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CAUSES AND EFFECTS OF COASTAL DUNES EROSION DURING STORM SURGE AXEL IN JANUARY 2017 ON THE SOUTHERN BALTIC POLISH COAST

Tomasz Arkadiusz Łabuz

Institute of Marine and Environmental Sciences, University of Szczecin, Szczecin, Poland

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Abstract: The study is dedicated to researching the storm surge Axel, the largest on the South Baltic coast in the 20th and 21st centuries. This unique event resulted in a very large erosion along the whole Polish Baltic Sea coast in January 2017 (max. H_{SL} = 1.65 m, the average for the coast 1.36 m). Storm surge effects on the coast were followed based on field observations of dune retreat and analysis of hydrodynamic and meteorological parameters of the surge and its passage through the Baltic Sea. The material of dune erosion was collected based on cross-shore profiling of almost every 1 km, along the whole Polish sand barrier coast, before and after this storm. The work also studies the parameters of smaller storm surges from the end of 2016, which caused the lowering of beaches and dune erosion. A relationship was observed between erosion, and beach height and sea level (SL). The higher the beach, the lower the erosion that occurred. The average dune toe retreat was 5.1 m, and the largest exceeded 9–19 m (max. 42 m). The most important for dune erosion was the height of run-up, beach height and shore exposition for a surge. The largest dune erosion was observed during the heaviest SL with wave run-up higher than 3.8 m above mean sea level (AMSL). Each coast section was eroded, which also caused losses in infrastructure.

Key words: storm surge, sea level, run-up, dune erosion, Baltic Sea, the Axel surge

Corresponding author: Tomasz A. Łabuz, tomasz.labuz@usz.edu.pl

Introduction

The stormy season in the southern part of the Baltic Sea varies each year due to joint effects of meteorological and hydrological factors (Sztobryn et al. 2005, Gräwe, Burchard 2012, Hünicke et al. 2015, Weisse, Weidemann 2017). The most important is the passage of low-pressure systems from the North Atlantic over the Baltic Sea (Samuelsson, Stigebrandt 1996, Johansson et al. 2001, Sztorbyn et al. 2005, Richter et al. 2007, Wolski, Wiśniewski 2020). Winds occurring during an eastward passage of a low-pressure system are responsible for meteorological forcing resulting in short-term sea-level variations. Those among these characterised by a high velocity, above 10 m · s^{-1}, are termed storm surge winds (Trzeciak 2001, Sztobryn et al. 2005, Stont et al. 2012), and are observed mostly from W, NW to NE directions. The annual probability of the heaviest winds (above 15 m · s^{-1}) is about 6% (Zeidler et al. 1995, Trzeciak 2001). The heaviest storms (Beaufort scale 10–12) result from very strong NW and NE winds, the annual probability of which is low (1%) (Zeidler et al. 1995, Wolski, Wiśniewski 2020).

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The storm surge on the Baltic coast is understood as short-term, rapid growth in the water level caused by the passage of a low-pressure centre accompanied by wind stress (Sztobryn et al. 2005, Hünicke et al. 2015, Surkova et al. 2015). The length of this phenomenon is usually in the range of 1–3 days. Surges at the southern Baltic coast are most frequent during the autumn–winter period, November to February (Sztobryn et al. 2005, Dailidienė et al. 2006, Surkova et al. 2015). Their number varies each year (Johansson et al. 2001, Sztobryn et al. 2005, Richter et al. 2007, Kont et al. 2008, Gräwe, Burchard 2012, Jaagus, Suursaar 2013). The largest with high sea levels (SL) appear every 2–3 years (Orviku et al. 2007, Surkova et al. 2015, Weisse, Weidemann 2017).

At present, the highest water level during storm surges on the Baltic Sea coast exceeds 1.4–1.5 m above mean sea level (AMSL). This has been observed in most Baltic countries, with a resultant heavy shore erosion (Suursaar et al. 2003, Dailidienė et al. 2006, Eberhards et al. 2006, Orviku et al. 2007, Richter et al. 2007, Pruszak, Zawadzka 2008, Tõnisson et al. 2008, 2013, Koltsova, Belakova 2009, Furmańczyk et al. 2011, Łabuz, Kowalewska-Kalkowska 2011, Ryabchuk et al. 2011, Łabuz 2015, 2022, Jarmalavicius et al. 2016, MacPherson et al. 2019, Wolski, Wiśniewski 2020). Additionally, numerous studies have been conducted on dune erosion by storm surges, both in the field and through numerical modelling (van de Graaff 1977, Nielsen, Hanslow 1991, Basiński 1995, Schüttrumpf, Oumeraci 2005, Eberhards et al. 2006, Mendoza, Jiménez 2006, Stockton et al. 2006, Roelvink et al. 2009, Kortekaas et al. 2010, Furmańczyk et al. 2011, Łabuz, Kowalewska-Kalkowska 2011, Bobykina, Stont 2015, Castelle et al. 2017, Kelpšaite-Rimkiene et al. 2021). The rate of coast retreat depends both on the sea surge height and its duration (van de Graaff 1977, Nielsen, Hanslow 1991, Tõnisson et al. 2008, Kelpšaite, Dailidienė 2011, Ryabchuk et al. 2011, Jarmalavicius et al. 2016, Łabuz 2022). However, the variability within the duration of such events, as well as the implications for coast erosion, is less well understood. Also, several studies focussed on the wind-wave run-up to the shore (Didenkulova, Pelinovsky 2008, Di Luccio et al. 2018) but without comparison to erosion of the coast or shore.

In January 2017, a strong low-pressure system passing over the Baltic Sea produced very strong winds from the NW to NE direction. This system, named Axel, has produced one of the biggest storm surges along the southern Baltic coast so far. This resulted in large erosion of the shores and coast from Germany to the Eastern Baltic States.

This study aimed to describe and compare dune coast changes along the Polish Baltic coast, associated with the January 2017 surge named Axel. The objectives of this study are: (1) to present a hydrodynamic analysis of the surges in the autumn–winter period 2016/2017 with the heaviest among these being Axel, (2) to present the rate of coastal dune erosion, (3) to explore the relationships between the hydrological and meteorological parameters associated with the Axel storm and the coast erosion rate, and (4) to explain high value of coast (dune) retreat caused by this surge.

Study area

The Polish coast is 500 km long and is mainly exposed to the north; and it includes 440 km of the open coast (Fig. 1A). Over 80% of this coast consists of dune systems developing on sandbars made by loose sand (Zawadzka-Kahlau 1999, Pruszak, Zawadzka 2008, Łabuz 2013) of different sandbar width and coastal dune height (Fig. 1B). Only 15% of them are in a more or less accumulative state and 35% are eroded after every higher storm surge with SL >1 m AMSL (Łabuz 2013).

The South Baltic coast is mostly aligned and mainly exposed to the north (Fig. 1A). The middle part of the coast in the Koszalin and Ustka Bays forms a concave coastline exposed to surges developed from W to NW. On the two sandbars Świna and Vistula the shoreline is concave. The eastern shore of both sandbars is exposed to the NW direction and the western to the NE. For this reason, the greatest erosion on both occur during storms originating perpendicular to the shore from the NW or NE sector. In the Gdańsk Gulf, part of the coast is exposed to the east, where erosion is usually smaller due to the absence of strong surges from that direction. This occurs during rare surges originating from the NE direction. On the Hel Peninsula (Hel Spit) exposed to the northeast, erosion occurs mainly during

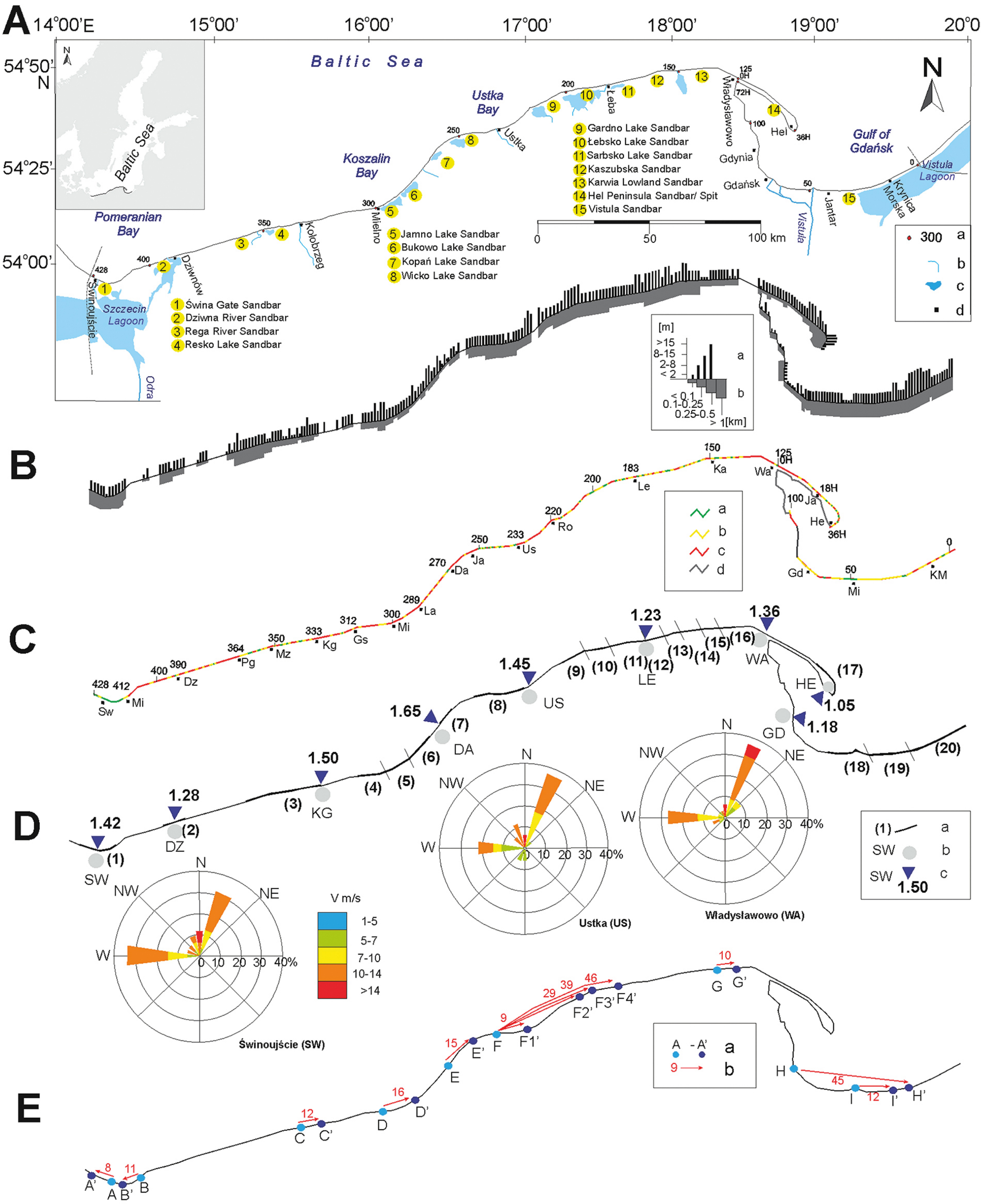

Fig. 1. The Polish Baltic coast.
A – coastline with sandbars' location, a – coast kilometrage 0–428, b – rivers, c – lakes and lagoons, d – main towns. B – sandbars' morphology, a – height, b – width. C – the average trend of coast dynamics with kilometrage division (Łabuz 2013), a – accumulative, b – stable, c – erosive, d – no data. D – analysed sections of the coast, highest sea level (SL) and wind roses during Axel, a – investigated sandbars, see Table 3, b – gauge stations, c – maximum sea level. E – location change of artefacts washed from the land and shifted by surge Axel (Table 4), a – from location A to new position A', b – No. of shifted kilometres.

