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The temporal and spatial variability of coastal dune erosion in the Polish Baltic coastal zone

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Abstract The study looked at the temporal and spatial variability of dune erosion in the Polish Baltic coastal zone in the period 1972–2008. The dynamics of coastal dune erosion in the area are presented in relationship to the main hydro-meteorological factors: storm surges and types of atmospheric circulation. The greatest destruction of the coastal dunes in Poland was observed on sandbar sections, where the erosion was over 100,000 m^3 per 1 km, causing dune baseline retreat by several tens of meters. The main causes of this considerable coastal erosion are the sudden rise of the sea level and the waves during extreme storm surges, when the loss of dune sediment across the entire Polish Baltic Sea coastal zone can reach about 400,000 m^3. These extremely erosive storm surges are particularly generated by cyclonic atmospheric circulation, which accounts for more than 52% of such surges from the north-west, north, and west. It was also found that sea level increases of more than 1 meter (about 602 cm) above the mean sea level (about 500 cm) can result in significant erosion of coastal dunes in Poland (>100,000 m^3). However, there is a relationship between the intensity of the dune erosion and sea level. The results of the present study could be applied to studies of Baltic coastal dunes functioning in the lagoon-spit coastline, especially in the stretch from Estonia to Germany.

Keywords • *dune erosion • Baltic coast • extreme storms • threshold values*

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INTRODUCTION

The current changes in the shoreline as a result of climate change and sea transgression is of high importance, both in European research (Morton, Sallenger 2003; Li *et al.* 2013), as well as in studies of the Baltic area (Jegliński 2003, Uścinowicz 2006; Pruszak *et al*. 2011). This coastal change is due to climate change, rising sea levels and the substantial frequency of storm surges observed in the Baltic Sea coastal zone. (Borówka 1990; Basiński 1995). The erosion processes occur not only in the cliff coast, but also in the dune coast. Intensive erosion of dunes particularly occurs during extreme storm surges, whose current attendance is especially high (Wiśniewski, Wolski 2011). Dune erosion is very important not only in terms of the irreversible changes it causes to the geographical environment, but also in the context of the development and management of the marine coastal zone (Zeidler 1997). The research of coastal dune erosion have a practical dimension associated with the spatial management and seashore protection. Especially important are studies from the southern and eastern coast of the Baltic Sea (from Germany to Estonia), because there is mainly a dune coast and other scientific papers provide good reference material, e.g. Rivis, *at. al.* (2009), Kobelyanskaya *et. al.* (2011), Morkūnaitė (2011), Česnulevičius, *at al.* (2017).

The main objective of the study is to present the temporal and spatial variability of coastal dune erosion in the period 1972–2008 (indication of coastal sectors with intense and limited erosion, timing analysis of dune erosion). The study provides data on the quantitative levels of the dunes erosion as a result of intensive storm surges. It also gives the hydro-meteorological origin of intensive dune erosion in relation to the atmospheric circulation types which generate erosive storm surges. Other aims of the present work include examination of the following problems: Is there a statistically significant trend in coastal dune erosion (increase or decrease)? How is extreme dune erosion spread over time (is it secular, seasonal or episodic)? Is there a statistically significant relationship between the sea level and coastal dune erosion?

RESEARCH AREA, MATERIALS AND METHODS

The Baltic Sea is a shallow inland sea (mean depth 52 m), where sea tides (few centimeters) are not significant in the geomorphological changes of the coastal zone. The Baltic coast in Poland is built entirely of loose quaternary forms, most often fluvioglacial sands, post-glacial clays and organogenic structures (Mojski 2000). The origin, relief and geological structure of coast is mainly related to last glacial period and fluctuations of Baltic Sea levels due to ice melt and its recession (Uścinowicz 2003). Dunes on sandbars in Poland occupy more than 80% of the Southern Baltic coast. Polish coast of the Baltic Sea has a total length of ca. 468 km (without internal lagoonal coasts). It is 428 km from Russian to German border (without Hel Peninsula) plus 36 km of Hel Peninsula (or 72 if taks into account both sides of the peninsula). Dune (barier type coast) its 358 km. The white dunes (foredune ridges) development on the Polish Baltic coast since 0.5 ka BP, e.g. on the Vistula Sandbar (Fedorowicz *at al.* 2006), on the Świna Gate (Piotrowski 1999). Foredune ridges have various heights. They can be up to a 4–8 m high, less frequently they reach 12 m a.m.s.l. Low ridges, up to 6 m, characteristic of a quickly progradating coast, can be found on the Świna Gate Sandbar, the Łebsko Lake Sandbar, the Hel Peninsula and at the mouth of the Vistula River. Higher foredunes, up to 12 m high, occur between Pogorzelica and Mrzeżyno, west of Kołobrzeg and Mielno, and near Darłówek (Łabuz 2013).

The study included an assessment of the quantitative loss of dune sediments in 1972–2008. Measurements were made by the Maritime Offices at selected sections of dune coasts most severely affected by the loss of sediments due to extreme storm surges. The dune erosion levels, given as the loss of sandy sediments in cubic meters (m^3), are provided together with their area (in kilometres) along the Polish Baltic Sea coast, except the Hel Peninsula (Fig. 1). The quantitative characteristics of dune coast erosion reference the loss of sediments in selected 1 km coastal sections. All the quantitative measurements were performed immediately after storm surges leading to dune loss. The quantitative loss of the coastal dunes was measured in the first relatively durable zone, most commonly in foredune ridges. The measurements were not performed in the embryo dunes zone. The volume of losses was estimated using simple geodetic methods. Measurements were made with compasses, measuring tapes and rods, sometimes with a levels. A network of field markers was used. The depth, length and width [m] of the dunes under the storm surges were measured. In this way the volume of dunes losses [m^3] were obtained. Despite the simple methods of measurements short-term data (volume of dune losses [m^3/km^2]) were obtained which and they were most accurate for the research period. Erosion-related data were obtained from the Maritime Offices in Gdynia, Słupsk and Szczecin.

