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Multiparametric Subaqueous Dataset for the South Baltic Sea: Lubiatowo case study

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Abstract. This study presents bathymetric and side-scan sonar surveys conducted in the remote nearshore zone of the southern Baltic Sea, approximately 1–2 nautical miles offshore near Lubiatowo, at water depths of 16–20 m. Measurements were collected during five field campaigns in November 2017, December 2018, and three in 2023 (April, September, and December), and processed to generate detailed bathymetric maps and sonar mosaics. These maps accurately reflect seabed conditions and highlight morphological changes over time.

In addition to the bathymetric surveys, divers performed seabed observations, documented bedform appearances, and collected seabed soil samples for grain size analysis. Underwater videos and photographs were captured using an underwater drone equipped with a ruler, ensuring precise measurement references.

The analysis includes differential bathymetric maps showing seabed elevation changes ranging from a few centimeters to more than 1 m over time intervals spanning several months to multiple years. Sonar imagery and subaqueous photographs document ripple fields and other seabed features of varying scales, providing complementary information for interpreting seabed morphology.

1 Introduction

This research explores bathymetric and sonar survey data collected from the remote nearshore zone of the South Baltic Sea, located about 1–2 nautical miles from the Polish coast near Lubiatowo, in the vicinity of the Coastal Research Station (CRS) in Lubiatowo, where water depths range from 16 to 20 m. The surveys, conducted with a high-resolution multibeam echosounder, spanned five field campaigns: November 2017, December 2018, and three in 2023 (April, September, and December). These data were processed to produce detailed bathymetric maps and sonar mosaics.

Alongside the surveys, divers undertook direct observations of the seabed, recorded bedform features, and gathered sediment samples for grain size analysis within the measurement polygon. To ensure accurate measurements an underwater drone equipped with a visible ruler for scale reference was used to capture video and photographic evidence.

The diverse seabed surveys in the vicinity of the Coastal Research Station (CRS) in Lubiatowo represent an extension of previously conducted studies (Stella et al., 2019; Ostrowski and Stella, 2020; Stella, 2021; Ostrowski and Stella, 2023; Stella-

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Bogusz, 2023). These advanced surveys enhance our ability to detect and monitor subtle changes in seabed morphology that may not have been captured in earlier studies. A key objective of the ongoing research is the investigation of seabed dynamics beyond the traditional depth of closure.

Previous studies conducted in the Lubiatowo area have documented significant bathymetric changes at depths exceeding the theoretical depth of closure and revealed the presence of large-scale bedforms in the remote nearshore zone (Stella et al., 2019; Ostrowski and Stella, 2020; Stella, 2021; Ostrowski and Stella, 2023; Stella-Bogusz, 2023). These findings have improved understanding of sediment transport processes and seabed morphodynamics beyond the surf zone. Building upon these earlier investigations, the present study extends the existing dataset with new high-resolution measurements collected in 2023, providing additional insight into the formation and evolution of seabed features in the remote nearshore environment.

This paper presents the data from the surveys conducted in 2023, and compares the results with those obtained from previous measurements. For a more in-depth analysis and detailed description of the measurements from 2017 and 2018, refer to Stella (2021) and Stella-Bogusz (2023).

1.1 Study site

The study site is located in the southern Baltic Sea, near the village of Lubiatowo in northern Poland, within the coastal zone of the Pomeranian Voivodeship (Figure 1). It lies along the central Polish coastline, known for its sandy beaches, dune systems, and shallow nearshore waters (Uścinowicz and Szarafin, 2019). This region holds significant environmental and geological interest, making it a frequent subject of research related to coastal dynamics and sediment transport.

The seabed in the vicinity is predominantly sandy, shaped by the interaction of waves and currents (Cerkowniak et al., 2017, Ostrowski et al., 2015, Ostrowski et al., 2017). The nearshore area features a gently sloping seabed, with depths gradually increasing further offshore (Pruszak et al., 2011). Hydrodynamic conditions in coastal areas in this part of the Baltic are influenced by moderate to high wave energy, with prevailing waves typically coming from the western directions: W, NW (Ostrowski et al., 2016). Wind patterns, dominated by west, southwest and northeast winds, play a key role in shaping local wave behavior and sediment distribution (Pruszak et al., 2008, Szmytkiewicz et al., 2021). In deeper areas (beyond the theoretical outer depth of closure) the influence of wave-driven currents diminishes, and seabed morphology is primarily shaped by the synergistic nonlinear interaction between waves and wind-driven currents, particularly during extreme storm events (Stella et al., 2019, Ostrowski and Stella, 2020, Ostrowski and Stella, 2023).

Lubiatowo's coastline is dynamic, experiencing cycles of erosion and sediment deposition. Sand bars along the cross-shore profile provide natural protection to the shoreline, although they are subject to the impacts of wave action (Ostrowski et al., 2016, Uścinowicz and Szarafin, 2019).

The region is not only valued for its natural features but also serves as a hub for scientific research. Studies often focus on coastal engineering, sediment management, and the development of renewable energy projects, such as offshore wind farms.

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Lubiatowo is a location of exceptional strategic importance, uniquely positioned between two of the most significant energy investments in Poland's modern history. This small coastal locality in northern Poland finds itself at the intersection of two key directions in the country's energy transformation: to the north, northeast and east, Lubiatowo borders the planned area of Poland's offshore wind farms, a pioneering initiative in the development of renewable energy. The nearest offshore wind farm infrastructures are: Baltic Power (already completed), C-Wind, Orlen Neptun VIII, Baltica-1, Baltica-2, Baltica-3 – source: SIPAM website. To the west, the first Nuclear Power Plant in Poland is planned (Szmytkiewicz et al., 2021).
This juxtaposition places Lubiatowo at the symbolic and geographical heart of Poland's energy transition - a place where renewable and nuclear technologies may meet. As such, Lubiatowo represents not only a unique case of spatial planning in the energy sector but also a broader vision for a balanced, future-oriented energy policy. The coexistence of these two groundbreaking projects reflects a dynamic approach to meeting climate obligations while maintaining energy stability and economic growth. Lubiatowo's dynamic environment and strategic location make it an essential area for advancing understanding of coastal and marine processes.

