bitinas ir kt., 2005). Todėl net esant beveik tolygiems erdviniams poveikiams, paplūdimių ir kitų kranto sistemos elementų reakcija žemyniniame ir Kuršių nerijos krantuose gali reikšmingai skirtis. Kuršių nerijos krantas yra akumuliacinė aplinka, kurią sudaro smėlinga nuosėdinė medžiaga (Bitinas ir kt., 2005). Priešingai, žemyninis krantas yra geomorfologiškai įvairus, jame paplitusios stambesnio smėlio, akmenuotos pakrantės ir skardžiai bei vyrauja eroziniai procesai (Bitinas ir kt., 2005, Bagdanavičiūtė ir kt., 2012). Šiaurinėje žemyninės pakrantės dalyje vyrauja smulkus smėlis (0,25–0,1 mm), pietinėje ir centrinėje – vidutinio rupumo (0,5–0,25 mm) ir stambus (1–2,5 mm) smėlis (Bitinas ir kt., 2005). Ši kranto zona yra svarbus ekologinis ir kultūrinis kraštovaizdis, palaikantis gausią augalų ir gyvūnų rūšių įvairovę bei vietos bendruomenes, kurių pragyvenimas priklauso nuo jūros (Inácio et al., 2022; Jurkus et al., 2021). Tai unikalus ir vertingas išteklius, kuriam būtinas atidus, tvarumą užtikrinantis valdymas (Baltranaitė ir kt., 2021; Inácio ir kt., 2022).

Lietuvos priekrantė visiškai atvira Baltijos jūros hidrometeorologiniams poveikiams. Tai sudėtinga ir dinamiška aplinka, kurią formuoja bangos, srovės ir orų sąlygos; jai būdingas palyginti švelnus bangų režimas (Björkqvist ir kt., 2018) ir dvi vidutinių bei stiprių vėjų sistemos (Soomere, 2003). Dažniausi pietvakarių vėjai, o retesni šiaurės vakarų ar šiaurės–šiaurės vakarų vėjai gali būti net stipresni.

Kranto sistema prisitaikiusi prie iš vakarų krypties atkeliaujančių bangų, kurių didžiausi aukščiai siekia ~0,9 m (vidutiniškai), tuo tarpu vidutiniai bangų aukščiai iš pietų – ~0,6 m, iš šiaurės – ~0,5 m, iš rytų – ~0,3 m (Jakimavičius ir kt., 2018; Kelpšaitė ir kt., 2008). Vyraujanti nešmenų pernaša išilgai Lietuvos jūros kranto vyksta iš pietų į šiaurę, su keliais laikinais vyraujančios pernašos krypties pokyčiais metų eigoje (Viška ir Soomere, 2013). Atitinkamai skirtingos pakrantės atkarpos, abipus Klaipėdos sąsiaurio, į poveikį reaguoja skirtingai: Kuršių nerijos krantai į pietus nuo

Klaipėdos paprastai yra stabilūs (Bitinas ir kt., 2005), o žemyninėje pakrantės dalyje dažniau vyrauja erozija (Bitinas ir kt., 2005; Viška ir Soomere, 2013).

Siekdama išsaugoti paplūdimius, Lietuva dažnai taiko paplūdimių papildymą nešmenimis – efektyvią erozijos mažinimo priemonę. Pavyzdžiui, Palangoje papildymas buvo naudotas paplūdimiui praplatinti ir rekreacinei erdvei didinti (Kelpšaitė-Rimkienė ir kt., 2021; Pupienis ir kt., 2014). Vis dėlto ši priemonė pirmą kartą pritaikyta ir Klaipėdos uosto molų poveikio zonoje; III straipsnyje šis atvejis detaliai analizuojamas, siekiant nustatyti, kaip hidrodinaminiai veiksniai iškart po papildymo perklosto nešmenis.

Klaipėdos uostas – didžiausias ir intensyviausias Lietuvoje (Žilinskas ir kt., 2020), svarbus tarptautinės prekybos ir logistikos mazgas Baltijos šalims ir platesniam regionui (Inácio ir kt., 2022). Jo molai siekia didesnius nei efektyvus bangų poveikio gylis (~6 m) šioje akvatorijoje (Soomere ir kt., 2017), todėl beveik visiškai sustabdo bangų varomą išilginę nešmenų pernašą. Dėl šių masyvių statinių, statmenų nešmenų srauto krypčiai, susidaro nešmenų deficitas. Todėl kranto papildymas nešmenimis yra efektyvus būdas atkurti nešmenų balansą molų šiaurinėje pusėje.

Skersinio profilio ir kranto linijos raida

Tyrimo teritorijoje (I ir II straipsniai) esantys kranto profiliai buvo matuojami nuo kranto linijos iki apsauginio kopagūbrio viršaus, iš viso buvo išskirti 40 profilių intervalais kas 500 metrų. Kranto profiliavimas buvo atliekamas naudojant Emlid Reach RS+ RTK GNSS imtuvą (kuris užtikrina duomenis centimetro tikslumu), ir dviejų dažnių GPS imtuvą Leica 900 (1 lentelė). Lauko darbams planuoti ir palyginamumui užtikrinti profiliai buvo parinkti ir suderinti taip, kad jų erdvinė padėtis ir orientacija atitiktų Lietuvos geologijos tarnybos 1993–2022 metų kranto profilių duomenis (1 lentelė). Surinkti profilių duomenys buvo naudojami nešmenų tūriui krante apskaičiuoti, taikant lygtį (Guillot et al., 2018) (I ir III straipsniai):

$$v_1 = \frac{\sum_{p=1}^{n}(SI)}{L}\,, \tag{1}$$

kur p yra kranto profilio eilės numeris, n – bendras tokių profilių skaičius atitinkamame kranto segmente, S – paviršiaus aukštis, I – interpoliacija tarp dviejų gretimų profilių, o L – atstumas tarp profilių, naudojamas pokyčių įverčiams normalizuoti taip, kad (1) lygties rezultatas būtų išreikštas tūrio pokyčiais m^3/m (t. y. vienam kranto linijos metrui).

Kranto linijos padėtis 1993–2022 m. buvo nustatyta naudojant aerofotonuotraukų žemėlapius, ortofotografijas ir tiesioginius GPS matavimų duomenis (1 lentelė). Kranto linijos padėtis, bangų plūsmo zonoje, matuota dviejų dažnių Leica 900 GPS imtuvu. Kranto linijos padėties pokyčiai buvo analizuojami naudojant skaitmeninę kranto linijos analizės sistemą (DSAS) v. 5.0 (Himmelstoss et al., 2018), ArcGIS (Esri, 2023) plėtinį, kurį sukūrė Jungtinių Valstijų geologijos tarnyba (USGS). Pokyčiams fiksuoti buvo pasirinkta 800 transektų kas 25 metrus. Ilgalaikių kranto linijos pokyčių analizė parodė, kad procesai, susiję su kranto linijos formavimusi suintensyvėjo dėl antropogeninio, uosto rekonstrukcijos, poveikio.

Norint įvertinti kranto linijos pokyčius (II straipsnis), naudojant skirtingų šaltinių ir laikotarpių duomenis (1 lentelė), buvo apskaičiuotos trijų tipų paklaidos, susijusios su kranto linijos aptikimu ir padėties nustatymu (Crowell et al., 1993):

4) aerofotografinėms diagramoms

$$U_t = \sqrt{E_s^2 + E_d^2 + E_p^2 + E_{tc}^2 + E_c^2}\ , \tag{2}$$

5) ortofotografinėms nuotraukoms

$$U_t = \sqrt{E_s^2 + E_d^2 + E_p^2 + E_r^2 + E_c^2}\ , \tag{3}$$

6) GPS tyrimo duomenims

$$U_t = \sqrt{E_s^2 + E_c^2}\ , \tag{4}$$

kur E_s – jūros lygio svyravimo paklaida, E_d – skaitmeninimo paklaida, E_p – pikselių paklaida, E_c – kranto linijos aptikimo/skiriamosios gebos paklaida, E_{tc} – T–lapų braižymo paklaidos, o E_r – ištaisymo paklaida.

Nuosėdinės medžiagos ėminių analizė

Istoriniai nuosėdinės medžiagos granuliometriniai duomenys 1993–2003 m. gauti iš Lietuvos geologijos tarnybos (Bitinas ir kt., 2004) (1 lentelė). 2003–2019 m. (1 lent.) ėminiai buvo rinkti Klaipėdos universiteto Geofizinių mokslų katedros komandos, o 2019–2022 m. – I straipsnio autorių, vadovaujantis Lietuvos geologijos tarnybos metodika, kiekvieno skersinio kranto profilio trijuose vietose: dinamiškoje kranto linijoje (bangų plūsmo zonoje), paplūdimio viduryje ir ties apsauginiu kopagūbriu. Tada šie mėginiai laboratorijoje buvo apdorojami naudojant 19 sietų rinkinį su tokio dydžio frakcijomis: >2500 μm; 2500–2000 μm; 2000–1600 μm; 1600–1250 μm; 1250–1000 μm; 1000–800 μm; 800–630 μm; 630–500 μm; 500–400 μm; 400–315 μm; 315–250 μm; 250–200 μm; 200–160 μm; 160–125 μm; 125–100 μm; 100–80 μm; 80–63 μm; 63–50 μm; <50 μm. Rezultatai buvo analizuojami naudojant GRADISTAT papildinį, skirtą MS Excel (Blott and Pye, 2001), kuriame naudojamos Udden (Udden, 1914) ir Wentworth (Wentworth, 1922) nuosėdinės medžiagos dydžio klasifikavimo skalės, siekiant nustatyti smėlio grūdelių dydžio pasiskirstymą krante.

Šiame darbe kartu su Lietuvos geologijos tarnybos pateikta klasifikacija buvo naudojami istoriniai smėlio granulometriniai duomenys iki 2003 m., o Uddeno (1914 m.) ir Wentwortho (1922 m.) pagrindu sukurta klasifikacija buvo naudojama nuo 2004 m. (I straipsnis). Siekiant užtikrinti šių dviejų klasifikacijų duomenų vientisumą ir palyginamumą, buvo atliktas koregavimas, kad būtų suderinta su šiomis smėlio dydžio frakcijomis: 2500–2000 μm: labai smulkus žvyras; 2000–1000 μm: labai šiurkštus smėlis; 1000–500 μm: šiurkštus smėlis; 500–250 μm: vidutinis smėlis; 250–100 μm: smulkus smėlis; 100–50 μm: labai smulkus smėlis; <50 μm: dumblas.

Batimetriniai duomenys

1993–2022 m. batimetriniai duomenys gauti iš trijų šaltinių. (i) Klaipėdos valstybinio jūrų uosto administracijos priekrantės uosto įplaukos kanalo zonoje batimetriniai matavimai su 0,5 m raiška, tęsiasi ~5 km į šiaurę ir pietus nuo molų. (ii) Lietuvos geologijos tarnybos visos Lietuvos priekrantės batimetrija su 1,5 m raiška (1 lentelė) (I straipsnis). Abu šie duomenų rinkiniai buvo surinkti naudojant Kongsbergo EM2040C daugiaspindulinį echolotą pagal Tarptautinės hidrografijos organizacijos hidrografinių tyrimų standartą IHO S–44 (I, III straipsniai). Gylio duomenys buvo apdorojami naudojant Hypack Max (HYSWEEP), specializuotą hidrografinių duomenų įrašymo ir apdorojimo programinę įrangą. (iii) Trečias batimetrijos duomenų masyvas buvo rinktas 2022 m. birželio 24 d., prieš paplūdimio papildymą, į šiaurę nuo Klaipėdos sąsiaurio, ir 2022 m. spalio 01 d., praėjus keliems mėnesiams po papildymo darbų (III straipsnis), naudojant 3 dažnių „Deeper“ sonarą. Gyliai (z) matuoti 10 skersinių transektų kas 500 m, nuo kranto linijos iki ~6 m gylio, apimant ~5 km ilgio ruožą į šiaurę nuo šiaurinio molo, tęsiant antžeminės dalies skersinius kranto profilius. Visų rinkinių paklaidos – kelios centimetro dalys.

Siekiant pavaizduoti tiriamo paviršiaus morfologiją, „Global Mapper 2022“ (Marbel, 2019) aplinkoje buvo sukurtas netaisyklingas trikampių tinklas (TIN), naudojant duomenis iš taškinio debesies duomenų rinkinio (III straipsnis). Taip pat buvo sukurtas skaitmeninis aukščio modelis (DEM) (Hell, 2011; James et al., 2012) skirtas batimetriniam paviršiui sudaryti ir nuosėdų tūrių pokyčiams įvertinti, lyginant skirtingų datų paviršių gardeles. „Global Mapper 2022“ programoje pasirinktas *Path* profilio įrankis (Marbel, 2019), sugeneravo analizuojamo paviršiaus skerspjūvį, kad būtų galima tiksliau įvertinti tiriamos teritorijos batimetrines savybes ir gylio pokyčius. Z altitudės pokyčiai buvo apskaičiuoti 114 profilių suskirstytų kas 25 m palei tiriamą priekrantės ruožą. Bendras nešmenų pernašos intensyvumas priekrantės ilgio vienetui tam tikroje skersinio profilio vietoje tarp bet kurių dviejų laiko momentų () apskaičiuojamas taip (Baldock et al., 2011, 2010):

$$Q(x_n) = Q(x_{n-1}) - \int_{x_{n-1}}^{x_n} (1-p)\frac{\Delta z_b}{\Delta t}\,dx, \tag{5}$$

kur $Q(x_n)$ yra bendras nešmenų pernašos tūris (m^2/s) taške n, z_b – gylio (altitudės) skirtumas tarp gretimų matavimo intervalų (mm).

Bendras nešmenų perneštas tūris $\hat{Q}$ tarp dviejų laiko momentų buvo apskaičiuotas integruojant vietinį transportuojamą tūrį visame profilyje:

$$\hat{Q} = \Delta t \int_{x_{min}}^{x_{max}} Q(x)\,dx. \tag{6}$$

$\hat{Q}$ parodo nešmenų kiekį, tam tikrame profilyje, pernešta arba kranto link (teigiamos vertės), arba įjūrin (neigiamos vertės). Šis dydis buvo naudotas bendrai paplūdimio būsenai klasifikuoti kaip eroduojama $\hat{Q} < 0$, akreacinė $\left(\hat{Q} > 0\right)$, ar stabili $\left(\hat{Q} \approx 0\right)$, Alternatyvus (normalizuotas) parametras, kuriuo atsižvelgiama į paplūdimio ar paplūdimio segmento plotį tam tikroje vietoje, yra $\hat{Q}/(x_{max} - x_{min})$ kur $x_{max} - x_{min}$ yra aktyvaus paplūdimio profilio plotis. Šis kiekis rodo vidutinį nešmenų tūrį, pernešta per profilio ilgio vienetą.

Efektyvus bangų poveikio gylis (angl. Depth of Closure) h_c reiškia jūros link esančią profilio kintamumo ribą ilguoju laikotarpiu (sezoniniai arba daugiamečiai). Hallermeier (1978, 1981) sukūrė pirmąjį bangų poveikio gylio įvertinimo metodą, pagrįstą lauko ir laboratoriniais tyrimais. Hallermeier (1981) šį gylį apibrėžė kaip slenkstį, žemiau kurio bangos sistemiškai nebeformuoja jūros dugno ir paprastai nesukelia sistemingo nuosėdų judėjimo. Jo bangų poveikio gylio vertinimas buvo paremtas intensyviausių bangų parametrais, tokiais kaip reikšmingas bangų aukštis H_e ir periodas T_e. Reikšmingas bangų aukštis H_e apibrėžia bangų aukštį, kuris buvo viršytas tik 12 val.

per metus, arba 0,14 % laiko, ir juos atitinkantis reikšmingas bangų periodas T_e. Ši lygtis apytiksliai nurodo efektyvų bangų poveikio gylį:

$$h_c = 2.28H_e - 68.5\left(\frac{H_e^2}{gT_\mathrm{e}^2}\right). \tag{7}$$

Skaičiavimams atlikti buvo taikytos šios aproksimacijos:

$$H_e = \overline{H} + 5.6\sigma_H \ , \tag{8}$$

$$h_c = 2\overline{H} + 11\sigma_H \ , \tag{9}$$

kur $g \approx 9{,}81$ m/s² – pagreitis dėl sunkio jėgos, $\overline{H}$ – metinis vidutinis kontrolinis aukštis, o σH – metinis bangos aukščio standartinis nuokrypis. Be to, $hc = 1{,}57\ He$ pateikia pirmąją efektyvaus bangų poveikio gylio aproksimaciją (Soomere ir kt., 2017) (III straipsnis).

Hidrometeorologiniai duomenys

Hidrometeorologiniai duomenys, įskaitant vidutinį vėjo greitį (m/s) ir kryptį (º) nuo 1993 iki 2021 m., taip pat vidutinį bangų aukštį (m) ir bangų sklidimo kryptį (º) nuo 1993 iki 2019 m., buvo panaudoti I straipsnyje ir apdoroti naudojant "Origin Pro 2021" programinę įrangą statistinei analizei ir vizualizavimui. Šie duomenų rinkiniai buvo gauti iš kelių institucijų: Aplinkos apsaugos agentūros (AAA) Jūros aplinkos vertinimo skyriaus, Lietuvos hidrometeorologijos tarnybos prie Aplinkos ministerijos, Palangos aviacijos meteorologijos stoties ir Klaipėdos uosto administracijos (1 lentelė).

1960–2019 m. meteorologiniai duomenys (vidutinis vėjo greitis ir kryptis) buvo analizuojami siekiant nustatyti vėjo savybių režimo pokyčius, daugiausia dėmesio skiriant vėjo kryptims II straipsnyje. Meteorologiniai duomenys gauti iš Aplinkos apsaugos agentūros (AAA) Jūros aplinkos vertinimo skyriaus ir iš Lietuvos hidrometeorologijos tarnybos prie Aplinkos ministerijos. Siekiant nustatyti režimo pokyčius analizuojamose laiko eilutėse, buvo taikomas STAR (nuoseklios t–testo režimo poslinkių analizės) algoritmas (https:// www.beringclimate.noaa.gov/, žiūrėta 2021 m. spalio 10 d.). Algoritmas buvo pagrįstas nuosekliu t–testu, kuris gali signalizuoti apie realaus laiko režimo pasikeitimo galimybę (Rodionovas, 2004). Algoritmas gali apdoroti duomenis nepriklausomai nuo to, ar jie pateikiami anomalijose (nukrypimai nuo vidurkio), ar kaip neapdorotos laiko eilutės. Jis gali automatiškai apskaičiuoti režimo pokyčius dideliuose kintamųjų rinkiniuose (Rodionov ir Overland, 2005; Rodionovas, 2004). Šiame tyrime buvo naudojamas toks įvesties parametrų rinkinys: ribinis ilgis (I) buvo nustatytas 10 metų, o Huberto parametras (HWP) – 1. HWP nustato išskirtinių reikšmių reikšmingumą apskaičiuojant režimo pokyčio vidutines reikšmes.

2022 m. hidrometeorologiniai duomenys (vėjo greičio (m/s) ir krypties (º), vandens lygio (cm) ir bangų aukščio (m) duomenys) gauti iš Aplinkos apsaugos agentūros (AAA) Jūrų aplinkos vertinimo skyriaus ir Lietuvos hidrometeorologijos tarnybos prie Aplinkos ministerijos (III straipsnis).

TYRIMŲ REZULTATAI IR JŲ APTARIMAS

Pateiktą informaciją sudaro svarbiausi rezultatų fragmentai ir diskusija išvadoms pagrįsti. Ją apima penki į disertaciją įtraukti moksliniai straipsniai.

Viename iš tyrimų buvo analizuojami duomenys apie jūros kranto geomorfologijos raidą Lietuvoje, esant bendrai antropogeninio poveikio (jūrų uosto veiklos) bei gamtinių veiksnių, tokių kaip hidrometeorologinių sąlygų pokyčiai, įtakai (I straipsnis). Kranto erozija žemyninėje tyrimo teritorijos dalyje yra susijusi su vietinėmis hidrodinaminėmis sąlygomis ir hidrotechniniais statiniais, daugiausia jūrų uosto molais. Nešmenų transporto dėsningumams Kuršių nerijoje ir Lietuvos žemyninėje kranto dalyje įtakos turi kampinis vėjų pasiskirstymas, kai kranto linijos padėtis yra į šiaurę palei Kuršių neriją ir Lietuvos žemyninį krantą. Šis nešmenų transporto dėsningumas veikia nešmenų biudžeto pasiskirstymą į šiaurę nuo Klaipėdos (2 pav.).

Siekdamas suvaldyti erozijos paveiktus krantus, Klaipėdos uostas 2014–2018 m. inicijavo paplūdimių maitinimo akciją, kurios metu Melnragės ir Girulių priekrantėse buvo išpilta 237,78 × 10^3 m^3 smėlio. Smėlio granulometrinis pasiskirstymas yra natūralus nešmenų transportavimo proceso rezultatas, daugiausia susijęs su erozijos ir akumuliacijos poveikiu. 2003–2022 m. tiriamuoju laikotarpiu žemyninės kranto dalies smėlio frakcijų dydis tapo šiek tiek smulkesnis ir tolygiai pasiskirstęs (3 pav.), galimai dėl Klaipėdos uosto direkcijos atliktų paplūdimių papildymo darbų. Nepaisant to, per tą laiką Kuršių nerijos krante aptikta stambesnės frakcijos nuosėdinė medžiaga.

Pasikeitus hidrometeorologinėms sąlygoms (4 pav.; II straipsnis), gali pasikeisti vyraujanti nešmenų pernešimo kryptis ir tūris, o tai lemtų pokytį erozijos ir akumuliacijos procesuose. Tyrimo laikotarpiu vėjo greičio dažnių pasiskirstymas atskleidė dažnesnį vėjo greičio pasireiškimą 2–4 m/s ir 4–6 m/s intervaluose (I straipsnis). Šios vėjo sąlygos turi vienodą ar didesnį poveikį hidrodinaminiams procesams, lemiantiems kranto vystymąsi ir geomorfologiją. Mažesnis vėjo greitis nuolat veikia krantą, todėl kranto regeneracijos procesas yra lėtesnis, kaip aprašyta Eelsalu ir kt., 2022 darbe.

Šio tyrimo išvados atitinka ankstesnius kranto linijos pokyčių ir nešmenų dinamikos tyrimus (II straipsnis). Morfologiniai smėlio paplūdimio pokyčiai vyksta greitai laiko ir erdvės skalėje, kaip atsakas į natūralius procesus, tokius kaip vėjo kryptis ar greitis, bangų režimas ir jūros lygio svyravimai. Baltijos jūroje klimato kaitą galima pastebėti vyraujančio vėjo ir bangų režimo pokyčiais, kurie gali pakeisti priekrantės nešmenų pernašos dydį ir dominuojančią kryptį (Soomere et al., 2015). Vėjo krypties pokyčiai stebimi nuo 1992 m., o antrasis poslinkis pastebėtas 2012 m. siejami su kranto procesų ir evoliucijos pokyčiais.

Vėjo krypties pokyčiai (4 pav.) sutampa su kranto erozija tiek Kuršių nerijoje, tiek žemyninėje dalyje (II straipsnis). XIX a. kranto linija daugiausia slinkosi jūros link tiek Kuršių nerijoje, tiek žemyninėje dalyje. 1990–1995 m. erozijos greitis tiriamame kranto ruože buvo 4,57 ± 0,09 m/m, o 2015–2019 m. – 4,24 ± 0,12 m/metus.

Nustatytos tendencijos ir dėsningumai yra labai svarbūs siekiant įgyvendinti tvarų kranto zonos valdymą. 2022 m. birželio 29 d. prasidėjo Klaipėdos sąsiaurio gilinimo darbai. Pirmiausia buvo nustatyta, ar iškasta medžiaga atitinka fizinių ir cheminių savybių reikalavimus (Filipkowska et al., 2011; Staniszewska ir Boniecka, 2017) ir po to išpilta netoli šiaurinio molo. Apie 120 m nuo kranto, kur gylis prieš papildymą siekė 2–3,5 m, buvo išpilta apie 180 000 m^3 reikalavimus atitinkančio smėlio, kad būtų suformuotas 700–750 m ilgio povandeninis sėklius (https://portofklaipeda.lt/naujienos/smelingam–i–melnrages–papludimiui–povandeninis– pylimas/, žiūrėta 2024 m. birželio 14 d.). Smėlio papildymo ir tolesnių kranto erozijos valdymo procesų efektyvumas Lietuvos Baltijos jūroje nagrinėtas III straipsnyje. Išvadose pabrėžiami keli kritiniai nešmenų dinamikos po papildymo darbų aspektai. Papildytas smėlis pasižymėjo dideliu perskirstymu net ir esant vidutinėms bangoms. Konkrečiai, apie 1 profilį buvo perklostyta apie 10 000 m^3 nešmenų, o apie 2 profilį – apie 5 000 m^3 (5 pav.). Šis greitas nešmenų perklostymas įvyko vos per šešias savaites, esant daug švelnesnėms nei vidutinės bangų sąlygoms. Šis netikėtas atradimas pabrėžia dinamišką nešmenų pernašos pobūdį tyrimo teritorijoje ir kranto valdymo iššūkius. Nešmenų pernešimo išilgai kranto kryptis buvo labai įvairi. Stebėtas transportas daugiausia buvo į pietus netoli 1 profilio ir į šiaurę netoli 2 profilio (5 ir 6 pav.). Tikėtina, kad šį kintamumą lemia Klaipėdos uosto molo artumas, kuris veikia vietinę hidrodinamiką, apsaugodamos piečiausią paplūdimio dalį nuo pietvakarių bangų. Toks kintamumas apsunkina prognozes ir reikalauja adaptyvių valdymo strategijų, kad būtų atsižvelgta į konkrečias vietos sąlygas.

