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Short-term coastal dynamics and implications for energy infrastructure safety: insights from the Baltic Sea coast

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Safety and location suitability is a vital issue for offshore wind farms and their transmission infrastructure, including cable landing stations. Geomorphological and geological features are one of the key determinants of durability and operational reliability of energy infrastructure. We analyse the dynamics of the coastal zone at the two locations (Ustka and Lubiatowo) planned for the landfall of marine transmission infrastructure on the Polish southern Baltic coast. Average centennial coastal changes were determined by comparing the shoreline from 1875 (1:25,000 topographic map) and 2022 (LIDAR). Statistical rates of change were calculated using *DSAS* software by analysing changes in shoreline position (1:10,000 topographic maps and LIDAR) over 7 to 8 time intervals between 1985 (1986) and 2022. Over a period of one and a half centuries, in the Lubiatowo landfall area, there was slight local erosion (max. ~80 m; ~0.5 m/yr) and accretion (max. ~90 m; ~0.6 m/yr). In the Ustka area, the situation was similar, but the extent of the changes was greater - the shoreline retreated locally by ~270 m (~1.8 m/yr) and local accretion amounted to ~270 m. Analysis of changes in the position of the shoreline on a timescale of three decades (1985–2022) showed a slight expansion of the erosion areas and a shift of the erosion and accretion centres to the east, as well as higher rates, of both erosion and accretion, compared to the period 1875–2022. Locally, the average erosion rate in the Lubiatowo area was 1.7 m/yr and the average accretion rate locally reached 1.5 m/yr. Similar trends and magnitudes of changes occurred in the Ustka area, where the average erosion rate was 1.6 m/yr and the accretion rate 1.2 m/yr. These examples of erosion-accretion systems show that data on the position of erosion and accretion centres as well as on the rate of change of the shoreline position are strongly dependent on the time intervals analysed. Therefore, it is necessary to analyse not only the current litho- and morphodynamic processes on the coast, but also the trends of change at different time scales, when determining the landfall sites of power cables and as the design of their protection.

Key words: coastal system, barrier coast, Baltic Sea, cable landfall zone.

INTRODUCTION

Energy security for nations and regions hinges not only on the economic capabilities of investors but also critically on the geographic and environmental suitability of investment sites. Geomorphological and geological conditions are key determinants of the long-term durability and operational reliability of energy infrastructure. A stark reminder of the risks posed by neglecting these factors is the Fukushima nuclear disaster, where an earthquake and tsunami compromised the facility's safety (Schneider, 2023; Ayoub et al., 2024; Liu et al., 2024). This serious event underscores the necessity of conducting comprehensive risk assessments for energy investments, particularly with respect to natural hazards (Raby et al., 2015).

This focus on safety and location suitability is just as vital for smaller-scale but equally significant projects, such as offshore wind farms and their associated transmission infrastructure. In recent years, the marine energy sector has seen rapid expansion worldwide, driven by the growing demand for clean, renewable energy sources. Offshore wind farms, in particular, are emerging as a major contributor to renewable energy production (Leung and Yang, 2012; Kara and Şahin, 2023), offering a sustainable solution to meet increasing energy needs while reducing carbon emissions.

The Baltic Sea region, including the Polish sector, is witnessing a surge in offshore wind energy developments, reflecting the broader global trend (Pronińska and Księżopolski, 2021). The Polish government has ambitious plans for the sector, with projections that offshore wind energy will account for 13% of the national energy production by 2030, and up to 19%

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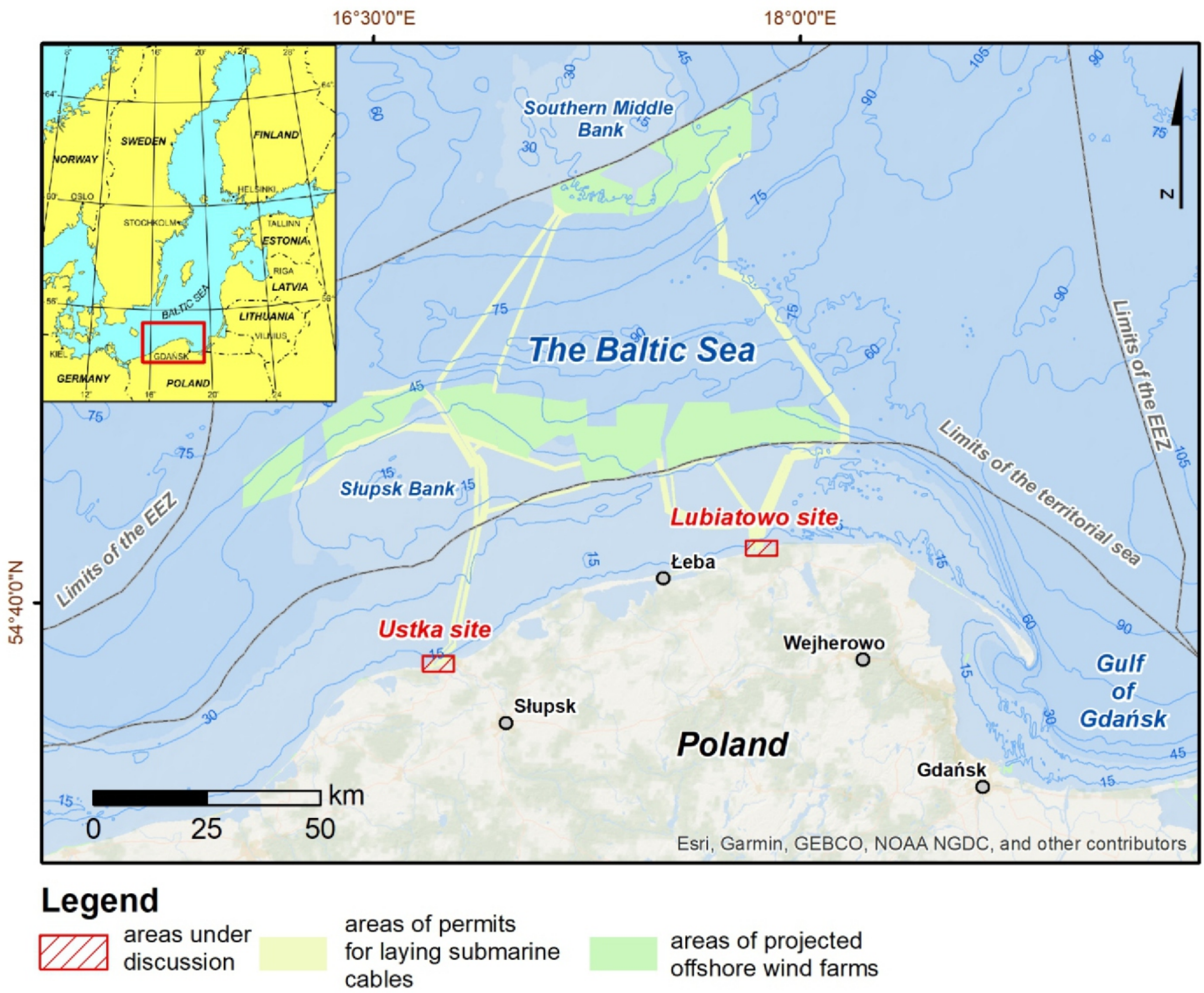

Fig. 1. Location of the study area

by 2040 (Program Rozwoju Morskich Farm Wiatrowych – page access 03.2025). Critical to this growth is the establishment of robust transmission infrastructure, which will carry energy generated at sea to the mainland. These transmission installations, forming a vital part of national energy infrastructure, must be carefully positioned, especially with respect to geological and geomorphological factors.

The stability and performance of both transmission systems and offshore wind farms are heavily influenced by the geological and geomorphological properties of the seabed. Substrate stability, erosion risks, and the likelihood of extreme weather events must all be carefully assessed to avoid structural damage and to ensure the longevity of the infrastructure (Carter et al., 2014; Clare et al., 2023). An inadequate assessment of these conditions could lead to costly repairs, operational disruptions, and even catastrophic failures. Therefore, a thorough geological analysis during the planning stage can significantly mitigate risks and optimize both construction and operational costs, enhancing the competitiveness and profitability of offshore energy projects (Barzehkar et al., 2024).

Given these considerations, collaboration between geologists, engineers, and planners becomes essential for the development of safe, resilient, and efficient energy systems that can withstand future challenges. By prioritizing geomorphological and geological factors in the planning process, energy developers can ensure that their infrastructure is both durable and adaptable, contributing to the long-term stability of the energy supply.

In the light of this, the objective of this study is to analyse the dynamics of the coastal zone at the location planned for the landfall of marine transmission infrastructure. Particularly, the study aims to assess the potential future risks posed by coastal erosion and other geomorphological processes for current projects while providing a methodological insight that will inform the design and placement of planned critical energy infrastructure.

STUDY AREA: HYDRODYNAMIC AND GEOLOGICAL SETTING

The study areas are located in the central part of the Polish southern Baltic coast comprising two distinct sites: Ustka (a town located ~16 km north-west of Słupsk) and Lubiatowo (a village situated ~20 km east of Łeba; Fig. 1).

The climate of the Baltic Sea region is strongly influenced by large-scale atmospheric variability. In particular, the North Atlantic Oscillation and, on longer timescales, circulation patterns related to the Atlantic Multidecadal Oscillation play important roles for the climate of the Baltic Sea region (e.g., Meier et al., 2022). The Baltic Sea is a microtidal, storm-dominated brackish, intercontinental sea (Leppäranta and Myrberg, 2009; Uścinowicz, 2014); therefore, the most important element of the climate that influences the dynamics of the water masses is wind. Variations in the wind climate and storminess over the Baltic Sea region are on average closely linked to atmospheric circulation and cyclonic activity over the North Atlantic (e.g., Meier et al., 2022). In general, winds from the western sector (SW–W–NW) dominate over the southern Baltic Sea region. Storm winds (>15 m/s) and waves also tend to come from the same directions. The measurement data that best characterize the wave climate of the central part of the Polish coast come from the Coastal Research Station in Lubiatowo operated by the Institute of Hydro-Engineering of the Polish Academy of Sciences. Waves from the western sectors occur in the study areas for ~50% of the year. Waves from NE, E, and SE occur for 32% of the year, and those from the N for 13.5% of the year. The mean wave height is usually 0.5–1.5 m (47% of the year). According to multi-year data, the mean wave periods (T_{mean}) vary from 3 to 7.5 s, and the periods of the significant wave (T_s) during heavy storms exceed 9 s. The following wave parameters were recorded during a hurricane on 6 December 2013: maximum single wave height H_{max} = 7.8 m, significant wave height H_s = 4.42 m, mean wave height H_{mean} = 2.8 m, T_s = 9.3 s, T_{mean} = 8.1 s. The longshore current velocity can attain 1.6 m/s (Ostrowski et al., 2016, 2018).