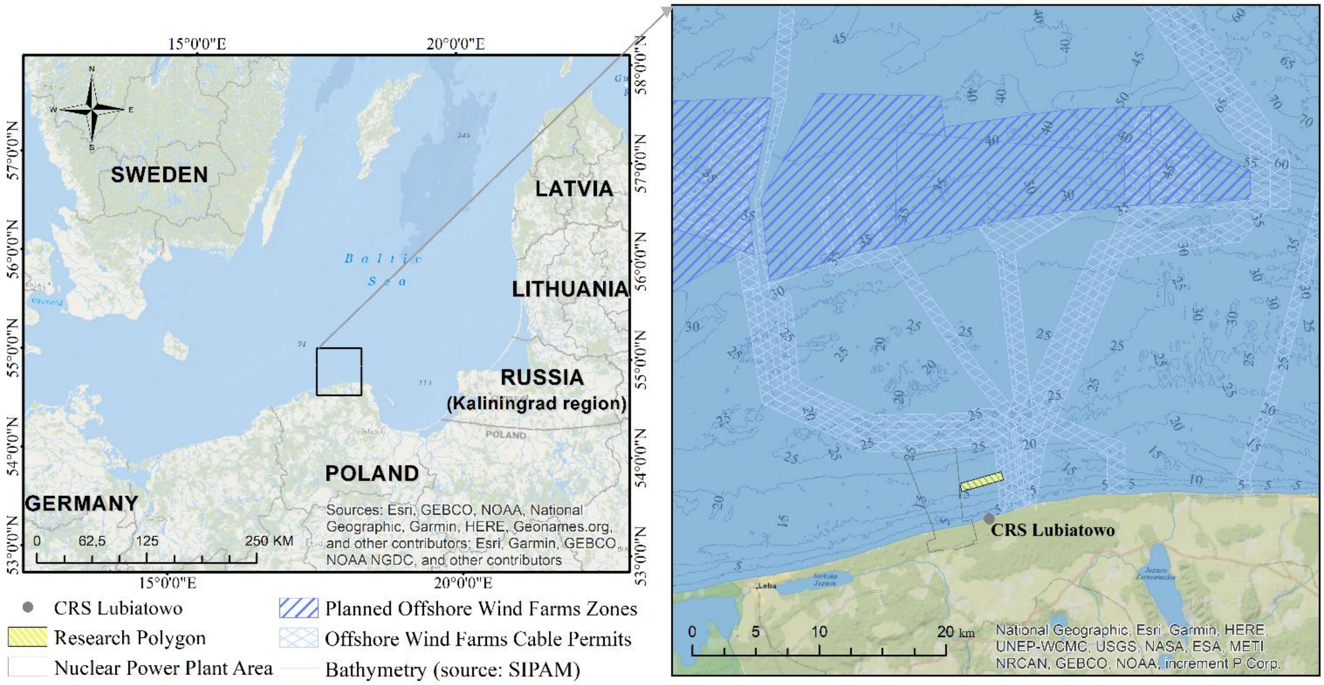

Figure 1: Location of the study site near CRS Lubiatowo, southern Baltic Sea. The base maps were designed and developed by Esri | Powered by Esri. For more information visit https://www.arcgis.com/home/item.html?id=1e126e7520f9466c9ca28b8f28b5e500 (left map) and https://www.arcgis.com/home/item.html?id=e35c5b72d6ac4928a8047ad95fec1618 (right map) (last access: 14 April 2026).

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2 Measurements methodology

2.1 Bathymetry and sonar imaging

The measurements were carried out with a multibeam Norbit Winghead i77 at a frequency of 400 kHz. During the measurements, 21 profile passes were made, each 3500 m long and spaced every 20 m. The echosounder was mounted centrally on the bow of the boat. Sonar measurements were carried out using a Klein 3900 sonar. A total of 18 survey lines were completed. The sonar was deployed on a 50-meter tow cable and towed approximately 5 meters above the seabed.
Before measurements, the echosounder was calibrated on the Margaret wreck. Prior to calibration and measurements, the sound velocity was measured in a water column at intervals of 0.2 m using a SWIFT SVP Valeport instrument. RTK corrections were downloaded from Leica SmartNet, which resulted in a position accuracy of up to 2–5 cm. A positioning compensator Applanix OceanMaster was also used to support positioning. The acquisition software NavAQ (BeamworX) was used for multibeam echosounder data.
Hydrodynamic and wind conditions during each survey are given in Table 1.

Table 1: Hydrodynamic and wind conditions during the bathymetric measurements

		22-24 April 2023	08-10 September 2023	07-08 December 2023
Wave direction		From the northeast and west	From the northeast	From the northeast
Significant wave height H_s [m]:	min [m]	0.08	0.05	0.25
	max [m]	0.49	0.32	0.75
	mean [m]	0.26	0.13	0.4
Wind direction:		Northeast to southeast	Southeast to south	Southeast to south
Wind velocity [m/s]		2–7	1–3	3–4
Sea state		1	1	2

3 Data Processing Methodology

Raw multibeam echosounder data were imported from .bwxraw files into AutoClean software for processing. The dataset was cleaned using a combination of automated filters and manual editing to remove noise and acquisition artefacts. The processed data were then reviewed and exported in a format compatible with Esri ArcMap, where the final bathymetric products and cartographic representations were prepared.
Raw side-scan sonar data were processed using SonarWiz software. Processing included adjustment of display parameters to enhance seabed features and improve image clarity. The final sonar products were exported as GeoTIFF mosaics.

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3.1 Data quality and uncertainty

The accuracy of bathymetric measurements was supported by calibration procedures and RTK positioning corrections, resulting in horizontal positioning accuracy of approximately 2–5 cm. Sound velocity profiles were measured prior to each survey to reduce depth calculation errors.

Bathymetric data quality was further improved through automated filtering and manual inspection. Under favourable survey conditions, the vertical uncertainty of the digital bathymetric models is estimated at ±5–10 cm. The main sources of uncertainty include vessel motion, environmental noise, and hydrodynamic variability during data acquisition.

Side-scan sonar mosaics were visually inspected to assess continuity and alignment between adjacent survey lines.

3.2 Technical validation

The reliability of the dataset was assessed through comparison of overlapping survey lines and repeated transects acquired during different campaigns. Additional validation was provided by subaqueous photographic documentation, which confirmed consistency between bathymetric patterns and observed seabed structures.

Differential bathymetric analyses further supported dataset consistency by revealing spatially coherent zones of erosion and deposition aligned with the prevailing regional hydrodynamic regime.

4 Digital Bathymetric Models (DBM)

The processed and verified multibeam echosounder data were utilized in ArcMap to produce high-quality maps, accurately reflecting the bathymetric conditions of the surveyed area (Figure 2). These maps may serve as the basis for further analysis and reporting..

Based on bathymetric datasets, three representative cross-sections were extracted along fixed transects to illustrate temporal seabed changes between November 2017, December 2018, April 2023, September 2023, and December 2023 (Figure 3). The locations of the transects were selected to capture areas of pronounced morphological variability and bedform migration.