Nešmenų perklostymo diapazonas buvo palyginti ribotas, 3, 4 ir 5 profiliuose didesniais atstumais nuo papildyto paplūdimio buvo pastebėtas nedidelis poveikis arba jo visai nebuvo (5 ir 6 pav.). Šis ribotas diapazonas rodo, kad papildymo poveikis yra labai lokalus ir priklauso nuo bangų krypties, šiuo atveju dominavo vakarų kryptis, ir hidrotechninių statinių buvimo. Šis lokalus poveikis rodo, kad nors papildymas gali būti veiksmingas tikslinėse vietovėse, platesnė jo įtaka gali būti ribota.

Tyrimas atskleidė būdingus nešmenų pernašos raidos dėsningumus: smėlio pernašą jūros kryptimi tose profilių vietose, kur atliktas papildymas, ir erozijos jūros link bei sausumos krypties pernašos derinį kitose vietose. Šie dėsningumai rodo, kad prireiks daugiau nei kelių savaičių, kol profiliai pasieks pusiausvyrą po papildymo.

Tiriamuoju laikotarpiu buvo pastebėtas žymus santykinai žemo jūros lygio įvykis, ypač nuo 2022 m. rugsėjo 6 d. iki rugsėjo 11 d. (7 pav.). Šis jūros lygio kritimas ir vyraujantys pietryčiu ir pietvakarių vėjai reikšmingai paveikė nešmenų perklostymą, nes net nedidelės bangos pasiekė išpiltą smėlį tose vietose, kurias veikia tik aukštesnės ar ilgesnės bangos, esant vidutiniam vandens lygiui (Eelsalu et al., 2022). Didžioji dalis nešmenų pernešimo pagal vėją ir jūros lygį, tyrimo metu įvyko skersine kranto kryptimi, o papildymo poveikis išilgai kranto buvo gana ribotas. Rezultatai rodo, kad išsamūs matavimai yra būtini norint suprasti platesnį papildymo poveikį tolimesniems kranto segmentams ir atitinkamai patobulinti valdymo strategijas. Tokie moksliniai tyrimai suteiktų holistinį supratimą apie paplūdimio papildymo poveikį ir pagerintų kranto zonos valdymo praktiką. Apskritai tyrime pabrėžiama, kad nors paplūdimių papildymas gali būti vertinga kranto erozijos valdymo priemonė, jo sėkmė priklauso nuo kruopštaus vietos sąlygų įvertinimo, nuolatinės stebėsenos ir pritaikomo valdymo, siekiant spręsti dinamiško jūros kranto aplinkos pobūdžio problemas.

Surinkti duomenys ir įgyvendinti moksliniai tyrimai paskatino sukurti sistemos architektūrą, kuri padėtų užpildyti žinių spragas, sukurtų dalijimosi žiniomis platformą ir nustatytų ribas, kurios galėtų apriboti veiklą arba pakeisti trumpalaikių ir ilgalaikių strategijų eigą (IV ir V straipsniai). Kadangi vien hidrometeorologiniai duomenys negali paaiškinti dabartinių pokyčių, reikalingas holistinis požiūris ir modeliavimas, siekiant užtikrinti, kad Klaipėdos kranto zonoje veiklą vykdantys asmenys būtų gerai informuoti apie kranto ir pakrančių dinamikos priežastingumą. EASTMOC sistemos kūrimas yra šio bendradarbiavimo rezultatas, kai suinteresuotosios šalys yra iniciatoriai.

Baltijos jūroje vis dar egzistuoja žinių spraga, susijusi su nešmenų pernaša išilgai ir skersai kranto. Šiai sričiai reikalingas mokslinių tyrimų finansavimas ir techniniai sprendimai. Darbo metu buvo atliktas bandomasis tyrimas su dešimčia atrinktų suinteresuotų šalių, tarp jų – Klaipėdos uosto direkcija, AB "Smiltynės perkėla", Lietuvos transporto saugos administracija. Svarbiausi duomenys apie gamtinius veiksnius, naudojami jų kasdienėje veikloje ir ateities planuose, buvo šie: paplūdimio plotis, povandeninio šlaito nuolydis, kranto linijos padėtis, reikšmingas bangų aukštis ir kryptis, vėjo greitis ir kryptis, srovės greitis ir kryptis, ledo danga ir matomumas. Nustatytos kritinės žinių spragos: priekrantės batimetrija, upių ir Kuršių marių hidrologiniai duomenys, lengva prieiga prie realaus laiko hidrometeorologinių duomenų. Suinteresuotųjų šalių veikla priklauso nuo įvairių kintamųjų ir jų veiklos pobūdžio bei masto. Pavyzdžiui, mažųjų laivų laivyba gali būti ribojama, kai vėjo greitis siekia 7 m/s, o bangos aukštis viršija 1,5 metro. Tad kuriama žinių dalijimosi platforma padėtų suinteresuotoms šalims nusistatyti jų veiklai pritaikytas ribas, taip pagerinant veiklos planavimą ir efektyvinant darbo našumą.

Kranto linijos padėtis yra dažniausiai naudojamas rodiklis, vertinant kranto erozijos ar akumuliacijos procesus (Bagdanavičiutė et al., 2012) ir yra svarbus ilgalaikiam planavimui. 1993–2022 m. kranto linijos judėjimo analizė atskleidė, kad 39 % kranto linijos patyrė eroziją, 34 % – akumuliaciją, o 26,5 % – išliko stabili ±5,02 m neapibrėžtumo ribose (8 pav.). Palyginus kranto linijos pokyčius 1993–2003 m. ir 2003–2022 m. laikotarpiais, nustatyta, kad eroduotos pakrantės teritorijos ilgis padidėjo 4,4 karto – nuo 2,73 km iki 11,90 km. Pažymėtina, kad didelė kranto erozija, iki 51,95 m, buvo pastebėta kranto segmente į šiaurę nuo Klaipėdos uosto molų (8 pav.). Tokia analizė galėtų pasiekti plačiąją suinteresuotų šalių ir vietos bendruomenių auditoriją, kai tik ji bus įtraukta į siūlomą sistemą. Surinkti duomenys patvirtina, kad reikia laiku dalytis žiniomis. Padaryta išvada, kad, nors galima aptarnauti atrinktas suinteresuotąsias šalis ir teikti stebėjimo duomenis bei asmeniniams poreikiams pritaikytus įspėjimus, duomenų rinkinius reikia nuolat atnaujinti. Norint paremti tyrimo idėją, reikalinga automatizuota sistema ir savalaikis duomenų įvedimas. EASTMOC sistema siekiama sukurti ryšį tarp ilgalaikių ir trumpalaikių stebėjimo ir monitoringo duomenų suinteresuotosioms šalims (vėjo greitis ir kryptis, bangų kryptis ir reikšmingas aukštis, vandens ir oro temperatūra, atmosferos slėgis, nešmenų dydis ir pasiskirstymas, kranto linijos padėtis, paplūdimio plotis, paplūdimio apsaugos priemonių pasikeitimas). Taigi, sisteminio mąstymo ir integruotų modeliavimo metodų taikymas gali reikšmingai pagerinti mūsų supratimą apie sudėtingas sistemas ir padėti kurti veiksmingesnes bei tvaresnes jų valdymo strategijas.

IŠVADOS IR REKOMENDACIJOS

1. Batimetriniai duomenys ir kranto profiliai buvo naudojami apskaičiuojant jūros gylio pokyčius ir nuosėdų tūrio pokyčius. Po Klaipėdos uosto rekonstrukcijos nuosėdinės medžiagos nuostoliai Kuršių nerijoje ir žemyninėje Lietuvos kranto dalyje padidėjo. Apskaičiuotas bendras nuosėdinės medžiagos nuostolis siekė apie 1,5 milijono m^3. Kuršių nerijos kranto dalyje nuosėdinės medžiagos praradimo greitis sumažėjo, o tai rodo, kad hidrotechninės struktūros daro įtaką nešmenų srautui priekrantėje. Šį procesą lydėjo povandeninių kranto profilių dalies statėjimas ties Klaipėdos uosto molais. Tai reiškia, kad krantą pasiekia didesnės energijos bangos. Rekreacinė veikla kranto zonoje nėra tiesiogiai paveikta šių pokyčių, kol išlieka smėlio paplūdimys. Tyrime pabrėžiamas poreikis stebėti nešmenų dinamiką, kad būtų galima taikyti specializuotus kranto zonos valdymo metodus.
2. Šiaurinėje jūros kranto dalyje pastebima intensyvesnė erozija, o eroduojamas kranto ilgis padidėjo tris kartus. Trumpalaikiai kranto linijos pokyčiai yra susiję su vėjo krypties pasikeitimais ir dugno gilinimo darbų poveikiu. Tyrimas taip pat atskleidė žemyninio kranto ruožą, kuriame vyrauja kiti požymiai, tokie kaip akumuliacija.
3. Rezultatai rodo, kad išsamūs matavimai yra būtini norint suprasti platesnį papildymo poveikį atokesniems kranto segmentams ir atitinkamai patikslinti valdymo strategijas. Tokie moksliniai tyrimai leistų visapusiškiau suprasti paplūdimio papildymo poveikį ir pagerintų kranto valdymo praktiką. Apskritai tyrime pabrėžiama, kad nors paplūdimių stiprinimas gali būti vertinga kranto erozijos valdymo priemonė, papildymo sėkmė priklauso nuo kruopštaus vietos sąlygų įvertinimo, nuolatinės stebėsenos ir adaptyvaus valdymo, siekiant spręsti dinamiško kranto aplinkos pobūdžio problemas.
4. Bandomasis tyrimas ir nustatytos ribos atskleidė, kad būtina sukurti žinių dalijimosi apie aplinką sistemą. Suinteresuotųjų šalių pastangos taip pat išryškino kranto zonos bruožus ir ypatybes, kurias reikia atidžiau stebėti. Jų dalyvavimas užtikrina, kad būtų įmanoma sukurti veikiančią sistemą. Aplinkosaugos pranešimų sistemos kūrimas leido tyrimų grupei suvokti skirtumus tarp abiejų tiriamojo regiono pusių. Be skirtingos geomorfologijos, abu regionai taip pat turi skirtingus prieigos taškus, socialines ir ekonomines vertes bei paskirtis. Todėl kiekvienam jų vertinimui sistemoje turėtų būti naudojamas skirtingas duomenų rinkinys.

8

Gyvenimo aprašymas

Disertacinio darbo autorė Ilona Šakurova gimė 1994 metų vasario 24 dieną. 2012 metais baigė Visagino technologijos ir verslo profesinio mokymo centrą. 2013 metais baigė Visagino technologijos ir verslo profesinio mokymo centrą (dabar Visaginas TECH) ir įgijo Kompiuterių derintojo kvalifikaciją. 2013 metais įstojo į Klaipėdos universiteto Gamtos ir matematikos mokslų fakulteto (dabar Jūros technologijų ir gamtos mokslų fakultetas) Hidrologijos ir okeanografijos (dabar Gamtinės geografijos ir okeanografijos) bakalauro studijų programą. Bakalauro studijas baigė 2017 metais, apgynusi baigiamąjį darbą „Izostazinių vandens lygio pokyčių modeliavimas pietrytinėje Baltijos jūroje“. Studijas tęsė Klaipėdos universitete Ekologijos ir aplinkotyros (dabar Tvaraus vandens ekosistemų valdymo) magistratūros studijų programoje. 2019 metais apgynė magistro darbą „Modeling of eutrophication processes in the Curonian lagoon“. 2019 metais įstojo į gamtos mokslų srities fizinės geografijos mokslo krypties doktorantūros studijas Klaipėdos universitete.

Publications

PAPER I

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Assessment of Coastal Morphology on the South-Eastern Baltic Sea Coast: The Case of Lithuania

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Abstract: The Port of Klaipėda, located at the Klaipėda strait, divides the Lithuanian coast into two different geomorphological parts: southern—the coast of the Curonian Spit, and northern—the mainland coast. Port jetties interrupt the main sediment transport path along the South-Eastern Baltic Sea's coast. Port of Klaipėda reconstruction in 2002 and the beach nourishment project which started in 2014 significantly influenced the northern part of the coast, which led to changes in the coastal zone evolution. The measurements in various periods are essential for cross-shore profile elevation to analyze seabed morphology and sedimentation patterns. These data highlight our understanding of the scale and timing of seabed erosion or sedimentation processes scale and timing. This study evaluates the impact of anthropogenic pressure and natural factors on coastal geomorphology and dynamics. In order to assess the latter changes, the cross-shore profile evolution and sediment budget were analyzed as well as nearshore bathymetry changes. The data illustrated a changing picture of the entire shore profile—on land and underwater.

Keywords: sediment volume; bathymetry; cross-shore profile; Baltic Sea

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1. Introduction

The unique relief of the Baltic Sea coast is and has always been formed by two main natural elements—the sea and the wind. Therefore, most coastal relief forms are related to their geological activity [1–3]. Depending on the sea level, wave parameters, underwater currents, and several other natural and often anthropogenic factors are forming wider and/or narrower beaches [1,2]. The litho- and morpho-dynamics processes play an important role in the shore formation mechanism. On land, they are mainly determined by aeolian processes, while at sea and on the beach, by hydrodynamic processes [2–4].

The coastal zone is under constant change and environmental pressure from various natural processes (sea level rise, increased storminess, shifting hydrometeorological conditions) and anthropogenic activities (port activities, dredging, coastal protective measures, coastal tourism) [5]. At the end of the 20th century, the anthropogenic impact became an independent geological factor affecting many coast formation processes [2,6]. Changes in the Lithuanian coastal area are related to human activity and natural factors [2,7]. Stronger storms, more intensive sand discharge from the coastal zone, rising global sea levels, development and dredging of the port area, and expansion of the recreational zone are the most common factors that are considered to mitigate the pressure affecting the coastal zone nowadays [2,7,8].

Aside from the natural factors and the various human activities to consider, a vast institutional framework and a set of national policies are in place to be satisfied in accordance with the major world climate action agreements: the Paris Agreement under the 1992 United Nations Framework Convention on Climate Change (UN-FCCC), the UN agreements on Disaster Risk Reduction (Sendai) and Finance for Development (Addis Ababa), and the Sustainable Development Goals (SDGs). Therefore, a holistic approach, coordinated policies, and cross-sector planning are crucial to ensure sustainable territory management and avoid or reduce trade-offs between mitigation and adaptation to climate change [9].

The characteristics of coastal morphodynamic processes—the interaction between bathymetry (topography) and hydrodynamics—largely determine the volume distribution during sediment transport [5]. Sediment budget and geology determine the morphology and dynamics of coasts, which affects the nature and health of coastal systems [10,11]. Human activities affecting sediment dynamics along the coast and inland can alter naturally occurring patterns of erosion and accumulation [10,11]. Of the various beach types around the world, sandy beaches are the most heavily used and geomorphologically complex, and the shoreline is constantly changing due to the interaction between natural and anthropogenic factors causing the erosion or accretion processes occurrence [11]. Although coastal geomorphology depends on complex processes in nature, knowledge of wind–wave climate [12–14], the correspondence of interactions with sediment particles, and a better understanding of coastal dynamics on the spatiotemporal scale make coastal evolution easier to predict [5,15].

Bathymetry data are important for analyzing seabed morphology and sedimentation patterns [16–19]. From the variation of bathymetry data, seabed erosion or sedimentation could be detected and evaluated [20]. The Baltic Sea has unique geomorphic, hydrographic, and hydrodynamic characteristics that shape the seafloor landscape and influence coastal zone dynamics [21,22]. Anthropogenic pressure among natural factors affecting the Baltic Sea seabed morphology is important to consider. The most significant human activities are harbor constructions, dredging, various cable and pipeline projects, and renewable energy constructions. This can cause coastal erosion or alter underwater mass direction [23], negatively affecting some areas of the Baltic Sea. Therefore, such risk factors should be considered before any construction work is undertaken [8,23,24].

Understanding the variability of the entire cross-shore profile, which includes on land and underwater parts, is crucial for sustainable coastal management, as it allows for a more accurate application of different coastal engineering operations: (i) coastal nourishment [25–27], (ii) design of coastal protection structures [24,27–29], (iii) coastal sediment balance calculations [23,24]. Cross-shore profiles and their calculations are used to evaluate longshore sediment transport rates and develop and predict erosion and accretion volumes [30]. Although it is challenging to observe changes in a swash zone (transitional area of the coastal profile) that is the most dynamic part of the coastal profile, a better understanding of sediment transport processes in the nearshore zone is necessary [31,32].

The main objective of this paper is to evaluate the impact of anthropogenic pressure and natural factors on cross-shore profile changes at the sandy, high-energy coast. In order to assess the changes in coastal geomorphology, the cross-shore profile evolution, the granulometric composition of sediments, and hydrometeorological data were analyzed as well as nearshore bathymetry changes. The data provided a changing picture of the entire shore profile—on land and underwater.

2. Materials and Methods

2.1. Study Site

The Lithuanian coast (90.6 km) of the Baltic Sea (Figure 1) represents a generic type of almost straight, relatively high-energy, actively developing coasts that (1) contain a large amount of fine, mobile sediment, (2) are open to predominating wind and wave directions, and (3) are exposed to waves from a wide range of directions [7,33]. The specific two-peak directional structure of predominant winds has created a subtle balance of lithodynamical processes on the Lithuanian coast [34,35]. This balance has changed during the last 50 years [36]. The shore is more actively eroded now, leading to the deterioration of recreational space, and endangering different coastal engineering structures and other infrastructure objects in the coastal zone [7,8].

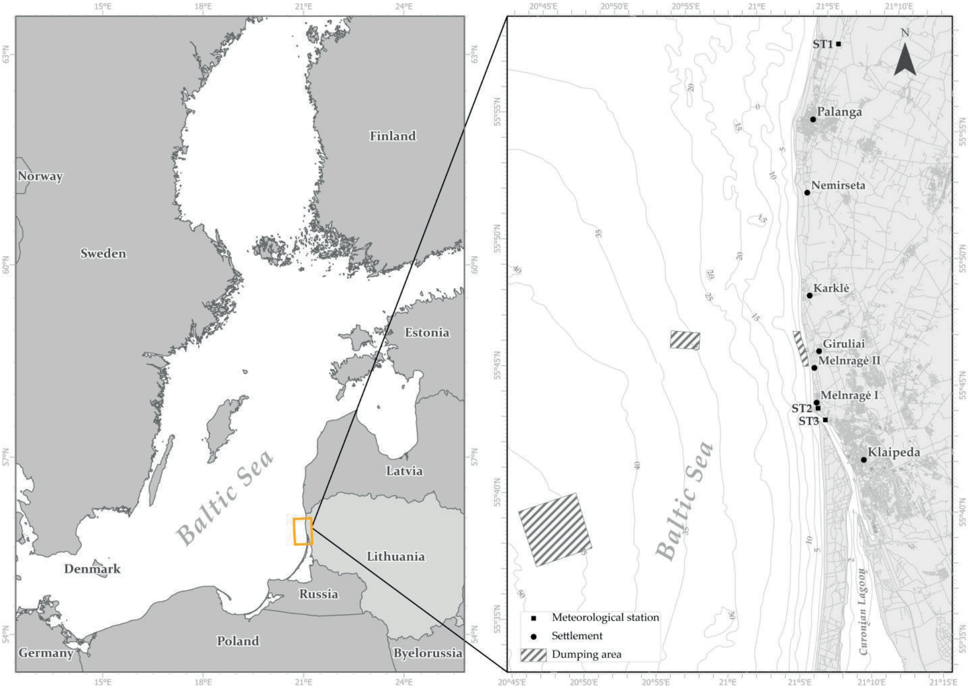

Figure 1. Overview of the study site. ST1—Palanga Aviation meteorological station, ST2—Klaipėda meteorological station, ST3—Port of Klaipėda station.

The Port of Klaipėda, located at the Klaipėda strait (the SE Baltic Sea), divides the Lithuanian coast into two geomorphologically different sites—southern and northern [3]. The southern part of the Lithuanian coast includes the Curonian Spit coast, which consists of sandy sediments and represents accumulation processes on the nearshore [2]. The distribution of the sandy sediments is mainly affected by longshore sediment transport, in which the main path is from south to north [37,38].

The northern part of the Lithuanian coast is the mainland coast, which extends north from the Port of Klaipėda jetties. This part of the Lithuanian coast is more geologically diverse than the southern part [2,7]. In the northern part of the mainland coast (Palanga–Būtingė), sandy sediments prevail, forming mainly in the Littorina and Post-Littorina seas [2,39]. The southern part of the mainland coast (Giruliai, Nemirseta, Melnragė) consists of the moraine (glacial deposits) and coarse sand (Figures 2 and 3) [2,39].

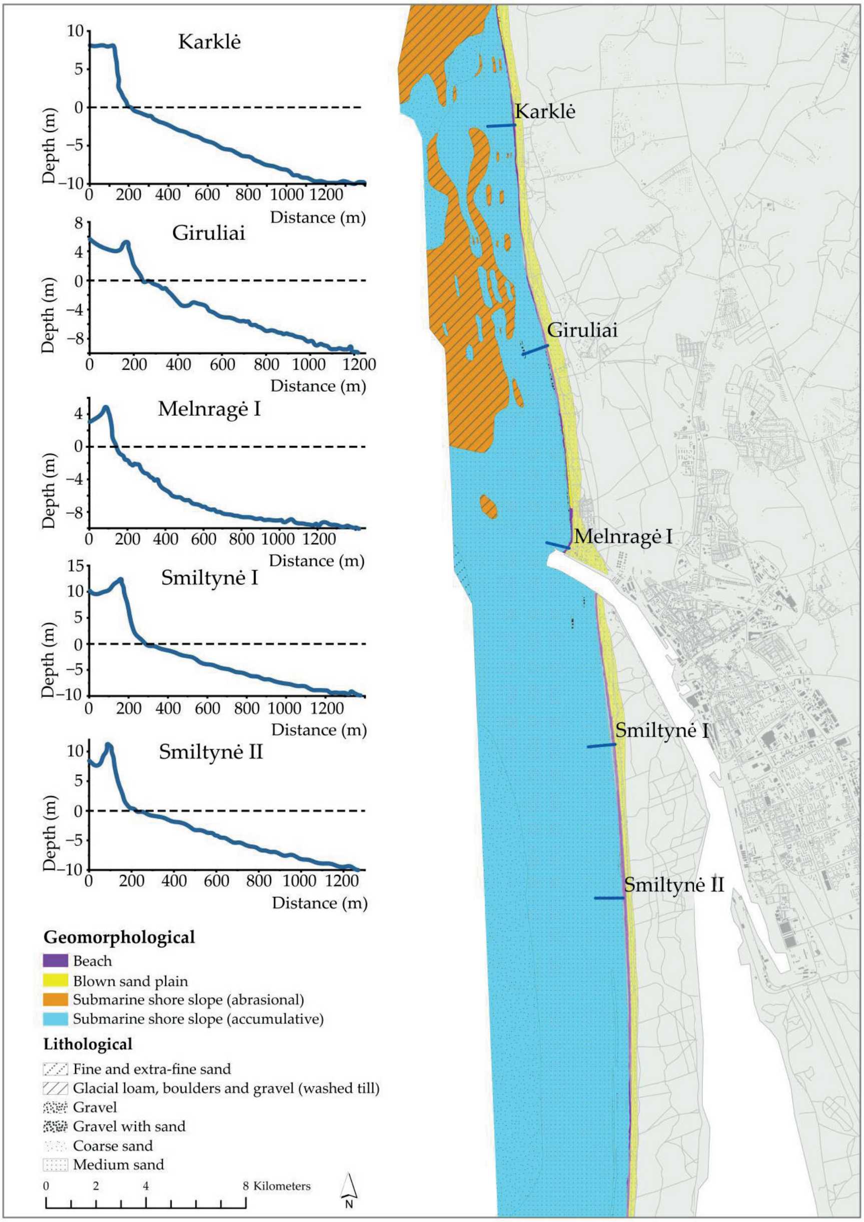

Figure 2. Geomorphological map of the study area.

(**a**) (**b**)

(**c**) (**d**)

(**e**)

Figure 3. Klaipėda district municipality's coast (**a**) Karklė; Klaipėda city municipality's official beaches: (**b**) Giruliai, (**c**) Melnragė I, (**d**) Smiltynė I, (**e**) Smiltynė II.

2.2. Hydrometeorological Data

The hydrometeorological data of mean wind speed (m/s) and direction (degrees) of 1993–2021, as well as mean wave height (m) and direction (degrees) data of 1993–2019 used in this study, were processed in Origin Pro 2021 software for statistical analysis and graphing [40]. These data were obtained from the Marine Environment Assessment

Division of the Environmental Protection Agency (EPA), Lithuanian Hydrometeorological Service under the Ministry of Environment, Palanga Aviation Meteorological Station, and the Port of Klaipėda administration. The data were initially collected at the Klaipėda meteorological stations on the Baltic Sea coast, Palanga Aviation Meteorological station in Lithuania, and the port area (Figure 1). Klaipėda meteorological station is located near the Port of Klaipėda jetties. As constructions surround it, there is no direct access to the Baltic Sea. The height above sea level is 6.2 m.