During heavy storm surges, the water level can reach ~1.5–2.0 m above mean sea level. The historically recorded maxima above mean sea level were 2.22 m in Kołobrzeg, 1.59 m in Darłowo, 1.68 m in Ustka and Łeba, and 1.38 in Władysławowo (Wolski et al., 2014). In general, sea level is rising along the entire southern Baltic coast. According to the mareographic stations located in Kołobrzeg, Ustka and Władysławowo the average rates of sea level rise in the period 1952–2015 were 1.66, 1.83 and 2.04 mm/yr, respectively.

The central part of the Polish coast is located on the East European Precambrian Platform and, since the early Holocene when glacio-isostatic rebound ceased in the southern Baltic coast, the area has been tectonically relatively stable. Recent vertical movements of the Earth's crust in the central part of the Polish coastal area (i.e. between Ustka and Władysławowo) are around 0 with a tendency to slight uplift up to 0.5 mm/yr (Wyrzykowski, 1985; Kotny and Bogusz, 2012).

The pre-Quaternary bedrock in the central part of the Polish coast, both in its inland and marine parts, consists of Oligocene and Miocene sand and silt, locally clay and lignite. Its ceiling lies at depths ranging from ~260 to 10 m b.s.l. The thickness of Quaternary deposits in the onshore part of the coastal region is around 10–12 metres in general, and only locally it is greater, with a maximum thickness of up to 260 m. Pleistocene deposits are represented by glacial till, glaciofluvial sand and gravel and ice-marginal lake sand, silt and clay. The Holocene is represented by peat and lacustrine sand and silt, as well as by marine and aeolian sands (Rotnicki and Borówka, 1995; Skompski, 1982; Morawski, 1987; Petelski, 2007; Uścinowicz et al., 2020a, b). The thickness of the Quaternary deposits in the marine part of the coastal zone is in general <30–40 m. The Pleistocene deposits in the marine area are similar to those in the inland part; however, their thickness is smaller because they were eroded to a large degree during the Holocene marine transgression. The thickness of marine sands and gravels rarely exceeds 3 m, and it is <2 m over large areas. Especially, a small thickness of marine sand and gravel is found in front of the cliffed coast and in lower shoreface and offshore areas, where Pleistocene deposits locally outcrop (Michałowska and Pikies, 1990; Uścinowicz and Zachowicz, 1991).

The coast of the study areas is characterized by dominance of barriers interrupted by short, ~10 km-long, cliff sections. The barrier hinterland contains coastal lowlands, and three lagoons which are called coastal lakes. The dune system separating the lowland and lagoons from the sea has a varying number of dune generations, of diverse shape and size. The Łebsko Barrier is the largest dune system in these areas. Several locally erosional embayments have no foredunes. They are directly adjacent to the beach and are erosional remnants of older dunes.

Due to the shoreline orientation and predominant wind and wave propagation directions, the eastern section of the Polish coast is dominated by west-to-east sediment transport. Intense eastwards sediment transport amounts to ~100,000 m^3/yr between Ustka and Władysławowo (Kaczmarek et al., 1997; Szmytkiewicz et al., 2000). More recent and detailed calculations (Szmytkiewicz et al., 2021) reveal that the resultant annual transport of sediment from west to east, of 111,000 m^3/y to 145,000 m^3/y, depends on the particular calculation model. There are no measurement or modelling data about cross-shore sediment transport in terms of amounts and resultant balance, both in short-term (seasonal to decadal) or long-term (centennial) timescales. According to rough estimates (Uścinowicz et al., 2024a, b) up to ~40–60% of the sand can be drained away from the shoreface to depths greater than the outer closure depth (*sensu* Hallermeier, 1981), to the offshore zone where we consider coastal processes in the long-term scale.

Thanks to extensive, systematic geological mapping conducted in the coastal zone, detailed data on the relief and geological structure of the seabed and adjacent land in the sites of planned cable landing are available (https://www.pgi.gov.pl/en/kartografia-4d.html; https://www.pgi.gov.pl/en/kartografia-4d/etapy-realizacji.html) (Fig. 2).

USTKA SITE

The Ustka site lies to the west of the town of Ustka, stretching ~7 km along the coast between kilometres 234 and 241 (based on the Polish coastline division system where 0 km = the Polish–Russian border; Fig. 2). The coastline within that site is aligned WSW–ENE in general. This site features a coastal barrier consisting of a beach strip of variable width, backed by dunes and, topographically, it can be divided into two main sections.

The western part (238–241 km) is marked by an erosional concavity, narrow beach and low dunes. Dunes and their relicts are protected by a seawall in the section between 239 and 240 km of the coast (Fig. 3). Behind low dunes in this area lie coastal lowlands, with elevations rarely exceeding 3 m a.s.l. The eastern and central parts (234–238 km) consist of higher terrain, with dune heights reaching ~35 m and widths ~1 km. In the eastern portion (~235 km), there is an old, partly destroyed ~100 m-long pier, and ~1.1 km farther east, there are jetties of the Port of Ustka extending ~400 m into the sea. Both these hydrotechnical structures enhance beach and dune accretion in the eastern portion of the Ustka site.

The coastal barrier consists of marine and aeolian sands. An extensive coastal depression filled with peat and covered by an aeolian sand sheet occurs beyond the narrow dune belt in the western part of the Ustka site, whereas outcrops of glaciolimnic clays, silts and glacial till, as well as Holocene peat, occur behind the wide dune belt in the eastern part.

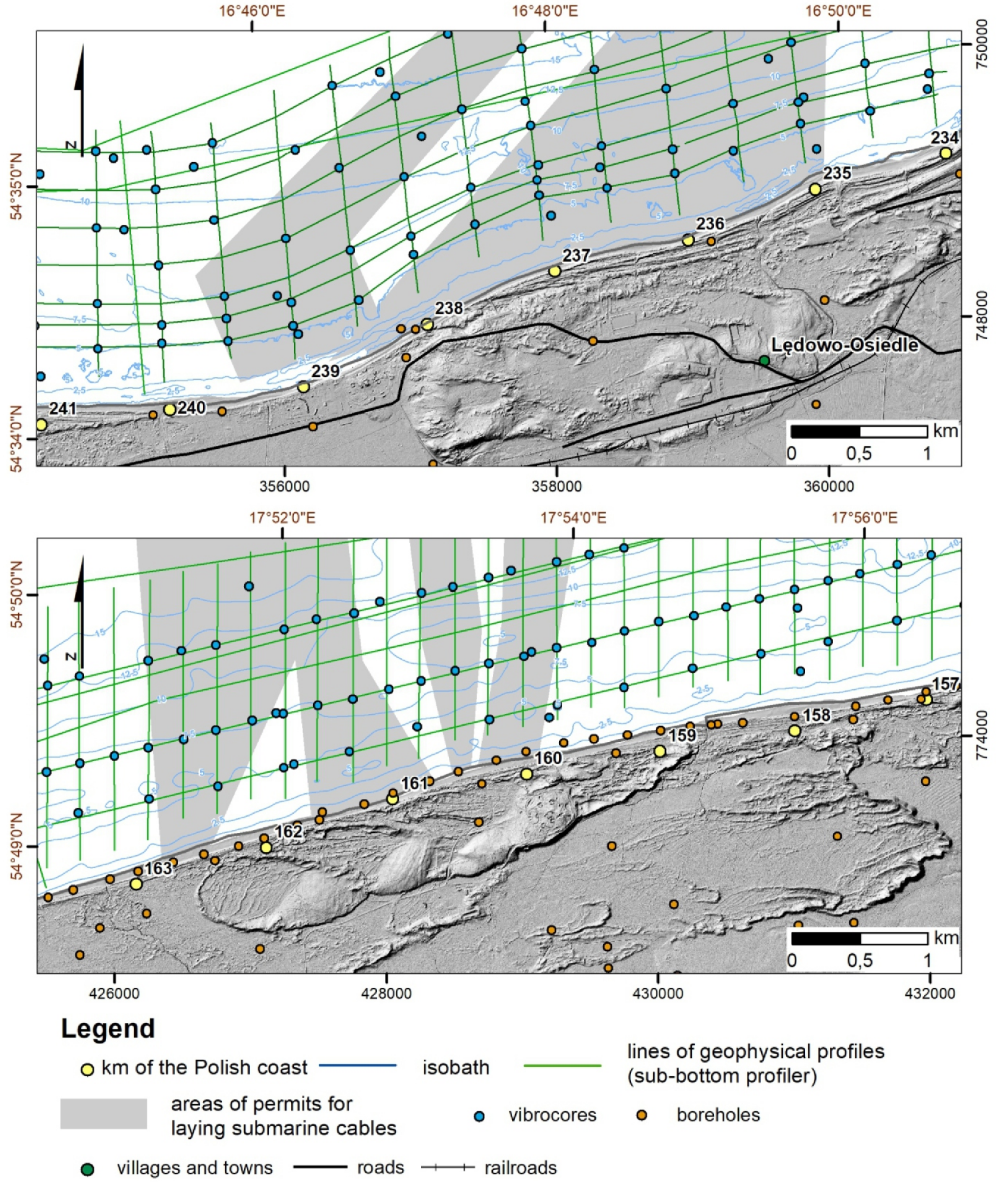

Fig. 2. Map of available geological data in the study area (Ustka – upper panel, Lubiatowo – lower panel)