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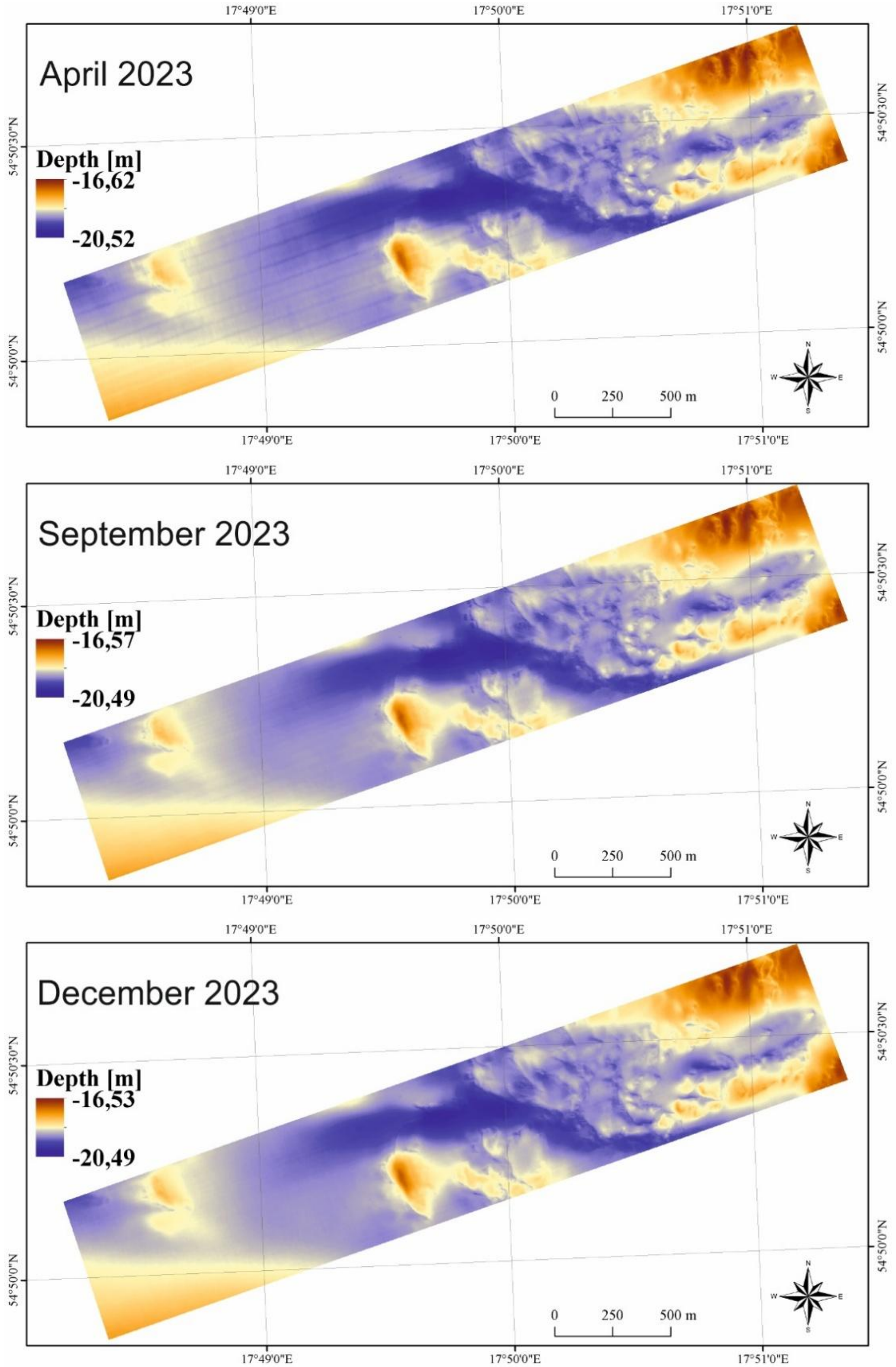

Figure 2: Bathymetric maps from April, September, and December 2023.

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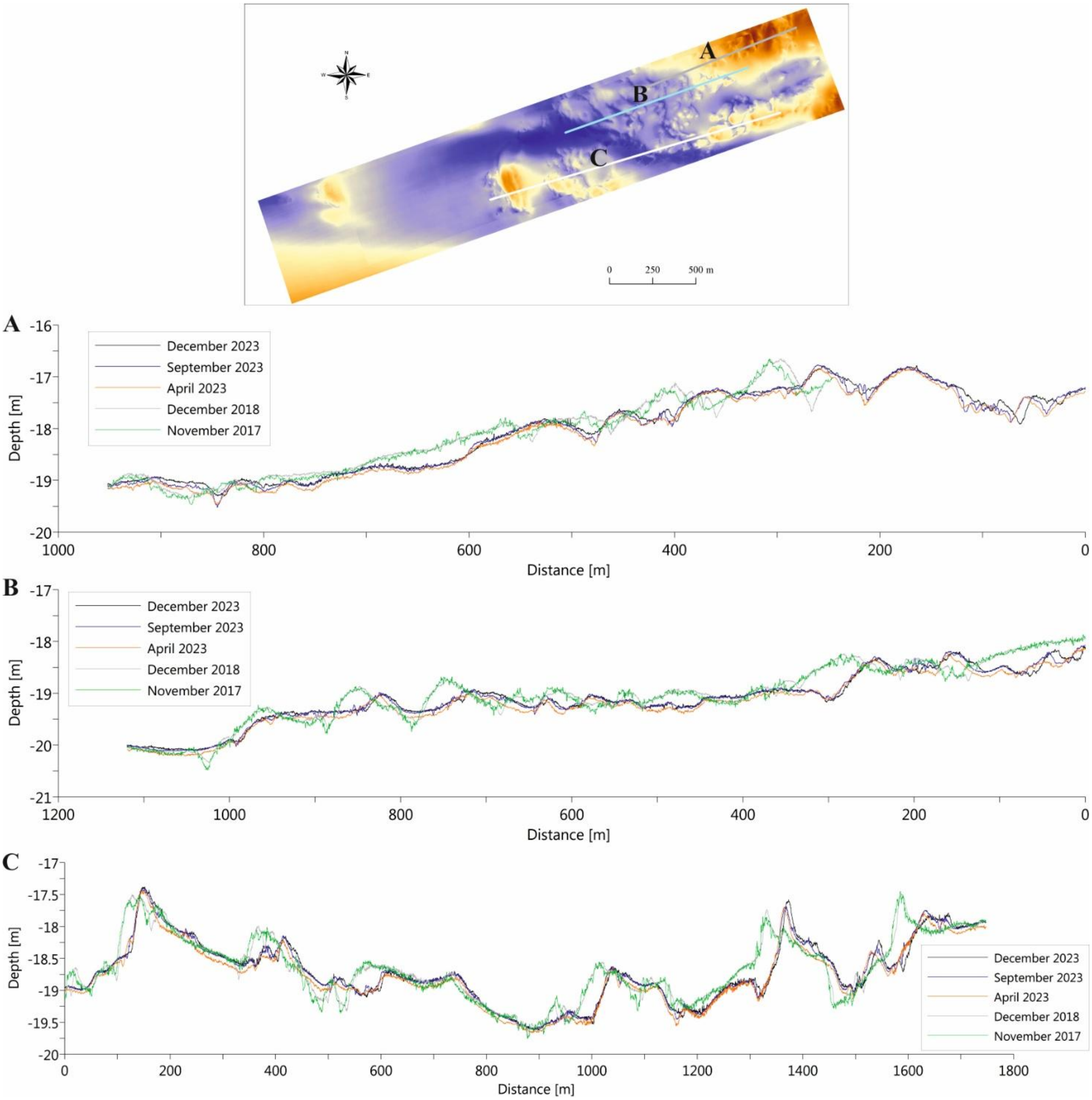

125 **Figure 3: Three representative cross sections illustrating seabed changes between November 2017, December 2018, April 2023, September 2023, and December 2023.**

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4.1 Differential maps

Based on differential maps calculated from the bathymetry measurements (November 2017, September 2023 and December 2023) of the area in the vicinity of the CRS Lubiatowo the changes of the seabed can reach up to 0.5 m over one month, 0.7 m over one year and 1.35 m over six years (Figure 4). Over a multi-year timescale, signs of bedform migration can be identified as alternating zones of accumulation and erosion on differential maps. The orientation of large-scale changes identified in the study area is consistent with the prevailing regional hydrodynamic regime. Their alignment reflects long-term sediment transport pathways controlled by dominant wave approach directions and associated wind-driven currents.