The dynamics of the dune erosion were analysed in the context of the main hydro-meteorological conditions causing loss of sediments along the coastline.

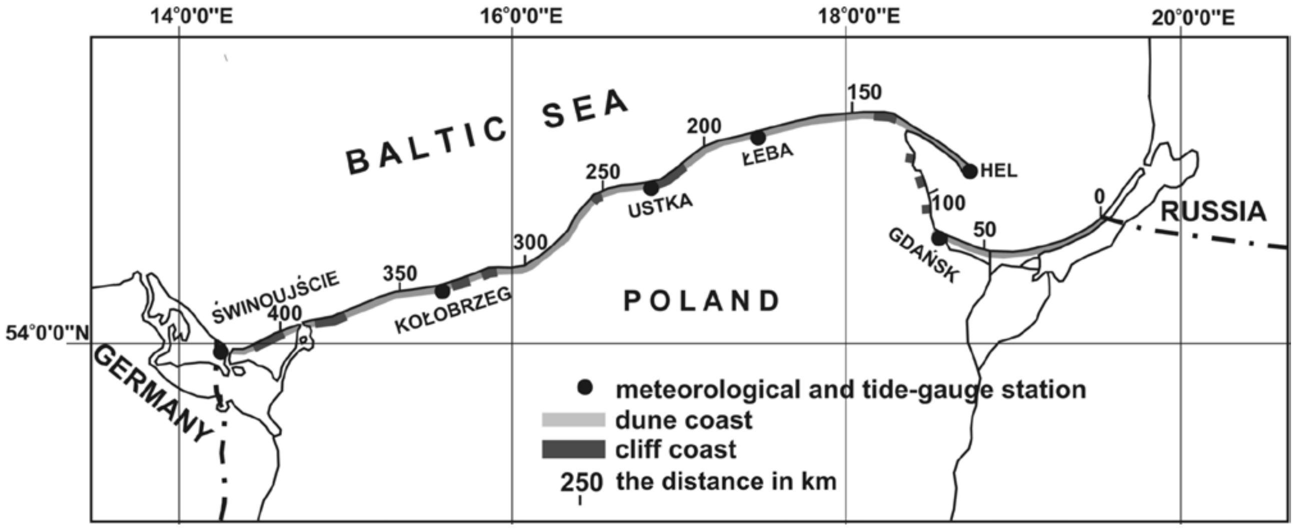

Fig. 1 Study area – location of the dune coast in the Polish coast of the Baltic Sea. Compiled by J. Tylkowski, 2017.

The study presents the temporal and spatial variability with respect to the average and maximum sea levels at the mareographic stations in Gdańsk, Hel, Ustka, Łeba, Kołobrzeg and Świnoujście (in cm, using only the Baltic High System (BHS) Kronstadt reference system; the estimated difference between NN and BHS based systems is about 15 cm (the Kronstadt system is higher). In Poland there is a height system based on Kronstadt. However, sea level registration has a link to the Normal-Null reference system (Wolski *et al.* 2014). Daily sea level data for 1972–2008 were obtained from the Institute of Meteorology and Water Management in Warsaw. This study also discusses what types of atmospheric circulation lead to heavy storms and – as a consequence – cause the erosion of the dune coast. Daily data on the atmospheric circulation types in 1972–2008 in the Polish Baltic Sea coastal zone were determined using the Grosswetterlagen classification supervised by the Deutscher Wetterdienst (Werner, Gerstengarbe 2010).

The paper uses statistical methods, for example, the Mann-Kendall trend test of sea level and dune erosion, Ward's cluster analysis of atmospheric circulation types in relation to coastal dune erosion, and the correlation and determination coefficients between sea level and dynamics of dunes erosion.

RESULTS

Atmospheric circulation

The occurrence of erosive storm surges is determined by, for example, extensively variable meteorological conditions, such as atmospheric circulation. An analysis of the circulatory origin of 126 storm surges in 1972–2008 showed that the majority of storms in the Polish coastal area of the Baltic Sea were generated by cyclonic circulation, which caused a shift of low-pressure baric systems and weather fronts (Table 1). Such cyclonic circulation generated almost 60% of storms, especially highly erosive storms. Most of the storms were caused by the following cyclonic circulations: north-western NWZ (20.6%), western WZ (18.3%) and northern NZ (12.7%). These types of atmospheric circulation cause an inflow of air masses from the W-N sector which most often – along the Polish coast of the Baltic Sea – lead to storm surges and waves generated by high winds. The storm waves in the Polish coastal area of the Baltic Sea also take place during anti-cyclonic circulation (less than 40%), in particular the following types: north-western NWA (8.7%), central European, high-pressure HM (7.9%) and western WA (6.3%). However, the storm accumulation caused by anti-cyclonic circulation and the resulting coastal erosion are significantly lower than those caused by anti-cyclonic circulation.

The spatial extent of storm surges and dune erosion does not include the occurrence of specific events in the entire Polish Baltic coastal zone. The configuration of the coastline and its exposure to storm waves, and the significant wave height at the Polish Baltic coast are all very diverse. Therefore the atmospheric conditions of storm surges and coastal erosion in the form of atmospheric circulation most frequently affect only specific sections of the Polish Baltic coastal zone. Table 1 shows the types of atmospheric circulation that generate storm surges and dune erosion.