2.3. Cross-Shore Profile Evolution

Cross-shore profiles along the study area were measured from the shoreline to the dune crest. In total, 40 profiles every 500 m were measured. Data were collected using an Emlid Reach RS+ RTK GNSS receiver with centimeter precision and a dual-band GPS receiver, Leica 900. Moreover, cross-shore profile data were obtained from the Lithuanian Geological Survey, covering the 1993–2022 period.

The cross-shore profiles were used to calculate a volume by applying the following equation [41]:

$$v1 = \frac{\sum_{p=1}^{n}(SI)}{L} \tag{1}$$

where p is the cross-shore profile, S is a surface, I is an extrapolation between two profiles, and L is the linear part of the coast concerned by the calculation to get the m^3/m linear alongshore variations.

2.4. Beach Sediment Sampling and Processing

Historical sediment data for 1993–2003 were obtained from the Lithuanian Geological Survey (Bitinas 2004). Sediment samples for 2003–2022 were collected in line with the Lithuanian Geological Survey methodology at 3 points in every cross-shore profile: the dynamic shoreline, the middle part of the beach, and the foredune. The collected sediment samples were processed in the laboratory using a set of nineteen sieves in the following fractions: >2500; 2500–2000; 2000–1600; 1600–1250; 1250–1000; 1000–800; 800–630; 630–500; 500–400; 400–315; 315–250; 250–200; 200–160; 160–125; 125–100; 100–80; 80–63; 63–50; <50 µm. In the second step, the obtained data were calculated using the GRADISTAT add-in in the Excel program [42]. The latter Excel add-in applied the Udden (1914) [43] and Wentworth (1922) [44] sediment size classification scale to calculate the grain size and distribution of sediments.

In this research, the historical grain size data until 2003 were used alongside the classification provided by the Lithuanian Geological Survey and the Udden (1914) [43] and Wentworth (1922) [44] classification-based data starting from 2004. To ensure data integrity and comparability, transitioning between the two classifications adjustment was made to use the following grain size: 2500–2000 very fine gravel; 2000–1000 very coarse sand;1000–500 coarse sand; 500–250 medium sand; 250–100 fine sand; 100–50 very fine sand; <50 silt [42].

2.5. Bathymetric Data

The bathymetric data for 1993–2022 were procured from the Port of Klaipėda administration with a 0.5 m grid resolution and the Lithuanian Geological Survey with a 1.5 m grid resolution. The provided data were collected with a Kongsberg EM2040C multibeam echo sounder following Standards for Hydrographic Surveys S-44 of the International Hydrographic Organization [45]; the depth data were processed using the hydrographic data recording and processing software Hypack Max (HYSWEEP).

In addition, nearshore bathymetry data were collected in 2022 using 3-frequency Deeper Sonar. Elevations were observed on cross-shore transects extending from the shoreline to ~6 m depth. Measurements were made in the mainland part of the study area, 10 km north of the northern jetty.

The triangular irregular network (TIN) was created using obtained data from a point cloud dataset in Global Mapper 2022 [46] to represent the studied surface morphology. This method connects 3D (X, Y, Z) point features into a network of triangles. From there, the program ran interpolation over the triangular faces using the feature elevation and slope values to generate an elevation grid layer. Then, the digital elevation model (DEM) was extracted and used to create a bathymetric surface to calculate volume comparing a studied period (1993, 2003, 2022) surface grids [47,48]. The Path Profile tool generated a cross-section of the analyzed surface to more accurately assess bathymetric features and seabed elevation changes. Elevation changes in 446 profiles every 50 m along the studied coast were calculated in the total.

3. Results

The bathymetry data were used to evaluate changes in the underwater bottom slope and calculate sediment volume changes. The GPS survey data from cross-shore profile measurements were used to estimate sediment volume changes in the beach area. Both data sets allowed to evaluate the alteration of sediment volume in a coastal zone. In order to identify the possible impact of the Port of Klaipėda reconstruction on coastal evolution, the study period was divided into two sections: 1993–2003 before reconstruction and 2003–2022 after the elongation of the port jetties. Hydrometeorological data were also analyzed for these periods separately.

According to calculations performed by Global Mapper (Figure 3) for the period 1993–2022, the net volume on the mainland coast was $-429{,}631.47$ m^3, while on the Curonian Spit coast, it was $-2{,}615{,}669.7$ m^3. Before Klaipėda seaport reconstruction, 1993–2003, the net sediment volume on the mainland coast was 348,070.61 m^3, and on the Curonian Spit $-4{,}633{,}217.1$ m^3. In the period after reconstruction, 2003–2022, sediment loss increased compared to the previous period to $-1{,}520{,}535.2$ m^3 on the mainland coast. However, sediment loss decreased on the Curonian Spit respectively to $-553{,}413.63$ m^3.

During the study period of 1993–2022 on both the Curonian Spit and the mainland coasts, average loss of sediments $Q = -1148.98$ m^3/profile ± 294.29 m^3/profile was observed. The average velocity of sediment volume change on the mainland was $q = -0.02$ (m^3/m)/year ± 0.004 (m^3/m)/year, while on the Curonian Spit coast, an average velocity of volume change was $q = -0.03$ (m^3/m)/year ± 0.01 (m^3/m)/year.

In order to represent geomorphological changes in the Lithuanian coastal zone, profiles from Karklė, Giruliai, Melnragė I, Smiltynė I, and Smiltynė II were chosen (Figure 4). In the period 1993–2022, in profile from Karklė (Figure 4), sediment loss was observed that reached -1253.68 m^3/profile. Overland to the shoreline (0 m isoline), the observed profile volume changed a 30.74 m^3/profile. In comparison, the underwater part to the -10 m depth experienced a sediment loss of -1290.84 m^3/profile. In the most dynamic part, sediment accumulation was observed from 0 to -2.5 m depth, and sediment volume was 101.61 m^3/profile.

In the profile from Giruliai (Figure 4), the total change in sediment volume was 94.34 m^3. Overland sediment volume increased to 20.23 m^3. In the swash zone, from 0 to -2.5 m depth, the sediment volume was 187.5 m^3. However, the underwater part from -2.5 to -10 m depth experienced a loss of sediments, and the change reached -126.98 m^3. The loss of sediment prevailed in profile from Melnragė I (Figure 4) and reached -159.51 m^3. In the land part of the profile, the observed sediment volume change was -71.45 m^3. From 0 to -2.5 m depth, the profile lost -62.45 m^3 of sediments; in total, the underwater part of the profile lost -83.94 m^3 of sand.

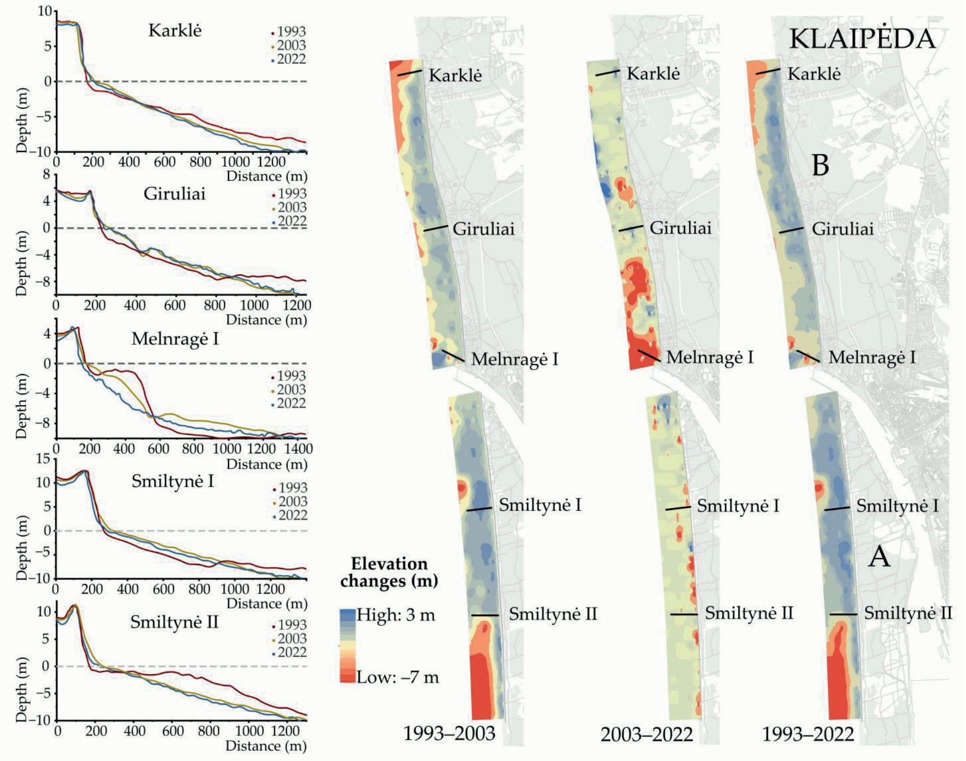

Figure 4. Elevation changes of the coastal zone on the Curonian Spit (**A**) and the mainland (**B**) coasts.

The positive shore formation processes were observed in the profile from Smiltynė I (Figure 4). Here, volume of sediment increased by 113.26 m^3. Overland sediment volume increased by 29.79 m^3. An accumulation was observed in a swash zone from 0 to −2.5 m depth, and the total change was 330.71 m^3. In the remaining underwater part, to −10 m depth, sediment volume decreased by −203.44 m^3. The total sediment volume change in profile from Smiltynė II (Figure 4) was −2089.22 m^3. However, the overland part of the profile experienced an increase in sediment volume and reached 60.30 m^3. From 0 to −2.5 m depth, sediment volume in this profile decreased by −20.58 m^3; from −2.5 to −10 m depth, the sediment loss was −2134.14 m^3.

According to hydrometeorological data analysis, during 1993–2021, westerly, southwesterly, and southerly winds prevailed in a study area, while during 1993–2019, wave directions were west and southwest (Figure 5). Throughout the study period, the prevailing wind speeds of 2–4 m/s and 4–6 m/s was observed, while the mean wave height was between 0–0.5 m and 0.5–1 m.

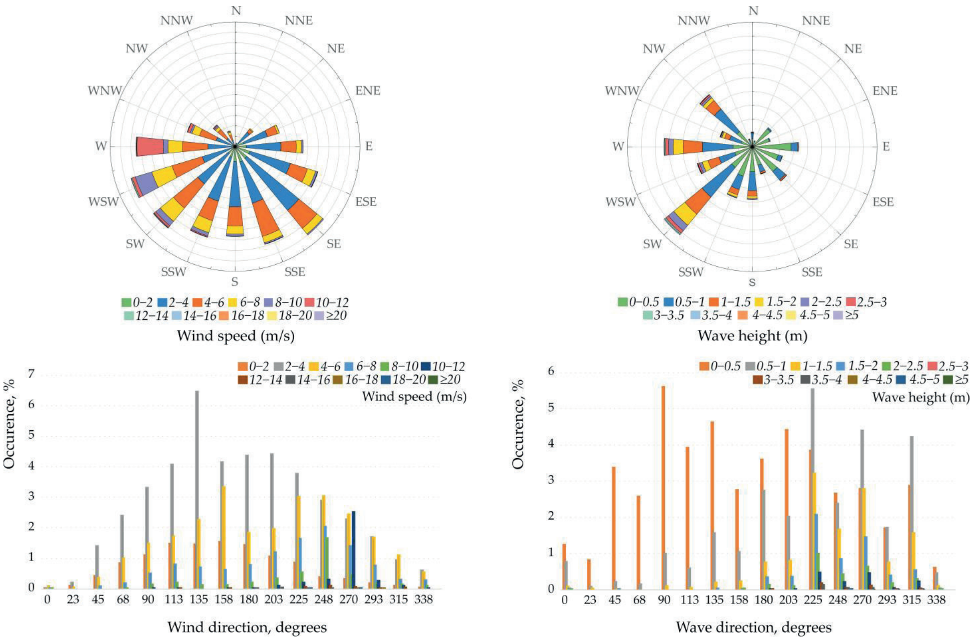

Figure 5. The wind rose diagram for wind direction, and wind speed (m/s) from 1993 to 2021, and wave rose diagram for wave direction and mean wave height (m) from 1993 to 2019, the frequency distribution of wind speed (m/s) from 1993 to 2021, and frequency distribution of wave height (m) from 1993 to 2019.

In 1993–2003, the sediment volume in the profile from Karklė (Figure 4) decreased by −1071.84 m^3. Overland part of the profile to the shoreline, the volume of sediments increased by 30.37 m^3/profile. The volume change reached −1287.77 m^3/profile in the underwater part to −10 m depth. However, from 0 to −2.5 m depth, sediment volume changed by 95.45 m^3/profile. The total change of sediment volume in the profile from Giruliai (Figure 4) was 77.23 m^3. Overland sediment volume increased by 20.19 m^3. The increase of sediment volume was observed underwater from 0 to −2.5 m depth and reached 185.29 m^3. In contrast, the underwater part from −2.5 to −10 m experienced sediment loss of −125.85 m^3. In the Melnragė I (Figure 4) profile, the sediment volume increase was observed and reached 913.66 m^3. Overland, the volume of sediments in this profile increased by 58.62 m^3. The sediment loss was observed from 0 to −2.5 m depth and reached −35.25 m^3. However, in total, the sediment volume of the underwater part of the profile increased by 851.22 m^3.

The volume of sediments in profile from Smiltynė I (Figure 4) increased by 428.31 m^3. The overland part of the profile represents the accumulation process; here, sediment volume increased by 71.61 m^3. In the swash zone of the profile (from 0 to −2.5 m depth), the sediment volume increased by 358.49 m^3/m. In the rest of the underwater profile (to −10 m depth), the sediment volume changes reached 328.65 m^3. In the profile from Smiltynė II (Figure 4), the total change in sediment volume was −1853.24 m^3. However, the accumulation process prevailed on land; the total increase in sediment volume reached

206.74 m^3. A total of −2066.66 m^3 of sand was lost in the underwater part. From 0 to −2.5 m isobath profile lost −51.71 m^3, and from −2.5 to −10 m, −2016.50 m^3.

In 1993–2003, the wind direction slightly shifted to southerly directions, and an increase in the southeast directions of the waves were observed. The 2–4 m/s wind speed still prevailed. However, the increase in wind speed was observed at 4–6 m/s and 6–8 m/s. The 0–0.5 m mean wave height prevailed in all directions, and waves higher than 0.5 m were observed in the south, west, and northwest directions (Figure 6).

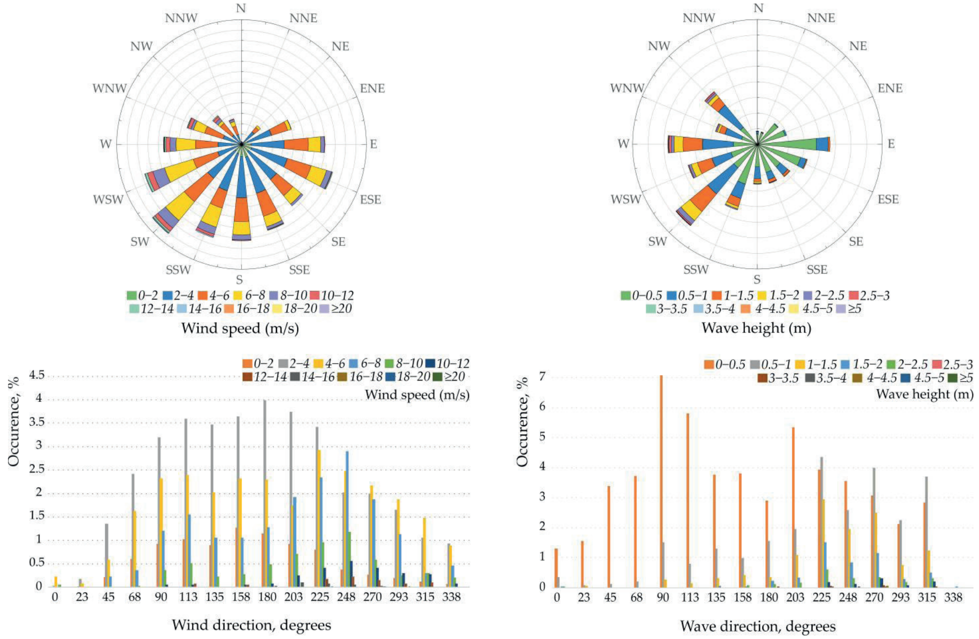

Figure 6. The wind rose diagram for wind direction and speed (m/s) from 1993 to 2003, a wave rose diagram for wave direction and mean wave height (m) from 1993 to 2003, the frequency distribution of wind speed (m/s) from 1993 to 2003, and frequency distribution of waves height (m) from 1993 to 2003.

Between 2003 and 2022, the profile from Karklė (Figure 4) experienced a sediment loss of −166.82 m^3/profile. However, on land up to the 0 m isobath (shoreline), the profile changed by 0.40 m^3/profile. In the underwater part up to −10 m depth, the change in sediment volume was −147.96 m^3/profile, and from 0 to −2.5 m isobath volume change in the profile was 1.47 m^3/profile. The total change of sediment volume in the profile from Giruliai (Figure 4) was 101.07 m^3. Overland, the volume changed to −1.60 m^3. In the underwater part of the profile, from 0 to −2.5 m isobaths, the total amount of sediment decreased by −6.59 m^3. However, the underwater part from −2.5 to −10 m isobath experienced an increase, which reached 110.32 m^3. In the profile from Melnragė I (Figure 4), the total sediment volume change reached −1072.98 m^3. Overland, the profile experienced a change of −65.36 m^3 of sediments. From 0 to −2.5 m isobath profile lost −202.30 m^3 of sand, in the total underwater part of the profile lost −1011.98 m^3 of sand.

In the profile from Smiltynė I (Figure 4), the sediment volume changed by −277.19 m^3. Overland, the loss of sediments was observed and reached −34.61 m^3. From 0 to −2.5 m isobaths in the underwater part, sediment loss reached −17.5 m^3. In the rest of the underwater profile, up to −10 m, the total sediment volume changed by −225.23 m^3. In the profile from Smiltynė II (Figure 4), the total change in sediment volume was −251.13 m^3. On land, the total change in sediment volume reached −96.69 m^3. In total, −153.98 m^3 of sand was lost in the underwater part, from 0 to −2.5 m isobaths, profile lost −4.07 m^3 of sand, and from −2.5 to −10 m depth, −149.99 m^3.

In the most recent decade of 2003–2022, the wind direction shifted to the south and southeast directions, and waves from westerly and south-westerly directions were observed. The prevailing wind speed was 2–4 m/s and 4–6 m/s, while the mean wave height was 0–0.5 m and 0.5–1 m (Figure 7).

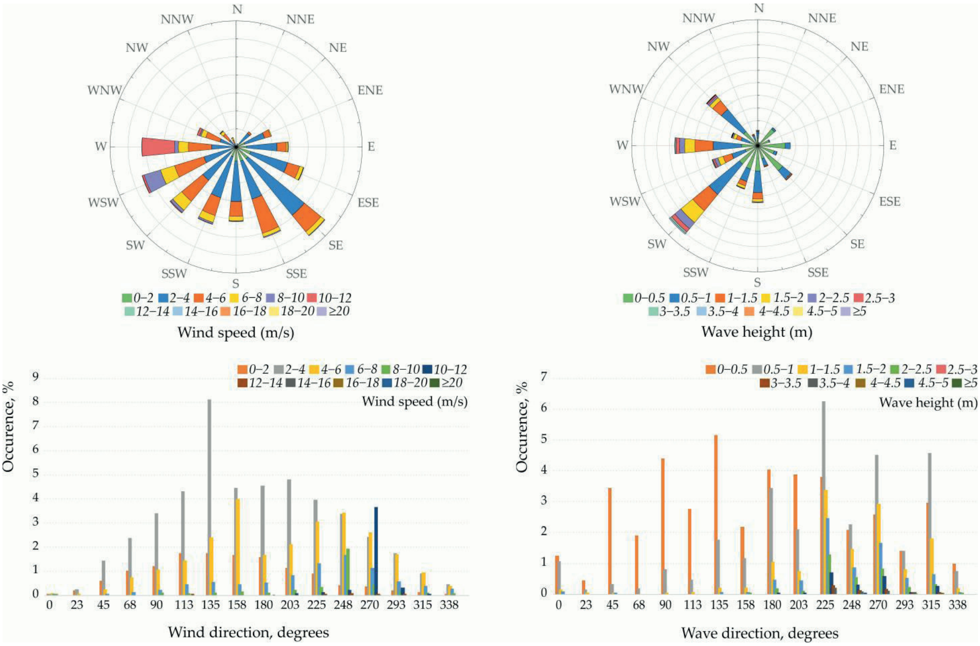

Figure 7. The wind rose diagram for wind direction and speed (m/s) from 2003 to 2021, a wave rose diagram for wave direction and mean wave height (m) from 2003 to 2019, the frequency distribution of wind speed (m/s) from 2003 to 2021, and frequency distribution of wave height (m) from 2003 to 2019.

Granulometric analysis was performed on the profiles by sampling at three points: the dynamic shoreline, the mid-beach, and the foredune (Figure 8). On the mainland coast, sediment type and sorting were dominated by well-sorted medium sand, slightly very fine gravelly coarse sand, slightly very fine gravelly medium sand, and very fine gravelly fine sand. The D_{50} size varied from 231.6 to 712.0 μm. On the Curonian Spit coast, sediment type and sorting were dominated by very well-sorted fine sand, well-sorted fine sand, and moderately well-sorted medium sand. The D_{50} size varied from 194.7 to 274.4 μm.

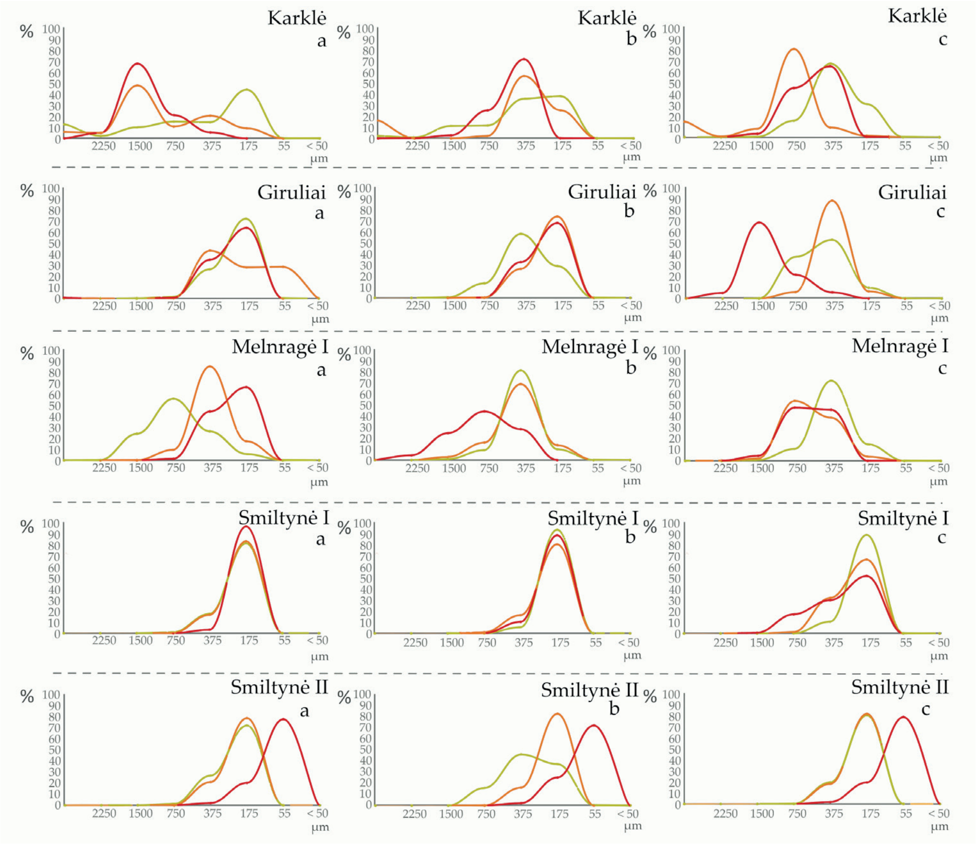

Figure 8. Grain size composition of surface sediments at profiles from Karklė, where a—dynamic shoreline, b—mid-beach, and c—foredune; Giruliai, where a—dynamic shoreline, b—mid-beach, and c—foredune; Melnragė I, where a—dynamic shoreline, b—mid-beach, and c—foredune; Smiltynė I, where a—dynamic shoreline, b—mid-beach, and c—foredune; Smiltynė II, where a—dynamic shoreline, b—mid-beach, and c—foredune, throughout 2003 (red line), 2012 (orange line), and 2022 (yellow line) years.

Profiles from Karklė, Giruliai, and Melnragė I represent the mainland coast, and according to grain size distribution since 2003, the sand is evenly distributed in the profiles but indicates a higher concentration of finer particles. At the same time, profiles from Smiltynė I and Smiltynė II represent the Curonian Spit coast. According to the grain size distribution, visible particles coarsen, indicating an occurring erosion process.

4. Discussion

The analyzed data allowed us to describe the evolution of coastal geomorphology affected by anthropogenic pressure (tourism, seaport activities, hydro-technical structures) and natural factors such as changes in hydrometeorological conditions.