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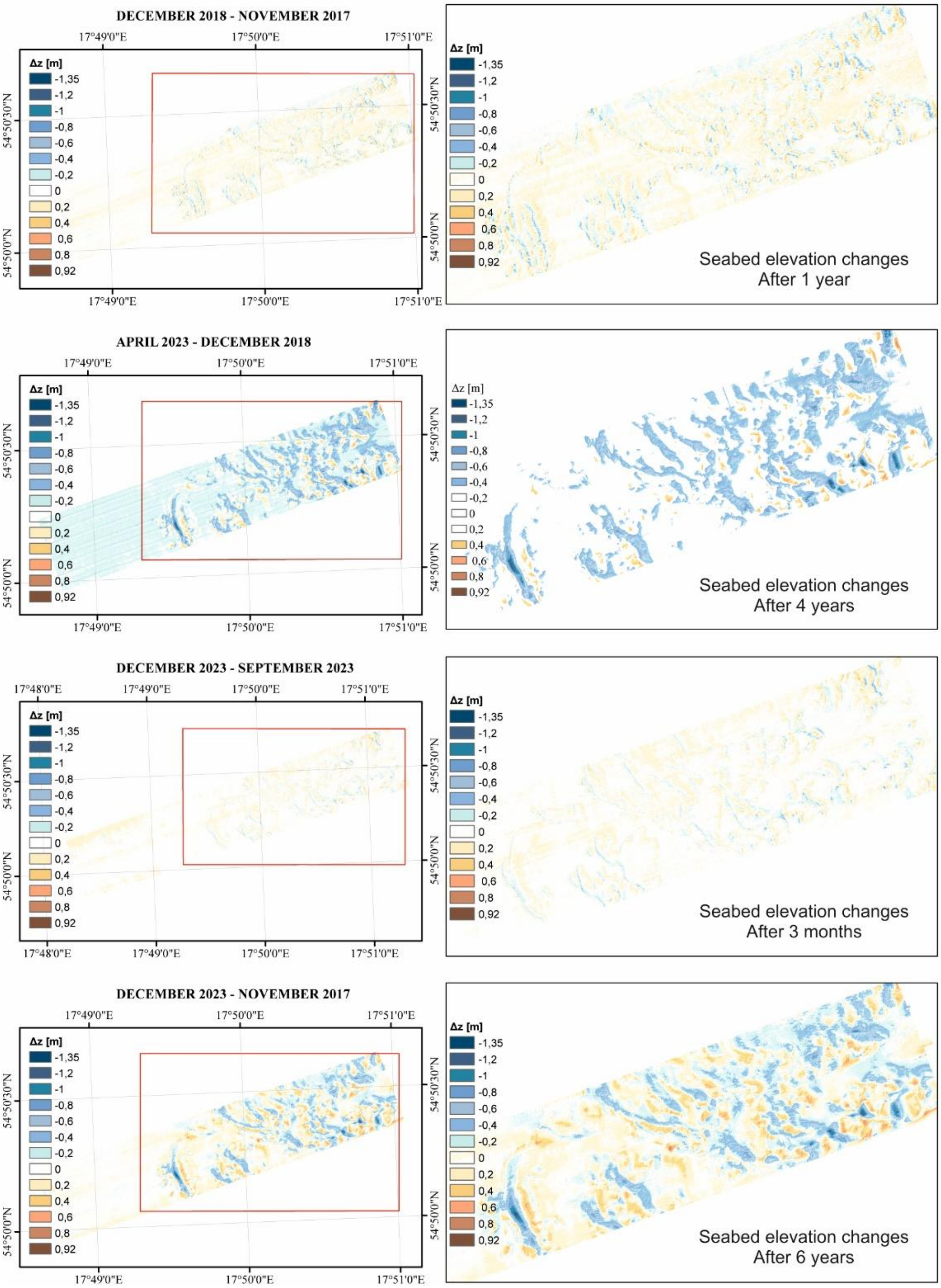

Figure 4: Differential bathymetric maps derived from surveys conducted by IBW PAN in the vicinity of the CRS Lubiatowo.

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4.2 Side-scan sonar images and subaqueous photos

Smaller-scale bedforms, such as ripple marks and mega-ripple marks visible in the side-scan sonar imagery, exhibit substantial spatial reorganization between survey campaigns. Their shape, orientation of the crest lines, and size can change entirely. These features may shift, appear in new locations, or become completely eroded and disappear. Such adjustments reflect the sensitivity of smaller bedforms to short-term fluctuations in wave and current conditions. Bedform morphology responds quickly to transient hydrodynamic variability, including shifts in wind direction and wave incidence, resulting in temporary reorientation or replacement of ripple fields. Representative examples of sonar imagery and photographic observations are presented in Figures 5–8.

In June 2024, additional seabed photographs were acquired using a subaqueous drone equipped with a ruler visible in the camera frame to provide a scale reference. The imagery enables direct visual validation of bedform dimensions and supports interpretation of sonar-derived morphological features.

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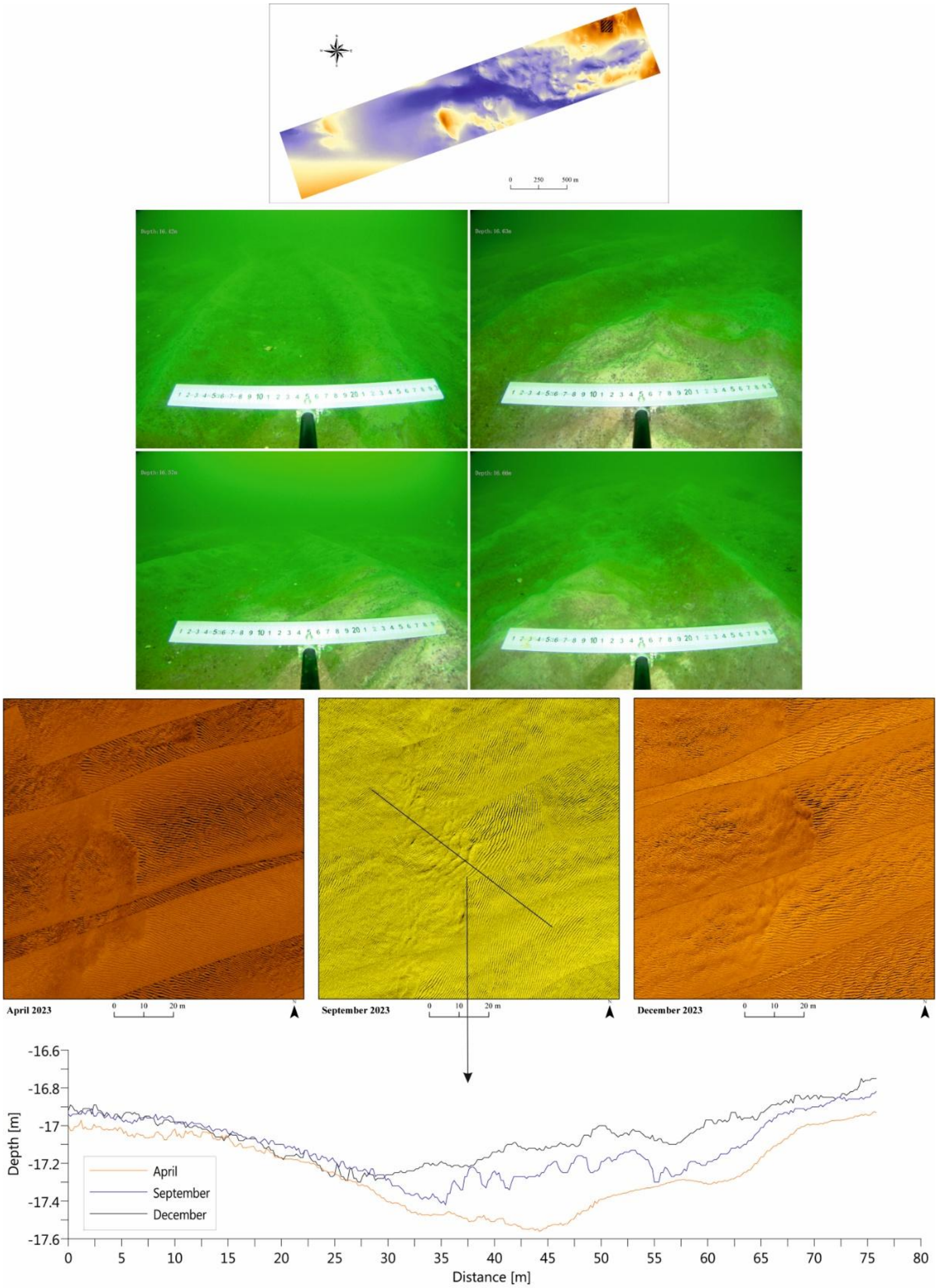