It was impossible to determine a directly proportional and statistically significant relation between the increase in sea level due to the specified atmospheric circulation, and the intensity of the dunes erosion. The intensity of the coastal erosion also depends, amongst other things, on the presence and the dynamics of storm surges and the morphogenetic nearshore and offshore conditions in the period preceding the occurrence of storm surges. Therefore, it is not always extremely high sea levels that cause extreme dune erosion (Tylkowski, Kolander 2014). However, it is possible to see a regularity in the high frequency

Table 1 The percentage of atmospheric circulation types in the generation of erosive storm surges along Poland's Baltic coastline (based on 126 recorded erosive events in 1972–2008 period)

Circulation type	Code	Attendance [%]
Northwest, cyclonic	NWZ	20.6
West, cyclonic	WZ	18.3
North, cyclonic	NZ	12.7
Northwest, anticyclonic	NWA	8.7
Central European high	HM	7.9
British Islands high	HB	6.3
West, anticyclonic	WA	6.3
North, Iceland high, anticyclonic	HNA	3.2
Central European trough	TRM	3.2
Central European ridge	BM	2.4
Norwegian Sea- Fennoscandian high, anticyclonic	HNFA	2.4
North, anticyclonic	NA	1.6
Western Europe trough	TRW	1.6
Southern West	WS	1.6
North, Iceland high, cyclonic	HNZ	0.8
Southeast, cyclonic	SEZ	0.8
Southwest, anticyclonic	SWA	0.8
Southwest, cyclonic	SWZ	0.8

of dune destruction events during storm surges due to western and north-western cyclonic circulation (Ward's cluster analysis). Low-pressure circulation from the NWZ and NZ directions are determined to the greatest extent by the occurrence of extremely high sea levels, which may be responsible for the greatest erosion of coastal dunes.

Sea level and storms

Due to their low elevation, dune coasts are particularly exposed to damage due to the rising sea level, especially during high storm waves. Currently, increasing statistically significant trends for the sea level in the Polish coastal area of the Baltic Sea have been observed (Wiśniewski *et al.* 2011). An analysis of the average sea levels in 1972–2008 showed a statistically significant rate of increase (Mann-Kendall trend test, $p<0.05$) from 3.6 mm per year in the eastern part of the coast, in Gdańsk, up to 3.9 mm per year in the western part, in Świnoujście (Fig. 2). This dynamic of Baltic Sea transgression in 1972–2008 is similar that found in any other publication for last 50 years of 20th century. For the Baltic Sea increase of sea level was about 4 mm per year in 1971–1990 period (Rotnicki, Borzyszkowska 1999). The global average increase of the sea level was estimated at 1–2 mm per year (Russel *et. al.* 2000).

The erosion of dunes and the shifting of sandy sediments occurs with high sea levels that significantly exceed their average level of about 500 cm in the Polish coastal area. Temporary analysis of the maximum sea level in 1972–2008 did not indicate any statistically significant variability trends, based on the Mann-Kendall trend test (Fig. 2). In the study period, the highest sea level (661 cm) was recorded in Pomeranian Bay, in Świnoujście, on 4 November 1995. In Kołobrzeg, the highest sea level (644 cm) occurred on 1 November 2006. The identical maximum level (as in Kołobrzeg) was recorded in the eastern part of the Polish coast, in Gdańsk, on 23 November 2004. The highest sea level (636 cm) was also recorded in the central part of the coast in Ustka, on the same day. In Łeba and Hel, the absolute maximum level was 620 cm, which occurred on 23 January 2007 and 19 January 1983, respectively. The absolute maximum sea levels were higher by about 1.5 m than the average. Such high sea levels, and the accompanying storm waves, were significant factors in the erosion of the sea coast.

In the period 1972–2008, the sea level was high on a considerable number of occasions, and this was a destructive factor of foredunes. Based on the assumption of Jania, Zwoliński (2011), the threshold value of the extreme sea level was defined as 10% of the probability of occurrence of the maximum daily sea level (Table 2). The extreme threshold values of the maximum sea level (10% of the probability of their occurrence according to the Gumbel distribution) increase towards the eastern coast. In Świnoujście, the extreme threshold is equal to 594 cm, increases to 603 cm in Ustka, and reaches 612 cm in Gdańsk. The defined 10% extreme threshold values are approaching the alarm level of ≥600 cm in the Polish coastal area of the Baltic Sea (Wiśniewski, Wolski 2009). They also approach the threshold values of dune erosion specified by Łabuz (2013). He stated that the coastal

Table 2 The occurrence of storm surges with the extreme maximum sea level (10% probability) along the Polish Baltic coast (1972-2008)