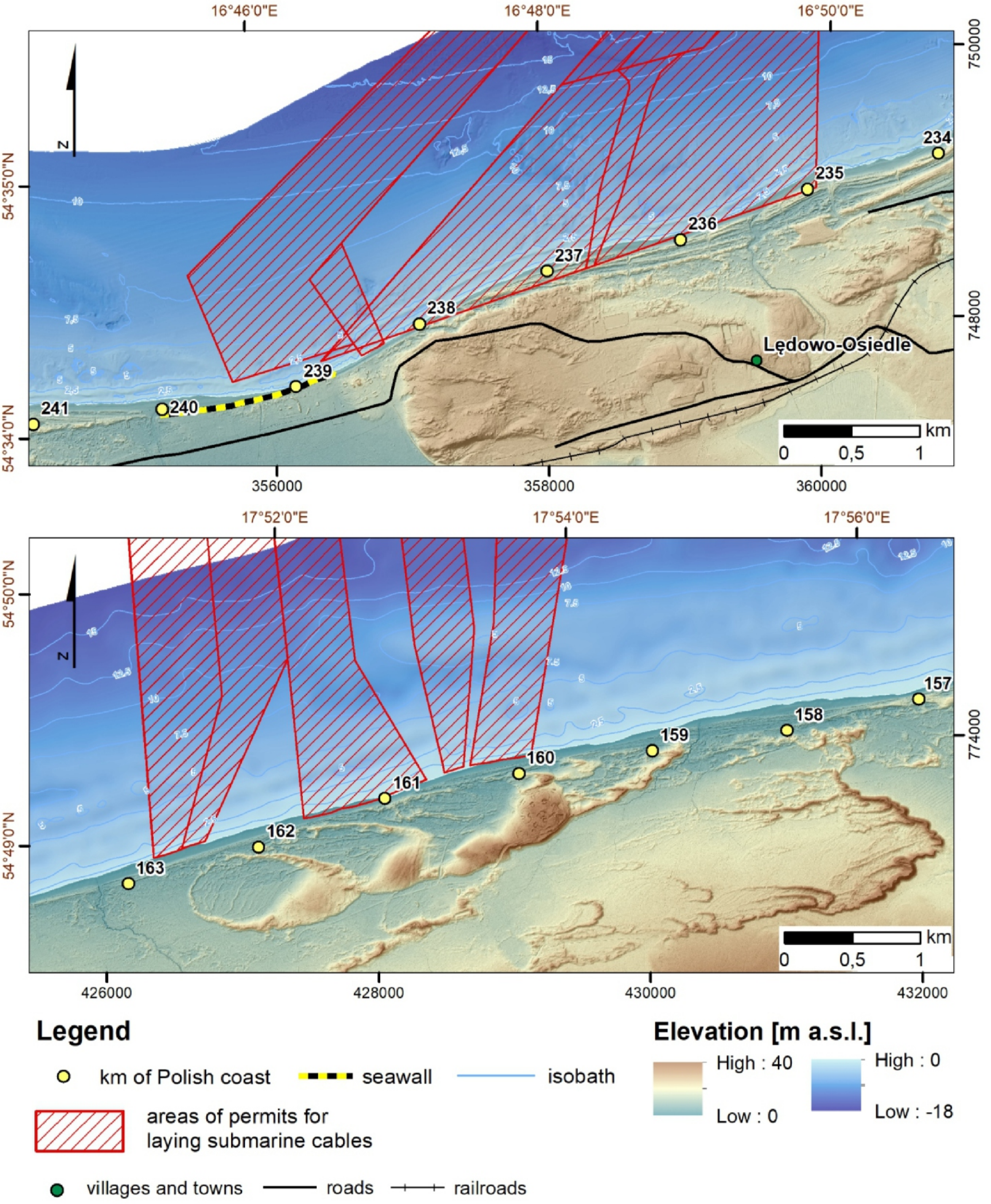

Fig. 3. Elevation map of the study area (Ustka – upper panel, Lubiatowo – lower panel)

Source of bathymetric data – Polish Geological Institute – National Research Institute; source of DTM – Maritime Office in Gdynia

The width of the shoreface at the Ustka site ranges from 1.5 to 1.6 km in the western section and from 0.9 to 1.1 km in the eastern section. The base of the shoreface is marked by a gentle change in the gradient of the seabed at a depth of ~10–12 m b.s.l. In the upper shoreface, up to a depth of ~5 m, there are two or three sand bars with a relative height of ~1.0–3.5 m. The lower shoreface and the area behind the shoreface is relatively flat (Fig. 3). The generally flat seabed also contains a shallow elongated depression (submarine valley) in the westernmost part of the Ustka site. The valley starts from a depth of ~7 m and runs from SE to NW. The width of the slightly rough valley bottom is ~0.5 km. Slightly rough seabed surfaces located in shallow depressions, oriented in the same direction, are also noticeable at depths from ~5 to ~15 m in the central part of the Ustka site (Fig. 3).

The seabed in the Ustka area is covered with fine marine sand. Its thickness ranges from several centimetres to ~8 m, usually being ~1–3 m. Only in the eastern part of the area, on the upper shoreface (in the sand bar zone), it exceeds 3 m. The maximum thickness occurs east of km 135 between the old pier and the breakwaters of the Port of Ustka. Thicknesses of <1 m occur only locally, in depressions with a rougher seabed. Outcrops of glaciolimnic clay and till also occur in those areas, indicating their erosional origin (Figs. 3–5).

LUBIATOWO SITE

The Lubiatowo site is located east of the town of Łeba, extending for ~6.5 km along the coast between kilometres 157 and 163.5 (Figs. 1 and 2). The coastline here is also oriented WSW–ENE. Only its eastern part is more E–W aligned. Similarly to the Ustka site, this site features a coastal barrier with a beach of varying width and dunes behind it. Behind a foredune zone, a series of parabolic dunes covers much of the area, some reaching heights of >30 m. Only in the westernmost part are the dunes less pronounced, and sand forms mainly an aeolian sheet. Aeolian sands cover almost the entire site, overlying older deposits, including fluvioglacial sands, gravels, and glacial till. There are some deflation basins, filled with organic soils (peat), between the dunes.

The shoreface extends ~1100–1500 m from the waterline and reaches a depth of ~10–12 m where the bottom gradient gently changes. There are 2–4 sand bars within the upper shoreface. The isobaths generally run parallel to the shoreline, although in the western part in the lower shoreface and offshore, slight deflections of the isobaths from the alignment of the shoreline can be observed. This feature probably indicates the presence of two or three low ridges and depressions obliquely connecting to the shoreface. The isobaths in the eastern part are more regular and mostly parallel to the shoreline, even beyond the sand bar zone within the upper shoreface. The prominent feature in the central and eastern part of this background is an ~4 km-long and 0.5–0.6 km-wide ridge delimited by the 7 m isobath and aligned parallel to the coastline. The relative height of the ridge is ~3.0–2.5 m, the sea depth being ~4.5 m at its shallowest point (Figs. 2 and 3).

The seabed in the Lubiatowo site is covered mainly by fine sands; however, it is different from the Ustka site in that coarse-grained sand occupies larger areas, mainly on the large ridge in the central and eastern part of the area. There are also elongated patches of medium-grained sand related to an outer (second, third or fourth) sand bar in the western segment (Fig. 4). The marine sand cover across the Lubiatowo site is thicker compared to Ustka. The maximum thickness exceeds 8 m, with values over 5 m being common over much of the area. Thinner sand deposits (<2 m) are mainly found in the upper shoreface of the western part of the Lubiatowo site as well as in its easternmost part (Fig. 5). Similarly to the onshore part, these marine sands overlie older Pleistocene glacial and fluvioglacial deposits.

MATERIALS AND METHODS

To analyse the coastal dynamics at the sites of planned energy infrastructure, various materials and methods were employed.

HISTORICAL SHORELINE POSITION RECONSTRUCTION

The historical shoreline from <150 years ago was reconstructed and overlain onto the current shaded terrain model (2022) using georeferenced German topographic maps (Messtischblätter – sheet Wittenberg, Saleske and Stolpmünde) at a scale of 1:25,000 produced around the year 1875. The Messtischblatt maps are known for their high accuracy, with a positional precision of up to 4–6 m when compared to modern cartographic sources (Deng et al., 2017a).The reconstructed shoreline is shown in green where it now falls on land, indicating accumulation trends, and in red where it falls in the sea, marking areas of erosion.

To visualize erosion and accumulation over the past 150 years, an equidistant representation of the current shoreline was generated at 25-metre-intervals using *ArcGIS Desktop* software.

MULTI-TEMPORAL DIGITAL ELEVATION MODELS

To illustrate changes in terrain elevation across the coastal zone over time, multi-temporal digital terrain models (mtDTMs) were generated using the *Spatial Analyst* extension for *ArcGIS Desktop* software. These models show the difference in terrain elevation between younger and older DTMs. Data for the mtDTMs were sourced from the Maritime Offices in Gdynia and Słupsk, as part of the Maritime Shoreline Monitoring Program (MSMP) in the form of a GeoTiff with a resolution of 0.5 m (Table 1).

For the Ustka area, DTMs from 2013, 2018, and 2022 were compared, while for the Lubiatowo area, DTMs from 2012, 2018, and 2022 were used. The PL-KRON86 elevation system was in use until 2014, so a correction of ~0.17 m was applied to account for the change in the elevation system to PL-EVRF2007-NH, which is currently in use.

The results are presented using shaded terrain models, with red indicating erosion areas and green representing accumulation areas. The intensity of the colours reflects the extent of sediment loss or accumulation, with areas experiencing a significant change of over 2 m showing higher intensity. To enhance clarity, areas that express relative equilibrium (±0.5 m) have been excluded from the presentation.