Figure 5: Representative sonar images and subaqueous photographs from surveys conducted by IBW PAN in the vicinity of the CRS Lubiatowo, including a representative cross section from bathymetric measurements.

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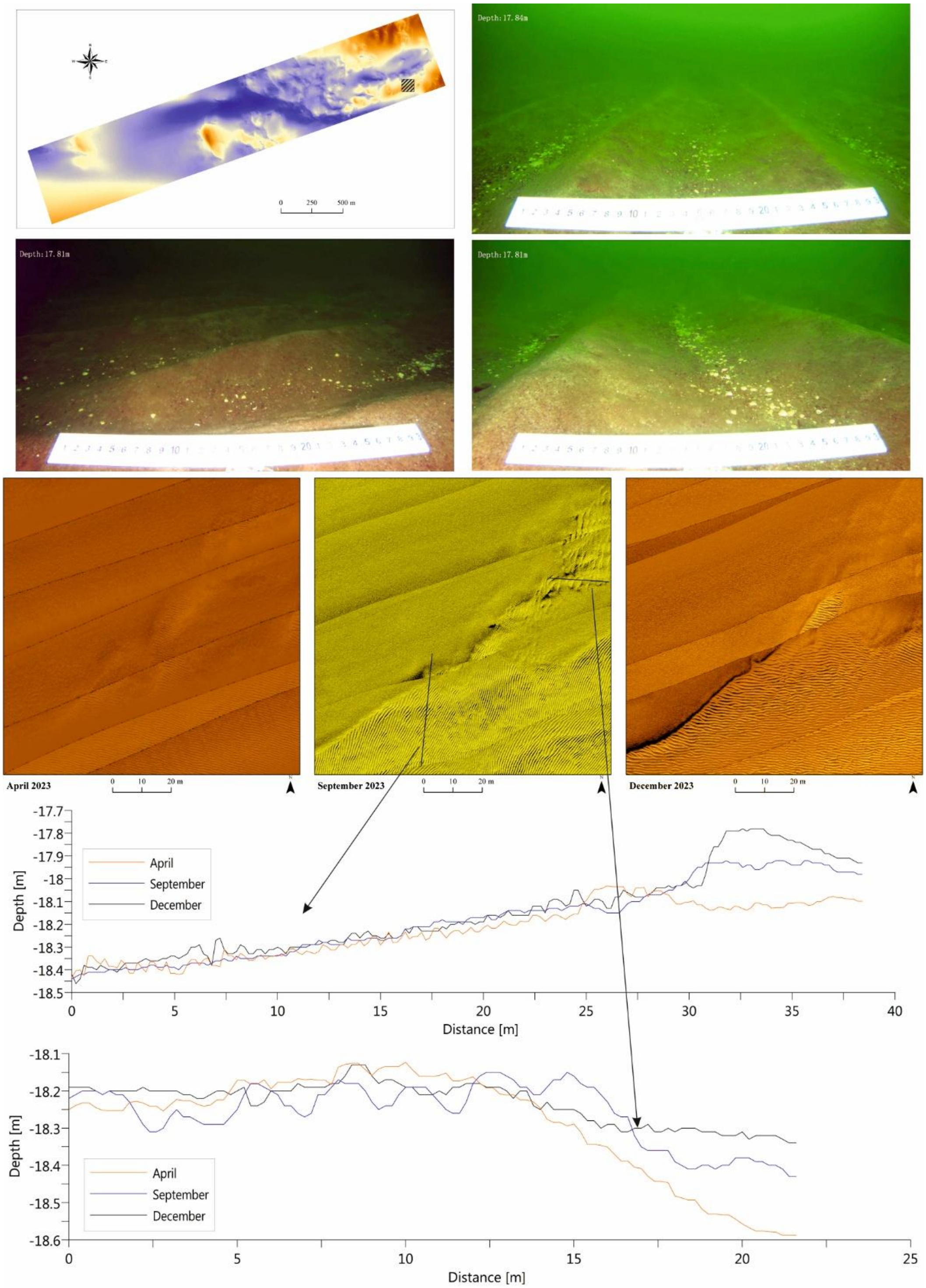

155 **Figure 6: Additional representative sonar images and subaqueous photographs from surveys conducted in the vicinity of the CRS Lubiatowo, including cross-sectional bathymetric information.**