Tide–gauge station	Sea level (cm), Date (yyyy-mm-dd)
Gdańsk	644 cm (2004-11-23), 638 cm (1983-01-19), 618 cm (1981-11-02, 1988-11-29, 2007-01-19), 616 cm (1983-01-29), 613 cm (1992-01-17)
Hel	620 cm (1983-01-19), 608 cm (1992-01-17), 607 cm (2007-01-19), 605 cm (1983-01-29, 2004-11-23)
Łeba	620 cm (2007-01-23), 616 cm (1992-01-17), 612 cm (1988-11-29), 610 cm (1995-04-08)
Ustka	636 cm (2004-11-23), 633 cm (1983-01-19), 620 cm (1992-01-17, 1995-04-08, 2006-11-01), 618 cm (2007-01-19), 616 cm (1988-11-29), 609 cm (1983-02-02), 607 cm (1995-01-03), 605 cm (2001-11-16)
Kołobrzeg	644 cm (2006-11-01), 640 cm (1992-01-17), 635 cm (1983-01-19), 634 cm (1988-11-29), 633 cm (1995-11-04), 623 cm (1983-02-02), 620 cm (1995-04-08), 619 cm (1983-01-20, 1993-02-21), 618 cm (1989-12-07), 616 cm (1995-01-03), 615 cm (1976-01-03, 2007-01-19), 612 cm (1983-11-28, 1986-12-19, 1997-04-11), 605 cm (1973-11-21, 2001-11-16), 604 cm (2003-12-22, 2007-01-25), 603 cm (1987-01-09), 602 cm (1978-01-04, 1986-12-20, 1993-01-25, 2001-11-23), 600 cm (1988-12-14, 1988-12-20, 2000-01-18, 2002-01-02)
Świnoujście	661 cm (1995-11-04), 641 cm (1993-02-21), 620 cm (1976-01-04, 1983-02-02, 1995-01-03), 618 cm (1983-01-19), 617 cm (2007-01-25), 616 cm (1976-01-17, 1988-11-30, 1992-01-17, 2006-11-01), 612 cm (1983-11-28), 610 cm (1987-01-09), 609 cm (2002-02-21), 608 cm (1986-12-19, 1995-04-08), 607 cm (1973-11-20), 605 cm (1976-12-26, 1989-11-28), 604 cm (2003-12-06, 2006-11-02, 2007-01-22), 602 cm (1989-12-07, 2004-11-23, 2007-01-29, 2008-10-30), 601 cm (1973-11-29), 600 cm (2002-01-02), 598 cm (1974-12-30, 1983-12-10, 2001-11-09), 597 cm (1993-01-25, 2000-01-21), 596 cm (1981-11-06, 1984-01-09, 1995-08-31, 2001-11-23), 595 cm (1976-01-13, 1989-10-03, 2000-01-18)

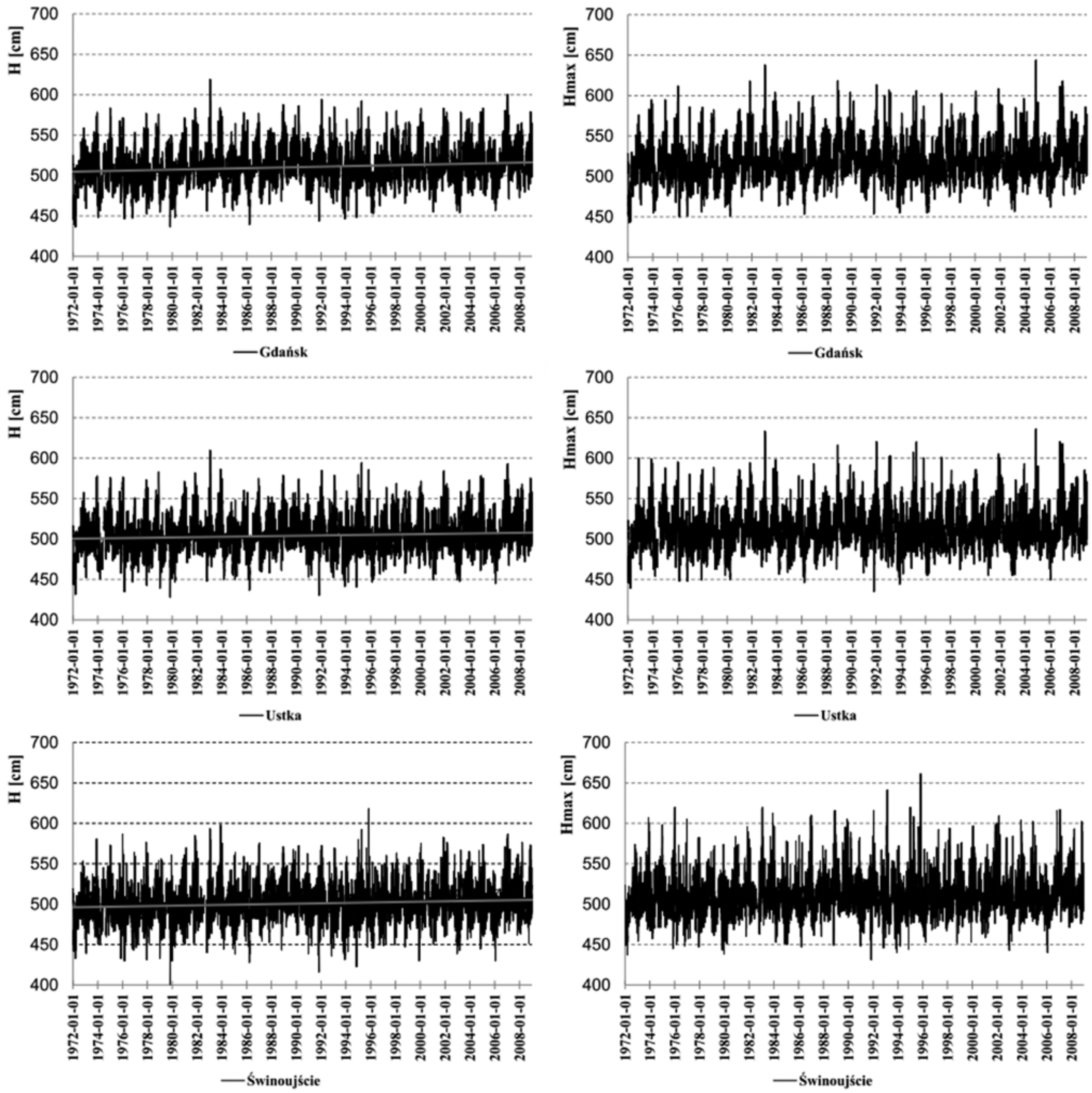

Fig. 2 Trends in the average values of sea levels H (cm), and variability of the maximum sea level Hmax (cm) on the Polish coast of the Baltic Sea. Compiled by J. Tylkowski, 2017.

dunes erosion occurs most often during storm surges, when the sea level is about 1 m higher than average sea level (500 cm).