The authority of the Port of Klaipėda, in 2014–2018, ordered 237.78 × 103 m^3 of sand to be dumped on the nearshore of Melnragė and Giruliai beaches at 4–6 m depth [7] (Figure 1). This amount of sand was extracted while deepening the Klaipėda strait and used to nourish the mainland coast affected by erosion processes. Coastal erosion on the mainland coast is associated with local hydrodynamic conditions and hydro-technical constructions, mostly seaport jetties. On average, wave-induced longshore sediment transport is caused by the angular distribution of winds, and the position of the shoreline is northwards along the Curonian Spit and the Lithuanian mainland coast [37,38]. This prevailing sediment flow pattern means that changes in sediment availability or transport patterns along with these areas substantially affect the sediment budget northwards from Klaipėda. While sediment flows along the spit predominantly occur under natural conditions, further sediment transport to the mainland coast of Lithuania is blocked by jetties and breakwaters of Port of Klaipėda, out–flowing currents from Klaipėda Strait, and dredging of the port entrance channel [33,37]. Therefore, on the Curonian Spit coast, the predominant coastal process is accumulation, while on the mainland coast, erosion prevails [7].

The regime shift in wind direction discussed in previous works by authors [7] indicates morphological changes in the coastal zone. The morphology of most sandy beaches changes under wave conditions and is generally highly variable at the seasonal scale, with winter erosion and summer accretion [49]. In the Lithuanian coastal zone, wind-driven waves are observed [50]. Therefore, the shift in hydrometeorological conditions could alter the predominant sediment transport direction as well as the transported volume of sediments, and the erosion and accumulation processes could alternate.

The frequency of occurred wind speeds during the study period revealed the increased number of 2–4 m/s and 4–6 m/s wind speeds, which means lower wind speeds have an equal or more significant influence on the hydrodynamic processes that determine coastal geomorphology and development. Winds of those speeds continuously affect the shore, leading to a slower shore regeneration process.

Grain size distribution is a natural result of sediment transport processes, primarily related to the effects of erosion and accumulation [51,52]. Throughout the study period of 2003–2022, the grain size of the sediments on the mainland coast slightly became finer and evenly distributed in the profiles. This could be related to the beach replenishment work performed by the Port of Klaipėda Authorities. However, sediments became coarser on the Curonian Spit coast during 2003–2022. This observation proves the statement made by authors in earlier works where coastal erosion on both coasts has been detected by analyzing shoreline evolution [7].

The detection of changes in volumes of sediment during the study period was possible due to the analysis of bathymetry and cross-shore elevation data. The results revealed that in the period of 2003–2022, after the reconstruction of the Port of Klaipėda in 2002, both the Curonian Spit and the mainland coasts experienced the loss of sediments on land and underwater. This led to a steepening of underwater slopes and narrowing beaches on both coasts. The sediment loss after the seaport reconstruction is linked to the hydro-technical constructions and their configuration changes. The position of the north jetty of the Port of Klaipėda was changed, and the entrance channel has narrowed, causing the alteration in nearshore hydrodynamics and sediment circulation [53]. Throughout the entire study period from 1993 to 2022, steepening of the underwater bottom profile was observed in the nearest proximity to the Port of Klaipėda jetties (Figure 3); waves, therefore, reach the shore with higher energy. On the social aspect, such changes could be contradictory for beachgoers as a narrow beach could be less attractive for sunbathers that frequent recreational areas of the coastal zone. However, the strong winds are most favorable for extreme sports that are widely practiced along the coast.

Research in sediment transport both improves knowledge and provides diagnoses to decision-makers. Initially developed for civil engineering, this topic has been recognized as a scientific field. Science, to serve society, must make it possible to assess environmental hazards and vulnerability and identify early warning signs of critical transitions, and the general society should perceive sediment dynamics as a critical matter requiring attention [49]. Therefore, it is necessary to understand the involved processes better and to monitor and analyze the evolution of sediment budgets to adapt the information to be transferred to decision-makers in suitable forms for strategic planning [49,54].

5. Conclusions

In this study, the use of bathymetric data and cross-shore profiles to calculate elevation changes underwater as well as to estimate sediment volume and overland changes revealed that during a study period of 1993–2022, loss of sediments on both the Curonian Spit and the mainland coasts was on an average $Q = -1148.98\ m^3/\text{profile}$. After the Port of Klaipėda reconstruction, 2003–2022, sediment loss increased compared with the period before the renewal of jetties, and the net sediment volume on the mainland coast was $-1{,}520{,}535.2\ m^3$. Nevertheless, sediment loss decreased on the Curonian Spit coast, and the net sediment volume was $-553{,}413.63\ m^3$, verifying that the position and construction of the hydro-technical structures influence sediment flow along the coast.

Together with anthropogenic factors, hydrometeorological conditions are the key driver for coastal development tendencies. The evaluation of the coastal profile indicates a tendency for steepening of the underwater profile next to the jetties, causing the waves to reach the shore with higher energy. Recreational activities in the coastal zone are not among contributing factors of change. They are, however, under the direct influence of changes and highly dependent on planners' decisions on how to adapt and mitigate the influencing ones.

The results of this study emphasize the need for monitoring sediment dynamics in the coastal zone to provide customized coastal development management methods such as beach nourishment or hard construction. Observing coastal processes specifies a need for strategic coastal management plans and demonstrates the current adapted tools work.

Author Contributions: Conceptualization, I.Š. and V.K.; methodology, I.Š. and V.K.; software, V.K.; validation, I.Š. and V.K.; formal analysis, I.Š.; investigation, I.Š.; data curation, I.Š., V.K. and E.B.; writing—original draft preparation, I.Š.; writing—review and editing, E.B. and L.K.-R.; visualization, V.K. and E.V.; supervision, L.K.-R. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest: The authors declare no conflict of interest.

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PAPER II

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Article

Natural and Anthropogenic Factors Shaping the Shoreline of Klaipėda, Lithuania

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Abstract: Port of Klaipėda is situated in a complex hydrological system, between the Curonian Lagoon and the Baltic Sea, at the Klaipėda strait in the South-Eastern part of the Baltic Sea. It has almost 300 m of jetties separating the Curonian Spit and the mainland coast, interrupting the main path of sediment transport through the South-Eastern coast of the Baltic Sea. Due to the Port of Klaipėda reconstruction in 2002 and the beach nourishment project, which was started in 2014, the shoreline position change tendency was observed. Shoreline position measurements of various periods can be used to derive quantitative estimates of coastal process directions and intensities. These data can be used to further our understanding of the scale and timing of shoreline changes in a geological and socio-economic context. This study analyzes long- and short-term shoreline position changes before and after the Port of Klaipėda reconstruction in 2002. Positions of historical shorelines from various sources were used, and the rates (EPR, NSM, and SCE) of shoreline changes have been assessed using the Digital Shoreline Analysis System (DSAS). An extension of ArcGIS K-means clustering was applied for shoreline classification into different coastal dynamic stretches. Coastal development has changed in the long-term (1984–2019) perspective: the eroded coast length increased from 1.5 to 4.2 km in the last decades. Coastal accumulation processes have been restored by the Port of Klaipėda executing the coastal zone nourishment project in 2014.

Keywords: Baltic Sea; Port of Klaipėda; shoreline changes; DSAS; clusterization; regime shift detection; dredging; sand nourishment

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1. Introduction

Erosion is a significant problem affecting sandy beaches that will worsen with climate change and anthropogenic pressure. Sandy shorelines are highly dynamic due to altering wave conditions, sea levels and winds, geological factors, and human activity [1]. Therefore, identifying the most vulnerable areas to erosion is crucial for nearshore communities since it could significantly affect their socio-economic state through destruction of infrastructure, loss of land and property on the coast, and valuable beach areas used for recreation.

Shore regeneration is a slow process lasting for more than one year, while erosion usually occurs in a matter of a few days, making it difficult to detect visually. As short-term measurements do not reflect actual multi-annual dynamic trends, studies involving several shoreline decay and regeneration cycles are necessary to determine long-lasting changes in the shoreline dynamics. Typically, coastal research to assess and predict long-term shoreline dynamics and the erosion rates is based on the data covering up to 10 years (short-term), 10–60 years (medium-term), and more than 60 years (long-term) of shoreline position [2–4].

Shoreline dynamics depend on different causes, mainly on the sediments in the sea-land system [5–7]. Furthermore, the different coastal stretches have particular favorable hydrometeorological conditions for the accumulation or erosion processes. The rapid urbanization of the coastal zone has a significant impact on shoreline development [8–10]. Sustainable coastal development requires knowledge of the coastal processes combined with incorruptible urbanization and properly chosen shoreline erosion mitigation methods [10,11]. Often, an insufficient understanding of the coastal processes causes costly incidents.

A number of studies [8,12,13] show the impact of anthropogenic factors in particular port activities on shoreline positions. Erosion and accumulation are naturally occurring processes that often coincide in a dynamic equilibrium [14]. However, increasing anthropogenic pressure at the coast has disrupted the natural development of the coast, accelerating erosion processes in some places and causing accumulation in others [14]. Analysis of shoreline changes is a well-developed field that has progressed complex data processing and analytical protocols [15]. However, quantifying coastal development trends is only one aspect of the problem; it is necessary to understand the drivers of change and address local impacts in a broader regional context that is important from a decadal to a centennial timescale [15]. Understanding the causes of atypical coastal development is important to make sustainable coastal zone management plans. Such knowledge is crucial not only for the coastal dynamics experts, but also for the port managers, as it can serve as the basis for future decisions on how to reduce port damage to the coasts.

This paper analyses the shoreline dynamic in the context of climate change and increased anthropogenic pressure, focusing on identifying long- and short-term shoreline movement tendencies and identifying the direct impact zone of the Port of Klaipėda. As well as answering the question of whether and how shoreline evolution is affected by the artificial sand nourishment carried out in accordance with the Port of Klaipėda management plan.

2. Study Site

The Lithuanian coast of the Baltic Sea represents a generic type of almost straight, relatively high-energy, actively developing coasts that (i) contain a large amount of fine mobile sediment; (ii) are open to predominating wind and wave directions; and (iii) are exposed to waves from many directions [16]. The study area extends 10 km from Klaipėda seaport jetties to the north and 10 km to the south. This particular area was chosen based on the following aspects: (i) the broad demand spectrum of recreational uses [17]; (ii) the high risk of coastal erosion [18,19]; (iii) the possibility of direct and indirect anthropogenic impacts [20,21].

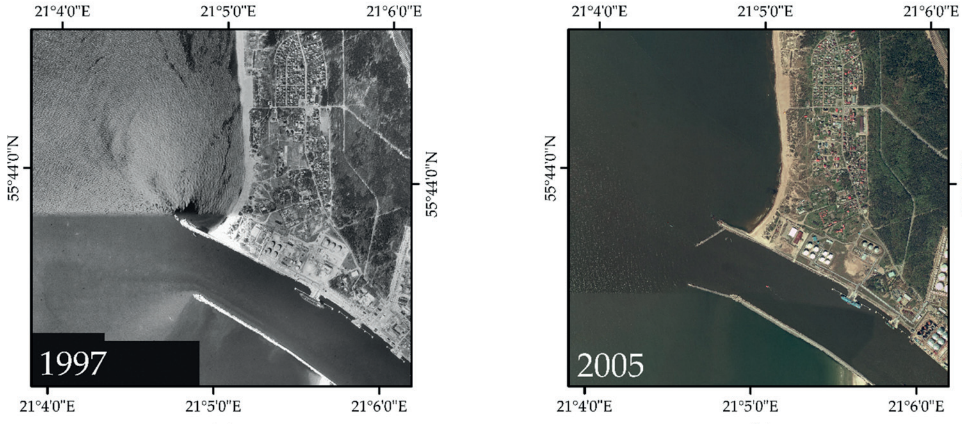
The South-Eastern coast of the Baltic Sea is formed by the presence of the Port of Klaipėda [21,22]. Historically, the Port of Klaipėda has been known from the 13th century when vessels of Lubeck and Bremen merchants used to moor in the small port neighboring the Klaipėda castle [23]. Port expansion to the Klaipėda strait started in 1745, and the chronicle of 1797 mentions that Port of Klaipėda consists of the Dane river port and a big water basin in the strait of the Curonian Lagoon. In the 19th century, wooden jetties were constructed [22]. 1924–1939 was a period when Klaipėda seaport was at its flourishing peak—new stony jetties and quays were assembled [24,25]. Since the occurrence of the first jetties, ongoing coastal engineering problems were encountered relating to wave exposure, siltation within the port, extensive dredging requirements, and seiching within the confines of the present harbor [22,26].

After the construction of the first port jetties, at the end of the 19th century, the shoreline moved seawards significantly on both sides of the jetties [20]. This insight raises doubts about the predominant sedimentary direction from south to north [6]. The dumping of the dredged sand can partly explain this accumulation tendency in the northern part of the jetties from the Klaipėda strait [22]. Up until the beginning of the 20th century, sand dredged from the port had been dumped at shallow depths north of the jetties, initiating coast accumulation [22].

After the prolongation and construction of new concrete jetties at the beginning of the 20th century (works finished till 1934) [21] alongside changed dredging policies [13], observations were made that sand dredged next to the port jetties returns into the inlet and continues dredging works to ensure the depth of the entrance channel.

Due to depth restrictions in the Danish Straits, vessels with a maximum draft of 16.5 m, and in some cases, vessels with a draft of up to 17 m can enter the Baltic Sea. Another limitation for ships entering the Baltic Sea is the bridge height to about 65 m entering the strait of the Great Belt, which connects the Danish islands of Zeeland and Funen. These restrictions prevent vessels with a draft greater than 16.5 m from entering the Baltic Sea from those of Class Panamax (Baltmax). The long-term competitiveness and sustainability of the Klaipėda seaport can be ensured only by increasing the technical capability of the port to receive and service ships of the maximum capacity [27].

Therefore, in 1999, the final design for reconstruction of the Port of Klaipėda jetties was established. The seaport jetties system was reconstructed by narrowing the entrance channel and changing the position of the northern pier. In 2002 the northern pier was extended by 205 m (up to 733 m) and the southern pier by 278 m (up to 1374 m) (Figure 1) [28]. At the same time, the entrance channel was dredged to a depth of 14.5 m. According to the recent port development plan, the entrance channel will be dredged up to 17 m by 2023.



(**a**) (**b**)

Figure 1. The Klaipėda seaport jetties before and after the reconstruction of 2002, (**a**) 1997, and (**b**) 2005.

The Port of Klaipėda, located at the Klaipėda strait (Figure 2) (South-Eastern coast of the Baltic Sea), divides the Lithuanian coast into two geologically and geomorphologically different parts: southern—the coast of the Curonian spit, northern—mainland coast (Figure 3) [29]. Port jetties interrupt the main sediment transport path and significantly influence the Lithuanian coast's northern (38.49 km long) part [6,20]. Only Quaternary sediments are found on the Lithuanian coast of the Baltic Sea [6,30]. From the geological point of view, the mainland coast and the Curonian Spit coast are not homogenous (Figure 4). The geological structure of the mainland coast was mainly determined by the sediments formed during the last few glaciations. The sediments of the Curonian Spit coast were formed in the Baltic Sea basin—starting with the Baltic Ice Lake and ending with the modern Baltic Sea [6,30].

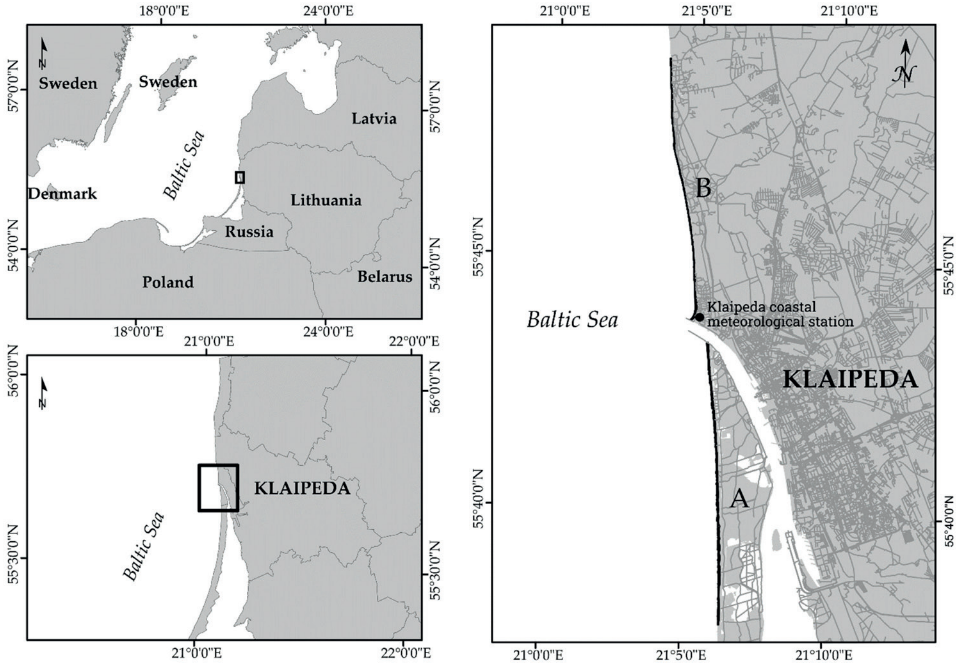


Figure 2. Location of the study site in the south-eastern Baltic Sea, A: the Curonian Spit coast, B: the mainland coast.

The sandy sediments form the part of the Curonian Spit coast: this Lithuanian coastal sector is characterized by accumulation relief [6]. The mainland coast of Lithuania is geologically heterogeneous: the northern part of the mainland coast is mainly formed of fine-grained sand (0.25–0.1 mm), while the southern and central parts of the mainland coast are formed by the medium-grained (0.5–0.25 mm) and coarse-grained (1–2.5 mm) sand [6,14]. A detailed description of the Lithuanian coast geomorphological and geological structure is provided by Bitinas et al. (2005)

According to the granulometric analysis of sediment samples from 2019 along the study area (Figure 4), on the Curonian Spit coast (A, a), very well and moderately sorted (σ = 1.21–1.47 mm) fine sand (Md = 0.20–0.37 mm) prevails, while on the mainland coast (B, b, c), the sorting of the sediments differs in a cross-shore profile. In profile *b,* moderately well-sorted (σ = 1.44 mm) medium sand (Md = 0.32 mm) prevails in a shoreline area, well-sorted (σ = 1.19 mm) slightly very fine gravelly medium sand (Md = 0.21 mm) prevails in a beach area, and moderately well-sorted (σ = 1.47 mm) sand prevails (Md = 0.36 mm) in a foredune area. In profile *c*, poorly sorted (σ = 3.84 mm) very fine gravelly fine sand (Md = 0.24 mm) prevails in a shoreline area, poorly sorted (σ = 10.69 mm) medium gravelly fine sand (Md = 0.23 mm) prevails in a beach area, and poorly sorted (σ = 18.21 mm) sandy very fine gravel prevails (Md = 1.12 mm) in a foredune area.

(**a**) (**b**)

(**c**) (**d**)

Figure 3. Study site shoreline features: (**a**) the Curonian Spit coast Smiltynė I beach (© I. Šakurova); (**b**) the Curonian Spit coast Smiltynė I beach (© I. Šakurova); (**c**) the mainland coast Giruliai beach (© L. Kelpšaitė-Rimkienė); (**d**) the mainland coast Melnragė I beach (© V. Kondrat).

During the dredging of the Klaipėda strait, the glaciogenic moraine deposits and alluvial sediments are mainly excavated—sand (0.002 mm 10–30%–2 mm 50%) and silt (0.002 mm 10–30%–2 mm 30–50%). All lithological sediment types are dumped in dumping area I (Figure 4) at a depth of 45–50 m. The II dumping area (Figure 4) is intended only for the dumping of sandy sediments—fine (0.25–0.1 mm > 50%) and aleuritic (<0.063 mm 10–30%) sand at a depth of 28–35 m. Since 2001, clean sand that meets sanitary–hygienic requirements excavated from the port entrance channel has been dumped in the dumping area III (Melnragė-Giruliai) at a 4–6 m depth. This area is intended to replenish the sediment balance and restore beach sand reserves [24].

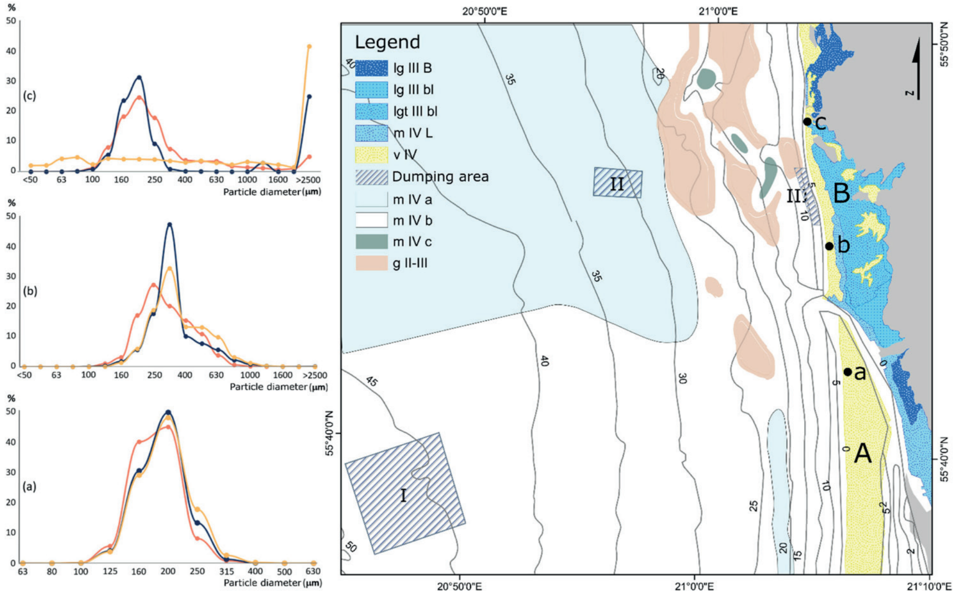


Figure 4. Map of Quarternary sediment type of coastal area and dumping zones of dredging material. Lg III B—glaciolacustrine sediments of the Baltic Ice Lake (fine sand); lg III bl—glaciolacustrine sediments (various sand); lgt III bl—marginal glaciolacustrine deposits (fine sand); m IV L—Litorina Sea sediments (fine sand); v IV—aeolian deposits (fine sand); m IV a—nearshore sediments (extra fine sand (0.05—0.1 mm)); m IV b—nearshore sediments (fine sand (0.1—0.25 mm)); m IV c—nearshore sediments (gravel with sand); gII-III—glacial deposits of Middle and Upper Pleistocene (unseparated), glacial loam, boulders and gravel (washed till). I—distant dumping area; II—near dumping area; III—nearshore dumping area (adapted from Bitinas et al., 2004). Grain-size composition of surface sediments at Smiltynė I (**a**), Melnragė I (**b**), and Karklė (**c**). Orange color line—western part of the dunes (foredune); blue line—the middle of the beach; red line—a dynamic shoreline in July of 2019.

3. Materials and Methods

3.1. Analysis of Cartographical Data

In this paper, we evaluate a period of 35 years of shoreline position variation tendencies for 1984–2019. All shoreline position changes were determined using the available high accuracy (1:10,000) cartographic data for the years: 1984, 1990, 1995, and 2005 (Table 1) obtained from Lithuania's National Land Service under the Ministry of Agriculture and GPS survey data for 2015 and 2019. The shoreline position was established at the middle of the swash zone by dual-band GPS receiver "Leica 900".

Shoreline position changes were analyzed with the ArcGIS extension DSAS v. 5.0 (Digital Shoreline Analysis System) package, developed by the United States Geological Survey (USGS) [31,32]. The DSAS is executed in five steps: (1) shorelines digitizing and uniforming to WGS-84 coordinate systems (UTM Zone 34); (2) computation of the uncertainties; (3) baseline creation and transects generation; (4) computation of distances between baseline and shorelines at each transect; and (5) computation of shoreline change statistics.

Three statistical parameters—net shoreline movement (NSM), end-point rate (EPR), and the shoreline change envelope (SCE)—were estimated and analyzed along with each transect every 25 m along the shoreline (796 transects in total). NSM values report the net change of the shoreline in the study period between the oldest and most recent shoreline.

EPR rate (m/yr) indicates change rates between the earliest and most recent shoreline positions. SCE capacity provides the envelope of shoreline variability, and it is the only measure of the total shoreline change among all the available shoreline positions [33].

Table 1. Shoreline positioning and detection errors. Ed—digitization error, Ep—pixel error, Es—sea-level fluctuation error, Ec—shoreline line detection or resolution errors, Etc—T-sheets plotting errors, Er—rectification error, Ut—shoreline capture error.

Data Source	Errors (m)						
	Ed	Ep	Es	Ec	Etc	Er	Ut
T-Sheets (1984)	2.961	0.987	0.680	3.948	7.500		9.058
T-Sheets (1990)	2.760	0.920	0.570	2.680	7.500		8.498
Orthophotos (1995)	2.500	0.506	0.490	2.024		0.500	3.331
Orthophotos (2005)	2.500	0.513	0.720	2.052		0.500	3.390
GPS (2010)			0.590	0.295			0.660
GPS (2015)			0.610	0.295			0.678
GPS (2019)			0.570	0.295			0.642

3.2. Data Reliability and Limits of Uncertainty

The shoreline position is highly variable in short time scales due to heavy storms, waves, and wind setup when extreme natural variations induce significant temporary shoreline retreat. Mapping the historical shorelines introduces additional uncertainties [34]. Although most researchers have similar techniques for estimating shoreline value changes, the methodology used to estimate changes varies considerably, significantly altering the accuracy and reliability of the data collected or determined. The dynamics of the shore itself may also cause certain differences and inaccuracies in shoreline surveys. Therefore, the values of the same shoreline determined by two independent scientists in the same field of science can vary considerably in their size and accuracy [35].