storm surges from the N to NE direction. The rest of the coast is aligned but with several northerly shifting sand promontories, where coast orientation is changing from more or less WNW to N exposition (Zawadka-Kahlau 1999), which is why, every few kilometres, it has a different exposition for the impact of wind and waves (Łabuz 2013). Based on an analysis of long-term coast retreat, it could be stated that the coastline is divided into numerous accumulative and erosive circulation systems (Zawadzka-Kahlau 1999). The erosive tendencies prevail (Fig. 1C).

Material and methods

Hydro-meteorological data

Information on the occurrence of storm surges in autumn–winter 2016/2017 and their characteristics were collected from gauge stations of the Polish Maritime Bureau and the Harbour Master's Offices located along the coast. The highest surges that appeared in the analysed period were characterised (Table 1). The main descriptors of the storm magnitude included the height of sea level (H_{SL}), the main wave direction (and its change during time), the duration of surge (hours, T_{SL}) and time with SL higher than 1 m (T_{SL} with H_{SL} >1 m). The run-up (SLr) caused by the SL rise and wave height observed on the shore was also taken into account (as explained further on).

The wind information pertaining to velocity and direction changes was extracted from data from the Polish Maritime Bureau and hourly readings at the Institute of Meteorology and Water Management (IMGW) for selected coastal weather stations. Some data were analysed for each important surge before the Axel storm (Table 1). The wind data, surge changes and length were studied in detail for surge Axel (Table 2).

Table 1. Characteristics of storm surges during autumn–winter 2016/2017 along Polish gauge stations (location in Fig. 1D).

No.	1	2	3	4	5	6	Mean SL [m]
Date	4–6.10.2016	3–4.11.2016	27–28.11.2016	12–14.12.2016	27–28.12.2016	4–6.01.2017	–
Name	Angus	NN	NN	NN	Barbara	Axel	–
Wind velocity (m · s^{-1})	13–17	11–14	12–15	11–14	13–18	13–18	–
Wind direction	NE–NNE	W–NNW	WNW–NNW	W–WNW	NW–N	NW–NE	–
Świnoujście (SW)	1.13	0.48	0.93	0.66	0.90	1.42	0.92
Kołobrzeg (KG)	0.63	0.53	0.72	0.64	1.12	1.50	0.86
Darłowo (DA)	0.42	0.44	0.56	0.55	0.89	1.65	0.75
Ustka (US)	0.40	0.46	0.56	0.53	0.88	1.45	0.71
Łeba (LE)	0.42	0.40	0.57	0.47	0.74	1.23	0.64
Wład. (WA)	0.54	0.32	1.01	0.46	0.92	1.36	0.77
Hel (HE)	0.36	0.25	0.71	0.44	0.84	1.05	0.61
Gdańsk (GD)	0.40	0.18	0.82	0.35	0.75	1.18	0.61
Mean SL (m)	0.54	0.38	0.74	0.51	0.88	1.36	0.74

Table 2. Characteristics of the Axel January 2017 storm surge along Polish gauge stations (location in Fig. 1D).

Harbour, gauge station	Świnoujście (SW)	Kołobrzeg (KG)	Darłowo (DA)	Ustka (US)	Łeba (LE)	Władysławowo (WA)	Gdańsk (GD)
Location of harbour	53°55'N 14°16'E	54°11'N 15°33'E	54°26'N 16°22'E	54°45'N 16°51'E	54°46'N 17°33'E	54°47'N 18°25'E	54°21'N 18°39'E
Wind V max [m · s^{-1}]	14–15	14–16	15–18	13–15	14–15	12–16	12–14
Wind duration V > 10 [m · s^{-1}] (t, h)	62	65	57	54	55	50	42
Storm duration H > 0.8 m (t, h)	39	36	30	33	31	34	27
Storm duration H > 1 m (t, h)	28	26	23	20	14	19	11
Storm duration H > 1.2 m (t, h)	18	15	12	9	3	7	0
Max. SL, 4 Jan (h)	10	10	11	11	14	14	17
Max. sea level [m AMSL]	1.42	1.50	1.65	1.45	1.23	1.36	1.18

Field measurements of shore morphology

The whole Polish coast with sandbar sections was under investigation. In the study, they were divided into 20 coast sections separated by cliff coast, river mouths or natural promontories (Fig. 1A, C, and Table 3). Changes in the relief of the coastal forms were determined based on the analysis of cross-shore profiles stretching from the stable dune surface to the waterline (Fig. 2). More than 240 profiles with different coast orientations were analysed on each section of the studied sandbars. The profiles are located mostly each 1 km along the investigated sandbars and are part of a longer study of the Polish coast. Such accurate data resulted from annual measurements carried out in the autumn and spring of each year since 2010. The fieldwork for this study was carried out from September to December 2016. It was repeated after Axel's surge from January to May, 2017. Measurements along the transects cover dune shore and coastal dune

Table 3. List and date of investigated sandbar sections, average dune toe erosion and selected SL parameters during Axel storm surge (location in Figure 1A, C).

No.	Investigated sandbar name/part	Length [km]	Measurement date, before, after surge (month)		Average dune toe retreat (m)		SL > 1 m (t, h)	Max. SL in gauge station, SL [m]	Max. run-up on the shore, SLR [m]	Harbour (gauge station), location
			Before, in 2016	After, in 2017	Mean	Median				
1	Świna Gate	16	9, 11, 12	1, 4	5.4	5.7	28	1.42	3.9	Świnoujście (SW) 53°55N 14°16E
2	Dziwnów	11	9	1, 6	7.3	7.5	28	1.42	3.7	
3	Liwia Lake to Rega river	15	9	2, 4	4.4	4.1	28	1.42	3.8	
4	Resko Lake to Parsęta river	14	9, 11	2, 5	6.0	5.9	26	1.50	3.7	Kołobrzeg (KG) 54°11N 15°33E
5	Jamno Lake	11	9	2, 9	6.2	5.2	26	1.50	3.7	
6	Bukowo Lake	12	9	1, 9	9.4	9.8	23	1.65	3.9	Darłowo (DA) 54°26N 16°22E
7	Kopań Lake	10	9	1, 9	8.4	9.0	23	1.65	4.1	
8	Wicko Lake	15	6	3, 6	5.3	4.0	20	1.45	3.8	Ustka (US) 54°45N 16°51E
9	Gardno Lake	10	9	4, 9	3.6	3.0	20	1.45	3.6	
10	Lebsko Lake 1/west/ Czołpińska Dune	10	9, 11	4, 9	5.4	3.5	14	1.23	3.5	Łeba (LE) 54°46N 17°33E
11	Lebsko Lake 2/east/ Łącka Dune	16	9, 11	4, 9	5.0	2.7	14	1.23	3.5	
12	Sarbska Sandbar	9	9, 11	4, 9	4.5	3.1	14	1.23	3.4	
13	Kaszubska 1/west/ Stilo Dunes	7	9, 11	4, 9	7.9	8.0	14	1.23	3.4	
14	Kaszubska 2/middle/ Lubiatowska Dune	6	9	5, 6	5.5	4.2	19	1.36	3.4	Władysławowo (WA) 54°47N 18°25E
15	Kaszubska 3/east/Biała Góra Dune	9	9, 11	5, 9	3.6	1.8	19	1.36	3.5	
16	Karwia	12	9, 11	6	4.9		19	1.36	3.6	
17	Hel Spit	35	9, 11	4, 6	6.8	8.0	19	1.36	3.8	
18	Vistula Sandbar 1/ west/channel mouth	10	11	2, 6	2.3	2.1	11	1.18	3.7	Gdańsk (GD) 54°21N 18°39E
19	Vistula Sandbar 2/ middle part	19	11	4, 6	4.2	4.1	11	1.18	3.7	
20	Vistula Sandbar 3/ east/Camel Hump Dune	24	11	6	4.4	4.5	19	1.36	3.9	Władysławowo (WA) 54°47N 18°25E

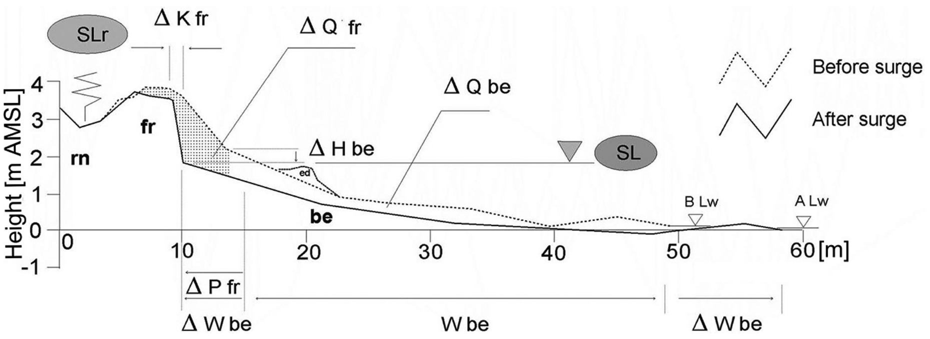

Fig. 2. Forms measured along the profile and indicators of their dynamics (B – before the surge, A – after the surge).
DH_{be} – beach height change; DK_{fr} – foredune top/edge change; DP_{fr} – foredune foot change; DQ_{be} – beach sand volume change; DQ_{fr} – foredune sand volume change; DW_{be} – beach width change; ALw – water line after the surge; BLw – water line before the surge; SL – sea level; SLr – water run-up; W_{be} – beach width.

relief before and after each main storm surge in autumn–winter 2016/2017 (Table 1). Those data included coast changes after each main surge in all selected areas.