Erosion of dunes

The erosion of dunes along the coastline of Poland can be observed in all coastal zones. Contemporary dune erosion is currently a significant problem in terms of spatial development, management and protection of the Baltic coast (Fig. 3).

The coastal sections from Karwia to Stilo (144 km to 172 km of the coast), and from Dziwnów to Świętouść (390 to 297 km of the coast), were particularly exposed to the loss of dune sediments (>50,000 m^3 over specific 1 km-long coastal sections). Considerable erosion occurred at some points in the area of the Wicko and Resko lakes sandbars (Fig. 3). Minor erosion and even accumulation of dune sediments could be observed, particularly in the stretch from Międzyzdroje to Świnoujście (415 km–420 km of the coast). Dune erosion in the Polish coastal zone mainly involves white and grey frontal dunes. Along the natural dune-formed coasts not damaged by erosion, there are sandy dune ridges of varied width, running parallel to the coastline and characterised by line-arranged vegetation.

In 1972–2008, no increase in the temporal tendency of the dunes erosion was recorded in the Polish

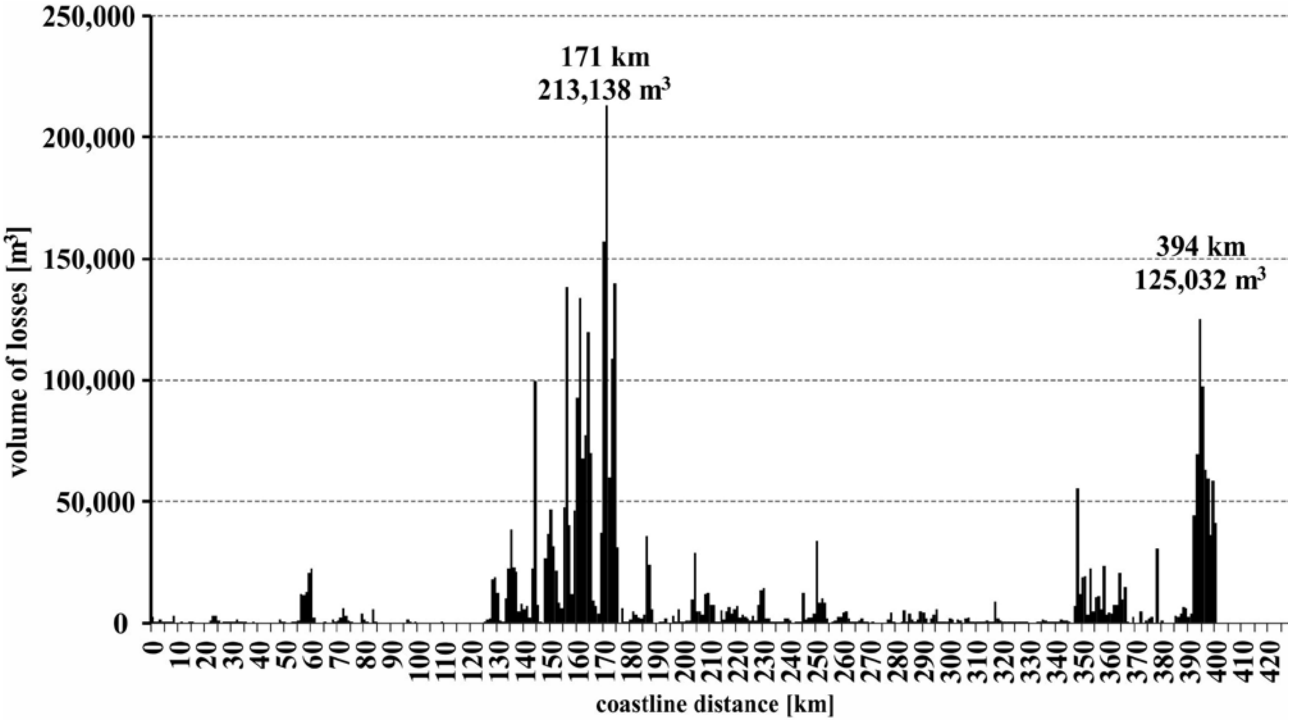

Fig. 3 Spatial variability of dune erosion along the Polish coast of the Southern Baltic Sea in 1972-2008. Compiled by J. Tylkowski, 2017.