The most significant differences in the data occur during the digitization and processing of cartographic material. The differences in the values of shoreline changes may also occur due to the different statistical research methods used to determine the degree of shoreline change (shoreline change rate). The primary data and the analysis methods are the main factors defining the shoreline variations and accuracies. Therefore, prior to choosing a statistical research method, it is imperative to estimate the errors in determining the shoreline position in the cartographic material [36].

In this study, we determined three shoreline positioning and detection errors (Table 1) based on [14,36,37]:

The error in the position of the shoreline when determining in the T-Sheets:

$$\mathrm{Ut} = \pm\,(\mathrm{Ed}^2 + \mathrm{Ep}^2 + \mathrm{Etc}^2 + \mathrm{Es}^2 + \mathrm{Ec}^2)^{1/2} \quad (1)$$

The positioning error of the shoreline in orthophotos equals:

$$\mathrm{Ut} = \pm\,(\mathrm{Er}^2 + \mathrm{Ed}^2 + \mathrm{Ep}^2 + \mathrm{Es}^2 + \mathrm{Ec}^2)^{1/2} \quad (2)$$

GPS data error:

$$\mathrm{Ut} = \pm\,(\mathrm{Es}^2 + \mathrm{Ec}^2)^{1/2} \quad (3)$$

Here: Ut—shoreline capture error, Er—rectification error, Ed—digitization error, Ep—pixel error, Ets—photo plan creation error, Ec—shoreline line detection or resolution errors, Eg—georeferencing error; Es—sea-level fluctuation error; Etc—T-sheets plotting errors.

The shoreline uncertainty limit for different periods is equal to the sum of the shoreline fixation errors for different periods:

$$\sum Ut = (Utn_1 + Utn_2 + Utn)^{1/2} \quad (4)$$

Here n_1, n_2,—shoreline detection errors for different periods.

The shoreline uncertainty threshold (minimum time criterion) in the statistical methods for deter-mining shore change (EPR) equals:

$$\sum Ut/n \quad (5)$$

Here n—research period.

3.3. Clusterization

K-Mean cluster analysis for the net shoreline movement (NSM) values was applied to identify shoreline zones with similar evolution tendencies [38]. The K-means algorithm is a simple and popular clustering approach used in various applications [39]. It is a point-based clustering approach that starts with cluster centers located initially in arbitrary locations and goes through each stage of the cluster center to reduce the cluster error [39–41].

$$E = \sum \|X_i - m_i\|^2 \quad (6)$$

where E is the sum of squared errors for all objects in the data, X_i is the point in a cluster, and m_i is the mean of cluster k_i. The objective of K-means is to minimize the sum of squared errors over all k clusters. The algorithm first places k points in the space represented by the objects clustered as initial group centroids. The second step is to assign each object to the nearest cluster center. Then, the mean of each cluster is calculated to obtain a new centroid. These steps are repeated until the centroids do not change. The within-cluster sum of squares measures the variability of the observations within each cluster. In general, a cluster with a small sum of squares is more compact than a cluster with a large sum of squares [38,39]. Clusters with higher values exhibit more significant variability of the observations within the cluster [38,39]. The number of clusters is chosen based on the elbow method [38], whose main idea is to define groups such that the total intra-cluster variation (or the total sum of squares within clusters (WSS)) is minimized. In this case, the elbow of the curve is formed for the five clusters (Figure 5).

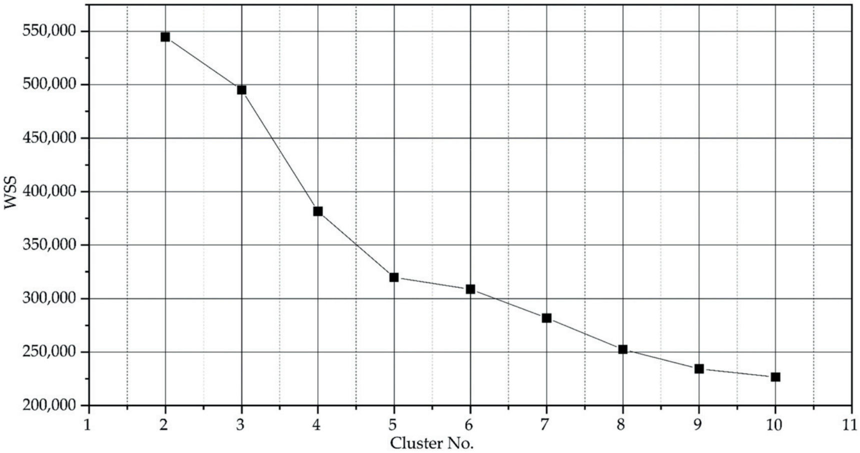


Figure 5. The number of clusters is chosen based on the within-cluster sum of squares parameter.

3.4. Analysis of Meteorological Data

The meteorological data (annual mean wind speed and direction) of the 1960–2019 time period were analyzed to detect the wind direction's regime shift. The meteorological data were acquired from the Marine Environment Assessment Division of the Environmental Protection Agency (EPA) and derived from the Klaipėda coastal meteorological station (Figure 2) under the Lithuanian Ministry of Environment's environmental monitoring program. The program has been prepared in line with the legislation of the European Union.

A STAR (Sequential T-test Analysis of Regime Shifts) algorithm was applied to determine regime shifts in the analyzed time series (https://www.beringclimate.noaa.gov/ (accessed on 10 October 2021)). The algorithm was built upon a sequential *t*-test that can signal the possibility of a real-time regime shift [42]. The algorithm can process the data regardless of whether it is presented in anomalies and/or absolute values or not. It can automatically calculate regime shifts in large sets of variables [42].

For this study, the following set of input parameters were used: cut-off length (I) was set to 10 years; Hubert's weight parameter (HWP) was set to 1. HWP determined the weight of outliers in the calculation of average values of the regime shift. The confidence level was set to 0.1.

4. Results

4.1. Long-Term Shoreline Changes

NSM for the entire study period **1984–2019** showed (Figure 6) that 60.43% of the shoreline was accumulative, 20.98% erosive, and 18.59% was stable or within the range of uncertainty ±9.08 m (Table 2). Generally, the studied coast can be described as accumulative with the average 14.46 ± 1.92 m shoreline movement offshore tendency; the average shoreline movement velocity was 0.42 ± 0.03 m/year.

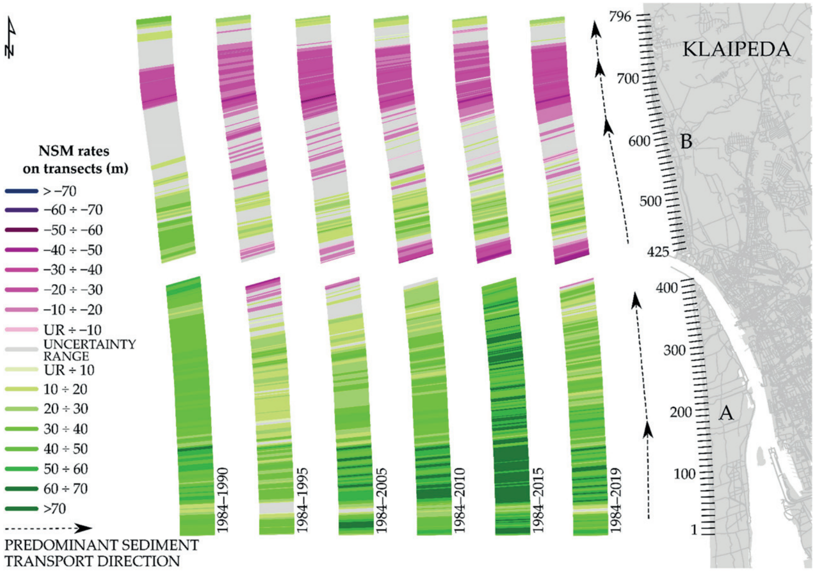


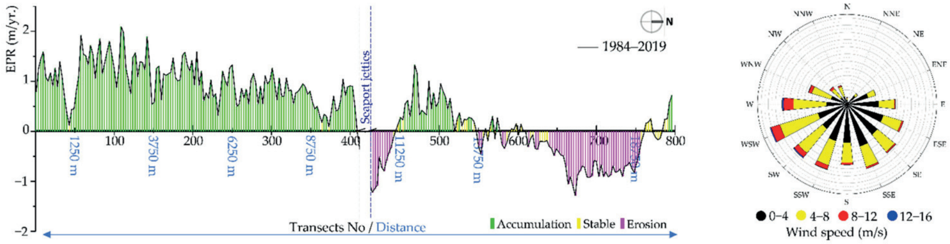
Figure 6. Net Shoreline Movement (NSM) rates 1984–2019 short-term vs long-term tendencies on the Curonian Spit coast (**A**) and the mainland coast (**B**). Annual shoreline change rates are shown on the transects graph. Purplish color tones on the transects indicate a trend of coastal erosion, while green tones indicate a trend of accretion, and grey color indicates shoreline variation values in its positioning and detection uncertainty range. Numbers and lines on the A and B coasts indicate transects distribution along the study site.

Table 2. Shoreline uncertainty range.

Years	±Uncertainty Range		Years	±Uncertainty Range	
	(m)	(m/yr)		(m)	(m/yr)
1984 * and 1990 *	±12.42	±2.07	1990 * and 1995 **	±9.13	±1.83
1984 * and 1995 **	±9.65	±0.88	1995 ** and 2005 **	±4.75	±0.48
1984 * and 2005 **	±9.67	±0.46	2005 ** and 2010 ***	±3.45	±0.69
1984 * and 2010 ***	±9.08	±0.35	2010 *** and 2015 ***	±0.95	±0.19
1984 * and 2015 ***	±9.08	±0.29	2015 *** and 2019 ***	±0.93	±0.23
1984 * and 2019 ***	±9.08	±0.26			

* T-Sheets; ** Orthophotos; *** GPS.

Comparing trends of shoreline changes in **1984–2019**, we found that the accumulation processes on the shores of the Curonian Spit accounted for 96.12% (396 out of 412) of transects. The shoreline moved towards the sea at an average speed of 1.01 ± 0.02 m/year (Figure 7), with the highest rates of the EPR 2.15 m/year. The NSM value was 35.97 ± 0.69 m, stable shoreline changes were found in 3.64% of transects and erosions in 0.24% of transects. The highest intensity of erosion processes at the Curonian Spit was recorded in 1984–1995. The negative shoreline shift towards the mainland was found in 6.07% (25 out of 412) of transects, where the average NSM value was −19.38 ± 2.50 m. Stable shoreline changes were found in 18.69% (77 of 412) of transects, and accumulation was detected in 75.24% (310 of 412) of transects with an accumulation rate of 2.17 ± 0.05 m/year, NSM value was 23.86 ± 0.52 m.



(**a**) (**b**)

Figure 7. Graph showing the distribution of EPR (**a**) and wind rose (**b**) for 1984–2019.

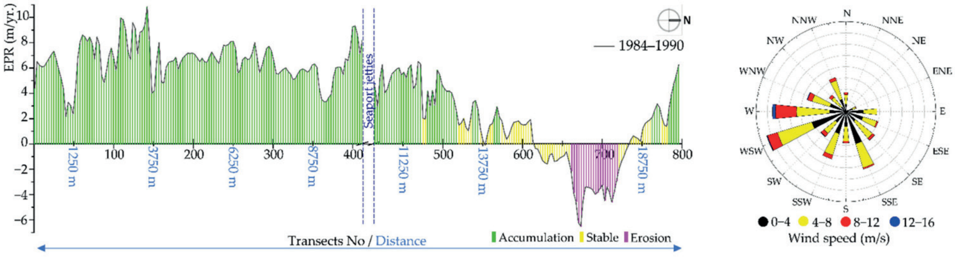
In **1984–2019**, accumulation processes occurred in 22.14% (85 out of 384) of transects on the mainland coast. The shoreline shifted towards the sea within 20.30 ± 1.04 m, with an average speed of 0.57 ± 0.03 m/year (Figure 7). Erosion during this period accounted for 43.23% (166 out of 384) of transects, and the shoreline shifted towards the mainland at an average velocity of −0.70 ± 0.02 m/year; the NSM value was −24.84 ± 0.74 m. Stable shoreline was found in 34.64% (133 of 384) of transects. Significant coastal erosion extends at the northern pier of the Port of Klaipėda −56.9 m in transect 413 (Figure 6). Accumulation processes in the accesses of Port of Klaipėda piers changed to intensive erosion, which in 2019 covered 700 m (28 transects) of the coast; the total NSM in them was −28.28 m, the EPR value was −0.76 ± 0.04 m/year.

4.2. Short-Term Shoreline Changes

Comparison of the shoreline changes in 1984–1990 and 1984–2019 showed that the area of eroded coast increased 2.7 times, from 1.50 km (60 transects) to 4.15 km (166 transects).

The effect of accumulation processes in 1984–2019 was recorded in 85 transects instead of 145 transects in 1984–1990. The accumulation rate decreased from 4.33 ± 0.11 m/year to 0.57 ± 0.03 m/year. The area of stable shores decreased from 3.325 km (133 transects) to 4.475 km (179 transects).

During the **1984–1990** period (Figure 8), the overall shoreline change was positive—the coast moved seawards on average 23.95 ± 0.76 m. During this period, the predominant wind direction was W, WSW, and the average wind speed variated from 0 to 16 m/s.



(**a**) (**b**)

Figure 8. Graph showing the distribution of EPR (**a**) and wind rose (**b**) for 1984–1990.

Accumulation was detected in all transects of the Curonian Spit coast, where the shoreline moved seawards by 12.99–65.08 m with an average velocity of 6.56 ± 0.08 m/year. On the mainland coast, the shoreline position changes were observed within the range of determination ± 12.42 m and can be considered as quasi-stable.

Coastal erosion was observed in a 1.5 km (60 transects) area to the north in the 6.2 km from the northern seaport jetty. The shoreline moved landward at an average velocity of −3.97 ± 0.13 m/year. The most significant negative change occurred in the 672nd transect and reached −41.58 m. Accumulation occurred in 37.8% of transects on the mainland coast, and here the shoreline moved seawards, with an average velocity of 4.33 ± 0.11 m/year.

In the **1990–1995** period (Figure 9), the coast has been intensively eroded, with the predominant 0–16 m/s W, WSW, SW wind direction. The shoreline moved landwards in 620 (77.9%) from 796 transects with an average of −22.85 ± 0.46 m. Significant changes in shoreline movement were observed in the immediate proximity of the seaport jetties. In the Curonian Spit coast, the maximum value of NSM was −100.85 m and was detected in the 412rd transect, next to the southern Klaipėda seaport jetty (Figure 8). The most significant shoreline movement landwards was observed in a 250 m (402–412 transects) coastal area to the south from the southern seaport jetty. Here the shoreline moved toward land on average 77.88 ± 1.11 m with an average velocity of (EPR) −15.58 ± 0.22 m/year.

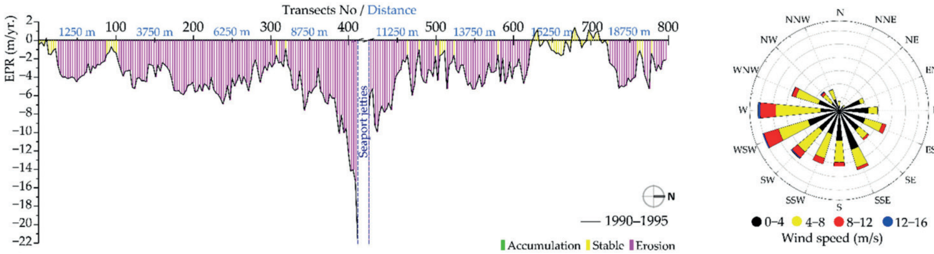
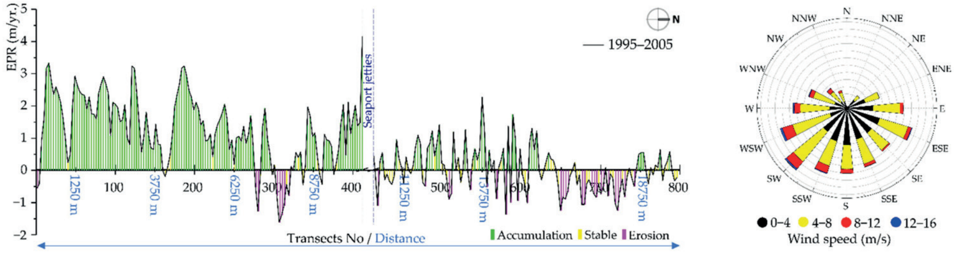


Figure 9. Graph showing the distribution of EPR (**a**) and wind rose (**b**) for 1990–1995.

65.9% of transects on the mainland coast can be described as erosive. The average change velocity reached −4.09 ± 0.10 m/year, and the shoreline moved landwards about −20.45 ± 0.51 m. The quasi-stable coast was observed in 131 transects (34.1%), and an average EPR value was 0.44 ± 0.08 m/year. The most significant shoreline movement >30 m was detected in the 419–443 transect. The maximum value was observed in the 424th transect and reached 49.61 m (EPR −9.92 m/year).

The following ten years, **1995–2005**, with the predominant SW, SSW, and WSW (0–16 m/s velocity) winds (Figure 10), had accumulative tendencies at the Curonian spit coast. The coast started recovery after the previous erosive period. Furthermore, hurricane Anatoly, which occurred in December 1999 [20], was not visible in the coastal evolution processes. It is evident that the quasi-stable part became erosive during the last five years at the mainland coast, and all other parts stayed accumulative.

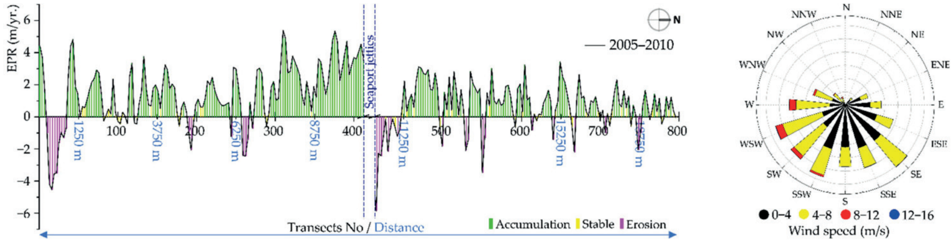


(**a**) (**b**)

Figure 10. Graph showing the distribution of EPR (**a**) and wind rose (**b**) for 1995–2005.

The total change of the shoreline in the studied area in 1995–2005 was positive and amounted to 6.72 ± 0.39 m with an EPR value of 0.67 ± 0.04 m/yr. The Curonian Spit coast was characterized as accumulative. Here accumulation processes were observed in 320 transects from 412, and the accumulation rate was 1.70 ± 0.044 m/yr. Erosion was observed in 27 transects (650 m). From 304 to 320 the transect EPR value was −1.00 ± 0.03 m/yr. From 277 to 282, the EPR value reached −0.86 ± 0.10 m/yr. The significant accumulation rate of 4.15 m/yr. (NSM 41.52) was noted in the immediate proximity of the jetties.

In the next five years, **2005–2010** (Figure 11), wind accumulation processes prevailed, with the WSW, SW, S, SE (0–12 m/s). In 61.1% of transects, the shoreline moved seawards with an averaged velocity of 2.12 ± 0.05 m/yr., and NSM value reached 10.62 ± 0.25 m.



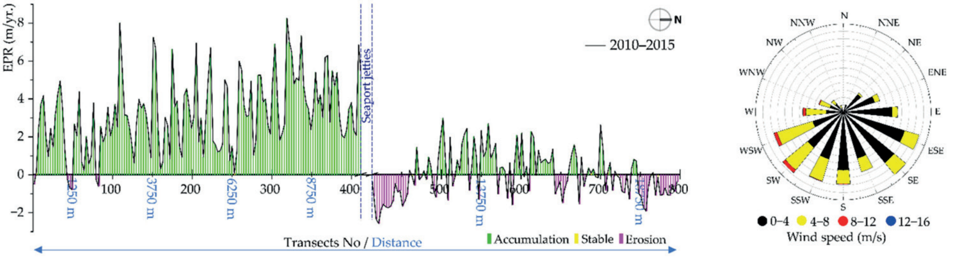
(**a**) (**b**)

Figure 11. Graph showing the distribution of EPR (**a**) and wind rose (**b**) for 2005–2010.

Accumulation processes were more frequent on the Curonian Spit coast, which was observed in 67.7% of transects. The average velocity of shoreline movement seawards was +2.42 ± 0.07 m/yr. During 2005–2010 the shoreline erosion on the Curonian Spit coast occurred only in 10.40% of transects that amounted to 1075 m out of 10.3 km. The significant erosive coastal stretch was found in the southern part of the Curonian Spit between 10 and 34 transects. In the 625 m section, the shoreline moved landwards, on average −12.82 ± 0.29 m (EPR −2.56 ± 0.26 m/yr). The maximum value of NSM was noted in the 26th transect and reached −26.69 m.

On the mainland coast, accumulation was detected in 53.9% (270 out of 384) of transects, and the shoreline moved towards the sea by an average of 8.62 ± 0.28 m. The average EPR value was 1.73 ± 0.06 m/yr. Stable shoreline changes or changes in the shoreline determination uncertainty range within ±0.69 m/yr were detected at 119 or 31% of transects. Coastal erosion was recorded in 15.1% of transects (58 transects), in which the shoreline moved landwards at an average speed of −2.01 ± 0.19 m/yr. The most significant adverse changes in the shoreline position were found between 413 and 446 transects. In this 850 m-long coast stretch, the shoreline shifted to the mainland on average by −9.64 ± 0.28 m (EPR was −1.93 ± 0.06 m/yr).

During the **2010–2015** period (Figure 12), with the predominant WSW, SW, S, SE (0–12 m/s) winds, accumulation processes were noticed in 94.9% of transects (391 out of 412 transects) on the coast of the Curonian Spit, in which the shoreline moved seawards at an average speed of 3.40 ± 0.09 m/yr. In 50% of transects (206 out of 412 transects), the shoreline shifted from land to sea by an average of 27.82 ± 0.04 m (NSM). The maximum value of NSM reached 49.67 m in the 318th transect.

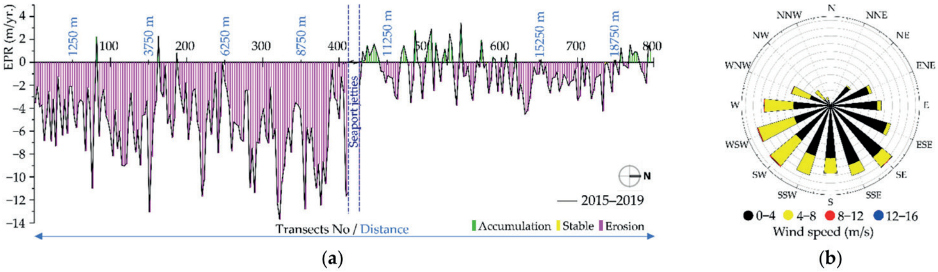


(**a**) (**b**)

Figure 12. Graph showing the distribution of EPR (**a**) and wind rose (**b**) for 2010–2015.

On the mainland coast, erosive processes were observed during 2010–2015. Negative tendencies of shoreline displacement landwards were recorded in 47.4% of transects (182 out of 384), in which the shoreline generally shifted at an average speed of −0.51 ± 0.07 m/yr. The significant shoreline movement towards land was recorded in the 1175 m shoreline section north of the northern seaport jetty (between tr. 413 and 459). The average EPR value was −1.49 ± 0.01 m/yr, and the average NSM value was −8.63 ± 0.07 m; the maximum value of EPR was −2.57 m/yr in 421 transects, and the maximum NSM value was −14.84 m. The section of the shore from 746 to 796 transects stands out. This shore of 1275 m in 2010–2015 moved towards the sea in total −5.10 ± 0.07 m, and the erosion rate reached −0.88 ± 0.01 m/yr. The central part of the mainland coast was mainly formed by accumulation processes, which accounted for 41.9% of all transects (182 out of 284). The average accumulation rate in these transects was 1.14 ± 0.06 m/yr, the value of NSM was 6.80 ± 0.34 m. Stable shoreline fluctuations of about ± 0.19 m/yr were recorded in the 41st transect.

During the last analyzed period **2015–2019** (Figure 13), the predominant wind direction was WSW, SW, SWS, S, SSE (0–12 m/s velocity) and all of the coast was erosive. Over these 4 years, the shoreline moved seawards in 80.9% of transects (644 out of 796) with the average EPR value −4.24 ± 0.12 m/yr., and NSM — −15.91 ± 0.46 m.



(**a**) (**b**)

Figure 13. Graph showing the distribution of EPR (**a**) and wind rose (**b**) for 2015–2019.

On the Curonian Spit coast, erosion processes were detected at 97.3% of transects (401 out of 412) and were 3 times more intense than on the mainland. Here the EPR value reached −5.72 ± 0.15 m/yr., and the NSM respectively was −1.80 ± 0.07 m/yr.

The mainland coast moved seawards in 63.3% of transects (243 out of 384). In the southern part of the mainland coast, 105 transects (27.3%) were accumulative with an average velocity of 1.30 ± 0.08 m/yr; here, the NSM value was 4.86 ± 0.29 m.

In 2015, the Klaipėda seaport authorities started a nearshore nourishment project in front of the mainland coast (Figure 2). As a result, the additional sediments in the longshore sediment transport system led to milder coastal erosion on the mainland coast.

4.3. Clusterization

K-Means cluster analysis was used to group the transects to identify stretches of shoreline with similar development tendencies. Net Shoreline Movement (NSM) values over the study period were grouped into five clusters (Figure 14). The NSM and SCE values and results of the cluster analysis distinguish different processes in different stretches of the Curonian Spit and the mainland coast and reflection of the influence of Klaipėda seaport piers on the morpho-lytodynamic processes of the coast.