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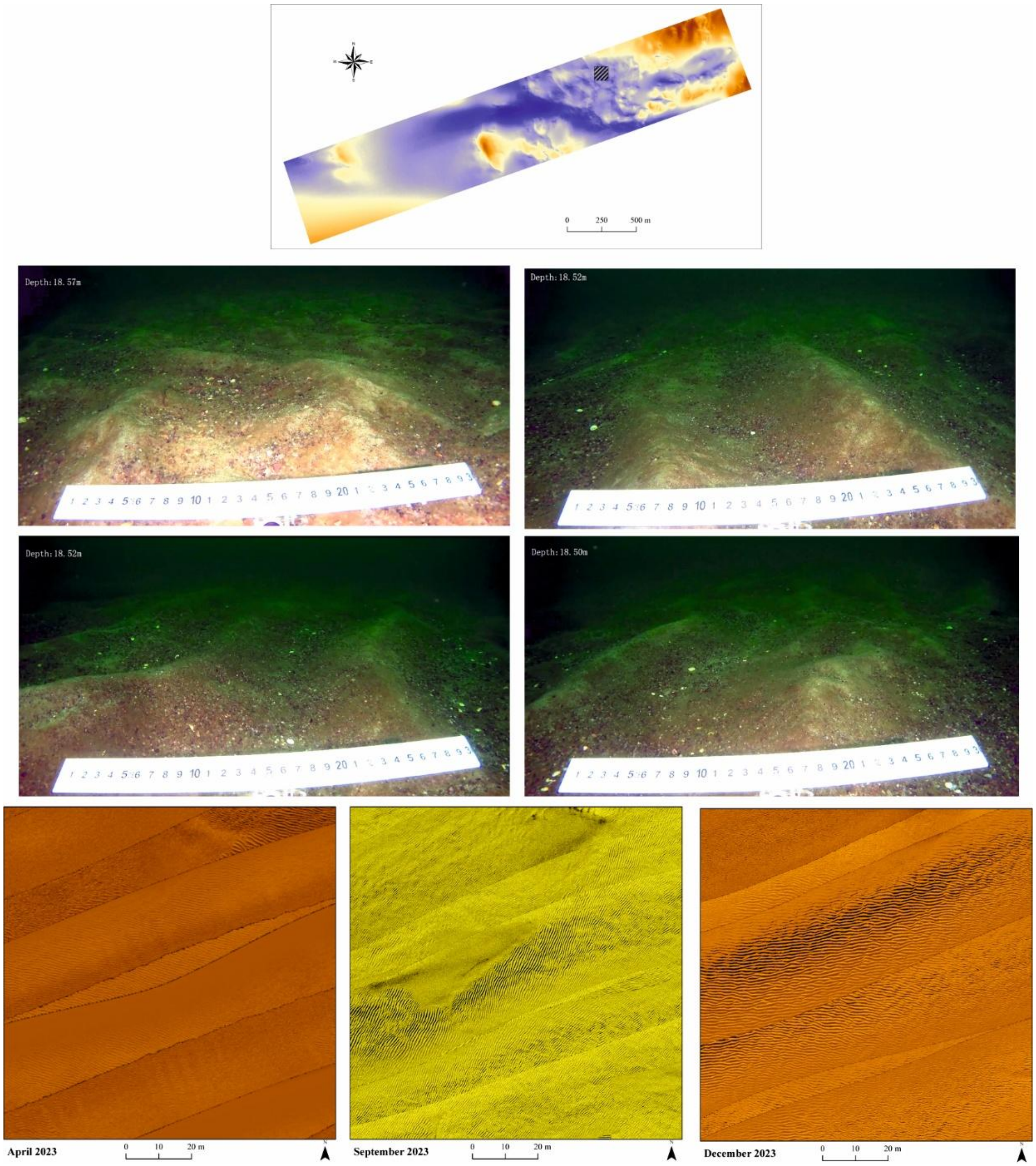

Figure 7: Representative side-scan sonar images and subaqueous photographs showing seabed bedforms from a selected part of the study area in the vicinity of the CRS Lubiatowo.

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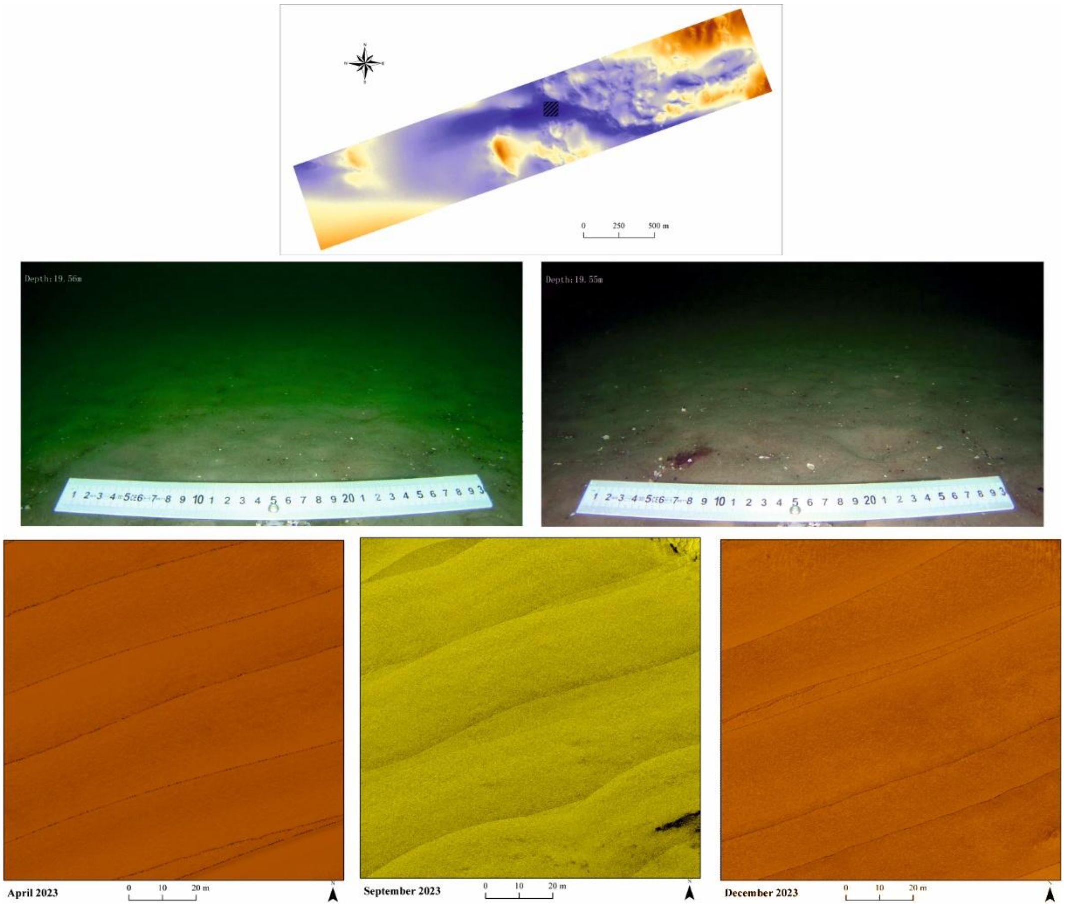

Figure 8: Representative side-scan sonar images and subaqueous photographs showing seabed bedforms from another selected part of the study area in the vicinity of the CRS Lubiatowo.

5 Grain size analysis

Grain size distribution analysis based on eight samples taken on 29 January 2024 (Figure 9) was carried out using the dry sieve method. Prior to the analysis, sediment samples were dried at a temperature of 75°C. After removal from the oven, the sediment was set aside to regain natural moisture. Organic fragments such as shells were removed from the sample. An excess sample was taken from the prepared and homogenized material, and its weight was determined with an accuracy of 0.1 g. The weight of the sample used for dry sieve analysis ranged from 150 to 300 g, depending on the macroscopic assessment of grain size. The particle size distribution analysis was conducted using standardized sieves in 0.5 φ intervals, according to the Krumbein scale (1934). A prepared sieve stack with mesh sizes of 2 mm, 1.4 mm, 1 mm, 0.71 mm, 0.5 mm, 0.355 mm, 0.25 mm, 0.18 mm, 0.125 mm, 0.09 mm, and 0.063 mm was placed on a vibratory shaker. The previously prepared sample was poured onto the top sieve and shaken for 25 minutes.