DIGITAL SHORELINE ANALYSIS SYSTEM (DSAS)

Shoreline changes were analysed in detail using the DSAS v 5.1 tool (Himmelstoss et al., 2021), compatible with ArcGIS Desktop. DSAS calculates shoreline change rates based on archived shorelines and associated metadata, enabling projections over 10- and 20-year horizons. For this analysis, transverse profiles were generated at 20-metre intervals, with DSAS calculating changes based on profile intersections with individ-

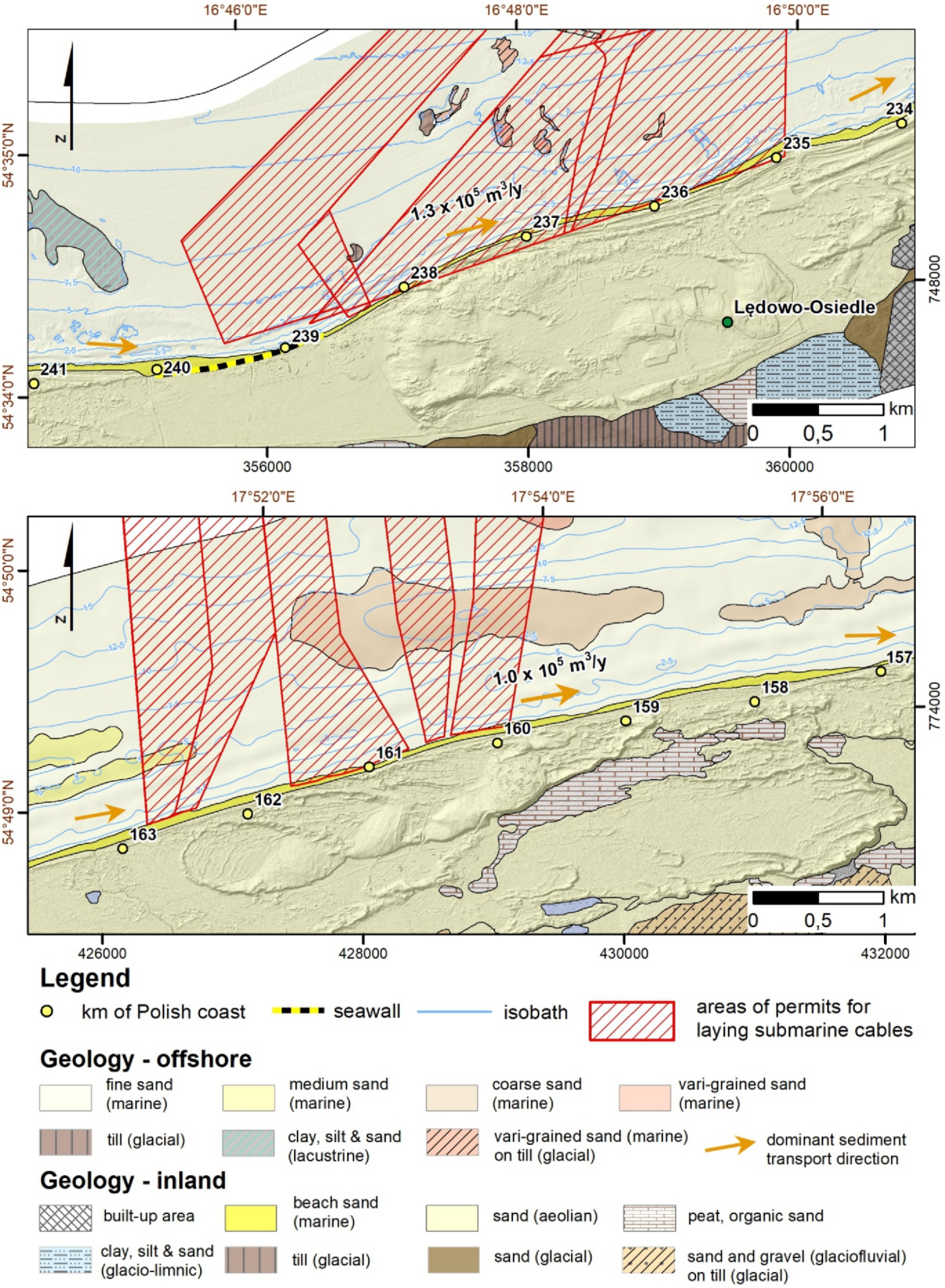

Fig. 4. Geological map of the study area (Ustka – upper panel, Lubiatowo – lower panel), Polish Geological Institute – National Research Institute materials

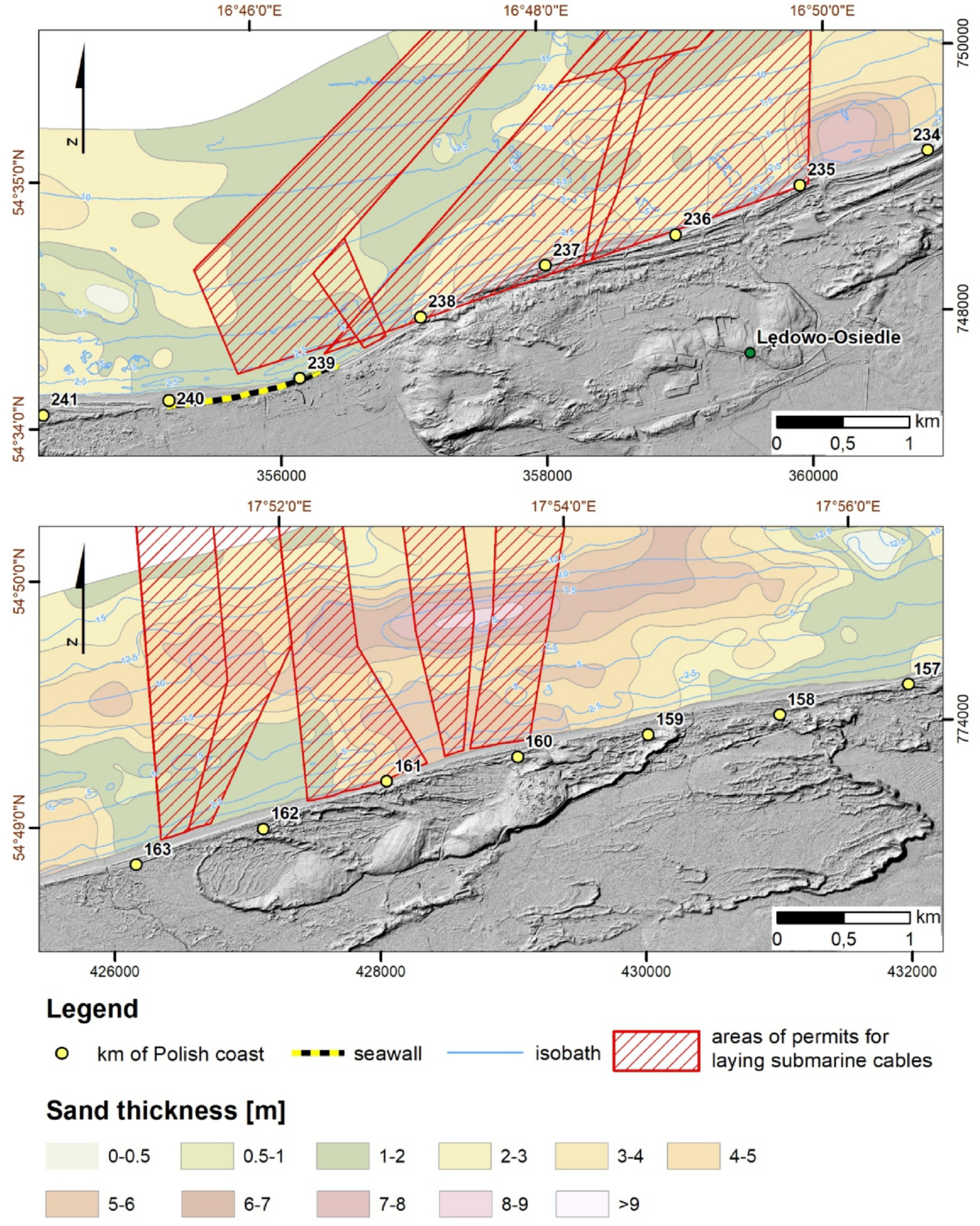

Fig. 5. Map of marine sand thickness (Ustka – upper panel, Lubiatowo – lower panel)

Table 1

Compilation of digital terrain models used to create multi-temporal DTMs

Area	Date of DTM acquisition	Average LiDAR point density	Height system	DTM pixel size	Data source
Ustka	2013.04	no data	PL-KRON86-NH	0.5 m	Maritime Office in Słupsk
	2018.04	6 p/m^2	PL-EVRF2007-NH	0.5 m	Maritime Office in Słupsk
	2022.04	13 p/m^2	PL-EVRF2007-NH	0.5 m	Maritime Office in Gdynia
Lubiatowo	2012.09	9.8 p/m^2	PL-KRON86-NH	0.5 m	Maritime Office in Gdynia
	2018.10	8 p/m^2	PL-EVRF2007-NH	0.5 m	Maritime Office in Gdynia
	2022.04	13 p/m^2	PL-EVRF2007-NH	0.5 m	Maritime Office in Gdynia

ual shorelines. The 20-metre spacing was chosen to ensure adequate data density relative to the size of the study area and to obtain a semi-continuous representation of shoreline changes appropriate to the scale of the materials presented.

In the Ustka and Lubiatowo areas, eight and seven shorelines, respectively, from 1985 to 2022, were incorporated into the analysis (Table 2). These shorelines were derived from topographic maps at a scale of 1:10,000, and orthophotomaps and DTMs provided by the Maritime Offices in Gdynia and Słupsk (as part of the MSMP) and the Head Office of Geodesy and Cartography.

To extract the shoreline from the digital terrain models (DTMs), the isoline representing 0 m above sea level was delineated and subsequently smoothed using ArcGIS software. By comparing the extracted shoreline from the DTM with an orthophotomap captured at the same time, the average positional uncertainty of the shoreline was estimated to be ~2 m.

The DSAS tool allows for the calculation of shoreline change statistics using several methods. Given that the shorelines were derived from various sources with differing levels of positional uncertainty, the weighted linear regression (WLR) method was selected for presenting the results. In WLR-based shoreline change analysis, greater weight is assigned to data points with lower positional uncertainty, ensuring more reliable trend estimation (Himmelstoss et al., 2021).The rate of change, expressed in metres per year (m/yr), is depicted using red for erosion and green for accretion, with the intensity of the colours corresponding to the magnitude of the change.

RESULTS AND INTERPRETATION

HISTORICAL SHORELINE POSITION

The analysis of historical shoreline positions over the past 147 years has revealed significant patterns of coastal change at both the Ustka and Lubiatowo sites, driven by erosion and accretion processes (Fig. 6).