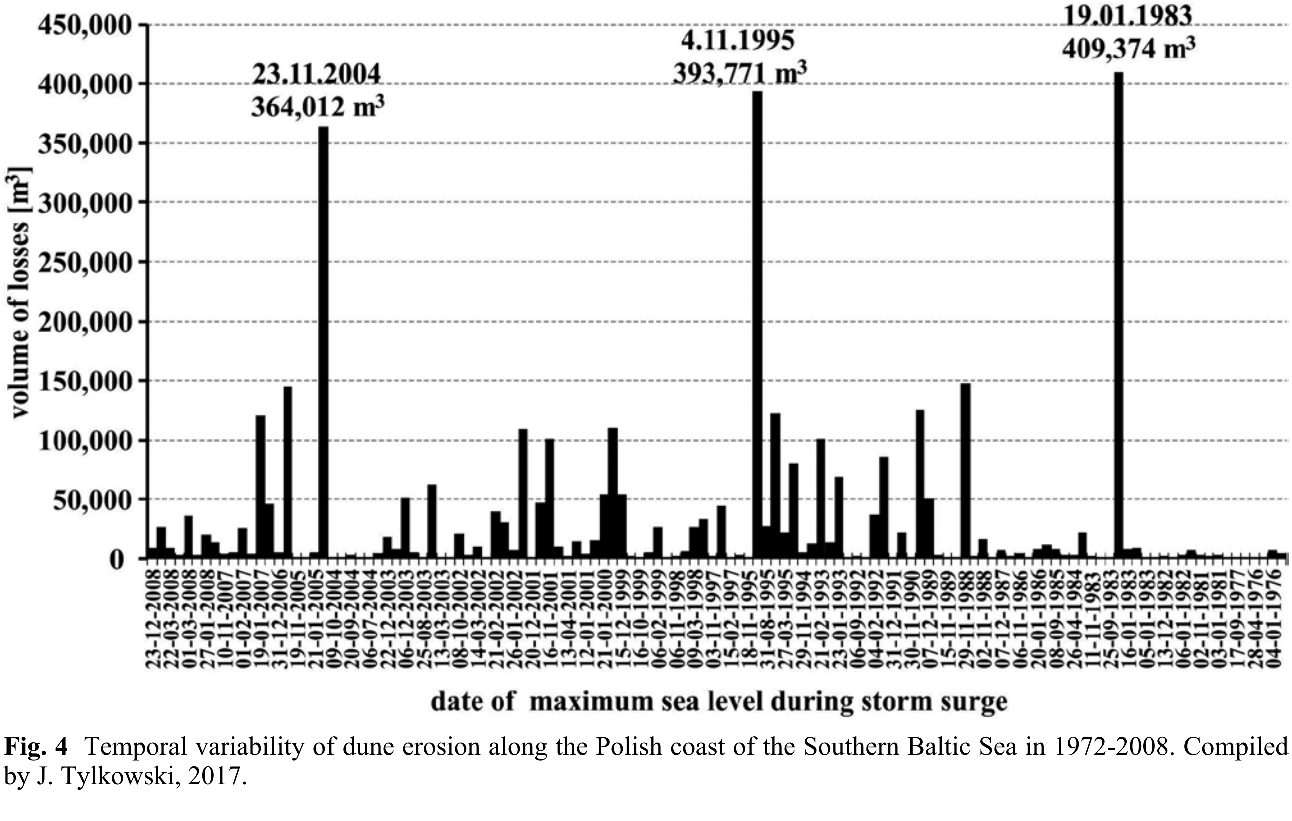

Fig. 4 Temporal variability of dune erosion along the Polish coast of the Southern Baltic Sea in 1972-2008. Compiled by J. Tylkowski, 2017.

coastal area of the Baltic Sea (Fig. 4). The largest loss of sediments was observed during occasional and random storm surges of extreme severity. The largest erosion of the coast (about 400,000 m^3) was caused by storm surges on 19 January 1983 and 4 November 1995, which occurred due to the formation of cyclonic atmospheric circulation from the north-west (19 January 1983) and west (4 November 1995).

An analysis of the spatial and temporal variability of the extreme dune erosion (>100,000 m^3) shows no

Table 3 The most erosive storms (volume of losses >100,000 m^3) along the Polish dune coast (1972-2008)

Volume of dunes erosion (m^3)	Date (yyyy-mm-dd)	Atmospheric circulation (code – see Table 1)	Most erosive stretch of shore (km-km)	Maximum sea level (cm) Tide-gauge station				
				Świnoujście	Kołobrzeg	Ustka	Łeba	Gdańsk
409,374	1983-01-19	NWZ	149-174	618	635	633	634	638
393,771	1995-11-04	NZ	392-400	661	633	600	574	587
364,012	2004-11-23	NWZ	347-366	602	625	636	637	644
147,931	1988-11-29	WZ	159-174	609	634	616	612	618
145,387	2006-11-01	NZ	392-398	600	644	620	619	611
125,298	1990-03-10	WA	160-164	546	551	582	582	588
122,468	1995-04-08	HB	149-174	608	620	620	610	606
121,283	2007-01-19	WZ	155-175	587	615	618	620	618
110,262	2000-01-21	NWA	158-175	595	600	586	582	598
109,301	2002-01-02	NWZ	159-175	600	600	600	596	590
101,066	2001-01-16	NWA	158-176	590	605	605	594	608
100,758	1993-02-21	NWZ	159-175	641	609	603	596	604

time-dependent trends, as it is random and episodic in nature. It was caused by storms with a maximum sea level higher than the alarm sea level (which on the Polish coast is predominatingly >600 cm). These were generated, first of all, by cyclonic atmospheric circulation from the W-N sector (67%). However, exceptionally extreme erosion of the dune coast (>300,000 m^3) was observed during storm surges generated only by north-western and northern cyclonic circulation. The high-erosion season for the dune coast along the Southern Baltic Sea was observed in the cold months, particularly November and January (Table 3).