The field measurements involved the use of geodesic tools such as the leveller (Nivel System Ni-20) and GPS RTK (real-time kinematic positioning system Hiper II made by TOPCON). Field observations on the storm surge impact on the shore morphology involved the positioning of the highest surge range, referred to as the run-up or swash (SLr). It is marked by erosional cuts in the beach, and dunes, as well as the presence of debris on the beach or in the runnel behind the eroded dune (as washover fan). All washover fan locations (see Fig. 15), sea flooding areas and infrastructure damage (pavements, stairs to the beach, coast protection and other infrastructure) were marked along the coast. These data will be used for other studies. Additional data have also been collected presenting the movement of a larger artefact by the Axel surge along the coast (Fig. 1E and Table 4). This was additional information on the resultant direction of the

Table 4. Characteristics of the transported large items during storm surge Axel (location in Fig. 1E).

No.	Item characteristics	Weight in ca. kg	No. of travelled km	Azimuth, from–to	Shift (sandbar/town, coast kilometrage start-end)
A	Wooden platform 5 m × 5 m	20	8	E–WNW	Świnoujscie to Ahlbeck, from 426 toward the west
B	Wooden board 6 m × 2 m	8–10	11	E–WNW	Międzyzdroje to Świnoujscie 411–422
C	Metal garbage can 1 m × 0.5 m	5	12	WSW–NNE	Rega, 350–338
D	Plastic parts from coast protection 0.5 m × 0.5 m	1–2	16	W–NE	Jamno to Bukowo, 300–284
E	Metal garbage can 1 m × 0.5 m	3–4	15	W–NE	Kopań, 270–258
F1	Wooden and metal construction/military aim 8 m × 5 m	5–8	9	W–ENE	Wicko, 242–233
F2	Wooden and metal construction/military aim 5 m × 5 m	3–5	29	W–NE	Wicko to Gardno, 242–213
F3	Wooden and metal construction/military aim 5 m × 5 m	4–6	39	W–NNE	Wicko to Łebsko, 242–203
F4	Wooden and metal construction/military aim 5 m × 5 m	4–6	46	W–NNE	Wicko to Łebsko, 242–196
G	Plastic parts from coast protection 0.5 m × 0.5 m	1–2	10	NW–SE	Karwia, 140–131
H	Wooden and plastic parts from harbour 2 m × 3 m	3–6	45	W–E	Vistula, 75–30
I	Floating trunk wood from Vistula river mouth, several, largest 12 m × 1 m	30–50	12–17	W–E	Vistula, 49–37 (32)

long-shore current, which was responsible for material transport. The collected data were supplemented by detailed photographic documentation and geographical position.

Numerical analyses

Coastal process-based indicators can be computed through empirical equations that are applied to representative shore profiles and water run-up inducting coast erosion (Nielsen, Hanslow 1991, Schüttrumpf, Oumeraci 2005, Stockton et al. 2006). These indicators are assembled and linked with data about shore exposure and potential damage caused by storms to perform an index-based coastal risk assessment (Mendoza, Jiménez 2006). The range of shore relief change variables included the shift of the foredune base/toe and ridge top or edge. The foredune toe height is equal to the beach height. Other variables included the beach width, as well as the occurrence of embryo dunes on the beach. The profile measurements were processed, using a range of software products (Microsoft Office Excel, Golden Software: Grapher, Surfer and Grab it!), to determine changes in selected shore variables. The difference chronicled between two profiles having their origin in the same place is on a par with the observed relief changes profiles. (Fig. 2). The relief changes among profiles is called the surface dynamics layer. Morphological changes were calculated for every square metre of each shore form (x) from the state determined before (B_{xi}) and after (A_{xi}) a measurement, where *i* is the length of a form in metres. This was followed by a calculation of the sediment volume displaced from every square metre of the shore (as in Fig. 4). Thereafter, the values obtained resultant to the aforesaid calculations were used for the commutation of dune volume erosion, toe retreat and beach height changes in the periods before and after the surge.

The variables associated with the surge and changes in the coast morphological forms (x) reflected the present and post-storm surge state and included:

1. wind: maximum velocity (V_w), time (T_w) V_w >10 m · s^{-1}, azimuth (Az_w),
2. sea: SL (H_{SL}), H_{SL} >1 m AMSL surge duration in hours (T_{SL}), water run-up (H_{SLr}),
3. beach (be): width (W_{be}), height (H_{be}), volume (Q_{be}) and changes in these variables (DX_{be}),
4. foredune (fr): width (W_{fr}), height (H_{fr}), toe (P_{fr}) and top (K_{fr}), volume (Q_{fr}), and changes in these variables (DX_{fr}), and
5. embryo dune on the beach (ed): height (H_{ed}), volume change (DQ_{ed}), width (W_{ed}) and changes in these variables (DX_{ed}).

Further comparisons involved the following selected indicators: the foredune toe retreat (DP_{fr}), the beach height change (DH_{be}) concerning the SL and the run-up (SLr). The final study was carried out to find similarities between the values of achieved data from field measurements and storm surge parameters. To investigate the dependence of selected storm parameters and changes in the relief of dunes, a correlation was made and the Pearson coefficient was calculated.

Results

Characteristic of small surges from autumn–winter 2016

During the period for which there was undertaken an analysis of the autumn–winter on the Polish Baltic coast, there were six storm surges, of which five featured an average SL of H > 0.5 m AMSL (Table 1). The analysed lower surges from 2016 were produced by storms lasting 1.5–2.0 days and caused by low-pressure systems. The first surge in October 2016 named Angus was produced by strong wind inflow from the NE–NNE direction (Table 1). The wind velocity exceeded 16 m · s^{-1} in Świnoujście. A maximum SL of H = 1.13 m was reached on the western part of the coast in Świnoujście, while on the eastern coast, the level was only 0.4–0.5 m AMSL. Coast erosion included almost 15 km of dune coast, mainly with a NE exposure on the Świna Gate and Vistula Sandbars as well as along the Hel Peninsula. Also, shore and dune erosion was observed on so-called promontories with a NE exposure. The dune retreat exceeded 4–6 m in these sections.

Another surge from 3 to 4 November 2016 reached a maximum of 0.53 m of SL with winds from W–NNW. The surge was too low to erode the dune coast. In some places during its duration, some low-lying beach (H_{be} < 1 m) was covered by water hitting the coast. The next larger surge from the end of November 2016 had a higher SL on the eastern coast (Table 1). The wind velocity exceeded 13–15 m · s^{-1} from WNW to NNW. Due to lower SLs, only parts of previously levelled beaches were washed away once again. The dunes were only eroded in the eastern part of the coast along erosive sections of the Kashubian Sandbar. The dune toe retreat was 1–2 m. Next came a low surge from mid-December with the highest SL = 0.6 m in the west and only 0.4 m on the eastern coast (Table 1). No further erosion was observed.

Fig. 3. Examples of dune retreat caused by lower surges in 2016 and Axel in 2017.
A – two cutoffs of the dune after October and November surge (black lines) vs large erosion after Axel surge, Hel Spit 33 km H. B – cut off during November surge vs retreat after January 2017 (red line), Kashubian Sandbar, 170 km. C – erosion after October and November surge vs retreat after January 2017 (red line), Resko Lake Sandbar, 341 km; 1–5 – the same clumps of pine trees.

The storm at the end of December 2016 named Barbara was induced by NNW–N winds of 13–19 $m \cdot s^{-1}$. It produced a medium surge, which resulted in the erosion of shore sections with low-lying beaches, up to 1.5–2.0 m AMSL. The SL reached 0.7–0.9 m AMSL in gauge stations. The main direction of the wind force was NW, and thus the coast with this exposure was prone to erosion. This time, erosion included the dune coast of the Koszalin and Ustka Bays, located on the central coast and with a W–NW exposure.

To summarise, the October surge Angus caused erosion of the coast and promontories exposed to the east (Figs 3 and 4). The November surges lowered the beaches and eroded the eastern part of the coast. The last average surge, Barbara, in December 2016 eroded low-lying beaches and coast facing W–NW, along the middle part of the Polish coast. After these surges, the beaches on the Polish coast were significantly lowered and the dunes were undercut, especially in places with low-lying and narrow beaches before the storm season. The dunes were eroded during these storms in places where the beaches were lower than 2 m AMSL. Figures 3 and 4 present the scale of dune toe erosion at the end of 2016 with different SL and then in 2017. Sections of the beach that had been subject to leverage as a result of the 2016 wind and storm activity aforesaid were the earliest and most-intensely affected during the final, strongest surge in January 2017, leading to a further and faster dune retreat in these sections.

Characteristics of storm surge Axel, 4–6 January 2017

Storm surge Axel was the result of strong winds caused by the eastwards movement of a low-pressure centre from the North Sea. On 1 January, the system was located north of Iceland. Over the course of the following days, it moved through Scandinavia and the Baltic Sea. The highly dynamic atmospheric circulation over the Baltic Sea caused the development and changes of strong winds from W to NNE (Fig. 5). Maximum wind velocity on the Polish coast exceeded 14–20 $m \cdot s^{-1}$, with gusts up to 30 $m \cdot s^{-1}$. A low named Axel caused a large storm surge on the southern coast of the Baltic Sea between 4 and 6 January 2017. In the western part of the Baltic coast, the SL in Wismar and Lübeck reached 1.5 m AMSL. In the middle Polish coast, the SL exceeded 1.45–1.65 m and 1.36 m AMSL in the eastern part.