At the Ustka site, notable coastal changes have occurred. The most pronounced transformation is the erosion of the western part of the area, specifically between 237.5 km and 240.5 km, where the shoreline has retreated by up to 270 m. This results in a maximum average erosion rate of ~1.8 m/yr, forming an extensive erosional embayment that poses a critical concern for future infrastructure placement due to its rapid development. In contrast, the central and eastern parts of the

Table 2

Summary of materials used in the DSAS analysis

Shorelines used for Digital Shoreline Analysis System					
Ustka area			Lubiatowo area		
source	year	estimated shoreline uncertainty [m]	source	year	estimated shoreline uncertainty [m]
Topographic map 1:10 000, PL-1965, 313.213	1986	10	Topographic map 1:10 000, PL-1965, 304.411	1985	10
Orthophotomap (LPIS87)	2010	3	Topographic map 1:10 000, PL-1992, N-33-48-D-b-1	2001	5
DTM (ISOK)	2011	2	Topographic map 1:10 000, PL-1992, N-33-48-D-a-2	2002	5
DTM (MSMP)	04.2013	2	DTM (MSMP)	2010	2
DTM (MSMP)	08.2013	2	DTM (MSMP)	2016	2
DTM (MSMP)	2018	2	DTM (MSMP)	2018	2
DTM (MSMP)	2019	2	DTM (MSMP)	2022	2
DTM (MSMP)	2022	2			

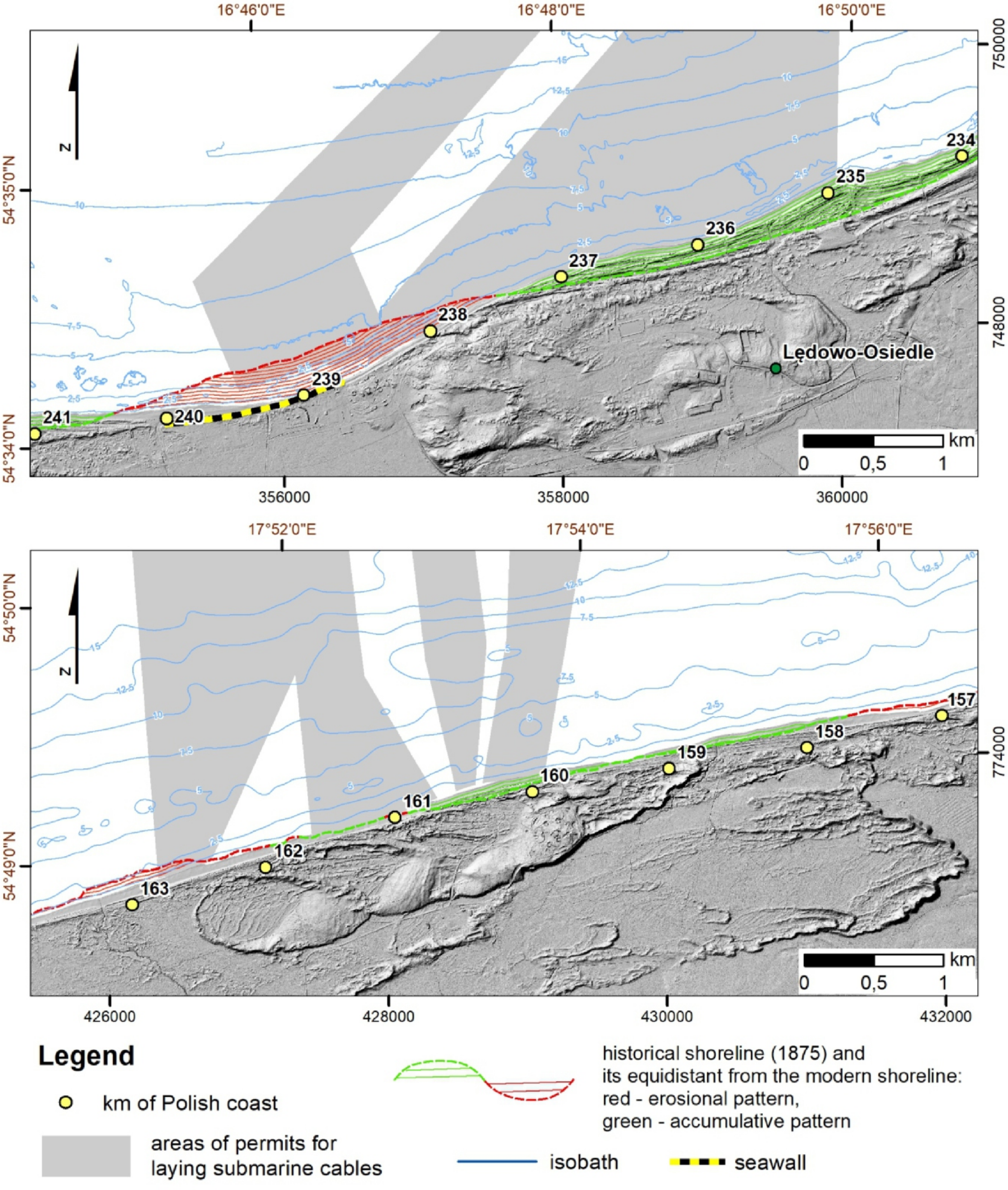

Fig. 6. Comparative analysis of shoreline changes between 1875–2022 (Ustka – upper panel, Lubiatowo – lower panel)

Table 3

Parameters of the rate of change of the shoreline position on a decadal scale

Site		Ustka	Lubiatowo
Parameter	Unit	WLR	
total number of transects	–	290	279
average rate	[m/yr]	0.1	–0.6
percent of all transects that are erosional	[%]	46.5	66.0
percent of all transects that have statistically significant erosion	[%]	27.2	31.5
maximum value erosion	[m/yr]	–3.1	–3.5
average of all erosional rates	[m/yr]	–1.6	–1.7
percent of all transects that are accretional	[%]	53.5	34.0
percent of all transects that have statistically significant accretion	[%]	20.0	8.6
maximum value accretion	[m/yr]	5.1	4.2
average of all accretional rates	[m/yr]	1.2	1.5

Ustka site have experienced accretion, leading to significant land growth. The most substantial accumulation has occurred around the 235 km marker, where the coastline has advanced by up to 270 m since the late 19th century. This extensive accumulation has been primarily influenced by the breakwaters of the Port of Ustka, which were already in place before 1875 (i.e., before the creation of the topographic map used for this analysis). This process was further intensified by the construction of ~100 m long pier at 234.9 km during World War II. These changes align with the alongshore sediment transport in the area, which moves sediment eastwards at an estimated rate of ~1.3 × 105 m^3/yr, playing a significant role in shaping the coastline's evolution.

At the Lubiatowo site, coastal changes over the last 147 years have also been characterized by both erosion and accretion, though generally at a lower magnitude compared to the Ustka site. Coastal retreat has occurred in the western part (west of km 161.9) and in the easternmost section (between 157 km and 157.7 km). However, significant erosion has been recorded only in a stretch between 162.5 km and 163.5 km, where the coastline has retreated by up to 80 m, translating to an average erosion rate of 0.5 m/yr. In other sections, the retreat has been much smaller, not exceeding 25 m. Between these eroding sections, the coastline has advanced by up to 90 m at a rate of 0.6 m/yr in an accretion area.

DIGITAL SHORELINE ANALYSIS SYSTEM (DSAS)

The analysis of shoreline changes along the Ustka site using DSAS was conducted based on eight shoreline positions spanning the period from 1986 to 2022. A total of 290 transects were analyzed (Table 3). The average rate of shoreline change at this site is slightly positive, at +0.05 m/yr. Erosion was observed along 47% of the transects, with 27% showing statistically significant erosion. The maximum erosion rate is –3.08 m/yr, and the average erosion rate among erosional transects is –1.61 m/yr. About 53% of the transects show accretion that is statistically significant in 20% of this site. The maximum accretion rate is +5.08 m/yr, and the average accretion rate among accretional transects is +1.19 m/yr. These results indicate that while erosion is prevalent in certain areas, there is also considerable sediment accumulation at Ustka. Importantly, the overall net change at the Ustka site is slightly positive, with an average rate of +0.05 m/yr. This suggests a modest net gain in coastline, despite the ongoing processes of erosion and accretion.

For the Lubiatowo site, shoreline positions were evaluated along 279 transects (Table 3). The average rate of shoreline change is negative, at –0.62 m/yr, indicating overall coastal retreat. Erosional transects account for 66% of the total, with 31.5% of these showing statistically significant erosion. The maximum recorded erosion rate is –3.46 m/yr, while the average erosion rate among erosional transects is –1.73 m/yr. Accretion was observed in 34% of the transects, although only 8.6% show statistically significant accretion. The maximum accretion rate is +4.19 m/yr, and the average accretion rate among accretional transects is +1.51 m/yr.

These findings indicate that while sediment accumulation occurs in some areas, the Lubiatowo site is predominantly erosional. The region's net shoreline change has a negative trend, with an average rate of –0.62 m/yr. This signifies a net retreat of the coastline, despite the presence of some stable or accumulating areas.

The spatial pattern of erosion and accumulation zones revealed at the Ustka site by the analysis of shoreline position changes conducted on a three-decade scale (1986–2022; Fig. 7) is significantly more complex than the long-term trends observed over the one-and-a-half-century scale (1875–2022) (Fig. 6). In general, the DSAS analysis for 1986–2022 identified three distinct erosion zones in the sections marked by 235.4–236.0 km, 237.0–239.0 km, and 240.5–241.0 km. This contrasts with the single, large erosion zone identified in the long-term analysis comparing shoreline positions from 1875 and 2022. Furthermore, the analysis highlighted a replacement of erosion zones with accretion in certain areas, along with a noticeable eastwards shift of these zones (Figs. 6 and 7).

A similar observation applies to the Lubiatowo site, where the DSAS analysis for 1985–2022 (Fig. 7) reveals a much larger extent of erosion than in the past. Notably, an extensive erosion zone emerged between the 158.4 km and 160.8 km markers in an area previously indicated as an accumulation zone in the historical shoreline analysis covering the period from 1875 to 2022 (Fig. 6).