Although the dunes extreme erosion occurs due to the presence of extreme storm surges, there is no linear correlation. The intensity of the coastal erosion in relation to maximum and average sea levels (126 events) is determined by a statistically significant ($p<0.05$) exponential function of high correlation at 0.7 and low coefficient of determination at 0.4, (Fig. 5). The high correlation shows that erosion of the dune coast is strongly related to storm surges. However, the low coefficient of determination shows that many more other factors (the sea level) determine the intensity of the coastal erosion, including wave height, the current morpho-lithodynamic condition of the under-shore area and beach, and the frequency of storms in the pre-erosion period. It should be noted that not every extreme storm surge generates significant erosion of the dune coast. The intensity of erosion also depends on other conditions, such as the level of exposure of the sea shore and the direction of the incoming storm wave. The coast of the Baltic Sea in Poland is characterised by varied exposure, and therefore the geomorphological effects of extreme storm surges are not of the same intensity in specific sections. Additionally, the existing instantaneous bathymetric and lithologic properties in the shallow-water zone are of significant importance. The greater

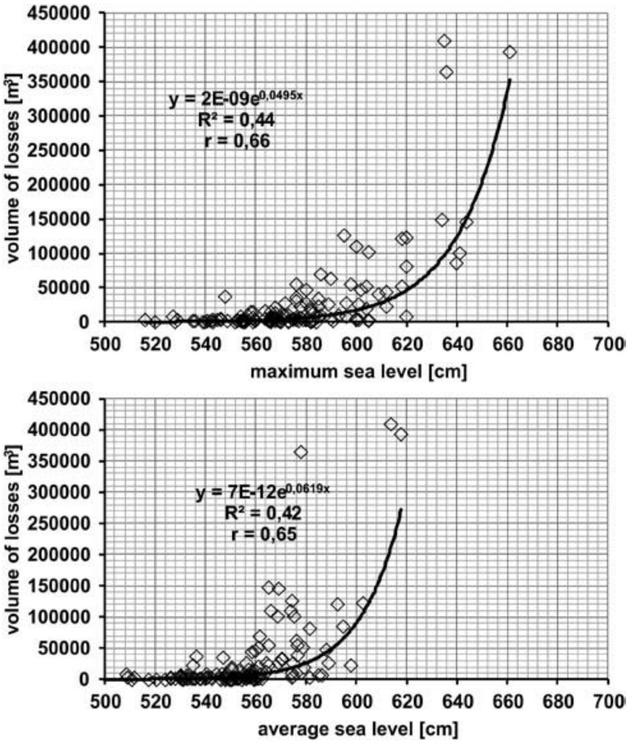

Fig. 5 The correlation between dune coast erosion and the maximum and average sea levels in Poland. Compiled by J. Tylkowski, 2017.

the depth of the surf zone at a given moment, and the greater the decline of the seabed and the lower the amount of non-consolidated sea-bottom material (sand, gravel), the more beneficial the conditions are for intensive coastal erosion. Given this, the study period quite frequently saw situations in which even extremely high storm surges (especially those occurring after a long storm-less period) did not generate any intensive coastal erosion. Moreover, it was observed that relatively low sea surges caused significant erosion of the dune coast after a series of storm surges.

DISCUSSION

The dynamics of the dune erosion do not present any proportional dependencies on high sea levels. It has not always been the case that storm surges cause intensive coastal erosion. The duration and frequency of inter-storm periods also play a significant role in the process of coastal erosion, when it comes to the accumulation of under-shore sediments (particularly in the tidal area) at the coast. With a considerable amount of clustered sediments, the tidal zone is the main area of concentration of wave energy, at the same time reducing dune coast erosion. The development of ephemeral dunes on the coast during the inter-storm periods can also limit the erosion of dune ridges in the above-shore area.

Analysis of changes and trends along the dune coast of the Southern Baltic Sea over the past half-century has shown that erosion is predominant (as opposed to accumulation). The Świna Gate is the longest section of the coastline showing long-term positive tendencies (up to +4 cm y^{-1}), where accumulation has prevailed over washout (Łabuz, Grunewald 2007). Very short sections of such accumulated dune coasts are located east of the Wicko Lake Sandbar, the Łeba Sandbar, the Hel headland and at the mouth of the Vistula River. Dunes reach coastal lines in the area of Ustka, Darłówek and east off Dźwirzyno. The Polish coastal area of the Baltic Sea is dominated by dune sections currently affected by erosion at 4 cm y^{-1} at maximum, e.g. in the area of the Hel Peninsula. Intensive dune erosion is also observable near Darłowo and Dziwnów, and over the sandbar sections in the region of the following lakes: Kopań, Jamno, Bukowo and Resko (Łabuz 2013).

Most often, extreme storm surges do not cause intensive dune erosion along the entire Polish coastal zone of the Baltic Sea. For example, the storm surges of 4–5 November 1995 caused a considerable level of erosion, in particular in the western part of the coast, at the Szczecin Coastland. On 4 November, the level of dune erosion was equal to 390,572 from the 392nd and 400th kilometre of the coast, near Dziwnów. On 5 November, a storm moving eastwards caused dune erosion of about 3,200 m^3 in the eastern part of the Słowiński Coastland, in particular between the 144th and 164th kilometre of the coast, near Lubiatowo. No effects of increased dune erosion were reported in November 1995 in the eastern part of the Polish coast of the Baltic Sea, in the area of the Kashubian Coastland and Vistula Sandbar. The storms of 4–5 November 1995 started during the formation of a deep low-pressure centre during western cyclonic atmospheric circulations. Western and north-western atmospheric circulation is the main atmospheric factor generating heavy storms along the Polish coastland of the Baltic Sea, and consequently increased dune erosion. On the night of 4 November 1995, the speed of the northern wind reached 35 m s^{-1} at the western coast, in Świnoujście, and caused an increase of the sea level of up to 669 cm (and up to 640 cm in Kołobrzeg). During this surge, the sea level was higher by nearly 2 m than average. The maximum water level increase was equal to 28 cm h^{-1} in the western part of the coast, and 21 cm h^{-1} in its central part (Sztobryn *et al.* 2005).