Due to the changing direction of the wind and waves, moving from west to east, several phases of the storm development were identified (Figs 1D, 5, 6 and Table 2). Naturally, the SL rise in the east was delayed in relation to the west coast. The surge developed with wind and waves first from

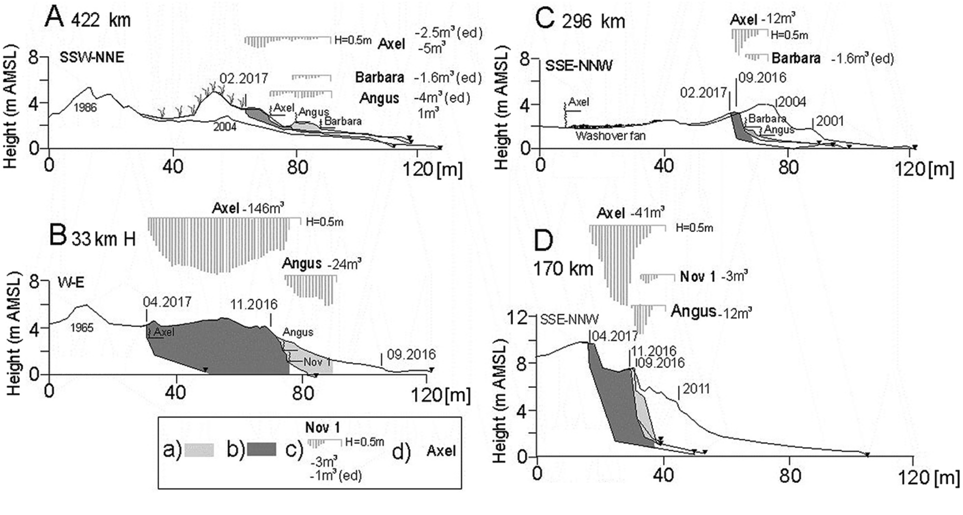

Fig. 4. Dune erosion related to beach height, coast orientation and SL during low surges in 2016 and Axel in 2017.

A – concave bay on the west coast exposed to NNE. B – cutoff of the promontory exposed to NE on the Hel Spit. C – concave bay with high beach exposed to NW from the middle coast. D – retreat of promontory exposed to NW on the east coast. a – erosion during surges in 2016, b – erosion during Axel in 2017, c – morphodynamic bars (dynamic layer) every 1 m and total volume of the eroded dune (DQ_{fr}) or embryo dune (DQ_{ed}), d – the height of surge run-up to the shore (H_{SLr}).

the W–WNW and the NW direction (3–4 January) and then from N to NNE (6 January). As was expected, the increase in SL lagged behind the growth in wind velocity (Fig. 6). Phase t –1 came on 3 January, before the surge rises with SL equal to average or lower. Between 3 and 4 January, the SL on the southern Baltic coast ranged from 0.2 m to 0.5 m AMSL with a wind speed of 6–7 m · s^{-1} from the W direction (Fig. 6). Phase t 0 occurred on the morning of 4 January when the SL was rising. During 4 h, with wind from WNW, the SL rose to 0.6–0.8 m AMSL.

Phase t +1 occurred on 4 January during strong NNW winds, which caused the highest SL rise (Figs 5A, B and 6). The maximum SL, from 1.2 m to 1.5 m AMSL, was observed with the wind from the NW direction. The highest SL was recorded on the central coast: up to 1.5 m AMSL in Kołobrzeg and as much as 1.65 m in Darłowo. On the western coast, the maximum level was 1.42 m in Świnoujście, while on the eastern coast, it was 1.36 m in Władysławowo and below 1.2 m in the Gulf of Gdańsk (Fig. 6B and Table 2). A SL of more than H = 1 m AMSL was observed for 26 h in Świnoujście, 17 h in Kołobrzeg and 15 h in Gdańsk. During that phase, erosion was the most extensive on the NW-facing coast. Phase t +2 represents a SL drop to 1 m AMSL on 5 January (Figs 5C and 6). This was caused by a change in wind strength and direction to NNE with the velocity remaining above 13 m · s^{-1}. This phase lasted 20 h.

Phase t +3 was related to a surge drop to 0.6 m AMSL on average, accompanied by a slower NNE wind (Figs 5D and 6). At this time, a higher level was still observed on the western coast due to wind from NNE (Fig. 6B, SW-Świnoujscie). During phase t +4, on 6 January, only NNE wind was observed. Its strength dropped to 10–12 m · s^{-1} (Fig. 6A). The water level was still higher than 0.4 m AMSL (Fig. 6A). By the middle of 6 January, the storm had started to subside on the western and central coast. The SL in Świnoujście and Kołobrzeg fell to 0.2 m AMSL. On that part of the coast, the wind changed direction to W and its velocity dropped below 6 m · s^{-1}. On the east coast, the storm continued until the end of 6 January with NE winds up to 6 m · s^{-1}, while the SL was still 0.25 m AMSL (Fig. 6).

During the Axel storm, the wind direction and velocity on the western, central and eastern coasts shifted, resulting in changes in the SL (Fig. 6). For this reason, a minor relationship was observed between the duration of maximum wind

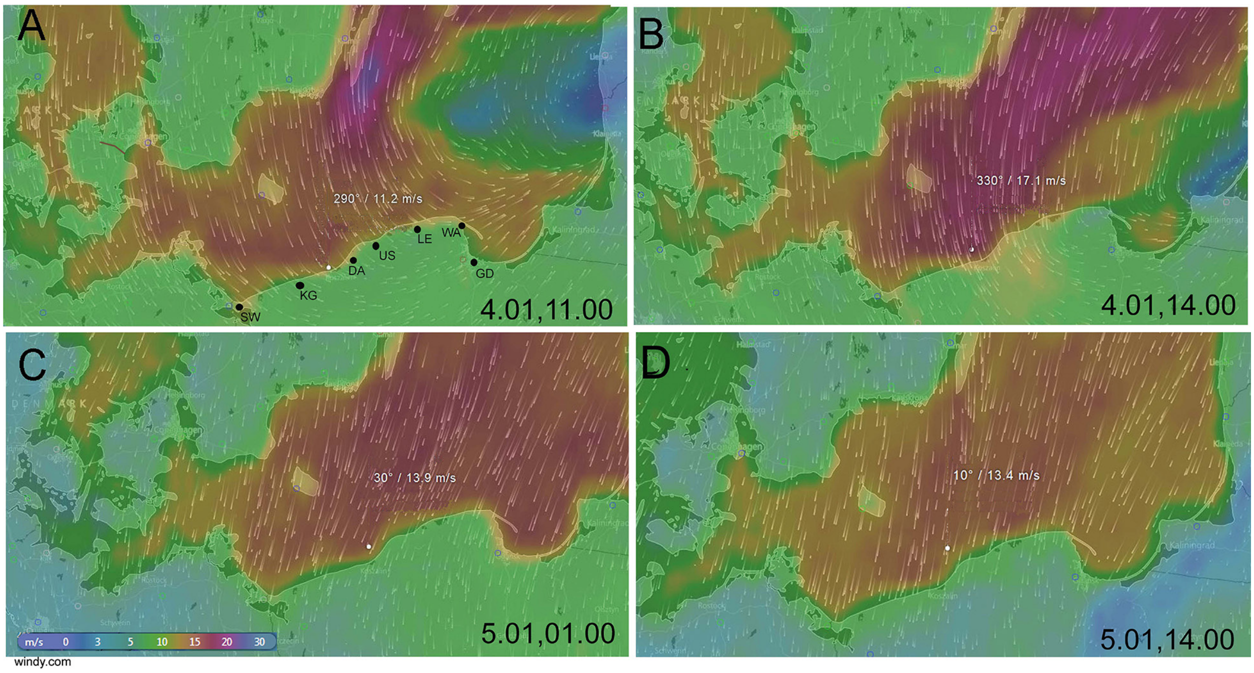

Fig. 5. Phases of wind course during storm surge Axel in 2017 (SW to GD – gauge stations).
A – NW to NNW, rapid SL growth. B – N to NNE, maximum surge. C – NNE, slow SL drop. D – NNE to NE, wind decrease and sea level drop.
Source: windy.com.

Table 5. Coefficients correlation of selected input and output variables of storm surge Axel in January 2017.

Dependent variables Independent variables	Max. SL (H_{SL}, m)	SL length (T_{SL} H > 0.8 m, h)	SL length (T_{SL} H > 1.0 m, h)	SL length (T_{SL} H > 1.2 m, h)	Max. run-up (H_{SLr}, m)	Dune toe retreat (DP_{fr}, m)
Max. SL (H_{SL}, m)	×	0.40	**0.82**	**0.76**	**0.62**	0.42
SL length (T_{SL} H > 0.8 m, h)	0.40	×	–	–	0.38	0.17
SL length (T_{SL} H > 1.0 m, h)	**0.82**	–	×	–	0.51	0.45
SL length (T_{SL} H > 1.2 m, h)	**0.76**	–	–	×	**0.75**	0.42
Max. wind vel. (V_w, m · s^{-1})	**0.79**	0.18	0.50	0.49	**0.83**	**0.83**
Time V > 10 m · s^{-1} (V_w, h)	**0.70**	**0.72**	**0.81**	**0.83**	**0.86**	0.39
Max. run-up (H_{SLr}, m)	**0.62**	0.01	0.40	0.43	×	**0.55**
[1] Beach height before (H_{be} B, m)	×	×	×	×	×	0.49

[1] H_{be} before to DP_{fr} equal to *r* = 0.6–0.7 on some sections (see in text).