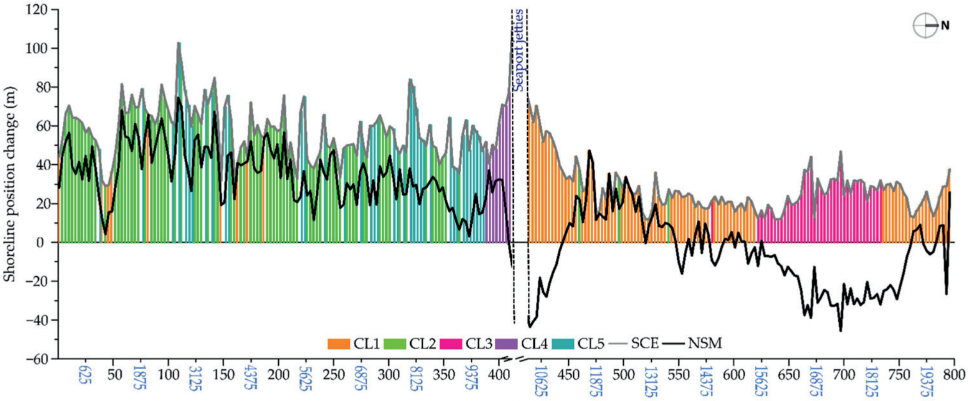


Figure 14. Graph showing the distribution of shoreline change envelope (SCE) (gray line) and net shoreline movement (NSM) (black line) along the study area for 1984–2019, and five clusters: cluster No. 1 (CL1), cluster No. 2 (CL2), cluster No. 3 (CL3), cluster No. 4 (CL4), cluster No. 5 (CL5).

The SCE corresponds closely with the NSM, implying that progressive and continuous change is more common than cyclical or reverse behavior in the spatial pattern of shoreline variability along the Curonian Spit. This stretch of coast connects Clusters No. 2 and No. 5, where the shoreline shifted towards the sea at an average of 38.93 ± 1.53 m and 27.66 ± 2.17 m, respectively (Table 1). Both clusters indicate accumulation processes on the coast. In cluster No. 2, the accumulation rate was 1.10 ± 0.04 m/yr., the SCE range was 65.14 m. In cluster No. 5, the shoreline moved towards the sea at an average velocity of 0.78 ± 0.06 m/yr. The SCE ranged between 38.01 m and 102.62 m (64.61 m). Moreover, on the coast of the Curonian Spit, Cluster No. 4 enters the southern port pier impact zone, which includes 27 transects (675 m long shoreline), where the shoreline may have different trends onshore dynamics at different times depending on hydrometeorological conditions. During the study period, the total change of the shoreline position in this cluster was positive and reached 20.74 ± 5.52 m, and the accumulation speed was 0.58 ± 0.16 m/yr. NSM values in this cluster ranged from −11.66 to 37.07 m.

The SCE closely corresponds with NSM along the mainland coast, except for the 445 and 547 transect section. The section of Cluster No. 1 is alternating, mainly due to anthropogenic activity, such as beach nourishment.

The majority (67.2%) of the mainland coast transects belong to cluster No. 1 (No. 2—3.1%, No. 3—29.7%). Four coast sections can be distinguished in this area, where the shoreline has different movement tendencies in the transects in the 675 m long section of the coast (from 415 to 442 tr.) North of the northern port jetty, erosion processes took place during the study period. The average erosion rate (EPR) was −0.64 ± 0.04 m/year, and the NSM value was −24.59 ± 1.31 m. The NSM range covered values from −4.19 m to −43.49 m, with a mean SCE of 56.74 ± 0.96 m. From 445 to 547 transects, the shoreline position changed at an average speed of 0.47 ± 0.01 m/year. The total NSM in transects was 16.67 ± 0.36 m. from −0.33 m to 47.25 m. SCE from 11.8 m to 47.25 m. In 2014–2018, by order of the Klaipėda seaport Authority, 237.78×10^3 m^3 of sand was dumped on the coast near the beaches of Melnragė-Giruliai (Figure 2).

Another group of transects from 519 to 619 in Cluster No. 1 showed slightly negative shoreline position changes, in which the shoreline moved towards the mainland during the study period by −0.05 ± 0.01 m/yr., the mean NSM value was −1.93 ± 0.30 m. SCE ranges from 15.78 m to 26.37 m, NSM from −16.07 to 10.73 m. In the northern part of cluster No. 1, from 736 to 796 transects, changes in the shoreline influenced by erosive processes were recorded. Here the shoreline changed at an average velocity of −0.20 ± 0.02 m/yr. NSM was −7.15 ± 0.72 m (from −29.23 to 25.7 m), SCE covered an overall change of 23.83 ± 0.32 m and ranged from 12.82 m to 37.52 m.

Cluster No. 3 covers the central part of the mainland coast and indicates transects in which negative trends in shoreline dynamics have occurred during the study period. The shoreline of the 117 transects of this cluster moved towards the mainland at an average velocity of −0.64 ± 0.05 m/yr. The overall change in NSM was −22.70 ± 1.74 m.

This indicates the accretion processes in the Curonian Spit coast. The clusterization approach also suggests the accretion processes on the Curonian Spit coast with positive values of SCE and NSM (Table 3).

Table 3. Net Shoreline Movement (NSM) values and Shoreline Change Envelope (SCE) values per cluster.

Clusters	Transects	SCE (m)			NSM (m)		
No.	No.	Mean	Min	Max	Mean	Min	Max
1	285	29.34 ± 1.38	11.8	70.36	4.07 ± 2.07	−43.49	65.62
2	255	55.74 ± 1.44	27.29	92.43	38.93 ± 1.53	4.3	69.97
3	117	25.41 ± 1.41	11.92	46.76	−22.70 ± 1.74	−45.53	0.7
4	27	64.25 ± 6.91	40.51	108.85	20.74 ± 5.52	−11.66	37.07
5	114	62.68 ± 2.18	38.01	102.62	27.66 ± 2.17	3.13	74.44

4.4. Meteorological Data Analysis

Changes in the wind direction are determined as the primary driver for sediment transport and drive coastal erosion [1,16,43,44]. The long-term wind direction and velocity at the studied area were analysed to indicate such changes.

The time series of yearly mean wind direction at Klaipėda is presented in Figure 15, and demonstrates changes in the regime of wind direction in the 1960–2019 period and suggests that at least two regime shifts have occurred during this period. The regime shift timings are found using a cut-off length of 10 years and Hubert's weight parameter of 1 [42]. This method detected that from 1960 till 1992, the wind direction on average was 216° (SW), then an average direction shifted to 188° (S), and the recent shift that occurred in 2011 was to 177° (S). The applied Rodionov regime shift method indicates that the average wind direction is shifting to the southern direction.

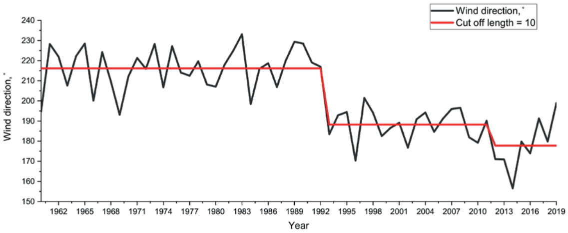


Figure 15. A shift in the annual average wind direction in Klaipėda in 1960–2019.

The first observed regime shift in the mean values of wind direction occurred in 1992 (Figure 15). At this point, we observed that the wind direction shifted to the west–south direction. This change in the regime coincides with the changes in the shoreline that occurred when erosion was observed both on the Curonian Spit and on the mainland coast. Another detected regime shift occurred in 2011 with the same shift to the southern direction. During this period on the mainland coast, erosion processes were observed, and accumulation prevailed on the Curonian Spit coast.

The frequency distribution (Figure 16) of the predominant wind direction at Klaipėda in the 1960–2019 period determines that the predominant wind, up to1995, was 270° (W). The applied Rodionov shift detection method (Figure 15) confirms that in 1995 the predominant wind direction shifted to 209° (SSW).

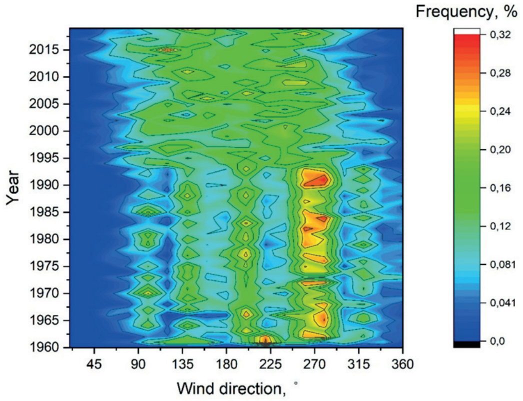


Figure 16. Frequency of occurrence wind directions at Klaipėda in 1960–2019.

5. Discussion

The Port of Klaipėda jetties location interrupts the natural longshore sediment transport path from the south to north at this point of the South-East Baltic Sea [6,23,45,46]. This should create favorable conditions for the two different processes: accumulation on the Curonian Spit south of the jetties and erosive—north of the jetties. Although the long-term analysis of shoreline changes in the whole study area indicates a total positive shoreline shift towards the sea, on the average velocity of 0.43 ± 0.03 m/yr, over the 35 years, the shoreline had different trends in both geomorphological and temporal changes. From the long-term perspective, the 10 km long Curonian Spit coast to the south of the southern Klaipėda seaport jetties is attributed to the accumulating coastal stretch. The mainland coast encompassing the northern part of the study site is affected by erosive processes.

The jettie's seaport systems on a straight sandy shore block the natural littoral drift [47,48], which determines the development of shoreline configurations. Typically, an up and down littoral drift is formed when hard breaking structures interrupt the predominant sediment transport direction. Due to the prevailing W and SW winds off the coast of Lithuania, sand transport is directed from south to north [49–52]. As a result, up-drift accretion occurs on the Curonian Spit coast on the south side of the jetties. Down-drift erosion occurs after losing its replenishment to maintain stability on the mainland coast (on the north side of the jetties).

The morphological changes of sandy beaches occur rapidly on a spatio-temporal scale as a response to natural (wind direction and speed, wave climate, sea-level fluctuations, etc.) processes [53]. Signs of climate change in the Baltic Sea can be more than just seawater level rise [54–56], increase in storminess [1], but also changes in the predominant wind and wave climate [43]. The climate change indicator in the wind regime is characterized as increasing in the wind velocity or intense wind events and changes in the predominant wind direction. This indicates changes in the cyclone patches over the Baltic Sea [57]. Changes in the wind direction and wave climate can alter longshore sediment transport magnitude and the dominant direction [58,59].

During this study, changes were observed in the predominant wind direction since 1992 (Figure 14), when the first regime shift occurred. The second shift in the wind direction regime was observed in 2012 (Figure 14). Significant changes in the predominant coastal evolution processes were observed after the wind direction shifts. Observed shifts of wind direction regime correspond with short-term changes of shoreline dynamics.

Shifts of wind direction regimes influenced intensified coastal erosion on both the Curonian Spit and the mainland coasts. In particular, the change in the wind direction regime influenced the short-term development of the Curonian Spit coast. In the periods of 1990–1995 and 2015–2019, the degree of erosion on this coast reached the respective levels of 4.57 ± 0.09 and 4.24 ± 0.12 m/year. The shoreline movement tendency of the 19th century was observed when the shoreline shifted towards the sea on both the Curonian Spit and the mainland coast [21]. This tendency reoccurred in the period of 2015–2019, on the usually accumulative Curonian Spit coast, which became erosive, while the average rate of erosion processes on the mainland coast decreased. In order to identify shoreline movement changes related to shifts in hydrometeorological conditions, a detailed investigation of wave climate (height, direction, period), sea-level fluctuations, and stormy events is required. Wave climate is driven by the wind climate [1,60] combined with the wind-driven coastal currents, and these are the major drivers for erosion and sedimentation, especially along the sandy sections of sandy beaches, dunes and soft moraine cliffs [2,61]. Future coastal process predictions are complicated as potential changes in the long-term mean and extreme wind speeds have a high uncertainty rate [1,62].

Moreover, significant changes in shoreline dynamics were observed in periods after the 2002 Klaipėda seaport reconstruction. Intensive erosion was observed on the mainland coast in the nearest proximity to the seaport jetties. Erosion after the reconstruction is acknowledged in other authors' [13,63] research. However, nowadays, as well as in the past, the main factor for the coastal erosion processes was attributed to dredging works in the Klaipėda seaport and especially in port jetty area [22,64].

Dredging works are carried out to maintain proper water levels in fairways, waterways, and ports. Work related to the extraction of bottom sediments includes various areas of activity related to their extraction, transportation, storage, cleaning, and practical use. Dredging works disturb the natural integrity of bottom sediments (benthos) and directly and indirectly impact all marine environment elements [65,66]. Sediments excavated from the Baltic Sea coast are stored in designated areas at sea or on land. Such sites are usually located near port areas for economic motives [65]. Current environmental trends encourage the recycling or practical use of excavated sediments. One of the essential practical advantages is the beach nourishment with extracted sand if it meets the established physical and chemical properties. Artificial sand nourishment can be used as a coastal erosion mitigating measure by adding sediments directly to the coast or supplementing the natural longshore sediment transport budget.

In 2014–2018, by order of the Klaipėda seaport Authority, 237.78×10^3 m^3 of fine sand was dumped on the nearshore beaches of Melnragė-Giruliai at 4–6 m depth (Figure 4). The extracted sediments from the Klaipėda strait were used to restore the mainland sediment budget and replenish the coast. Beach sand nourishment is a widely known method to widen and restore the subaerial beach and decrease coastal erosion [67–69]. The nourishment material redistribution is driven by local hydrodynamic conditions (waves and currents). The predominant longshore current is directed from south to north along the Lithuanian coast [49,51]. Therefore, to mitigate the disrupted natural sediment transport by Klaipėda seaport jetties, the sediment dumping areas are located north of Klaipėda seaport jetties (Figure 4). The grain size distribution of the sand is dominated by grains with a size of 0.1–0.25 mm, representing 70–96% of grains with an Md between 0.14 mm and 0.22 mm, which corresponds precisely to the composition of the beach sand. Such sand composition detected on the mainland coast indicates that the nourishment material is transported in a predominant longshore direction and significantly influences cross-shore profile evolution.

Understanding the short- and long-term variability of the shoreline changes could help design shore nourishment in such a way that anthropogenic activity would be carried out in coherence with natural processes rather than in conflict [70,71]. Usually, shoreline change rates are best suited for the quasi-linear trend analysis. However, values of the shoreline variation are often non-linear and have different trend reversals. It is possible to single out the behaviors of certain groups that have the same or similar tendencies of change when using a joint shoreline change rates trend and cluster-based segmentation analysis.

According to K-means clustering of long-term changes in five different short-term periods in 796 transects, 369 transects covering clusters No. 2 and No. 5 are essentially distributed at the Curonian Spit and indicate accumulation processes. The positive dynamic characteristics of this coastal stretch are essentially in line with the multi-year shoreline changes in this coast type. Moreover, they reflect the main geomorphological and sedimentary conditions of the Curonian Spit.

The Klaipėda seaport impact zone was reflected in clusters No. 1 and No. 5. Still, cluster No. 1 identifies significant anthropogenic activities or impacts on the mainland coastal stretch due to shore replenishment. At the same time, on the mainland coast further from the direct port jetties impact area [20,28], Cluster No. 3 shows the presence of other factors with a more significant impact on the shoreline evolution. The trend in the SCE indicator also distinguishes the accumulative stretch of shore from 445 to 550 transects, which proves the impact of damping of the dredged sand from the Klaipėda strait.

6. Conclusions

Forecasting and continuous estimation of the intensity of the sandy South-Eastern Baltic Sea coast dynamics are essential to customizing coastal development management methods and techniques that affect the nature and economics of the coastal environment. The analysis of long- and short-term shoreline changes should provide the required knowledge for reducing the extent of the anthropogenic intervention factors into the natural coastal system with long-lasting consequences.

This study aims to qualitatively and quantitatively identify the sandy South-Eastern Baltic Sea coast shoreline evolution tendencies. The reconstruction of Klaipėda jetties disrupted the settled equilibrium stage, interrupted the longshore sediment transport, and activated erosion processes. As a result, in the long-term (1984–2019) perspective, the northern part of the coast became abrasive, eroded coast length increased three times, from 1.5 to 4.2 km.

Assessment of short-term shoreline changes combined with K-means cluster analysis has helped identify the direct impact zone of the Port of Klaipėda. In this study, short-term shoreline changes correspond with shifts in wind direction and reflect the effect of the dredging works in the Klaipėda strait. The research helped identify the part of the mainland coast (transects from 445 to 550) that acquires other dynamic properties of the shore—accumulation. Although according to the hydrometeorological and litho-geomorphological characteristics and the impact of the port, erosion processes should prevail. It occurs due to coastal zone nourishment works. Therefore, this site needs continuous research because it is sensitive to anthropogenic and meteorological conditions. It also requires regular monitoring of the coast nourishment, as the development of coastal infrastructure, coastal use for recreational purposes, and planning of coastal protection measures depend on it.

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PAPER III

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RESEARCH ARTICLE

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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.

Keywords:
coastal erosion, coastal profiles, sediment transport, bathymetry changes

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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

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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).

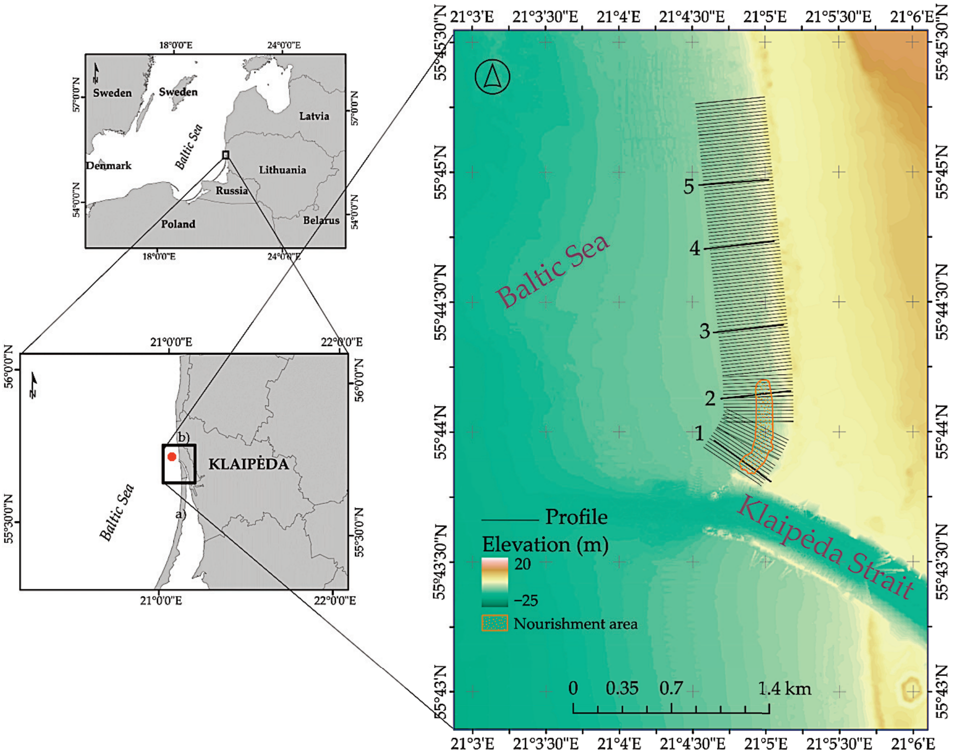

Fig. 1. Schematic map of the study site, the nourishment area, and the network of beach profiles. The red dot marks the location of the wave model grid cell centered at 55.75° N, 21.04° E: a) Curonian Spit, b) Giruliai Beach. The Port of Klaipėda is located about 2 km to the southeast along the Klaipėda 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 $Q(x_n)$ ($\mathrm{m}^2/\Delta t$) 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, $\overline{H}$ 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

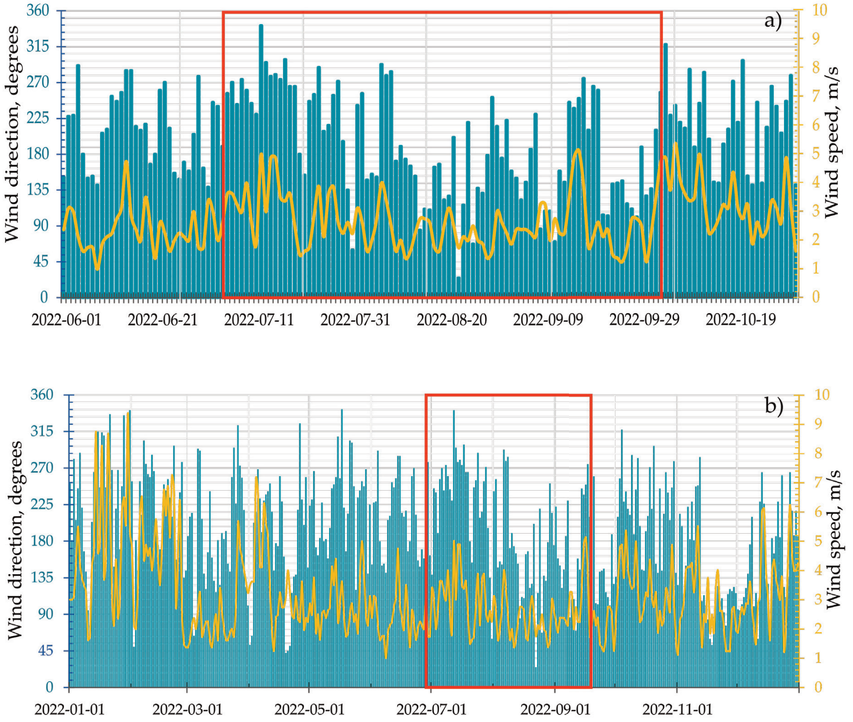

Fig. 2. Wind direction (blue bars) and speed (yellow bars) during **a**) the study period (highlighted in a red box) and **b**) the year 2022.

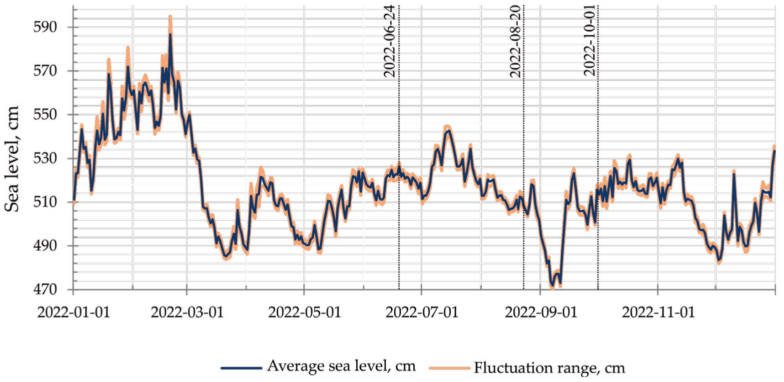

Fig. 3. Sea level during the year 2022 with the highlighted survey dates.