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After sieving, the content of each sieve was weighed with an accuracy of 0.1 g. The content of individual fractions was calculated as a percentage of the total sample weight, after distributing the error. The error was distributed across all fractions proportionally to their mass. The fraction content was calculated using the formula:

$$Z_i = (m_p/m_n) \times 100$$

where:

Z_i – content of the given fraction (%),

m_p – mass of residue on a given sieve,

m_n – sample weight.

The sediment type was determined according to Folk's classification (1954). Grain size parameters (d50) and sediment classification are presented in Table 2 and grain size distribution graphs are given in Figure 10.

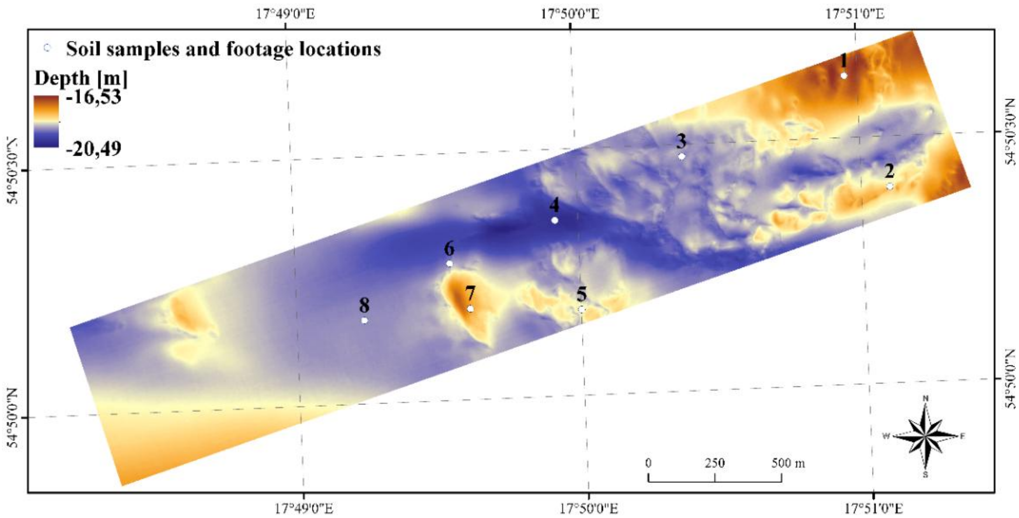

Figure 9: Location of sediment sampling points.

Table 2: Grain size parameters (d_{50}) and sediment classification

Sample no.	Folk (1954) Name	Code	d50 [mm]
1	slightly gravelly sand	(g)S	0.64
2	slightly muddy sand	(m)S	0.18
3	gravelly sand	gS	0.63
4	slightly gravelly muddy sand	(g)mS	0.15
5	slightly muddy sand	(m)S	0.17
6	muddy sand	mS	0.15
7	slightly gravelly sand	(g)S	0.39
8	slightly gravelly sand	(g)S	0.40

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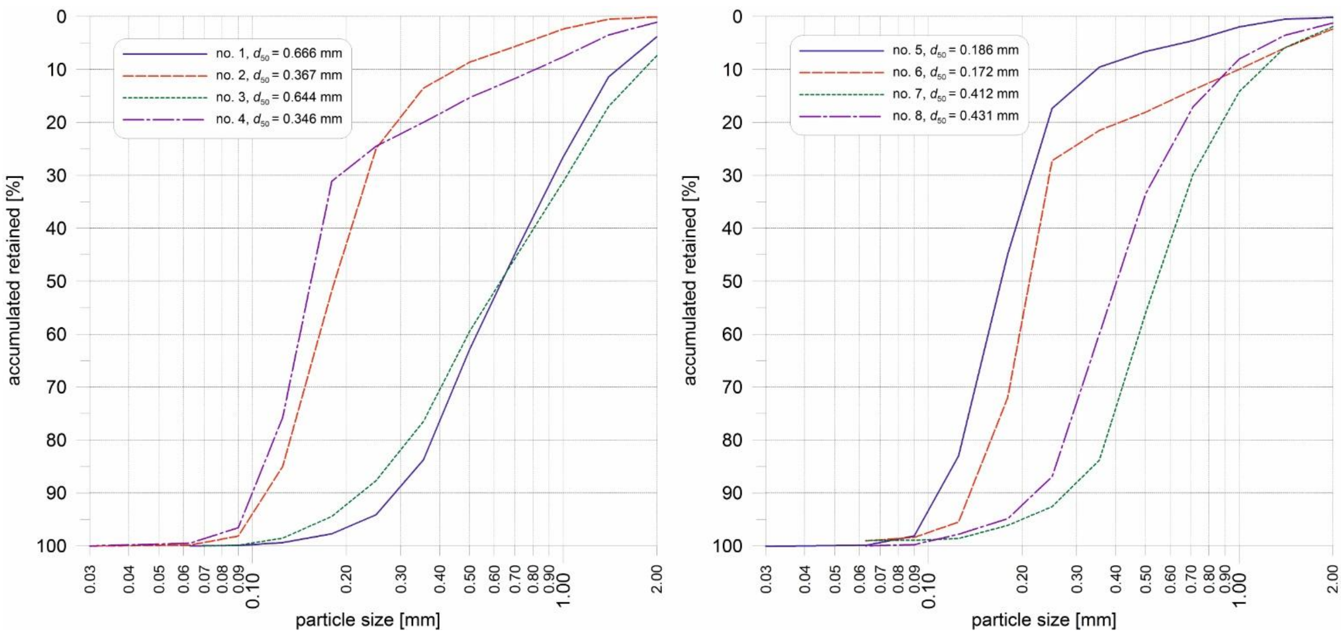

Figure 10: Grain size distribution curves for sediment samples collected in the study area.

6 Hydrodynamic conditions of the study site

Hydrodynamic conditions in the investigated area are governed primarily by the combined action of wind waves and wind-driven currents, typical of the non-tidal southern Baltic Sea environment (Stella et al., 2019; Ostrowski and Stella, 2020; Stella-Bogusz and Ostrowski, 2025). This type of hydrodynamic forcing dominates sediment transport processes beyond the surf zone and governs seabed evolution at depths exceeding the classical depth of closure (Ostrowski et al., 2017; Stella-Bogusz, 2023).

Long-term measurements conducted at approximately 18 m water depth show that wave approach in the investigated area is generally oriented from the western sector, with a dominant direction close to 275°. Energetic wave events are typically associated with northwestern sectors, particularly WNW–NNW, whereas the strongest generating winds usually occur within the SW–W directional range (Stella-Bogusz and Ostrowski, 2025).

Measurements indicate that currents in the remote foreshore most commonly flow eastward, with dominant directions clustered within the ENE–E sector. The observed directional range between approximately 50° and 100° indicates the development of an alongshore transport tendency toward the northeastern sector, consistent with the regional coastline geometry (Ostrowski et al., 2017; Stella-Bogusz and Ostrowski, 2025). This confirms that the dominant water motion in remote nearshore is primarily wind-driven and reflects the hydrometeorological climate typical for the southern Baltic Sea (Stella et al., 2019).

Vector-based directional comparisons between wind, wave and current datasets reveal a pronounced alignment of these processes within similar directional sectors. The strongest directional agreement is observed for wave propagation from western to northwestern sectors, accompanied by currents oriented from the western sector. Similarly, wind–current interactions show that winds originating from southern to northwestern sectors are commonly associated with westward-oriented currents. These results confirm that wind forcing constitutes the primary mechanism driving steady water circulation in the investigated offshore zone and therefore represents the principal control on sediment transport pathways and seabed reorganization (Stella-Bogusz and Ostrowski, 2025).