An impact analysis of the storm surges in relation to the threshold values of the dunes erosion (Furmańczyk, Dudzińska-Nowak 2009; Furmańczyk *et al.* 2012) provided evidence of 170 heavily erosive storms at the Polish coastal from 1972 to 2008, which caused dune loss of more than 350 m^3 km^{-1} (including 84 extreme erosive storms with the loss of dune sediments of more than 2,200 m^3 per km of the coast). There were no statistically significant trends in storm frequency causing heavy and extreme dune erosion during the study period.

The positional changes (m) of the dune bases in the study period (1972–2008) can be estimated based on the height of the dunes (m) and the loss of sediments (m^3). In general, the recession of the dune bases over the erosion-affected dune sections of the Polish coast of the Baltic Sea was equal to about 0.9 m. Similar tendencies along the coastline in erosion-affected dune sections were reported by Łabuz (2009, 2013) and Zawadzka-Kahlau (2012). The greatest potential risk of recession of the dune coast was observed along the Słowiński Coastland, from Jastrzębia Góra to the Sarbsko Lake (-27.7 m km^{-1} on average, from the 134th up to the 175th km, max. -106.6 m/km at the 171st km), and on Wolin Island, west of Dziwnów (-18.9 m km^{-1} from the 392nd up to the 400th km, max. -35.7 m km^{-1} at the 394th km). Such considerable recession of the coastland was prevented by natural and artificial phenomena related to the accumulation of sediments along the coastline. The natural phenomena included, for example, the present littoral and aeolian accumulation of sediments in the coastal area. The artificial forms of reconstruction of sediment resources in the area of the dune coast included cyclic infilling of beaches and construction of protective hydro-engineering structures (e.g. rock- and concrete-based bands and blocks) and bio-technical structures (e.g. fascine hurdles, plantings, reconstruction of dune ridges).

CONCLUSIONS

Over the past 40 years, the South Baltic coastal zone has been exposed to dune erosion processes. The greatest destruction of the coastal dunes in Poland has been observed on sandbar sections, including in particular the Lake Kopań Sandbar and Dziwnów Sandbar, where dune coast erosion was more than 100,000 m^3 per 1 km (sum of erosion in 1972–2008 period) and the baseline of dunes have receded by several tens of meters. The main causes of this coastal erosion are sea level rises during extreme storm surges, when the loss of dune sediments along the entire Polish coast of the Baltic Sea can equal about 400,000 m^3 (the effect of a single event). Extremely erosive storm surges are mostly generated by north-western and western cyclonic atmospheric circulation systems.

Significant statistical trends in dune erosion have not been found. The occurrence of extreme dune erosion is episodic and accidental. Extreme erosion of dunes (>300,000 m^3) occurs during intense storm surges (max sea level >620 cm), which initiates cyclonic atmospheric circulation in the N-W sector. The relationship between sea level and erosion of dunes is not linear, but exponential. It should also be noted that it is not always high storm surges that generate high dune erosion. The intensity of dune erosion also depends on many other variables, such as the height and direction of wave inflow, coastal zone exposure, storm surge duration, type and amount of sediment on the beach and foreshore, morphometric conditions of coastal zone, bathymetric conditions of foreshore, and the presence of extreme hydro-meteorological events during the build-up to the storm, etc.

An analysis of the correlation between the sea level and the loss of coastal dunes in Poland has made it possible to define threshold values for potential erosion of the dune coast: erosion of the dune coast can be initiated at an average seal level of 503 cm and a maximum sea level of 516 cm. Conditions during an average sea level of 602 cm and maximum of 636 cm are potentially beneficial to intensive erosion of the dune coast (>100,000 m^3). On the other hand, an average sea level of 620 cm and maximum sea level of 658 cm are potentially the best conditions for extreme erosion of a dune coast (>300,000 m^3).

The general conclusions are as follows:

- there is no statistically significant trend of coastal dune erosion,
- there is no statistically significant correlation between the sea level increase and the intensity of costal dune erosion,
- coastal dune erosion is not a secular but episodic process. It is the result of extreme storm surges, which is generated mainly by cyclonic circulation from the N-W sector,
- we can estimate potential losses of coastal dunes in relation to sea level. But it is not linear, directly proportional relationship. The dynamics of coastal dune erosion is determined by a number of other determinants which distort straight-line dependencies between hydro-meteorological conditions and intensity of erosion processes. The most relevant factors which influence the dynamics of sea coast erosion include, among others: morphological conditions, exposition of slopes at the direction of approaching sea waves, height of major waves, qualitative and quantitative conditions of sediments within shore and shallow under-shore areas, dynamics and frequency of extreme hydro-meteorological incidents in the preceding period, human activities related to hydrotechnical built-ups.

Taking into account the current sea level increases and the dune coasts development, dune accumulation processes should not be expected to intensify in the near future.

The results of this work could also be applied to studies of Baltic coastal dunes functioning along the lagoon-spit coastline, especially from Estonia to Germany.

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