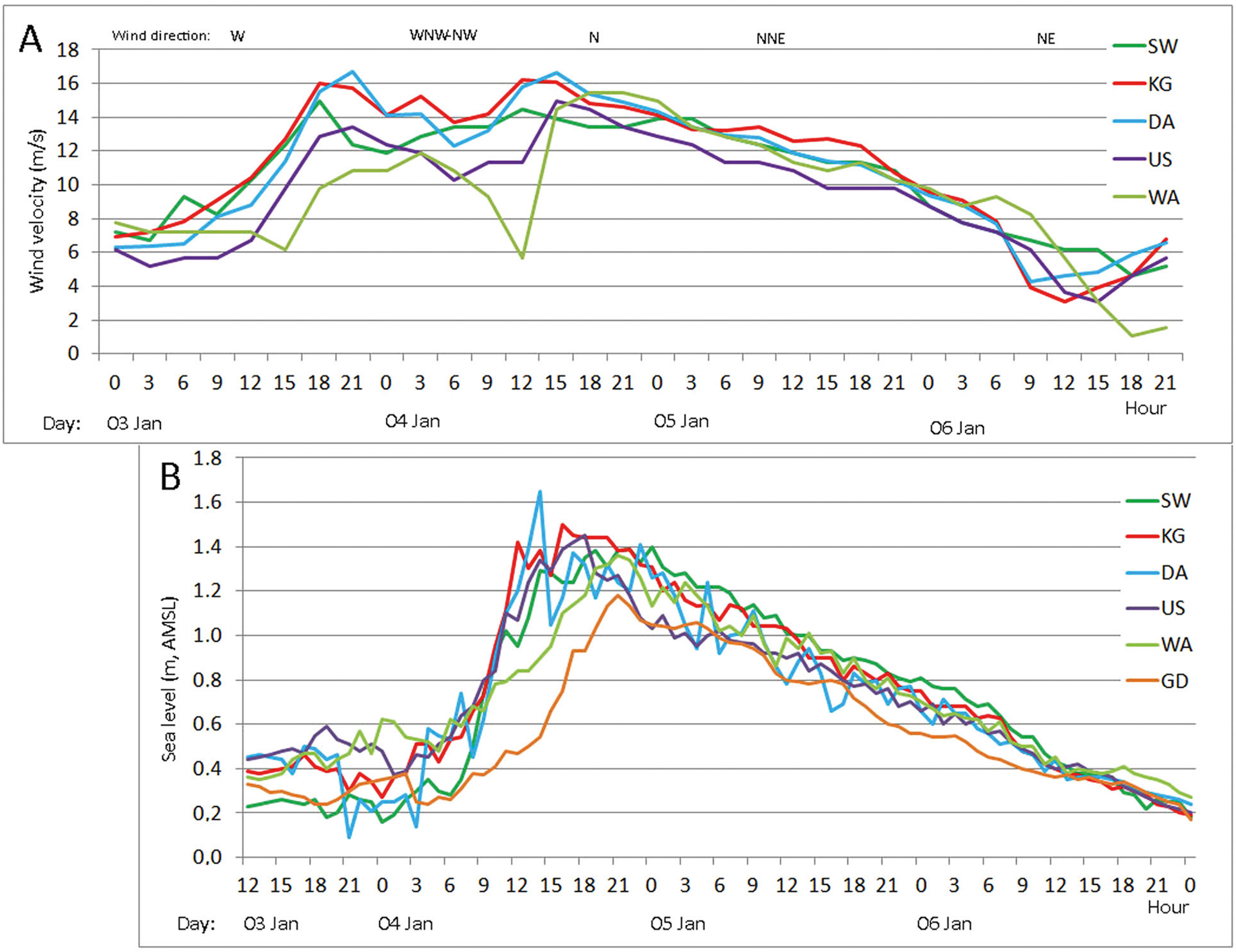

Fig. 6. Wind and sea level course during storm surge Axel in 2017 (SW–GD – main gauge and wind stations, see Fig. 1).

velocity (V max) and the duration of a high SL (H > 1 m), while the relationship with the highest observed surge was significant ($r = 0.79$, $r = 0.83$) (Table 5). It was observed that a greater degree of significance characterised the relation that the duration of strong winds (V > 10 m · s^{-1}) bore with high SL ($r = 0.7$–0.83), as well as with the highest SL and SLr ($r = 0.7$–0.86).

Instances of significant correlation are presented in bold, while the minus symbol indicates that analysis was not done.

The prevalent wind-wave shift during the Axel surge was related to the main wind force (Fig. 6). It was found that several observed artefacts eroded or washed from the land were transported eastwards by surge currents (Fig. 1E and Table 4). These were mainly floating wooden, but also metal, debris weighing between 5 kg and 10 kg. This is the first documented transportation of destroyed parts of infrastructure during an ongoing surge. On this basis, the drift direction caused by the wind force was visible. Many of the observed large anthropogenic particles were moved 10–50 km eastwards along the open coast. Some were taken westwards along the western part of the coast during surge phase t +3 from the NNE direction. This observation is crucial when it comes to understanding material drift along the coast during a surge.

Relation of surge duration and SL vs dune erosion

The duration of the high surge and the highest SL were variable along the coast (Fig. 7). The longer the high surge on a specified coast section, the greater the dune retreat that was observed. The maximum SL during storm Axel and the time duration of H_{SL} >1 m AMSL were correlated (0.82). It was found that erosion was more severe on coast sections with a higher SL and longer duration of H_{SL} >1 m (Fig. 7). The average dune retreat (DP_{fr}) exceeded 3.5–6 m on the section with H_{SL} <1.3 m AMSL and 5–8 m with H_{SL} >1.4–1.65 m AMSL (Fig. 8). As expected, the surge height, measured in gauge stations, was not strictly related to the observed erosion. The SL measured in the gauge station is not the main variable compared with dune erosion in adjacent areas. However, it is the one and only known variable and may be comparable with wave run-up to the shore (Fig. 9). The statistical relation between maximum SL and dune toe erosion for the whole coast was only 0.42 (Table 5). Based on SL only, it is difficult to find a linear relation between surge parameters and average values of erosion.

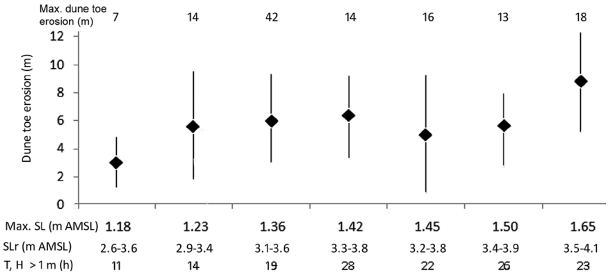

Fig. 7. Relation of surge parameters to mean (sign), average (line) and max. value of erosion rate during surge Axel in 2017.

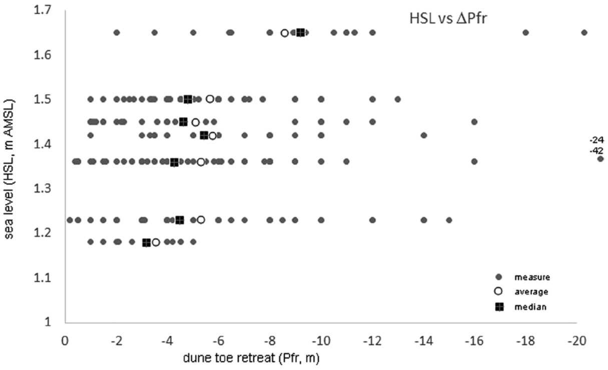

Fig. 8. Relation of dune toe retreat (DP_{fr}) to sea level (H_{SL}) along the Southern Baltic coast during surge Axel in 2017.

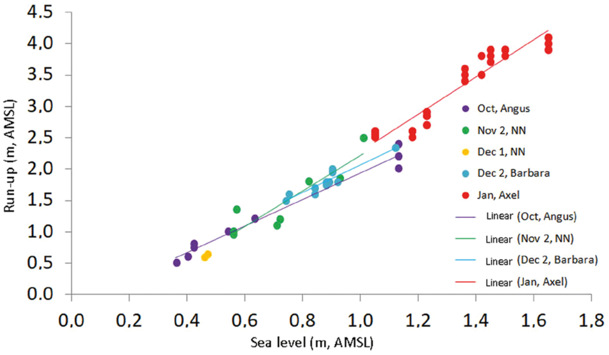

Fig. 9. Relation of sea level (H_{SL}) to water run-up height (H_{SLr}) on the coast during all surges in 2016/2017, each dot marks measured SLr in the field, surges in Table 1.

Relation of SL vs run-up

The maximum SL and wave height can be observed on the shore, based on remnants left after the maximum run-up to the shore (beach). Figure 9 presents the maximum run-up due to all investigated surges in 2016/2017. The lower surges exceeded up to 1 m of beach height, whereas some reached 2 m of beach height (Fig. 8). The run-up was relevant for selecting areas of coastal erosion. The highest observed run-up (SLr) was due to a high SL during the Axel surge. The maximum run-up reached the highest beaches, up to 3.5 m AMSL, and caused dune retreat along the coast. The maximum SL during storm Axel and the time duration of H_{SL} >1 m AMSL were correlated with the highest run-up observed on the shore (*r* = 0.62 to *r* = 0.51). The higher the SL observed, the higher the run-up on the adjacent coast sections. During the maximum surge, 1.5–1.65 m AMSL, the run-up on the closest coast sections was up to 3.6–4.1 m AMSL. The H_{SL} >1.2 m AMSL was equal in ca. 2.5 m of SLr. The H_{SL} >1.5 m AMSL was equal to 3.8 m of SLr. The maximum run-up that was observed on the measured coast section is a more accurate indicator of a retreat than the SL recorded in the harbour gauge station. The higher the SL observed, the higher the run-up on the adjacent coast sections. The relation of run-up (SLr) and dune toe erosion (DP_{fr}) was 0.55.

Relation of beach height to SL and run-up

An analysis of the beach morphology before and after the storm surge indicates that the beach surface was levelled after the storm. After the storm, beaches were 10–20 m narrower. In some places, the beach became even wider than before the surge. However, the beach width was generally observed to have increased after the surge in accumulative areas. That is because of material transportation and accumulation from adjacent eroded coasts. In these areas with wide and high beaches, a lot of debris material including litter was accumulated at the foot of the foredune. Also, larger observed particles were transported from the adjacent coast (Fig. 1E and Table 4). This explains why the beach height is not so important in that comparison.

The most important key factor related to dune toe retreat is beach height before the surge, which is comparable to dune toe height. During storm surges with a low SL, not only the lower part of high beaches but also whole beaches lower than the water run-up (SLr) were subject to erosion. The storm surge with SL = 0.8 m AMSL caused as much as 1.5 m water run-up (Fig. 8) and SL >1.2 m AMSL caused SLr up to 2.5 m. These calculations are made based on the assumption that, in terms of bringing about a height reduction effect, it is surge height presenting as SLr growth that affects a coast with a given beach height (Fig. 9).

Relation of dune erosion to run-up and beach height values

In areas of similar SL, erosion was small to large, due to output beach height, which allows for a lower or higher run-up. The higher the beach prior to the surge (H_{be} B), the less likely dune erosion (DQ_{fr}, DP_{fr}) was to occur (Fig. 10). On seriously threatened sections of the coast, the erosion exceeded 8–15 m (Figs 7, 8, 12–15). This was a typical situation on coastal sections with a beach lower than 2 m AMSL (Figs 10 and 11). Throughout the study area, the largest loss of sediment from a dune was observed on coasts with low-lying, usually narrower, beaches referred to as erosive (Figs 12 and 13).

The threshold of beach height was related to maximum SL growth and water run-up to the shore. Erosion understood as dune retreat was greater when a beach was lower than H_{SLr} ($H_{be} < H_{SLr}$). During an observed surge, dune erosion was larger on coasts with a lower and narrower beach (Figs 10–13). The average H_{be} to DP_{fr} was *r* = 0.49, while a higher score was observed on the eastern coast (*r* = 0.5–0.75) on the studied coastal sections with low-lying, and in some areas high, beaches. A lower score was observed

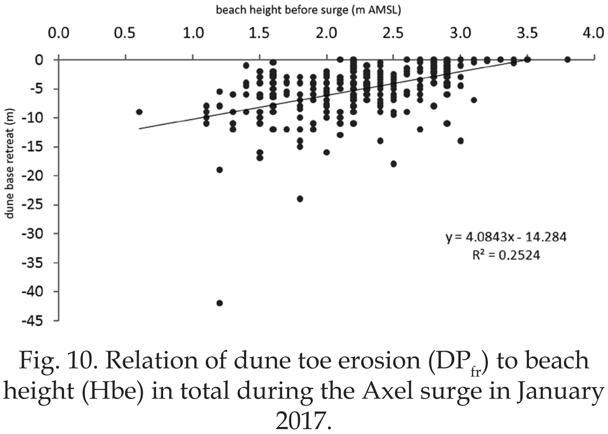

Fig. 10. Relation of dune toe erosion (DP_{fr}) to beach height (Hbe) in total during the Axel surge in January 2017.

on the central coast with higher beaches than in other areas (*r* = 0.4–0.47) but exposed to the highest SL >1.6 m AMSL. This is why the correlation coefficient was smaller overall.