MULTI-TEMPORAL DIGITAL TERRAIN MODELS

The patterns of erosion and accretion revealed by the analysis of multi-temporal terrain models for the Ustka and Lubiatowo sites (Figs. 8 and 9) are significantly more complex than those indicated by the analysis of shoreline position changes and on a centennial scale (Fig. 6). This complexity arises because the terrain models also capture changes within the beach, foredune, and areas beyond the foredune. Consequently, in the analysis of coastal changes, only the erosion or accretion of the beach and foredune was considered, while changes within dune systems located farther inland, beyond the foredune, were excluded.

The terrain elevation changes observed at the Ustka site between 2013 and 2022 (Fig. 8) are generally consistent with the DSAS results, though they show a certain contrast with the shoreline position changes recorded over the past 147 years (Figs. 6, 7 and 10).

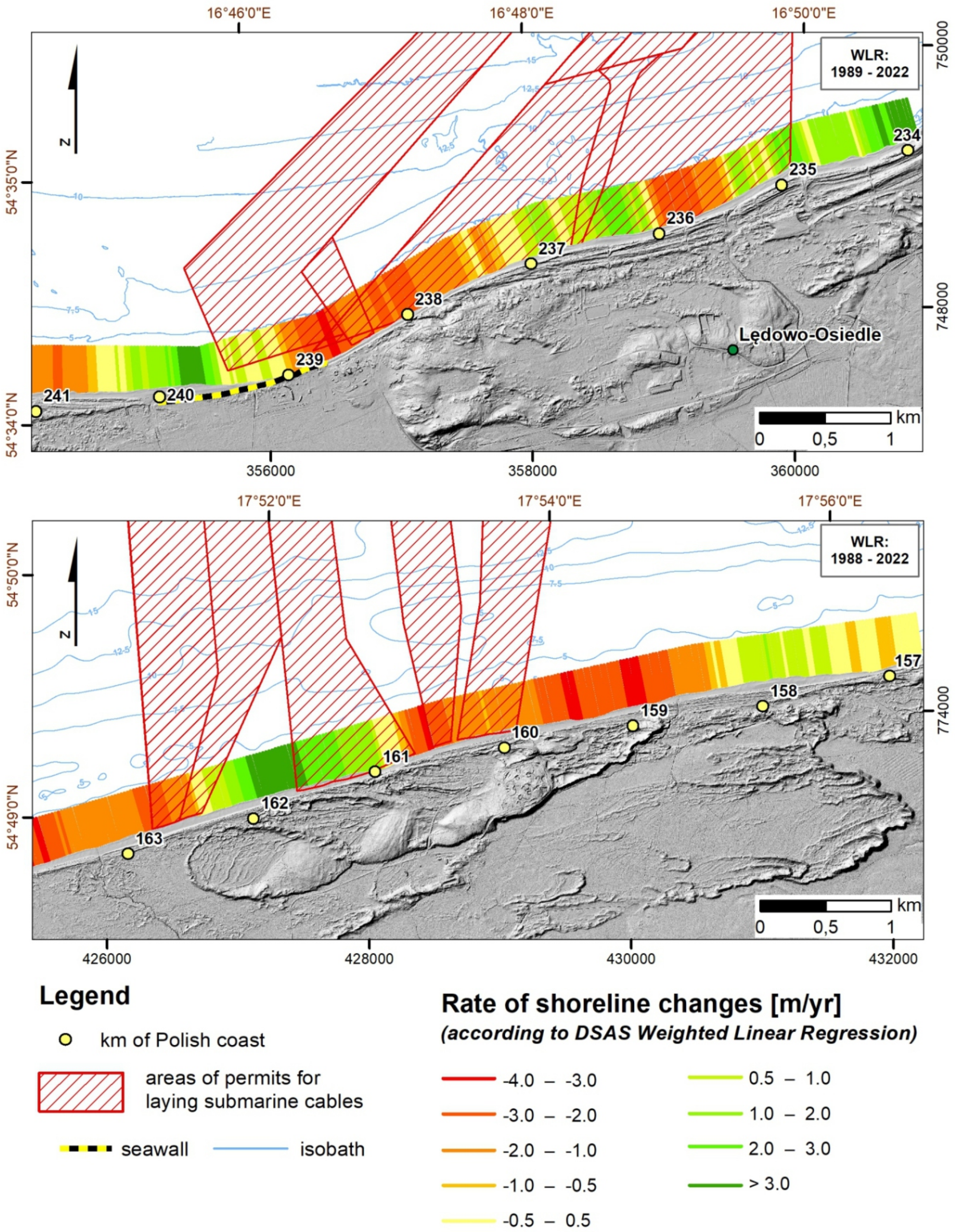

Fig. 7. Rate of shoreline changes based on the Weighted Linear Regression method (DSAS) calculated from shoreline position in years: Ustka site: 1986–2022 (upper panel), Lubiatowo site: 1985–2022 (lower panel)

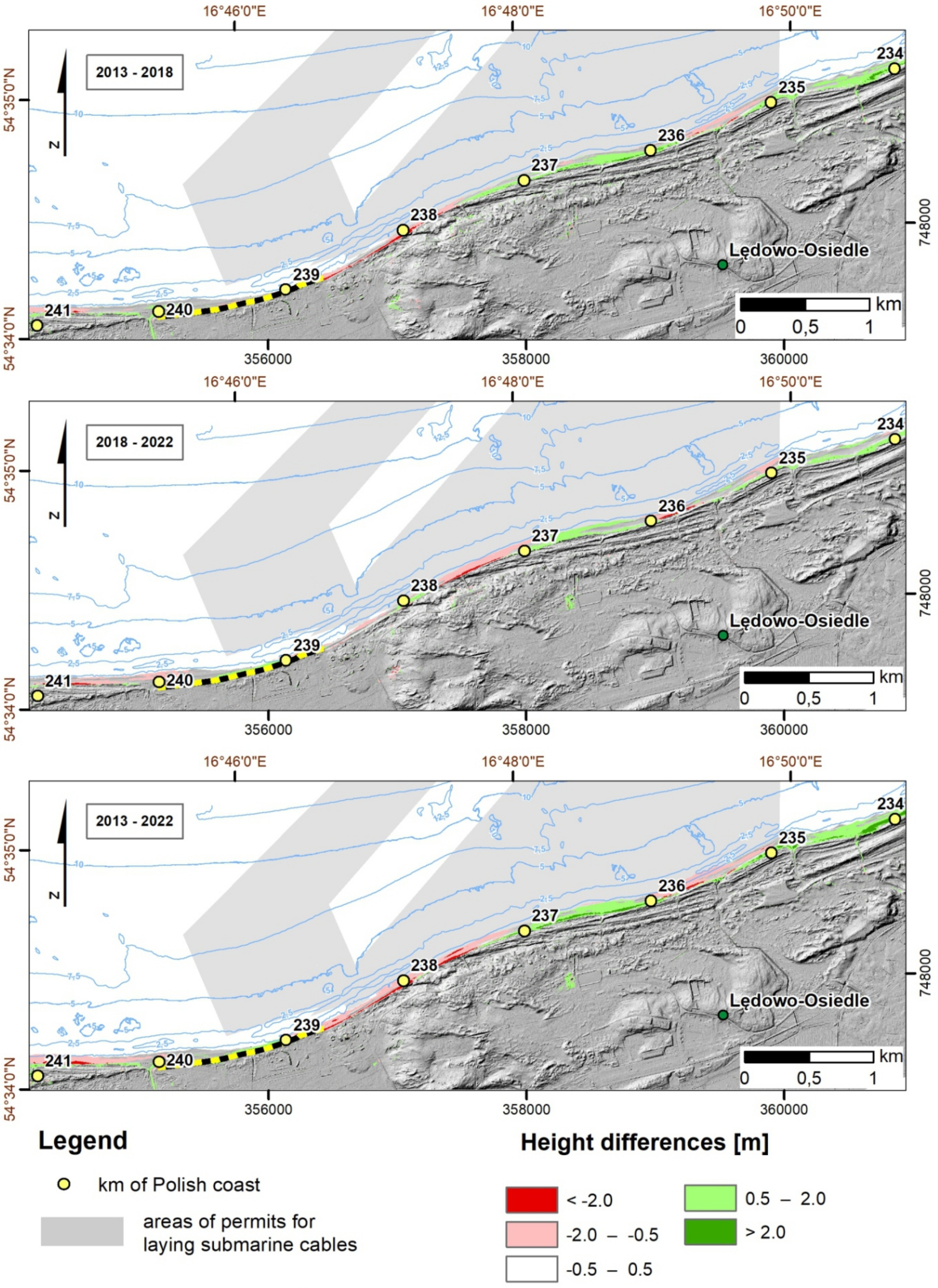

Fig. 8. Multi-temporal DTMs showing the vertical changes in beach and dune profile between 2013–2018, 2018–2022 and 2013–2022 (Ustka site)