Observations indicate that sediment mobility may extend beyond the commonly defined depth of closure during energetic hydrodynamic events. In the investigated remote foreshore, sediment transport is governed by bed shear stresses generated within nonlinear interactions between oscillatory wave motion and steady current flow in the near-bed boundary layer (Stella et al., 2019; Ostrowski and Stella, 2020; Stella-Bogusz, 2023). This type of combined hydrodynamic forcing represents a key mechanism controlling the development, migration and spatial reorganization of sandy bedforms observed in this depth range (Stella, 2021; Stella-Bogusz, 2023).

The hydrodynamic setting outlined above serves as a reference for analysing spatial variability detected in the bathymetric dataset. Areas showing elevation gain or loss between surveys correspond to redistribution patterns expected under dominant wave and current forcing conditions. In particular, the prevailing west-to-east wave propagation together with sustained currents oriented toward the northeastern sector indicates the formation of directional sediment transport pathways, consistent with the regional hydrodynamic regime (Stella et al., 2019; Stella-Bogusz, 2023).

The spatial variability observed in smaller-scale seabed structures, including ripple and megaripple fields identified in sonar imagery, can be linked to short-term variability in wave and current directions superimposed on the dominant regional transport regime (Stella-Bogusz, 2023). In contrast, larger bedforms reflect the long-term influence of prevailing hydrodynamic forcing and therefore tend to preserve crest orientations consistent with the dominant directions of sediment transport characteristic for the southern Baltic remote foreshore (Stella, 2021; Ostrowski and Stella, 2020).

Consequently, the observed changes in crest alignment, migration patterns and zones of accumulation and erosion recorded between successive bathymetric surveys are interpreted as geomorphic responses to the prevailing wave–current climate characteristic of the study region. The dominant western wave approach and persistent wind-driven currents directed towards ENE constitute the principal mechanisms governing sediment redistribution and the evolution of seabed morphology beyond the surf zone (Stella et al., 2019; Stella-Bogusz, 2023; Stella-Bogusz and Ostrowski, 2025).

7 Data availability

Bathymetric datasets and side-scan sonar imagery are publicly available from the following Mendeley Data repositories:

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Stella-Bogusz, Magdalena (2025), "High resolution bathymetry and side-scan sonar images of the southern part of the Baltic Sea in the vicinity of the Coastal Research Station (CRS) in Lubiatowo, 2023", Mendeley Data, V1, doi: 10.17632/tzjdm2c338.1

Stella-Bogusz, Magdalena (2024), "Bathymetry of the southern part of the Baltic Sea in the vicinity of the Coastal Research Station (CRS) in Lubiatowo - April, 2023", Mendeley Data, V1, doi: 10.17632/d3thy28yc2.1

Stella, Magdalena (2020), "Bathymetry of the southern part of the Baltic Sea in the vicinity of the Coastal Research Station (CRS) in Lubiatowo - year 2017 and 2018", Mendeley Data, V1, doi: 10.17632/cfss48v9gx.1

Waves and currents measurements as supplementary material in:

Stella-Bogusz, M., Ostrowski, R. Wave-current and wind climate in the remote foreshore of a non-tidal sea in view of field investigations. *Sci Rep* 15, 26492 (2025). https://doi.org/10.1038/s41598-025-12145-w.

Underwater drone video footage of seabed appearance, July 2023 from:

Stella-Bogusz, Magdalena (2026), "Underwater video footage of seabed type in the vicinity of CRS Lubiatowo, southern Baltic Sea", Mendeley Data, V1, doi: 10.17632/yrccjfcjwd.1

8 Conclusions

This study presents a multi-temporal, high-resolution bathymetric and side-scan sonar dataset collected in the remote nearshore zone of the southern Baltic Sea near Lubiatowo. The dataset comprises five survey campaigns conducted between 2017 and 2023 and is complemented by grain-size measurements and subaqueous photographic documentation.

The generated digital bathymetric models and differential maps reveal measurable seabed elevation changes of up to 0.5 m over 3 months, 0.7 m over one year, and 1.35 m over six years. These observations demonstrate that significant morphodynamic processes occur in the remote foreshore at depths exceeding the theoretical depth of closure.

The side-scan sonar mosaics and underwater imagery document both large-scale bedforms and rapidly evolving ripple fields, providing detailed spatial information on seabed morphology and sediment redistribution. Grain size analyses indicate the predominance of sandy sediments, with local variability related to hydrodynamic forcing conditions.

Overall, the dataset constitutes a valuable long-term resource for investigating sediment transport pathways, bedform migration, and seabed evolution in non-tidal seas. It provides a reference dataset for future coastal monitoring and may support a wide range of applications, including numerical model validation, coastal engineering, offshore infrastructure planning, and environmental impact assessments related to marine energy development in the Baltic Sea region.

Competing interests:

The author declares that there are no competing interests.

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Folk, R.L.: The Distinction between Grain Size and Mineral Composition in Sedimentary-Rock Nomenclature. The Journal of Geology, 62, 344-359, doi: 10.1086/626171, 1954.

Ostrowski, R. and Stella, M.: Potential dynamics of non-tidal sea bed in remote foreshore under waves and currents, Ocean Engineering, Elsevier Science B.V., 207, doi:10.1016/j.oceaneng.2020.107398, 2020.

Ostrowski, R. and Stella-Bogusz, M.: Modified logarithmic distribution of wind-driven flow velocity in remote foreshore of the non-tidal sea, Oceanologia, 65 (4), 556-563, doi:10.1016/j.oceano.2023.06.003, 2023.

Ostrowski, R., Schönhofer, J. and Szmytkiewicz, P.: South Baltic representative coastal field surveys, including monitoring at the Coastal Research Station in Lubiatowo, Poland. J. Mar. Syst. 162, 89—97, doi:10.1016/j.jmarsys.2015.10.006, 2015.

Ostrowski, R., Stella, M., Szmytkiewicz, P., Kapiński, J. and Marcinkowski, T.: Coastal hydrodynamics beyond the surf zone of the south Baltic Sea, Oceanologia, 60 (3), 264-276, doi: 10.1016/j.oceano.2017.11.007, 2017.

Pruszak, Z., Ostrowski, R. and Schönhofer, J.: Variability and correlations of shoreline and dunes on the Southern Baltic coast (CRS Lubiatowo, Poland). Oceanologia, 53 (1), 97–120, doi: 10.5697/oc.53-1.097, 2011.

Pruszak, Z., Szmytkiewicz, P., Ostrowski, R., Skaja, M. and Szmytkiewicz, M.: Shallow-water wave energy dissipation in a multi-bar coastal zone. Oceanologia 50 (1), 43—58, 2008.

SIPAM geoportal (Spatial Information System of the Maritime Administration): https://sipam.gov.pl/geoportal, accessed: 2 July 2025.

Stella, M.: Bathymetry of the southern part of the Baltic Sea in the vicinity of the Coastal Research Station (CRS) in Lubiatowo - year 2017 and 2018, Mendeley Data, V1, doi: 10.17632/cfss48v9gx.1, 2020

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