This relation prevailing between the impact of strong surges and beach height may be explained as measured varying values (E1–E4) of dune toe erosion (DP_{fr}) corresponding to beach height (H_{be}) and observed maximum height of the run-up (H_{SLr}), where:

- E1 > E2 > E3 > E4, E4 = 0 m,
- E1, when $H_{be} < H_{SLr}$, DP_{fr} average 5–8 m, highest more than 10–15 m,
- E2, when H_{be} £ H_{SLr}, DP_{fr} average 2–6 m, highest to 10 m,
- E3, when H_{be} ^{3} H_{SLr}, DP_{fr} average 0.5–2 m, highest to 3 m, and
- E4, when $H_{be} > H_{SLr}$, DP_{fr} is not eroded, accidentally 0.2–0.5 m of retreat.

The coast sections with beaches higher than 3.5 m ASML have almost not been threatened by the surge. Additionally, all beaches above 4 m ASML were not eroded. The erosion of the foredune or other frontal dune structure depends on beach height, related to the highest SL expressed as known SLr on the shore (Fig. 9).

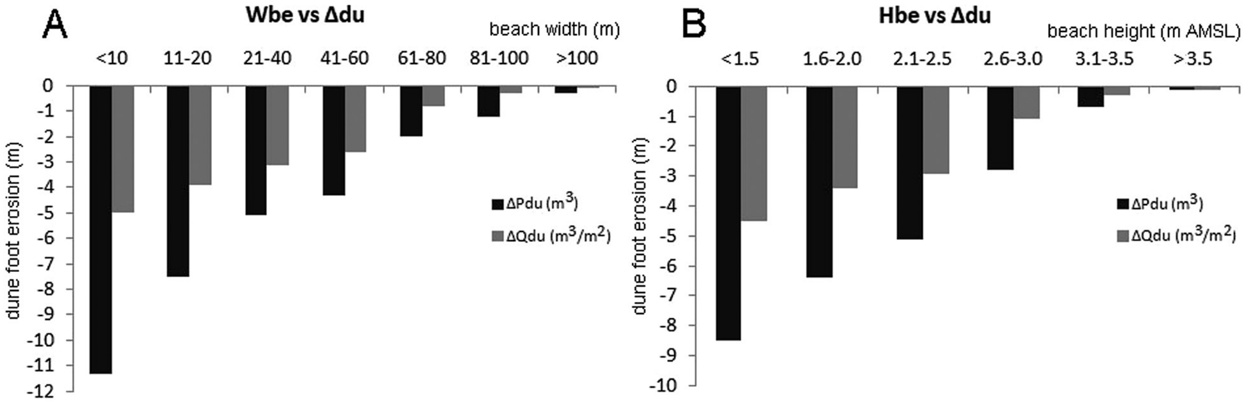

Fig. 11. Overall relation of dune toe erosion (DP_{fr}) to beach parameters (H_{be}, W_{be}) rate in January 2017.

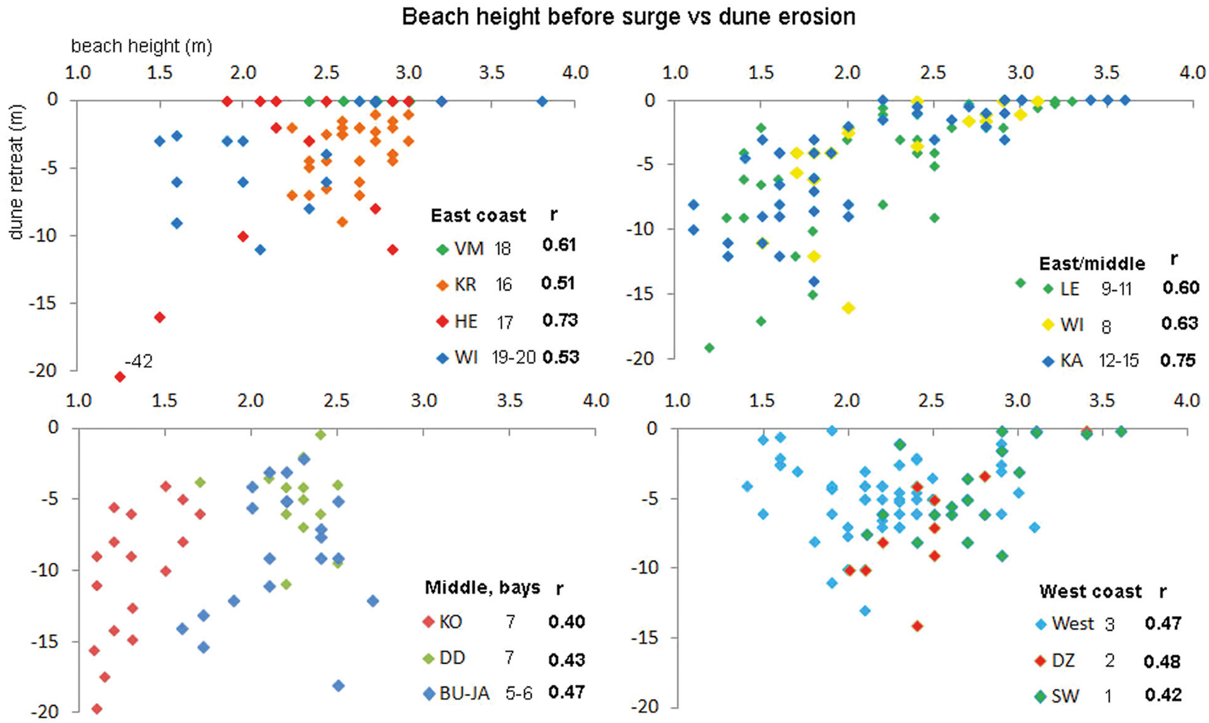

Fig. 12. Relation of dune toe erosion (DP_{fr}) to beach height (H_{be}) on investigated sandbars divided for coast sections (Nos 1–20, Table 3) and Pearson coefficient (*r*) in January 2017.

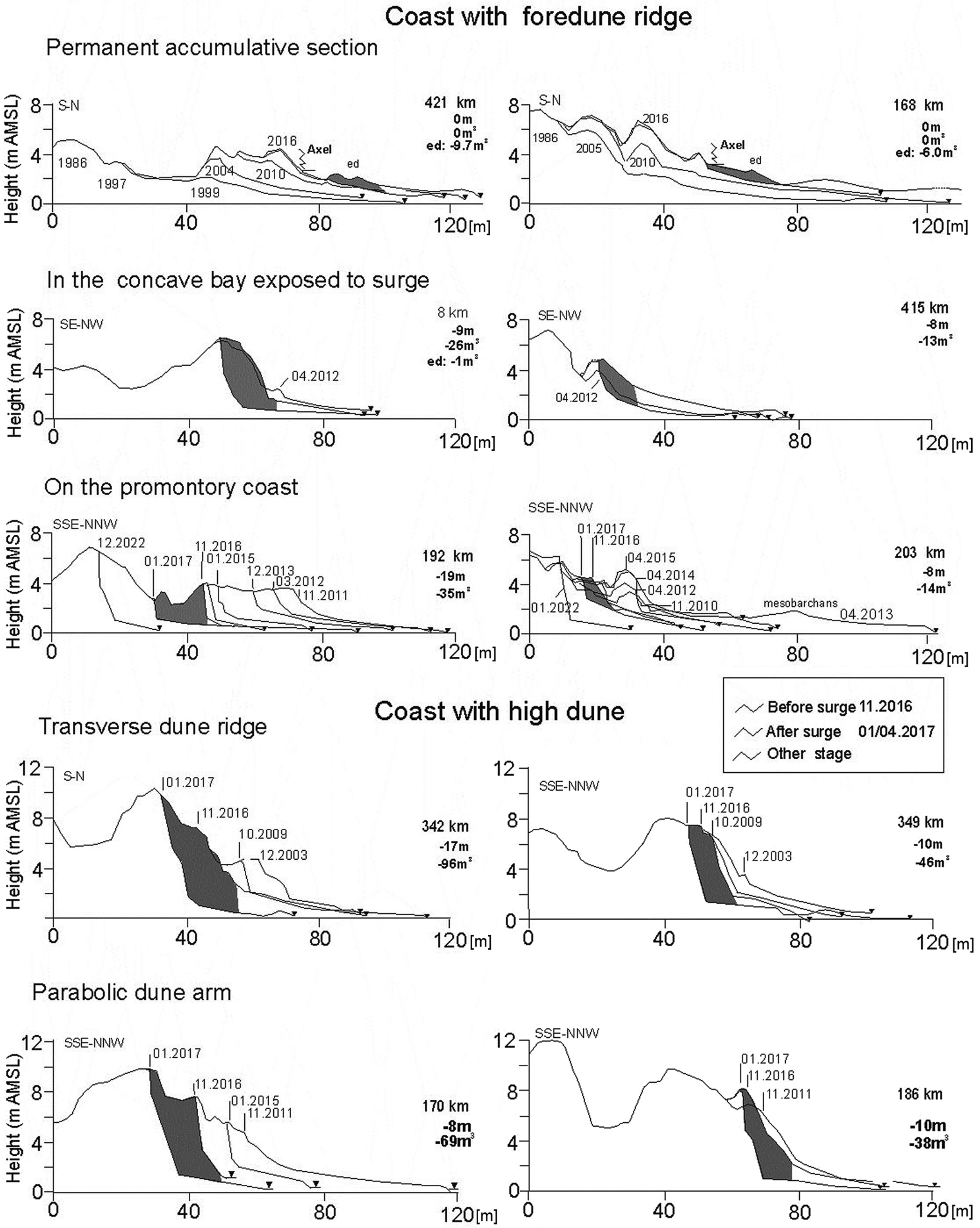

Fig. 13. Erosion rate of the dune on the coast with different expositions during storm Axel, given toe retreat (m) and sand volume in grey (m^3) of dune or embryo dune (ed), marked max. run-up and dates of dune's previous position.