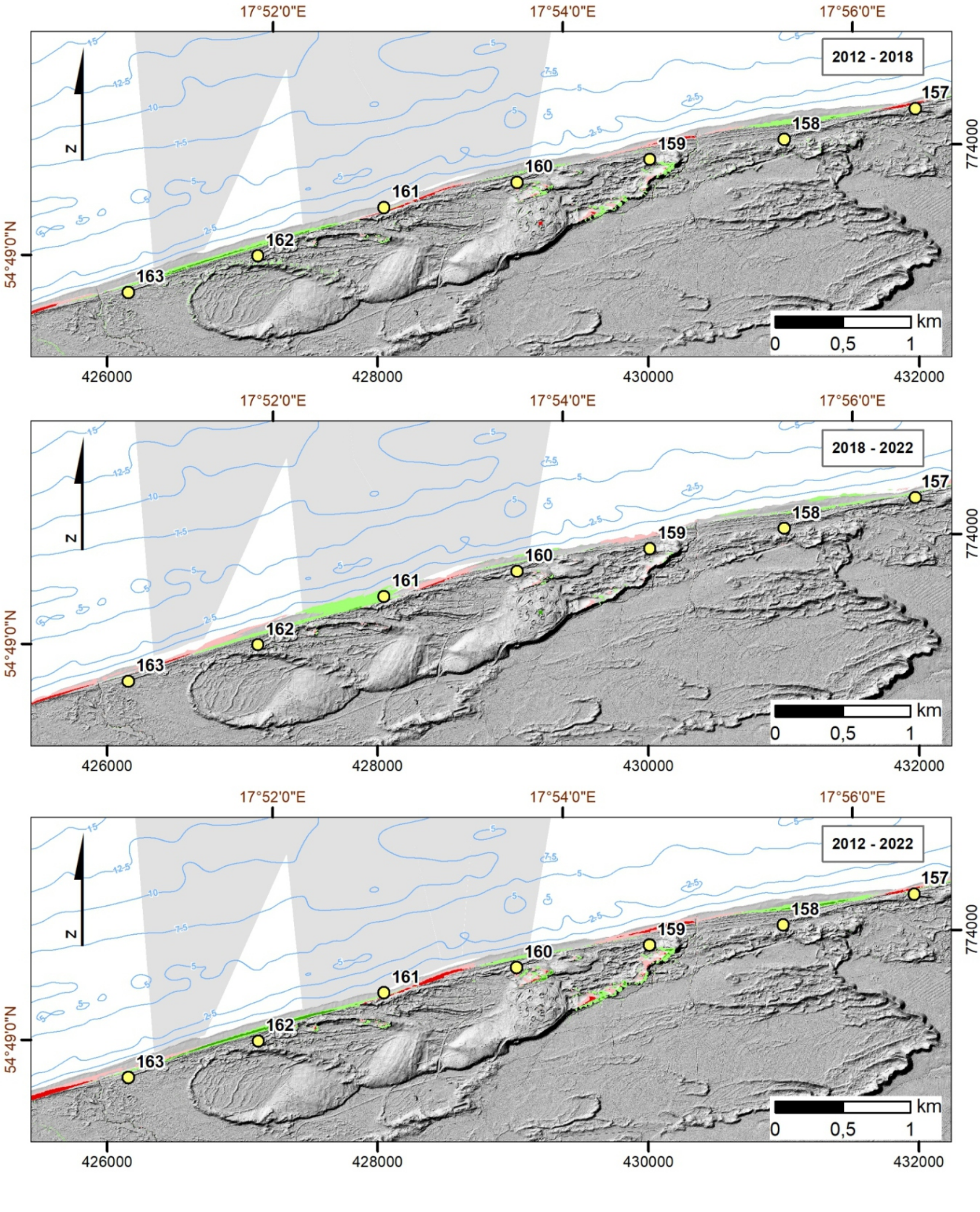

Fig. 9. Multi-temporal DTMs showing the vertical changes in beach and dune profile between 2012–2018, 2018–2022 and 2012–2022 (Lubiatowo site)

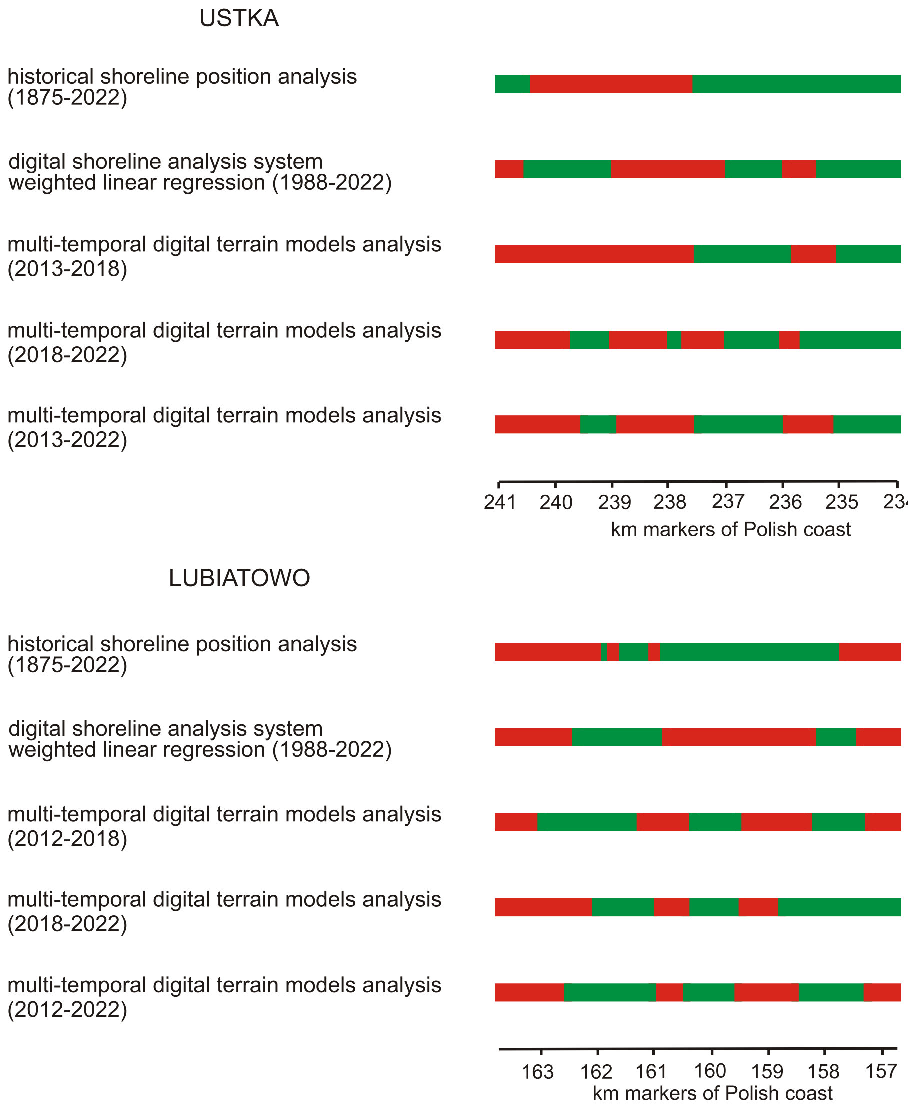

Fig. 10. Comparison of coastal erosion (red)/accretion (green) in the Ustka and Lubiatowo sites revealed by different methods and for different periods (for analysis of multi-temporal digital terrain models only erosion/accretion of beach and foredune areas were taken into account. Accretion of dunes systems beyond foredune is not shown)

Negative changes in terrain elevation (i.e., erosion) during the period 2013–2018 dominated the western part of the area, particularly between the 237.5 km and 241 km markers. A shorter eroded section was also observed between the 235.1 km and 235.8 km markers. By contrast, accumulation prevailed in other sections, especially in the eastern part of the site, notably between the 234.0–235.1 km and 235.8–237.5 km markers.

Terrain elevation changes in 2018–2022 show a greater presence of erosional zones, specifically between the 235.7–236.0 km, 237.1–237.8 km, 238.1–239.0 km, and 239.8–241.0 km markers. Despite this, accretion continued in some areas in the beach zone (Fig. 8). However, the 2018–2022 period marked a more significant shift in the extent of the erosional zone. During this time, the western erosion zone not only persisted but also expanded eastwards, reaching as far as the 237 km marker. This expansion suggests an increasing vulnerability of the coastline in this section.

A noticeable difference between the long-term trend (Fig. 6) and short-term changes, observed for the periods 2013–2018 and 2018–2022 (Fig. 8), is the formation of an erosional zone in the eastern part of the Ustka site, specifically in the section between the 235 km and 236 km markers. This contrasts with the long-term trend, which indicates the greatest coastal accretion in this area. Additionally, there is a slight acceleration of negative vertical changes within this section in 2018–2022, indicating intensified erosion of the foredune.

The analysis of terrain elevation changes at the Lubiatowo site (Fig. 9) also reveals a complex pattern of coastal dynamics over recent periods. Positive terrain elevation changes, up to 2.5 m (i.e., accretion), were observed in 2012–2018 between the 157.3–158.3 km and 161.3–163.0 km markers. Slightly lesser accretion occurred between the 159.6–160.3 km markers. Along other coastal sections, erosion, represented by negative terrain elevation changes, was recorded. This pattern of changes generally continued in 2018–2022 but showed some variation in its spatial extent. Notably, the erosional sections extended slightly by ~0.4 km, and both erosional and accretional sections shifted eastwards by ~0.2–0.5 km compared to their positions in 2012–2018. The spatially complex but relatively minor changes in terrain elevation at the Lubiatowo site in 2012–2022 underscore a relatively stable situation, with significant changes occurring only in very localized areas.

In general, the range of terrain elevation changes at both the Ustka and Lubiatowo sites in 2012–2022 ranges between -2 m and +2 m. Only in a few localized areas do these changes exceed ±2 m. The most significant changes are related to the erosion or accretion of the foredune area.

A detailed comparison of terrain elevation changes between the periods 2013–2018 and 2018–2022 reveals a shift in the centres of erosion and accretion domains at both the Ustka and Lubiatowo sites. Notably, these centres have migrated eastwards over time, indicating a gradual redistribution of sediment along the coastline.

In summary, the pattern of erosion and accumulation zones revealed by the analysis conducted on half-decadal and decadal scales (Figs. 8 and 9) is much more complex than that shown by the long-term trend over one and a half centuries (Fig. 6). However, the short-term patterns align more closely with the patterns revealed by the analysis on a three-decade timescale (Fig. 7).

DISCUSSION

Selecting an appropriate method for assessing coastal changes in space and time is essential for effective spatial planning in the coastal zone. However, different types of planned activities or investments may require assessments that vary not only in terms of the accuracy in identifying past changes but also in the ability to predict future developments.

As the objective of this study was to analyse coastal dynamics in the area of a newly planned landfall site for marine transmission infrastructure and to assess potential future risks posed by coastal erosion, several methodological issues must be addressed to provide insights that may support better planning of critical energy infrastructure along the Polish coast.

Accordingly, a number of important questions arise when coastal changes are analysed using different methods and across varying time scales. First, to what extent do the chosen analytical methods influence the identification of erosion and accumulation zones, including their spatial extent and rates of change? Second, what can be said about the temporal stability of these zones and why do analyses conducted over different time periods reveal such different patterns of change?

Finally, a critical and often previously overlooked question concerns the underlying causes of the formation and persistence of erosion and accumulation zones in specific locations.

Referring to the first issue, it is evident that the identification of erosion and accretion zones varies depending on the analytical methods used (Fig. 10). For example, traditional and relatively simple historical shoreline analysis (e.g., 1875–2022) captures only large-scale, long-term trends that reflect gradual coastal processes (Zawadzka, 1999; Deng et al., 2017b. Uścinowicz and Szarafin, 2018) and allows for indirect estimation of the maximum rate of erosion or accretion.