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

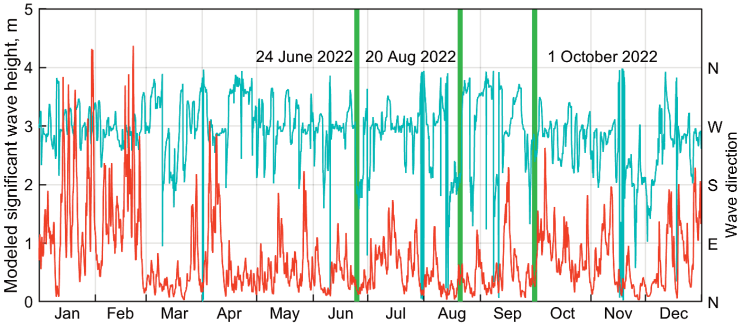

Fig. 4. Modeled significant wave height (red line) and wave direction (cyan line) during the year 2022, with the highlighted survey dates in the wave model grid cell at 55.75° N, 21.04° E (red dot in Fig. 1). Waves approaching from the east are generated by easterly winds. These short waves propagate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

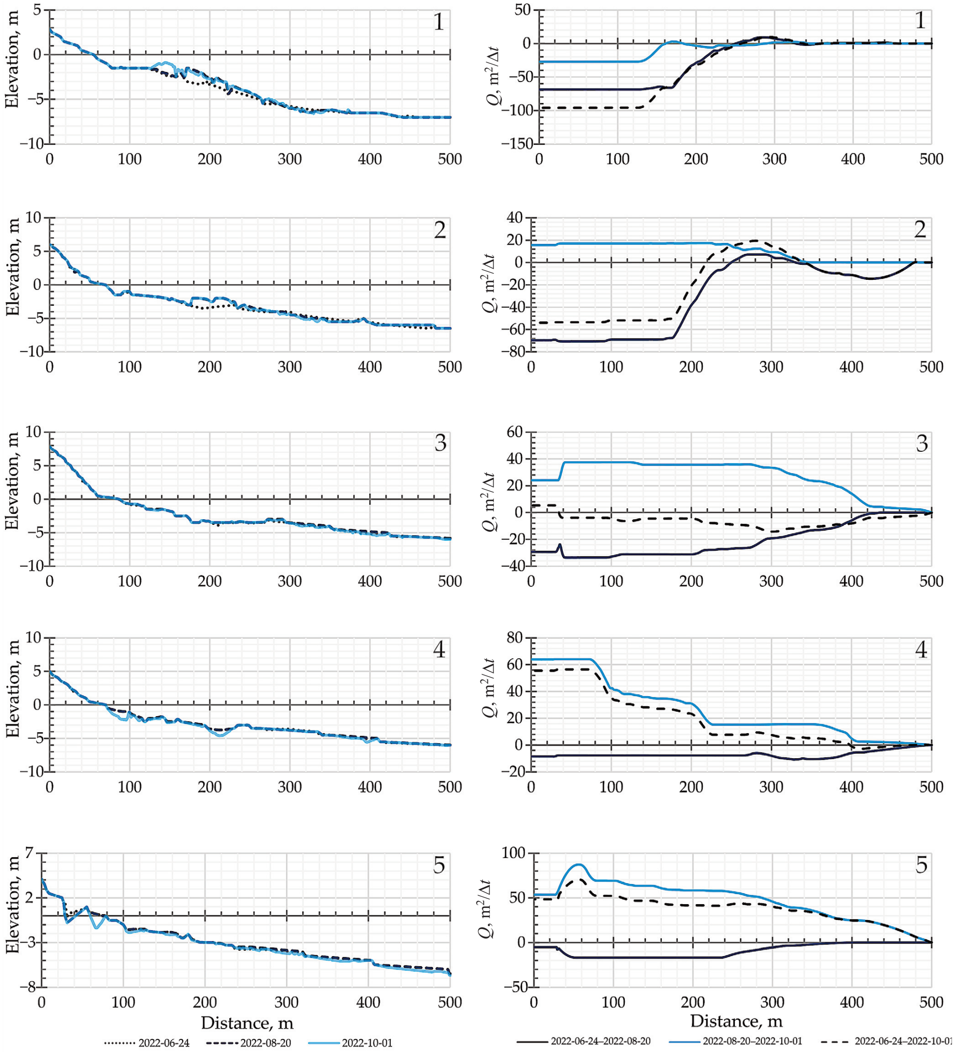

Fig. 5. Comparison of dry beach and seabed elevations along nearshore profiles (left column) and net sediment transport rates for three different periods (right column) on profiles 1 to 5 (numbers on panels; see Figs 1 and 6 for locations). The left-hand side of each panel represents the shore, while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

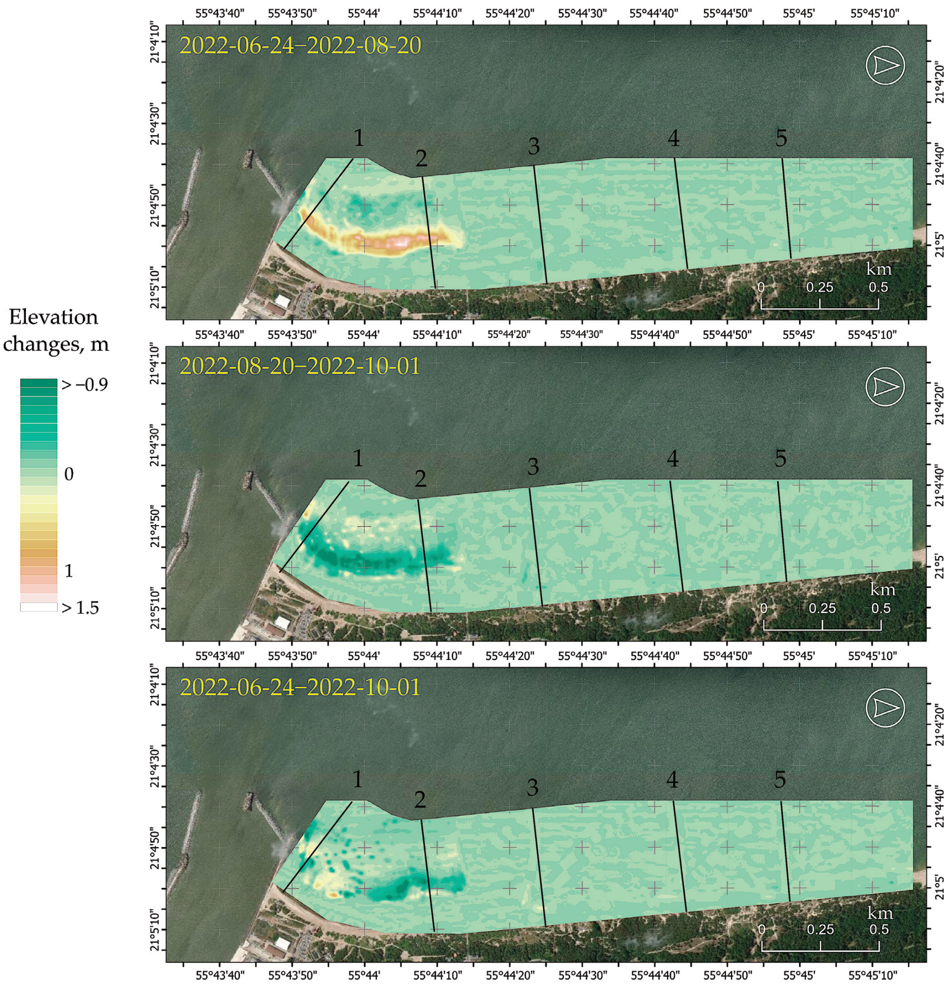

Fig. 6. Changes in seabed elevation in the nearshore area of the study site during the study period.

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, $Q = 2.6\ m^2/\Delta t$.

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 $Q = -4.1\ m^2/\Delta t$ 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 $Q = 31.2\ m^2/\Delta t$ 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 $Q = 27.1\ m^2/\Delta t$ 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 ($Q = -2.5\ m^2/\Delta t$). 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 $Q = 26.2\ m^2/\Delta t$ 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 $Q = 23.6\ m^2/\Delta t$ 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

Ilona Šakurova, Vitalijus Kondrat, Eglė Baltranaitė, Vita Gardauskė, Loreta Kelpšaitė-Rimkienė, Tarmo Soomere ja Kevin E. Parnell

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.

PAPER IV

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Review

The Need for an Environmental Notification System in the Lithuanian Coastal Area

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Abstract: The Lithuanian coastal area is divided by the jetties of the Port of Klaipėda and represents two geomorphologically distinct parts. Local companies and institutions contribute to shaping the coastal area through infrastructure development. Awareness of the changes in the coastal zone can play an important role in the planning and economic feasibility of activities in the Klaipėda coastal region. Therefore, developing a notification system that provides long– and short–term monitoring data for the Lithuanian coastal zone is necessary. In order to do so, the authors intend to create a system that should provide a link between long– and short–term observation and monitoring data for stakeholders, such as wind speed and direction, wave direction and significant height, water and air temperature, atmospheric pressure, sediment size, and distribution, height above sea level, shoreline position, beach width, change in beach protection measures, beach wreckage, and marine debris management, in order to provide timely notifications to end users.

Keywords: EASTMOC; shoreline; coastal morphology; stakeholder involvement

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1. Introduction

Sandy beaches are coastal environments that change in time and space depending on the depositional morphology and hydrodynamic behavior of the region in which they are located [1–3]. A detailed understanding of nearshore physical processes is critical to the planning and implementation of coastal development programs. Coastal geomorphology can be significantly affected by the longshore and cross–shore sediment transport in the surf zone, shoreline position changes, hydrometeorological conditions, and various human activities in the coastal area [4–7].

Hydrometeorological conditions and various human activities significantly alter the morphological characteristics of the coastal area [7–9]. The cross–shore profile is an important tool for equilibrium beach assessment, coastal structure design and construction, and coastal protection strategy planning. It is also needed in coastal models for predicting beach dynamics [10,11]. Shoreline movement is the most commonly used indicator for assessing coastal erosion or accumulation processes. It could indicate various causes, such as storms, changes in wave–wind regimes, and human activities [12–14]. Monitoring the latter features could help predict changes in morphodynamics in the coastal area. Therefore, a detailed plan for monitoring coastal morphological features, hydrometeorological conditions, and human activities is critical to establishing an environmental notification system. In addition, the forecast and early notification system also serve as a long–term management tool, as it can simulate the response to future scenarios related to changing environments, such as mean sea level rise and/or storm intensity [15].

Since local businesses and institutions are the actors that contribute to the development and planning of the study area, they are also the ones that contribute to shaping the coastal zone [16]. Timely knowledge of the changes can play an important role in the planning and economic feasibility of the activities in the coastal area of the Klaipėda region. To address this issue, the authors attempted to develop an environmental alert system for timely maintenance solutions of the coastal zone—EASTMOC. To ensure the sustainability and optimal functioning of the EASTMOC system, local stakeholders—businesses, public institutions, and NGOs operating in the study area—were approached. Interviews helped identify the data (wind, waves, currents) that stakeholders use in their day–to–day operations, data sharing practices, data gaps (depth of a slope, monitoring, and other scientific data), and relevant thresholds for different sectors. Hydrometeorological thresholds place short–term limits on daily activities in the harbor area for port authorities, passenger ferries, and commercial fishermen. They can also have long–term implications that lead to changes in strategic plans at the municipal and national levels.

As noted in previous studies by authors [17–20], air temperature and wind direction were more important than other natural factors based on Bayesian networks because their conditional probability was higher than other variables. The most influential predictors of natural factors were the temperature and the temperature of the bathing water, which were acceptable and preferable for bathing according to the recreational needs of the inhabitants of Klaipėda [17]. Hydrometeorological conditions and anthropogenic factors are the main driving force for coastal development trends [21–23]. Coastal profile assessment shows a tendency for the underwater profile to steepen near the jetties, causing waves to reach the shore with higher energy [20]. Recreational activities in the coastal zone are not among the factors contributing to the changes. However, the changes directly influence them and depend on planners' decisions to adjust and mitigate the influencing factors [20].

According to previous findings [18,19], a comparison of the shoreline changes in 1993–2003 and 2003–2022 revealed that the area of the eroded coast increased 4.4 times, from 2.73 km to 11.90 km. Significant coastal erosion extends north from the port jetties of Klaipėda with a net shoreline movement (NSM) value of −51.95 m [18,19]. Depending on the hydrometeorological and litho–geomorphological characteristics and the impact of the port, erosion processes should prevail [19,24]. Long–term changes in erosion might immediately impact society, influencing sectors such as coastal protection and shipping, among others [9,25].

The current phase of developing this concept includes creating a network of data sources to ensure the availability and accessibility of data among stakeholders. These sources are essential to the design of the overall notification system, as thresholds will be established based on these data. The aim of the EASTMOC concept is to bridge the gap in access to up–to–date data, serve as a hub for knowledge sharing, and provide early notification to various stakeholders according to thresholds established in accordance with the specifics of their activities.

The lack of a systemic approach to knowledge and data sharing is the main problem of this study. The authors of the paper operate under the premise that the shoreline, coastal evolution, and hydrometeorological data are the basis of the solution and a systemic approach to address the problem; EASTMOC being the delivery method.

This paper aims to demonstrate a proof of concept for EASTMOC and its practical potential for stakeholders operating in the study area. In addition, create an architecture for the system, address the knowledge gaps and create a knowledge–sharing platform, and determine thresholds that could limit activities or change the course of short– and long–term strategies. A pilot study was performed, and the results confirmed the feasibility of the system's idea [18].

2. Materials and Methods

2.1. Study Site

Lithuanian nearshore is a part of the Baltic Sea and has a short sandy shoreline of approximately 90.6 km [26]. The country's main harbor is located in the Klaipėda Strait on the eastern coast of the Baltic Sea, which connects it with the Curonian Lagoon [27,28] (Figure 1). During the last decade, the seaport rapidly developed and required several significant reconstructions. The last one was accomplished in 2002, including the construction of new quays and a fairway dredging [28]. These works have notably altered sediment transport processes in the Klaipėda Strait and nearshore [19,28,29]. Changes in the coastal processes are also presumed to be associated with natural factors such as regime shifts in the wind direction [19,20].

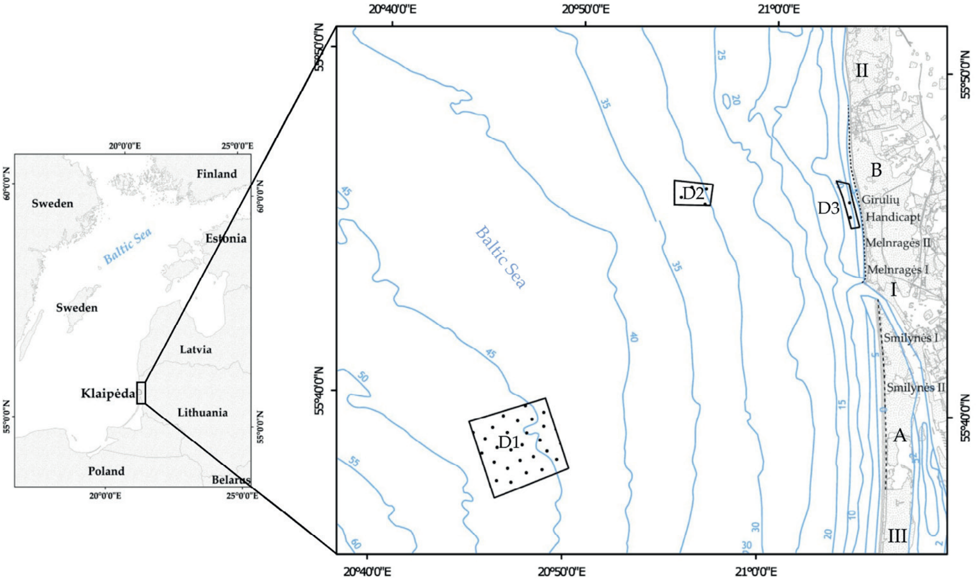


Figure 1. Overview of the study site, where I—Klaipėda, II—Klaipėda district, III—Municipality of Neringa, D1—distant dumping area, D2—near dumping area, and D3—nearshore dumping area, A—the Curonian Spit coast, B—the mainland coast.

The angular distribution of winds and the geometry of the coast is such that the wave–induced longshore sediment transport is, on average, to the north over the entire Curonian Spit and the mainland coast of Lithuania [30–32]. This prevailing pattern of sediment flux means that variations in sediment availability or transport patterns along with these areas significantly affect the sediment budget north of Klaipėda [19,20]. Although sediment flows in the spit mainly occur under natural conditions, the further transport of sediments to the mainland coast of Lithuania is hindered by the jetties of the Klaipėda port, the currents coming out of the Klaipėda Strait, the deepening of the port inlet channel and other factors [19,20].

The study area is important for recreation [17,33]. Official beaches, accommodations, restaurants, and various tourist infrastructures are located near the shoreline. Tourism is a growing sector in the region, supported by a cruise terminal that opened in 2003 [17] and increasing passenger numbers on ferry connections to Germany and Scandinavian countries. The study area is located between two national resorts—Neringa and Palanga—and has characteristics of a resort in many respects. Although Klaipėda has no status granted by law, it is a residential area that contains scientifically studied and recognized natural healing factors. It has infrastructure for the use of these factors for wellness, tourism, and recreation purposes [34]. The vegetation consists mainly of pine trees [35]. The area offers a large concentration of resources important for health tourism and health promotion, such as the coastal microclimate, the therapeutic sapropel of the lagoon, amber, coastal algae, and many others [36].

The Port of Klaipėda, located on the Baltic Sea's south–eastern shore, splits the Lithuanian coast into two geologically and geomorphologically distinct parts: southern—the Curonian Spit coast—and northern—the mainland coast. The port jetties disrupt the primary sediment movement and substantially impact the northern area of the Lithuanian coast [19,37]. Only Quaternary sediments are discovered on the Baltic Sea coast of Lithuania. Geologically, the mainland shore and the Curonian Spit coast are not homogeneous. The sediments produced during the past several glaciations largely impacted the geological structure of the continental coast [26]. The Curonian Spit coast's sediments developed in the Baltic Sea basin, beginning with the Baltic Ice Lake and ending with the present Baltic Sea stage [26]. Sandy sediments form the Curonian Spit coast: this Lithuanian coastal region is distinguished by accumulation processes. The Lithuanian mainland coast is more geologically diverse: the northern section is dominated by fine–grained sand (0.25–0.1 mm), and the southern and central parts are dominated by medium–grained (0.5–0.25 mm) and coarse–grained (1–2.5 mm) sand (Table 1) [19,38]. Since longshore sediment transport along the Lithuanian coast is directed from south to north, the mainland coast is affected by erosion, which explains the diversity of the sediment distribution [19,20,26].

Table 1. Key characteristics of the study site.

	A: The Curonian Spit Coast	**B: The Mainland Coast**
Nature protected areas	Kuršių Nerija (Curonian Spit) National Park	Baltic Sea Thalassological Reserve, Pajūris Regional Park
Natura 2000 sites	Coastal area, nearshore, and coastal zone's terrestrial areas	Coastal area, nearshore, and coastal zone's terrestrial areas
UNESCO World Heritage sites	Curonian Spit	
Designated resorts	Neringa	
Official beach	Smiltynės I, Smiltynės II	Melnragės I, Melnragės II, Handicapt, Girulių
Blue Flag sites	Smiltynės I	Melnragės II
State of shoreline	Mostly accumulative	Mostly erosive
Granulometry	Very well and moderately sorted fine sand prevails	S orting of the sediments differs in a cross–shore profile
Dumping	D1—distant dumping area	D2—near dumping area, D3—nearshore dumping area
2014	932,711 m^3	114,571 m^3 in a nearshore dumping area
2015	779,645 m^3	581,820 m^3 in near dumping area, 112,603 m^3 in nearshore dumping area
2016	672,778 m^3	47,772 m^3 in near dumping area, 29,548 m^3 in nearshore dumping area
2017	458,065 m^3	28,273 m^3 in near dumping area, 46,727 m^3 in nearshore dumping area
2018	945,482 m^3	48,898 m^3 in a nearshore dumping area
Accessibility	Waterway only	On land transportation

The two parts of the case study differ in more than geomorphological features alone (Table 1). Differences between the two areas are recognized and utilized differently by the users of the Klaipėda municipality, the district, and tourists. Both parts are held in high regard; however, their value is not equal. The entire Lithuanian coast is part of Natura 2000 sites and contains national nature–protected areas. However, only the Curonian Spit is inscribed in UNESCO World Heritage sites as a unique, vulnerable sandy wooded cultural landscape with documented Outstanding Universal Value.

Coastal areas are among the most developed and populated land areas in the world, as the majority of the world's population lives near the coast [39–42]. The same is true for tourists [43]. Beach tourism is an important pillar of the tourism industry due to the inevitable attraction of the beach [44,45]; proximity to the water and the world's oceans attracts tourists. Therefore, their preferences are the best determinant of the value of a particular destination [46]. The beaches on both sides have been used as recreational areas for many years [47]. Currently, there is a 3400 m stretch for official beaches in study area A and a 4420 m stretch in area B [17]. The larger part of the Lithuanian part of the Curonian Spit is located in the municipality of Neringa, which is a resort town. In connection with the state–recognized status of Neringa, the municipality of Klaipėda and inhabitants of Smiltynės settlement are driving a process to grant this part of the Spit the status of a resort area.

Since 2001, the Klaipėda Port entrance channel of Klaipėda harbour has been dredged, and the clean dredged sand, meeting sanitary requirements, is used to restore the sediment budget of the mainland and replenish the coast [19,29,37]. These sand replenishment campaigns have significantly impacted the Melnragė–Giruliai section of area B, where a decrease in the erosion process can be observed [19].

Since 2002, the beaches of the Curonian Spit in the municipality of Neringa have been awarded the Blue Flag. Since 2017 (Smiltynės I) and 2018 (Melnaragės II), the beaches in the study area have also received this recognition.

The Curonian Spit has a land connection via the Russian Federation, as the two neighboring countries share the Spit. However, this access is restricted by the visa regime in the usual circumstances. Currently, access is completely closed due to the closed border between the two countries, leaving locals and tourists to predominantly rely on the regular ferry connection and continue by road. Meanwhile, anyone wishing to visit the mainland coast has much easier access through various land transport options.

The construction of a bridge between Klaipėda and the Curonian Spit has been debated for decades. This highlights another significant difference between the two areas—building restrictions and development limitations that come with the exceptional value of the Curonian Spit [48].

2.2. Data Sources

Shoreline: aerial maps, orthophotos, and survey datasets from GPS determined shoreline positions from 1993 to 2022. A dual–band "Leica 900" GPS receiver measured the shoreline position in the swash zone's middle. Historical shoreline positions were measured every 25 m along the shoreline in 800 transects. Shoreline position changes were analyzed with the ArcGIS extension DSAS v. 5.0 (Digital Shoreline Analysis System) package [49], developed by the United States Geological Survey (USGS).

Coastal elevation: the analysis of coastal geomorphology and underwater elevation changes was calculated from bathymetry data from 1993–2022 using Global Mapper software [50]. It indicated that reconstruction works and continuous dredging of Klaipėda harbor affected the sediment budget along the study area. Bathymetry data were obtained from the Klaipėda Port Administration with a grid resolution of 0.5 m and from the Lithuanian Geological Survey with a grid resolution of 1.5 m. The data provided were obtained using a Kongsberg EM2040C multibeam echo sounder in accordance with the International Hydrographic Organization's Standards for Hydrographic Surveys S–44 [51].

Hydrometeorological: the hydrometeorological data used for this study were obtained from the Marine Environment Assessment Division of the Environmental Protection Agency, the Lithuanian Hydrometeorological Service, which is under the Ministry of Environment, the Palanga Aviation Meteorological Station, and the National Oceanic and

Atmospheric Administration. Data were initially collected at the Klaipėda meteorological station on the Lithuanian Baltic coast and processed by the authors. The Klaipėda meteorological station is located near the Klaipėda Sea port jetties.

2.3. Methods

Analysis of long–term trends in shoreline changes showed that the stable operating processes of shoreline formation, which determine and form the balance of shoreline change, have intensified due to the anthropogenic impact of port reconstruction.

Shoreline positions were determined from aerial photo charts, orthophotos, and GPS survey data sets. The shoreline position was measured in the middle of the swash zone by a dual–band GPS receiver, "Leica 900". Historical coastline positions are measured every 25 m along the coastline. Three coastline positioning and detection errors were calculated [52]:

(1) for the aerial photo charts

$$Ut = \pm(Es^2 + Ed^2 + Ep^2 + Etc^2 + Ec^2)^{1/2}, \tag{1}$$

(2) for the orthophotos

$$Ut = \pm(Es^2 + Ed^2 + Ep^2 + Er^2 + Ec^2)^{1/2}, \tag{2}$$

(3) for the GPS survey data

$$Ut = Ut = \pm(Es^2 + Ec^2)^{1/2} \tag{3}$$

where Es—sea–level fluctuation error, Ed—digitization error, Ep—pixel error, Ec—shoreline line detection or resolution errors, Etc—T–sheets plotting errors, and Er—rectification error. Shoreline position changes were analyzed with the ArcGIS extension DSAS v. 5.0 (Digital Shoreline Analysis System) package [49], developed by the United States Geological Survey (USGS).

Analysis of the coastal geomorphology and underwater slope changes were calculated from the bathymetry data using Global Mapper software [50] and helped identify that the reconstruction works and the continuous dredging of the Klaipėda port influenced the sediment budget along the study area. In the period of 2003–2022, about 2.5 km north of the port jetties, a bottom sediment deficit was observed, where the coastal elevation has lowered about 5–7 m. The sediment loss during seaport reconstruction corresponds to hydro–technical constructions and changes in their configuration. The Port of Klaipėda's north jetty site has been altered, and the entry channel has narrowed, creating changes in nearshore hydrodynamics and sediment movement [20]. Throughout the study period from 1993 to 2022, a steepening of the undersea bottom profile was detected in close proximity to the Port of Klaipėda jetties; as a result, waves reached the beach with more intensity [20].

3. Results and Discussion

3.1. Background for EASTMOC

The location of the Port of Klaipėda jetties interrupts, at this point of the south–eastern Baltic Sea, the natural path of longshore sediment transport from south to north [19,20,29,31,53]. This should create favorable conditions for two different processes: accumulation on the Curonian Spit south of the jetties and erosion north of the jetties. Although the long–term analysis of shoreline changes in the whole study area indicates a total positive shoreline shift towards the sea, at an average velocity of 0.43 ± 0.03 m/yr, over the 35 years, the shoreline had different trends in both geomorphological and temporal changes [19]. In the long term, the accumulated coastal stretch includes the 10 km shoreline of the Curonian Spit south of the southern Klaipėda seaport jetties [19]. The mainland coast, which comprises the northern part of the study area, is affected by erosive processes [19,20].

The grain size distribution of sediments is a natural result of sediment transport processes, mainly related to erosion and accumulation [54–56]. During the study period from 2003 to 2022, the grain size of sediments on the mainland coast became finer and more evenly distributed in the profiles. This could be due to the beach replenishment works carried out by the authorities of the Port of Klaipėda. On the other hand, sediments became coarser on the Curonian Spit coast between 2003 and 2022. This observation confirms the authors' statement of previous works, in which the coastal erosion on both coasts was determined [19,20].

Hydrometeorological data alone could not explain current changes. It is a common understanding that there should be a holistic approach to the question and use of modeling. This is to ensure that decision–makers operating in the Klaipėda coastal zone are well–informed about the causation of coastal dynamics. The authors of the study attempt to do so in a timely manner so that needed decisions can be made and implemented in due time. Development of the EASTMOC system results from this collaboration, where stakeholders are the initiators.