Erosion of Polish sandbars by Axel surge to their exposition and coast morphology

The described Axel storm surge shifted from WNW to NNE. All the Polish dune coast sections with NW or NE exposure were threatened by the storm. The dune retreat was varied for different sections' morphology and due to previous shore retreat during surges in autumn (Figs 4 and 5). These caused beach erosion and in some places dune retreat. The lowest erosion was on the coast where the beach was higher, or where coast orientation was not directly exposed to the surge, that is to say in bays with high beaches and north exposure (Figs 10–12). In areas where the beach was higher than the run-up, dune toe retreat was absent. These areas include only short, accumulative coast sections with high beaches, up to 3–3.5 m AMSL. The lowest dune erosion was observed on the eastern coast of the Gulf of Gdańsk, which is sheltered by the Hel Peninsula. The beaches were narrowed and lowered but foredunes survived the Axel surge. Only 10% of the open coast length has avoided retreat, that is to say ca. 50 km including 25 km of artificial protection.

In all the investigated sections (Figs 1D, Nos 1–20), erosion varied due to all the factors described above (Figs 7–12). The average retreat of the dune toe was 5.1 m. Sandbars sections of the coast that had hitherto been accumulative witnessed dune toe erosion at a rate of 2–4 m. The extreme values of dune toe retraction in different sections exceeded 10–20 m. The average amount of sediment removed from the dune was 23 m^3 per shore metre. The average erosion of dunes per square metre was 1.25 m^3 per linear metre. More severe dune erosion was observed on coast sections with erosive tendencies and characterised by low-lying beaches (Fig. 12). Figure 12 presents a single dune retreat related to beach height on investigated profiles located on the selected sandbar sections (Nos 1–20, Table 3). The eastern coast (sections 9–15) with varying beach heights experienced erosion amounting to a ca. 10 m retreat with a beach of up to 2 m AMSL and up to 5 m with H_{be} >2.5 m. There, the maximum SL was 1.23–1.36 m (max. SLr = 3.25 m). There, the coast with a beach height greater than 3 m was almost not eroded at all (Fig. 10). No erosion was observed on sections with H_{be} >3.8 m. On the eastern part of the coast from the Karwia Sandbar, through the Hel Spit to the Vistula Sandbar (section Nos 16–20), the dune toe retreat was 2.5–10 m. This was lower in the western part of the Vistula Sandbar, whereas in Gdańsk it was SL <1.2 m AMSL (SLr = 2.5 m). The middle coast is usually often erosive and exposed to the majority of surges from W to NW. There, the average erosion was the most severe, despite the presence of beaches high above the mean SL. It was caused due to beaches lowered by previous surges and the highest observed SL during Axel, 1.65 m (SLr = 3.5–4.1 m). On the western part of the coast, erosion varied from 3 m to 10 m on average due to different beach heights and an SL of 1.4–1.5 m AMSL (SLr 3.2–3.8 m). Figure 13 presents the dune volume erosion and retreat for the different coast sections. On the accumulative sections with the high beach, only embryo dunes were washed out, as on the Świna Gate Sandbar (section No. 1). More erosion occurred on coasts with longer exposure to the high surge.

Figure 14 presents the minimum, maximum, average, median and prevailing values of dune toe retreat for each sandbar section (Table 3). The difference in erosion was larger on sandbars with larger morphological diversification related to beach height as well as water run-up. On the west coast, the average and highest dune toe retreat were relatively smaller than on the east. The lowest retreat indicates more areas with higher beaches and accumulative sections. Conversely, the lower coast suffered more erosion. This can be an indicator of threshold values of prevailing morphology on each coast section to surge impact. The median dune toe erosion of 3–6 m is similar on sections facing more or less north (section Nos 1, 3, 4, 10 –12, 14–16 and 19, Fig. 1D). The average value was higher due to individual higher erosion on erosive sections, up to 12–14 m. As is presented in Figure 14, half of the measured sandbars are characterised by erosion between 4 m and 8 m. Nevertheless, statistically, half of the cases experienced dune retreat up to 4 m on north-facing sections, 8 m on west-facing and ca. 6 m on east-facing, mainly on the Hel Spit. The largest erosion was observed in the middle coast, which is directly exposed to the majority of surges and has prevailing tendencies to erosion, up to 9 m on average (section 6 and 7). On the Hel Spit, the largest dune retreat was observed on sections with rapidly changing coast exposure from NE to

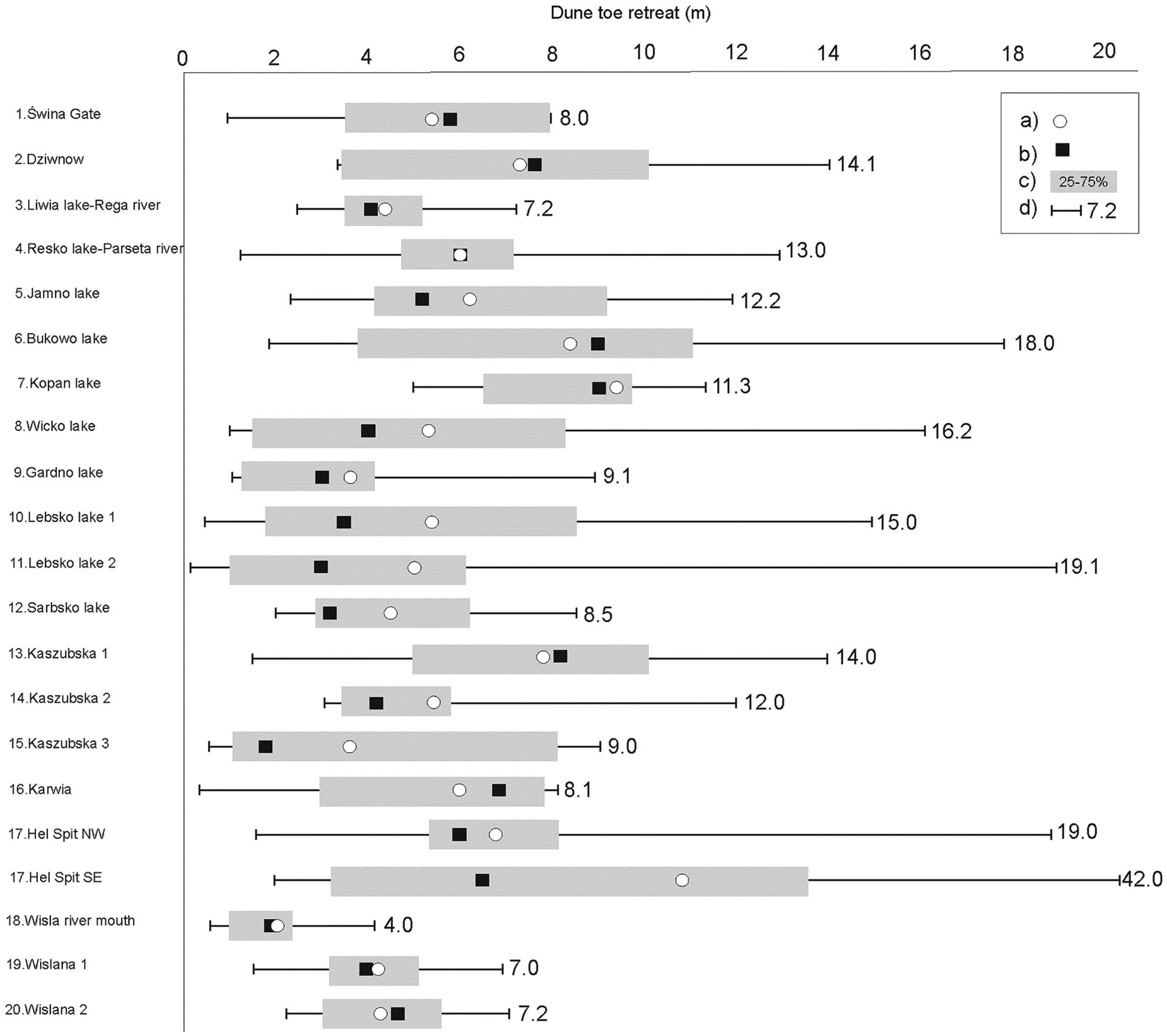

Fig. 14. Statistical threshold values of the dune toe erosion caused by storm Axel, on investigated sandbars' sections (Table 3).
a – average, b – median, c – 25–75 percentile of cases, d – min. and max. values.

ENE. There, erosion was caused by waves from N to NE direction in the last phase of the Axel surge. There, the largest dune retreat exceeded 24–42 m in two areas where shore exposure changes rapidly at short distances.

Locally, on a given north-facing section (west, central-eastern coast), the magnitude of erosion depended on changes in the orientation of the shoreline every 2–3 km, taking the shape of a northward-facing sinusoid. On this type of shoreline, the western edges of the promontories of such a sinusoid were eroded more severely. Their eastern banks were eroded to a lesser extent. This was also because eastern parts of promontories have accumulative tendencies, demonstrated by the wider and higher beach with embryo dunes. They are transformed into short accumulation sections. These end with another erosive bay, which is in turn followed by a subsequent promontory shifted towards the north. Each coast section exposed directly to wave action for a longer period faced a greater probability of erosion.

The importance of coast exposition for waves' action was clearly visible in both concave sandbars: the Świna Gate Sandbar, located on the western coast, and the Vistula Sandbar in the east. The coasts of both sandbars facing NW experienced larger erosion than NE-facing strips. The average erosion of the dune toe for both concave sandbars ranged from 3 m to 4 m.

Discussion

Major storm surges on the Baltic Sea coast with high SLs of 1.3–1.5 m AMSL occur every several years (Sztobryn et al. 2005, Orviku et al. 2007, Jaagus, Suursaar 2013, Weisse, Weidemann 2017, Łabuz 2022) and cause coast erosion in different Baltic states (Eberhards et al. 2006, Orviku et al. 2007, Tõnisson et al. 2008, 2013, Furmańczyk et al. 2011, Ryabchuk et al. 2011, Bobykina, Stont 2015, Jarmalavicius et al. 2016 *inter alia*). These observed surges usually affect coasts oriented perpendicularly to the surge landfall. On the north-eastern Baltic coast in Latvia or Estonia, the highest SL may reach 2–2.7 m during very high storm surges from the W–SW direction, such as Gudrun/Erwin in January 2005 or Anatol in December 1999 (Eberhards et al. 2006, Suursaar et al. 2006, Tõnisson et al. 2008, Wolski et al. 2014, Jarmalavicius et al. 2016). During these surges, the maximum dune retreat was 8–27 m. The lowest retreat occurred on the south-eastern coast of Lithuania and Russia (Bobykina, Stont 2015, Jarmalavicius et al. 2016). On the Vistula Sandbar, significant dune retreat exceeding 5–9 m was observed during the January 2012 surge moving from W to NW (Łabuz 2014, Bobykina, Stont 2015), with SL up to 1.3 m AMSL (named Andrea II).