In contrast, the Digital Shoreline Analysis System (DSAS) with the Weighted Linear Regression (WLR) method – applied in this study using seven or eight shoreline datasets from 1985 to 2022 – offers more precise and nuanced insights. It not only identifies the spatial distribution of erosion and accretion zones but also directly quantifies their dynamics, including the rate of shoreline change (Himmelstoss et al., 2021). The discrepancies in location and extent of shoreline movement revealed by these two approaches stem not only from the differing lengths of the time periods analysed (1875–2022 vs. 1985–2022) but, more importantly, from the fact that DSAS accounts for multiple shorter-term changes, averaging them to produce more robust projections.

In contrast to both approaches above, the use of multi-temporal digital terrain models (DTMs; 2012–2022) reveals not only shoreline displacement but also morphological changes across distinct coastal zones such as the beach, foredune, and hinterland dune systems – features that shoreline position analysis alone may not adequately capture. DTMs therefore provide a more comprehensive view of coastal dynamics, enabling analysis of changes in key morphological structures that are critical for understanding overall coastal stability (Mitasova et al., 2009; Mahmoud et al., 2021; Terefenko et al. 2024; Saye et al., 2025).

The divergence in outcomes between these analytical approaches underscores the necessity of employing complementary methods – especially when the results are intended to inform the planning of critical infrastructure, not only along the immediate coastline but also farther inland. This is particularly relevant in the context of planning landfall sites for energy and telecommunications cables or pipelines.

The second issue relates to the temporal stability of erosion and accretion zones, which remains relatively underexplored along the Polish coast. There is growing evidence that the location of such zones – at least in some areas – is not stable over time but instead shows significant temporal variability (Uścinowicz et al., 2024b). A long-term analysis of shoreline changes between 1875 and 2022 reveals broad patterns of erosion and accretion. However, when comparing shorter periods, such as 1988–2022 and 2013–2022, noticeable shifts in the location of these zones become apparent (Fig. 10).

For instance, at the Ustka site, erosion zones have migrated eastwards between 2013 and 2022, particularly between the 237 km and 241 km coastal markers. Similarly, at the Lubiatowo site, both erosion and accretion zones have shifted eastwards, especially in the 2018–2022 period. These shifts indicate that coastal dynamics are more complex than what long-term trend analyses alone may suggest.

The rate at which erosion and accretion zones relocate depends both on site-specific dynamics and on the period under analysis. At Ustka, for example, erosion has advanced by ~0.5 km eastwards between 2013 and 2022. At Lubiatowo, changes are generally smaller, but the movement of erosion and accretion zones by 0.2–0.5 km between 2012–2018 and 2018–2022 illustrates a subtle but steady eastwards progression. These findings suggest that while changes may appear gradual, they are significant when viewed over decadal timescales, and they vary depending on coastal segment.

Understanding why erosion and accretion zones appear or persist in specific locations is essential for planning any intervention to prevent or mitigate coastal erosion. While this was not the primary focus of the current study, the issue warrants preliminary discussion.

A range of factors likely influence the development and persistence of these zones, including geological and morphological conditions, alongshore sediment transport, meteorological events (especially wind and storms), and anthropogenic influences.

The geological and morphological characteristics of both the landward coast and the nearshore seabed play a central role in shaping coastal dynamics. One well-documented factor is the influence of shoreface sandbars on wave transformation and energy dissipation (Różyński and Szmytkiewicz, 2018; Harenda et al., 2024; Uścinowicz et al., 2024a, b). The architecture of these sandbar systems is closely tied to sediment availability, itself determined by seabed composition.

Less studied along the Polish coast is the influence of deeper seabed features beyond the shoreface, including submerged Pleistocene and Holocene landforms – valleys, ridges, hills, and hard substrate outcrops (e.g., glacial tills and boulders). For instance, the western part of the Ustka site (north of km 240–241) features an elongated seabed depression beyond the sandbar zone (Fig. 3) and lacustrine sediment outcrops (Fig. 4). These features may function as an "energy window" (*sensu* Uścinowicz et al., 2024a, b), concentrating wave energy and creating an erosion hotspot (*sensu* Kraus and Galgano, 2001). All analytical methods confirm this as a zone of persistent and significant erosion. Slight spatial variations in its extent are likely linked to alongshore sediment transport and differences in storm parameters between the periods analysed.

Thus, the differing seabed morphologies between the Ustka and Lubiatowo sites may help explain the spatial variability in erosion and accretion patterns across both short- and long-term timescales. However, these relationships merit further investigation.

Sediment transport along the shore can redistribute material and moderate the effects of geological and morphological controls, although this process is not yet fully understood. Coastal engineering structures also influence these dynamics. At Ustka, breakwaters and piers have significantly altered sediment transport, blocking eastward flow and resulting in accretion to the west and erosion to the east (Sitkiewicz et al., 2015).

Wind and storm events cause short-term changes in erosion and accretion patterns, especially on beaches and foredunes (Moskalewicz et al. 2024; Tanwari et al., 2025). The frequency and intensity of such events likely contribute to the observed variability in erosion zone locations. However, because this study focuses on decadal to centennial timescales, identifying the effects of individual storms was beyond its scope. Similarly, long-term sea level rise, though a critical factor on a centennial scale, was not analysed here.

Human interventions such as breakwaters and seawalls can profoundly alter sediment dynamics (Szmytkiewicz, et al. 2018; Saengsupavanich et al. 2022). At Ustka, substantial sand accumulation in the eastern part is likely linked to breakwaters constructed before 1875 and a pier built during World War II. By contrast, a seawall at the foredune toe in the western part of Ustka may have shifted the erosion zone eastwards. These structures have been key in shaping sediment distribution. Meanwhile, the Lubiatowo site remains free of human infrastructure, allowing coastal processes to proceed naturally, driven by geology, morphology, and variable hydrodynamic conditions.

The importance of understanding coastal dynamics cannot be overstated, especially for infrastructure planning and management, such as for energy transmission systems. Coastal zones are dynamic environments shaped by sediment transport, which directly impacts shoreline position and stability. This research illustrates the value of using a multi-temporal, multi-method approach to assess coastal change, as these processes critically affect the longevity and security of coastal and offshore infrastructure.

While the findings are broadly relevant, it is important to recognize regional differences. For instance, in the southern and eastern Baltic Sea, climate change is altering key coastal drivers, leading to different patterns of change (Eelsalu et al., 2025). As such, site-specific assessments are essential to effectively manage coastal risks.

Globally, geohazards such as earthquakes, seabed currents, submarine landslides, tsunamis, and extreme weather events are widely recognized threats to marine infrastructure (Carter et al., 2014; Pope et al., 2017; Clare et al., 2023; Munro et al., 2024; Zheng et al., 2024). However, the slower, cumulative effects of sediment transport and shoreline change are equally significant. Unlike sudden catastrophic events, these gradual processes are harder to detect but can result in substantial long-term impacts. The case studies presented here emphasize the importance of integrating sediment dynamics into hazard assessments for marine infrastructure.

As the demand for resilient, sustainable coastal energy systems grows, especially with the expansion of offshore wind power – adopting a holistic, long-term perspective will be crucial for minimizing risks and ensuring the durability of coastal investments.

CONCLUSIONS

The analysis of erosion and accretion systems reveals that the location of erosion and accretion centres, along with rates of shoreline relocation, are significantly influenced by the length of time interval under study. The variability of these processes across different timescales highlights the importance of considering long-term coastal dynamics when planning and managing coastal infrastructure.

Thus, when determining suitable landfall locations for energy transmission cables and designing protective measures, it is essential to analyse not only contemporary lithodynamic and morphodynamic processes but also long-term trends in coastal change. A holistic approach, incorporating both current and historical data, ensures that infrastructure placement accounts for potential future changes in the coastline, reducing the risk of damage and enhancing the stability and longevity of the infrastructure.

A key finding is that a planned landfall location for underwater cables – an essential component of transmission infrastructure – falls within an erosional embayment in the western part of the Ustka area. This area, marked by high erosion rates, raises concerns about the long-term viability of this infrastructure. By contrast, most other proposed landfall locations are situated in the accretion zone, where the coastline has been advancing, making these areas more suitable for this sort of infrastructure development.

At the Lubiatowo site, the centres of accretion zones offer a more stable environment for infrastructure placement, similar to the eastern part of the Ustka site. However, as is the case with the Ustka site, some planned permits for underwater cables target erosional sections of the coast, posing a potential risk to the stability of infrastructure of this kind.

The analysis of shoreline changes over the past three decades (1985–2022), when compared to the longer historical span (1875–2022), reveals a slight expansion of erosion zones and a shift of both erosional and accretion centres eastwards. These shifts, combined with fluctuations in erosion and accretion rates, underscore the dynamic nature of coastal processes influenced by various environmental factors. The expansion of erosional zones has significant implications for coastal management and infrastructure placement. If these shifts continue, further degradation of the coast could occur, necessitating proactive measures to protect infrastructure.

The dynamic nature of the coastline, as highlighted by these changes, emphasizes the need for continuous monitoring to anticipate and mitigate risks to infrastructure. Comparative analysis of multi-temporal Digital Terrain Models (mtDTMs) indicates that the centres of erosion and accretion are not static. Instead, they are shifting in response to evolving environmental conditions, including changes in wave dynamics, sediment supply, and coastal currents. These findings underscore the necessity of adapting coastal management strategies to account for the spatial and temporal variability of coastal processes, particularly when planning the location of critical infrastructure.

Finally, the absence of measurement or modelling data on cross-shore sediment transport, both in the short term (seasonal to decadal) and the long term (centennial) represents a significant gap in understanding the full scope of coastal change. Preliminary estimates (Uścinowicz et al., 2024a, b) suggest that, over longer timescales, as much as 40–60% of sand may be lost from the shoreface to the offshore zone due to processes such as rip currents and other sediment transport mechanisms extending beyond the shoreface. This resulting sediment deficit is a key driver of coastal erosion and shoreline retreat, posing a major challenge for the selection and planning of cable landing sites. These findings underscore the urgent need for further research to quantify sediment transport dynamics more precisely, thereby improving coastal management strategies and reducing risks to critical infrastructure.

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