Net shoreline movement analysis for the entire study period 1993–2022 confirmed that 39.05% of the shoreline was erosive, 34.04% accumulative, and 26.53% was stable or within the range of uncertainty ±5.02 m (Figure 2). The Curonian Spit coast's net volume was $-2{,}615{,}669.7$ m^3, whereas the mainland coast's net volume was $-429{,}631.47$ m^3, according to Global Mapper's (Figure 2) calculations for 1993 to 2022. Net sediment volume on the mainland coast was $-348{,}070.61$ m^3, and on the Curonian Spit was $-4{,}633{,}217.1$ m^3 in 1993–2003, before the reconstruction of Klaipėda seaport, which took place in 2002. Sediment loss on the mainland coast increased to $-1{,}520{,}535.2$ m^3 in the years following reconstruction, from 2003 to 2022, compared to the prior years. In contrast, the Curonian Spit experienced a decrease in sediment loss to $-553{,}413.63$ m^3 [20].

Endpoint rate shoreline change for 1993–2022 confirmed that accumulation processes dominate the Curonian Spit coast while the mainland coast is eroded (Figure 3). The most significant erosion occurrence was observed in the nearest proximity to the northern port jetty. In the period after the Port of Klaipėda reconstruction, erosion processes intensified on both the Curonian Spit and mainland coasts (Figure 3) [19]. During 1993–2022 on average, the shoreline changed by –0.01 ± 0.04 m/yr, meaning that the shoreline moved landward on both coasts. In the period before the Port of Klaipėda reconstruction, 1993–2003, the endpoint rate on average was 0.67 ± 0.07 m/yr, and in the period after reconstruction, 2003–2022, the erosion rate increased on average to –0.35 ± 0.04 m/yr (Figure 3).

The need for the alert system occurred after several meetings with stakeholders concerning the research the team is currently carrying out. In 2022 it was especially true when the planned coastal protective measures were carried out—the beach enrichment campaign in the northern part of the Klaipėda coast in Spring. Even though the weather conditions were stable, coastal erosion was prominent and raised the concern of the Municipality and port authorities. The Port of Kaipėda is also highly affected by the Curonian Lagoon processes [57,58], and the annual dredging campaign is essential to ensuring its activities' stability [59,60]. More context is needed to operate in the area and make informed, sustainable decisions. A knowledge gap exists regarding long and cross–shore sediment transport in the Curonian Lagoon and the Baltic Sea. Those processes are evaluated based on the literature [31,61–63], as no actual data or research has been done in this area. Researching long– and cross–shore sediment transport in the study area would require funding and technical solutions.

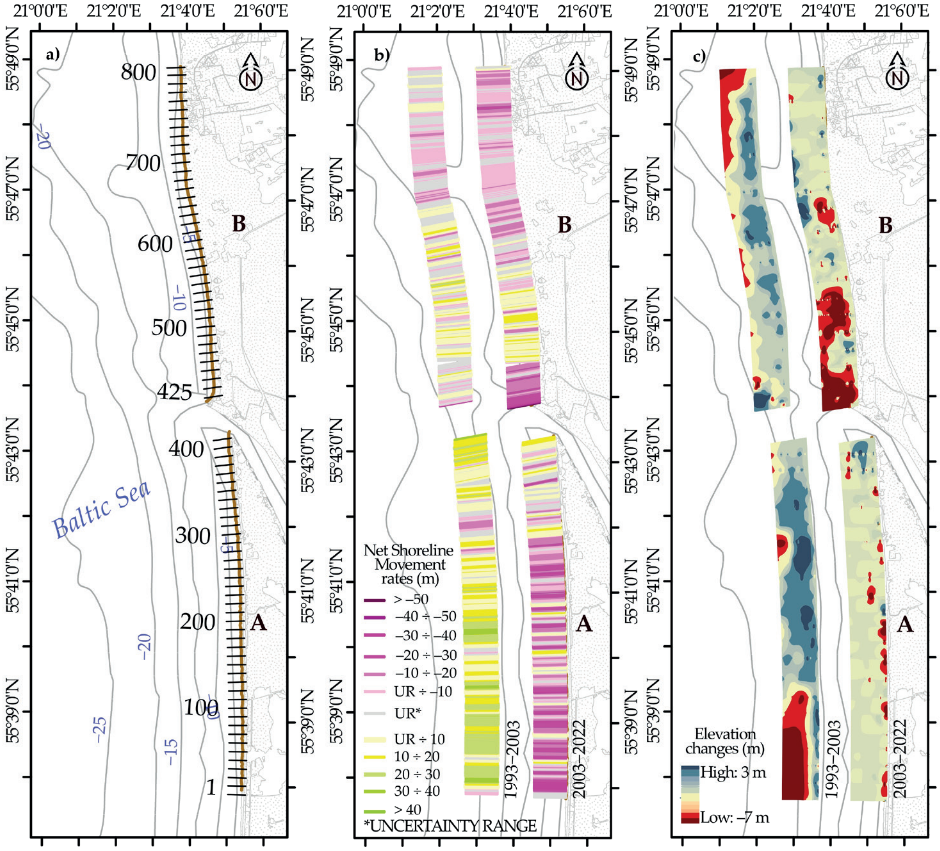


Figure 2. (**a**) Transect positions along the study area, (**b**) net shoreline movement (m) during 1993–2003 and 2003–2022 along the study area, and (**c**) elevation change for 1993–2003 and 2003–2022, including underwater and onshore parts on both the Curonian Spit (A) and mainland (B) coasts (Adapted from Kondrat et al. 2023 [18] and Šakurova et al. 2023 [20]).

3.2. Pilot Study

Stakeholder mapping was performed in the first step of the pilot study, and all actors in the Klaipėda Port impact area were identified alongside possibly affected institutions and organizations. The pilot study was performed in cooperation with ten selected stakeholders that provided the following data: relevant information on natural factors that is essential to their continuous operations, information gaps, and main thresholds limiting their day–to–day operations and/or planning strategies. Selected stakeholders include the main actors operating in the area: Klaipėda State Sea Port Authority, the biggest operator acting on the national level, SC "Smiltynės perkėla" provides regular passenger ferry connections to the Curonian Spit; Lithuanian Transport Safety Administration and others.

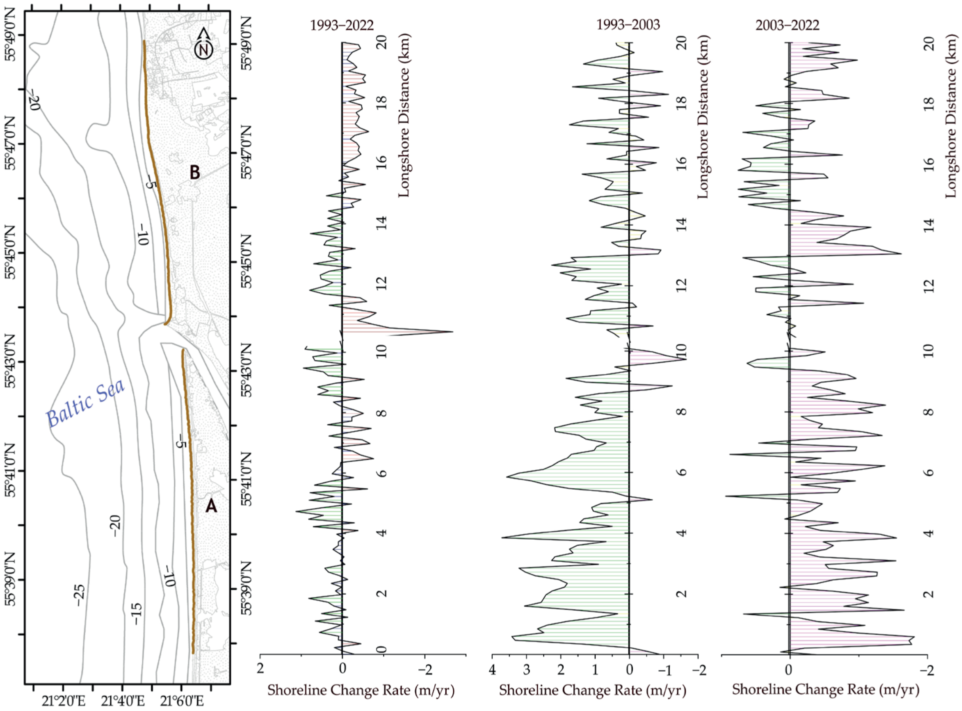


Figure 3. Endpoint rate shoreline change (m/yr) for periods 1993–2022, 1993–2003, and 2003–2022 on the Curonian Spit (A) and mainland (B) coasts.

The most relevant data on natural factors used for day–to–day operations and future plans were indicated as follows: beach width and length, underwater slope (depth), shoreline position, significant wave height and direction, wind speed and direction, and current speed and direction, ice cover, and visibility. First, important gaps were identified as nearshore bathymetry (0–6 m depth), hydrological data of rivers and the Curonian lagoon, and easy access to real–time hydrometeorological data.

Various stakeholders act in a small area, and their activities depend on different variables and the nature and scale of their operations. For example, the need to limit operations of passenger ferries occurs at the following conditions (to name a few): wind speed 14 m/s; southwest 240°, west 270° turning north 300°; long waves—southwest/west direction. Monitoring operations and shipping of small vessels in the nearshore area can be limited at a wind speed of 7 m/s and above a wave height of 1.5 m.

Stakeholders also identified that shoreline position is the most commonly used indicator for assessing coastal erosion or accumulation processes and is important for the long–term planning of their activities. Port reconstruction, planning, and beach nourishment depend on the long–term changes as they could serve as a prediction model.

The gathered data supports the need for sharing knowledge in a timely manner. The team concluded that, for the moment, it is possible to cater to several select stakeholders and provide monitoring data and personalized alerts. However, the datasets need to be continuously updated daily. This creates a need for an automated system and timely data input in order to support the idea of the study—to provide access to the database to every interested institution or possibly on a personal level.

3.3. EASTMOC System

In order to provide timely notifications to end users, the EASTMOC system (Figure 4) is intended to create a link between long– and short–term observation and monitoring data to stakeholders, such as wind speed and direction, wave direction and significant height, water and air temperature, atmospheric pressure, sediment size and distribution, cross–shore elevation, shoreline position, beach width, change in beach protection measures, beach wreck, and marine debris management.

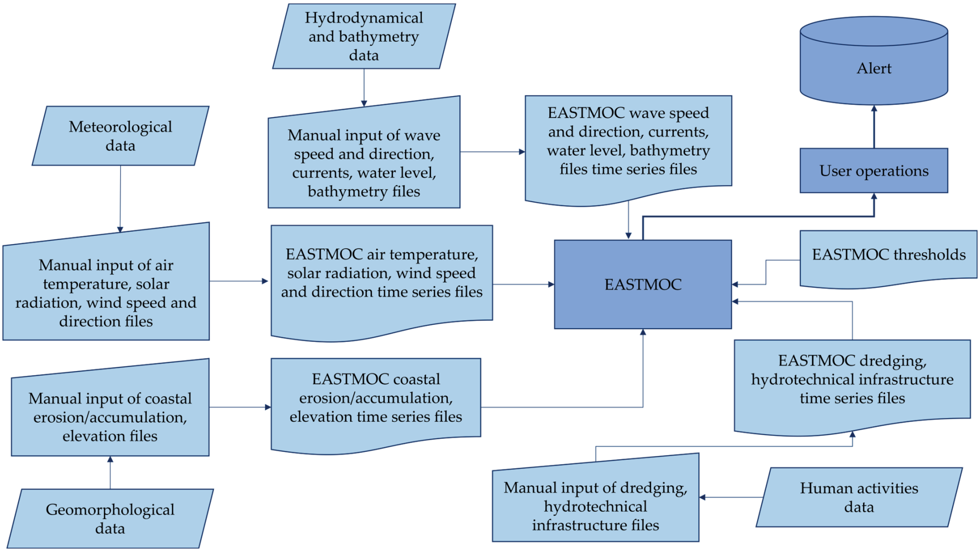
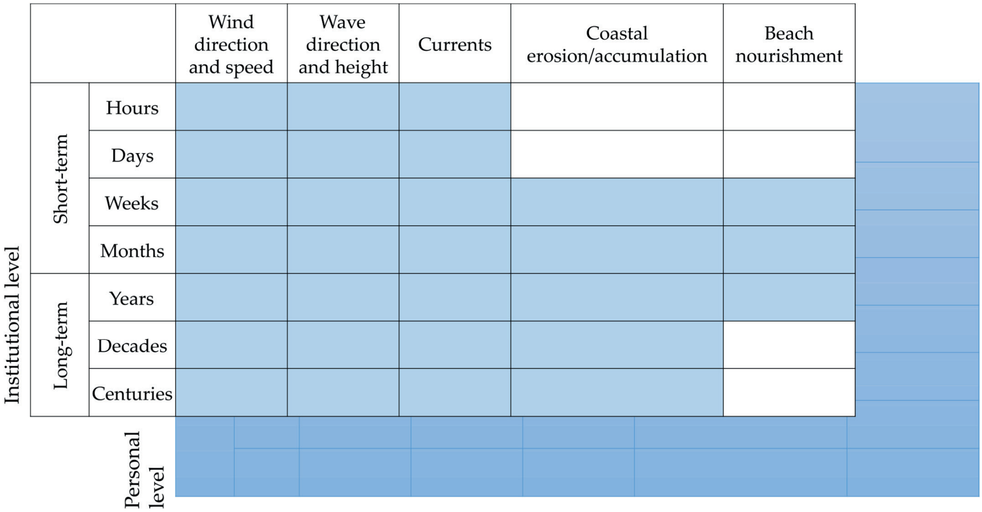


Figure 4. Conceptual diagram of the EASTMOC system.

Local businesses and institutions contribute to shaping the coastal area through infrastructure development. Awareness of the changes in the coastal zone can play an essential role in the planning and economic feasibility of activities in the Klaipėda coastal region. Therefore, to ensure the sustainability and optimal functioning of EASTMOC, local stakeholders—businesses, public institutions, and non–governmental organizations operating in the study area—were consulted. Discussions with stakeholders helped identify the data (e.g., wind, waves, currents) they use in their day–to–day operations, data sharing practices, data gaps (slope depth, monitoring, and other scientific data), and relevant thresholds for various industries that form the basis for the EASTMOC notification system (Figure 5).

To identify and predict trends in various processes, looking at long–term data spanning years, decades, or even centuries is necessary. Such time scales reveal how the system under study behaves under different processes or conditions. For example, how changing wind directions and velocities alter certain sections of the beach (erosion or accumulation). Such long–term data are important to companies and institutions operating in the coastal zone because they determine their long–term strategic plans, coastal zone infrastructure development, and beach replenishment needs. In the short–term, coastal zone changes may interest local residents, transportation companies, port operations, tourists, and extreme sports enthusiasts.



		Wind direction and speed	Wave direction and height	Currents	Coastal erosion/accumulation	Beach nourishment
Institutional level	Short-term	Hours	▨	▨	▨		
		Days	▨	▨	▨		
		Weeks	▨	▨	▨	▨	▨
		Months	▨	▨	▨	▨	▨
	Long-term	Years	▨	▨	▨	▨	▨
		Decades	▨	▨	▨	▨	
		Centuries	▨	▨	▨	▨	
Personal level							

Figure 5. EASTMOC database structure, where the personal level is planned as a further study step.

The chosen tool for implementing the EASTMOC system is Bayesian Networks (BNs). The Bayesian Network's approach is particularly useful in complex systems where multiple factors interact to produce outcomes [64]. By incorporating a wide range of variables, the model can capture the distinctions and interdependencies of the system, leading to more accurate predictions and better–informed decision–making. Additionally, the iterative nature of the modeling process allows for ongoing alteration and improvement as new data and insights emerge. This can lead to a more robust and adaptable model that can respond to changing conditions over time. Overall, the use of systems thinking and integrated modeling approaches has the potential to revolutionize our understanding of complex systems and inform more effective strategies for sustainably managing them.

As previous research from the authors shows [17], the Bayesian Networks application will provide a continuous evaluation of understanding as new information occurs, each time updating the probability that something is true. The BN modeling methodology helps to represent the causal relationships of a system in the context of variability, uncertainty, and subjectivity; elicits subjective expert opinion; and provides a framework for model improvement as new data and knowledge become available [64].

The pilot study results demonstrate a proof of concept for the EASTMOC and its potential value for stakeholders operating in the study area. The architecture of the system addresses the knowledge gaps. It has the potential to provide a knowledge–sharing platform as well as determine thresholds that could limit activities or change the course of short and long–term strategies in the study area or could be applied in other areas in the future.

4. Conclusions

The development of EASTMOC drew the research team's attention to the distinctions between two different sides of the study area. In addition to geomorphological differences, the two parts also differ regarding access, social and economic values, and use. Therefore, their evaluation in the system should be done separately and comprise unique data sets.

The pilot study and the identified thresholds proved the need for a notification system. Moreover, the stakeholder initiative has identified the features and characteristics of the coastal area that need to be monitored more closely. Their participation underpins the feasibility of a functioning system.

Further steps are needed to advance the development of the EASTMOC into a fully functional system. It is expected that stakeholders and various actors in the Klaipėda Port impact area will initially use the system. Additional funding will be required to make the system available to the general public.

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PAPER V

EASTMOC: Environmental Alert System for Timely Maintenance of the Coastal Zone

By Vitalijus Kondrat, Ilona Šakurova, Eglė Baltranaitė, and Loreta Kelpšaitė-Rimkienė

Healthy beaches are essential for managing the coastal zone, including growing coastal tourism, maintaining seaside property values, developing infrastructure, and sustaining coastal ecosystems and communities. Beaches worldwide face problems such as erosion and shoreline recession caused by both natural factors and anthropogenic pressures. Beach erosion is caused by short-term fluctuations such as storms or by longer-term processes related to sediment budget deficits, rising sea levels, and wave regime changes. Responsible beach management requires precise knowledge of the short-term fluctuations and long-term processes involved in coastal evolution in order to assess the risks to infrastructure and to identify acceptable weaknesses in future development or in coastal management. Knowledge of short- and long-term shoreline changes could also contribute to the design of beach nourishment plans so that human activities can be conducted consistent with natural processes rather than in conflict with them.

This study focuses on the need for an Environmental Alert System for Timely Maintenance of the Coastal Zone (EASTMOC) along Lithuania's Baltic Sea coast. It is based on coastal research conducted in the Port of Klaipeda. Because this area is affected by constant dredging of the port, intensive shipping, recreational zones, and continuous reconstruction of jetties, it is important to create an environmental alert system for timely port maintenance.

THE KLAIPEDA PORT IMPACT ZONE

The Lithuanian Baltic Sea coast is affected by wind and waves from a wide range of directions. The study site was chosen based on its (1) broad spectrum of recreational uses, (2) high risk of coastal erosion, and (3) possibility of direct and indirect anthropogenic impacts.

The Port of Klaipeda is located at the Klaipeda Strait and divides the Lithuanian coast into two morphologically and geologically diverse parts: the Curonian Spit coast to the south and the mainland coast to the north (Figure 1; Bitinas et al., 2005). The port's jetties disturb the main sediment transport path (from south to north) along the Lithuanian coast and significantly influence its northern sector.

Analysis of long-term trends in shoreline change show that shoreline formation processes, which determine and form the balance of shoreline change, have intensified due to port reconstruction. Net shoreline movement analysis for the entire 1993–2022 study period (Figure 2) shows that 39.05% of the shoreline was erosive, 34.04% was accumulative, and 26.53% was stable or within the range of uncertainty (±5.02 m). A comparison of shoreline changes for the periods 1993–2003 and 2003–2022 shows that the area of eroded coast increased 4.4 times, from 2.73 km to 11.90 km. Significant coastal erosion (−51.95 m) extends north from the port jetties of Klaipeda. Shoreline positions were determined from sets of aerial photo charts, orthophotos, and GPS survey data. Measurements of coastline position were collected in the middle of the swash zone using Leica 900 dual-band GPS receivers. Historical coastline positions were measured every 25 m along the coastline. Three coastline positioning and detection errors were calculated (see Crowell et al., 1993), and shoreline position changes were analyzed with the ArcGIS extension DSAS v. 5.0 (Digital Shoreline Analysis System) package developed by the US Geological Survey.

Coastal geomorphology and underwater elevation changes calculated from bathymetry data using Global Mapper software helped to identify that reconstruction and continuous dredging of the Port of Klaipeda influence the sediment budget along the study area. In the period 2003–2022, about 2.5 km north of the port jetties, a bottom sediment deficit was observed, with the coastal elevation reduced by about 5–7 m (Figure 2).

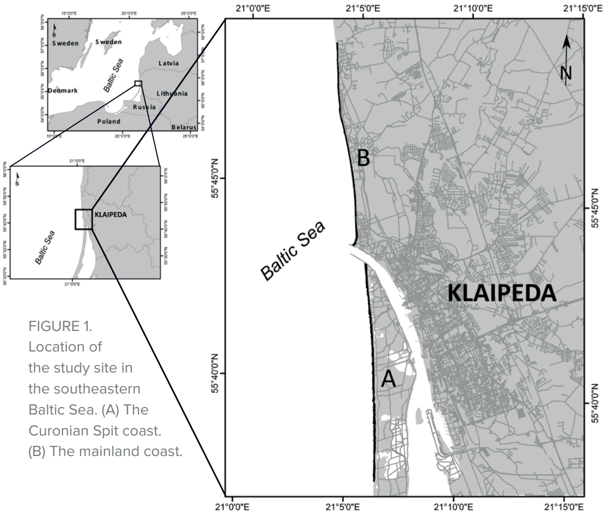

FIGURE 1. Location of the study site in the southeastern Baltic Sea. (A) The Curonian Spit coast. (B) The mainland coast.

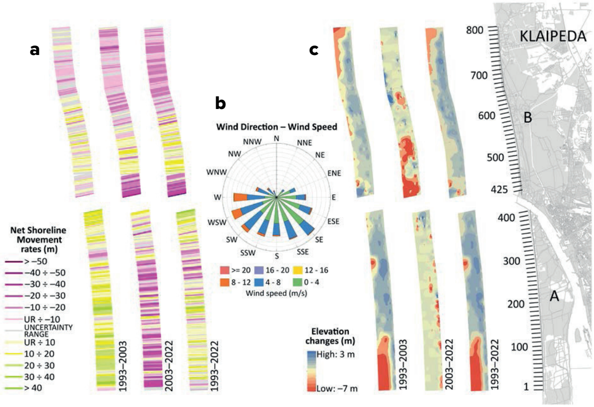

FIGURE 2. (a) Net shoreline movement rate tendencies on the (A) Curonian Spit coast, and (B) mainland coast. (b) Wind direction and speed (m s^{-1}) during 1993–2022. (c) Coastal zone elevation changes (m) on the (A) Curonian Spit coast, and (B) mainland coast.

FIGURE 3. Essential inputs to EASTMOC.

EASTMOC

EASTMOC combines research and monitoring of coastal morphological features, hydrometeorological conditions, and human activities, which are critical inputs to an environmental warning system (Figure 3). In order to ensure that EASTMOC addresses stakeholders' needs, interviews with stakeholders helped to identify the data they use in day-to-day operations (e.g., wind speed and direction, wave direction and height, water and air temperatures, atmospheric pressure), data gaps, and data sharing practices, as well as to determine the relevant thresholds for various industries. Stakeholders are interested in hydrometeorological thresholds because they limit the activities of port authorities, passenger ferries, and commercial fishermen. For example, strong winds (≥15 m s^{-1}) limit local passenger ferry traffic, interrupting transportation links to the Curonian Spit. They also disrupt port activities, sometimes resulting in port closures to ship traffic for several hours or days. In addition, the long-term effects of local hydrometeorological conditions can lead to adjustments in municipal to national-level strategic plans.

Bayesian networks are well suited for explicitly integrating both prior knowledge and information obtained from daily environmental observations. As determined in previous studies based on Bayesian networks, there is a correlation between socioeconomic and natural factors, such as air and water temperature, the presence of dunes and sandy beaches, and tourists' recreational needs (Baltranaitė et al., 2021). EASTMOC will include quantitative assessment and prediction modeling based on the Bayesian networks to ensure sustainable planning and operation of all parties active in the study area. The current stage of development of EASTMOC includes creating a network of data sources to ensure data availability and accessibility among stakeholders. These sources are essential to the alert system concept, as the thresholds will be set based on these data.

The database compiled in EASTMOC will be directed to the stakeholders and end users. Stakeholders involved in the development of EASTMOC will receive tailored alerts generated according to the thresholds that are relevant to their specific activities. While some end users require simple wind speed and direction warnings, others need more complex correlation of several data sets. However, EASTMOC may become relevant to the general population and further adapted on a smaller scale. For instance, beachgoers and extreme watersport enthusiasts may benefit from strong wind warnings while planning a day out, as strong winds may not be favorable for sunbathing but beneficial for extreme sports.

EASTMOC has the potential to fill the gap in access to current data, serve as a hub for knowledge sharing, and provide early warning to stakeholders in accordance with the thresholds set up in line with the specifics of their activities. Though our study area is significant on a regional scale, our research methodology can be adapted to assess similar coasts worldwide.

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Klaipėdos universiteto leidykla

Ilona Šakurova
ASSESSMENT OF SEDIMENT TRANSPORT ON LITHUANIAN SHORES OF THE BALTIC PROPER UNDER CHANGING NATURAL FACTORS AND ANTHROPOGENIC LOADS
Doctoral dissertation

NEŠMENŲ TRANSPORTO VERTINIMAS LIETUVOS KRANTO ZONOJE,
KINTANČIŲ GAMTINIŲ VEIKSNIŲ IR ANTROPOGENINĖS APKROVOS SĄLYGOMIS
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