On the southern Baltic coast, the SL during a storm event may rise to 1.4 m AMSL (Zeidler et al. 1995, Sztobryn et al. 2005, Wolski et al. 2014). During the Axel surge in January 2017, the SL was higher and reached 1.5 m or even 1.65 m AMSL in numerous gauge stations. It was the largest surge on the southern Baltic coast in the 20th and so far the 21st century, with the highest average SL recorded in Polish gauge stations, namely 1.36 m AMSL. Therefore, the erosion process affected almost the whole Polish coast. The average rate of dune erosion was 5.1 m, with a local maximum of 7–19 m. It was much more than that observed during a typical high surge with SL = 1.2 m AMSL, akin to that in January 2012 with 3 m of dune retreat on average (Łabuz 2014), or after numerous surges (including the Kyrill surge) during the autumn–winter period of 2006/2007 with SL = 1.38–1.48 m AMSL (Łabuz 2009). The surge in December 1988, with SL = 1.47 m on the western coast (Sztorbryn et al. 2005), caused a maximum measured dune retreat of 8–12 m (Basiński 1995). The surge from November 1995, with SL = 1.4–1.6 m on the west coast (Sztorbyn et al. 2005), caused dune erosion up to 9 m AMSL. The November 2004 surge with SL = 1.37 m AMSL caused 4–6 m of dune retreat on the western part of the coast (Łabuz, Kowalewska-Kalkowska 2011). Higher values of dune retreat were observed after storm surge Axel. A SL of 1.4 m AMSL on the western and eastern coast caused an average erosion of 3–5 m. Erosion was more severe on the middle coast, where SL reached 1.65 m AMSL.

Wind force plays an important role in SL rise on the Baltic Sea coasts (Trzeciak 2001, Sztorbyn et al. 2005, Stont et al. 2012). Wind velocity during the Axel surge reached 15–18 m $\cdot$ s^{-1} where the SL was 1.4 m AMSL and even 20 m $\cdot$ s^{-1} on the middle coast where the SL rose to 1.65 m AMSL.

The extent of the shore erosion and coast retreat depends on both the sea surge height and its duration (van de Graff 1977, Suursaar et al. 2006, Tönisson et al. 2006). The surge level is the most important factor in dune erosion (Orviku et al. 2007, Roelvink et al. 2009, Ryabchuk et al. 2011, Łabuz 2015, 2022). However, the wave run-up indicator is more accurate for analysing the sea effect on the coast (Nielsen, Hanslow 1991, Didenkulova, Pelinovsky 2008, Di Luccio et al. 2018). The run-up is related to the highest SL and highest waves produced by the strongest wind. During lower surges from autumn–winter 2016 with SL = 0.8 m AMSL, the ascent of water onto the beach reached 1.6–1.8 m AMSL. At a SL of 1 m AMSL, the run-up of a subsiding wave reached 2–2.5 m AMSL. The high and highest water level 1.5–1.65 m AMSL caused a run-up extending to 4–4.1 m AMSL. Therefore, after the Axel surge, dune erosion included almost 90% of the sandbars coast and all of the cliff coast, an observation mentioned but not studied in detail in the present research.

The rate of coastal erosion could be also related to the time during which the SL was reaching its maximum and inundating the shore. It has been stated that the storm surge height on the South Baltic coast coast bears with the dune retreat phenomenon a relation characterised by the presence of visible dependence (Łabuz 2014, 2022). The duration of Axel surge with SL >1 m AMSL was found to be strongly associated with the extent of shore erosion. The longer the duration of a high-level surge, the more extensive the beach (DQ$_{be}$) and dune (DQ$_{fr}$) erosion that was observed. The dune retreat was larger on coast sections exposed to the longest duration of high SL. This was observed on the middle part of the Polish coast, where SL 1.5–1.65 m caused up to 9 m of dune retreat on average.

The higher the SL, the more severe the erosion (Koltsova, Belakova 2009, Łabuz 2014, Kelpšaite-Rimkiene et al. 2021). Change in dune retreat value (m) or its volume (m^3) is related to the duration of the given SL and its run-up (SLr) to the beach at the present height (H_{be}). The beach height before the event is a key factor when comparing storm indicators and dune erosion. The beach height related to the dune toe was found to play an important role in dune erosion. This has been observed but not emphasised so far in other studies (Nielsen, Hanslow 1991, Stockton et al. 2006, Didenkulova, Pelinovsky 2008, Di Luccio et al. 2018). Lower-lying beaches up to 1 m in height are erosive and reflective, with adjacent dunes being affected by more severe erosion. The height of the beach and maximum surge with water run-up are interdependent. For the southern Baltic coast and probably the whole Baltic coast, if the beach is higher than 3.5 m AMSL, it may be able to withstand erosion (Łabuz 2022). Dunes protected by a high beach or embryo dunes, higher than the water run-up, are not eroded. This was proved while analysing the impact of the Axel surge. Only the strongest storm surges, such as Axel from January 2017, with water level higher than 1.5 m AMSL, produce run-up at the shore to the extent of 3.8–4.1 m AMSL. If the number of unpredictable surges grows due to climate change, beach height before a storm must be considered more relevant than other indicators. The SL value during a surge is not the main factor related to erosion. The more important factor is SL expressed as the run-up height to the shore and beach height before the surge. Nevertheless, the higher the SL observed, the larger the extent of the dune toe erosion observed. Erosion was observed almost everywhere along the southern Polish Baltic coast (Fig. 15) due to the duration of high SL and the predominance of low-lying beaches eroded by preceding surges in 2016.

Conclusions

The January 2017 storm surge associated with the Axel low-pressure system turned out to be one of the heaviest surges on the southern Baltic coast in the 20th and 21st centuries. Its average SL from all Polish gauge stations was the highest so far, exceeding 1.36 m AMSL. The retreat of the dune toe reached 5.1 m on average. The highest-ever water level was observed on the middle Polish coast, amounting to H_{SL} = 1.65 m AMSL. There, the total erosion was the most severe and average values compared to other coastal sections amounted to 9 m. The largest dune erosion of 8–15 m occurred in sections with so far erosive tendencies, marked by low beach height. In some places, due to high SL, beaches, even those as high as 3 m, failed to protect the dunes from erosion.

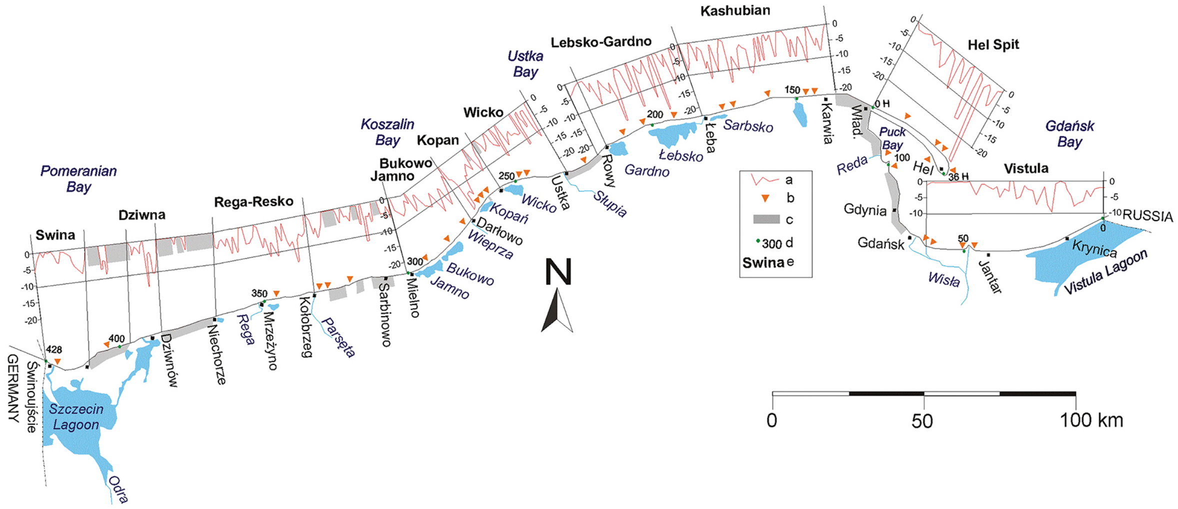

Fig. 15. Dune retreat along Polish South Baltic coast during storm Axel in January 2017.
a – dune retreat (m), b – washover fans on the coast, c – no data, cliff coast or wetlands in bays, d – main kilometre division, e – names of main sandbars.

The main factors determining the possibility and extent of likelihood of beach and dune erosion is the duration for which high water levels and waves are sustained during a surge. There was an observable correlation between the duration of the surge with H_{SL} >1 m and the magnitude of dune erosion. The rate of dune toe erosion also varied according to coast orientation to the Axel surge. The sections perpendicular to the highest wave action and the highest SL were mostly affected by dune and beach erosion. All coastal sections facing W–NW, such as barriers located in the middle area of the coast and eastern parts of the Świna Gate and Vistula Sandbars located in concave bays, experienced more dune toe retreat than other parts of the coast. Major dune erosion took place on small, but visible, coastal promontories where the shoreline protrudes to the north. There, coast exposure shifts from SSW–NNE to W–E. All dunes on NNW-facing promontories experienced the largest erosion, whereas N-facing adjacent locations were almost untouched. There, dune toe retreat was the most pronounced in single spots with mean values of 8–19 m. Along the promontories, there was a visible relation between beach height and dune retreat. Over the years, the NW parts of promontories have tended towards erosive and narrow beaches.

The SL value during a surge is not the main variable related to erosion. The more important factor determining dune retreat is SL expressed as the run-up height to the shore and beach height before the surge. These two factors indicate the probability of dune erosion related to the toe retreat or volume decrease. The beach height is the main factor preventing the coast from dune toe retreat. The width of the beach prior to the storm has no impact on dune erosion.

Field observations allow the direction of sand material transport to be determined during a surge based on larger particles' shift along the coast. It may be helpful to understand how the long-shore current transports sediment during a surge. The land retreat attributable to the impact of a storm surge should be studied in terms of the several variables highlighted in the empirical material laid on record in the present study.

The obtained data could be used in a long-term comparison of storm severity, and to predict coastal retreat, which is important for the consideration of coastal resilience in strategic management plans.

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