STORM SURGES VERSUS SHORE EROSION: 21 YEARS (2000–2020) OF OBSERVATIONS ON THE ŚWINA GATE SANDBAR (SOUTHERN BALTIC COAST)

Tomasz Arkadiusz Łabuz

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

Manuscript received: January 25, 2022
Revised version: May 7, 2022

Łabuz T.A., 2022. Storm surges versus shore erosion: 21 years (2000–2020) of observations on the Świna Gate Sandbar (southern Baltic coast). *Quaestiones Geographicae* 41(3), Bogucki Wydawnictwo Naukowe, Poznań, pp. 5–31. 14 figs, 4 tables.

Abstract: Based on observations spanning 21 years (2000–2020), the article studies the effects of storm surges on the shore of the Świna Gate Sandbar in the southern part of the Pomeranian Bay (southern Baltic Sea). Impacts of selected maximum storm surges in each year were assessed with respect to morphological data collected on the beach and the foredune. The data included parameters of beach-dune erosion as measured along a beach transect before and after each surge. Differences and trends in the shore erosion were related to the sea level (SL), duration of a storm surge [highest storm sea level (H_{SL}) > 1 m], wind-wave sector and wave run-up. The relationships were explored using a simple correlation analysis. The most serious erosion was observed during the heaviest surges [H_{SL} > 1.3 m above the mean sea level (AMSL)], with a wave run-up higher than 3.2 m AMSL. Such surges occurred at about 2-year intervals. The average SL during a surge was 1.2 m AMSL, with a run-up of 2.6 m AMSL. The beach and the lower part of the shore, below that level, were eroded each year. The heaviest surges resulted in an average 5.2 m and 7.0 m dune retreat on the high-beach-accumulative shore and on the low-beach-erosive shore, respectively. The dune was not eroded when the beach height exceeded the wave run-up. The heaviest surges eroded away 12–14 m^3 of the beach sand volume. The shore erosion was found to be related to the storm surge duration, the maximum SL, the run-up and the beach height prior to the surge.

Keywords: storm surge, sea level, run-up, dune erosion, beach erosion, sand volume changes, Baltic Sea

Corresponding author: Tomasz Arkadiusz Łabuz; tomasz.labuz@usz.edu.pl

Introduction

The southern Baltic Sea coast is a non-tidal area; the shores are affected by wind, waves and near-shore currents (Zeidler et al.1995, Zawadzka-Kahlau 1999). The stormy season and the sea level (SL) in the southern Baltic Sea vary from year to year due to joint effects of numerous meteorological and hydrological factors. The most frequent and important factors include the passage of low-pressure systems from the North Atlantic over the Baltic Sea from the south-west, west or north-west (Samuelsson, Stigebrandt 1996, Cyberski, Wróblewski 1999, Johansson et al. 2001, Suursaar et al. 2003, Kont et al. 2008, Gräwe, Burchard 2012, Wolski, Wiśniewski 2020). The southern Baltic Sea, including the Polish coast, is influenced by frequent SW and W winds (Fig. 1B) occurring during an eastward passage of a low-pressure system. Winds of high velocity (above 10 m · s^{-1}), termed the storm surge winds (Trzeciak 2001, Sztobryn et al. 2005, Stont et al.

https://doi.org/10.2478/quageo-2022-0023
ISSN 2082-2103, eISSN 2081-6383

2012), are observed mostly during colder parts of the year and most frequently arrive from NW, N and NE. Such winds account for about 10% of all winds in the western part of the Polish coast. The annual probability of the heaviest winds (above 15 m · s^{-1}) is about 6% (Zeidler et al. 1995, Trzeciak 2001). The heaviest (Beaufort scale 10–12) storms result from very strong NW and NE winds, whose annual probability is low (1%) (Zeidler et al. 1995). Winds, particularly the heavy ones, are responsible for meteorological forcing resulting in short-term sea-level variations. A storm surge is understood as a strong wind action producing high waves accompanied by an increase in the SL

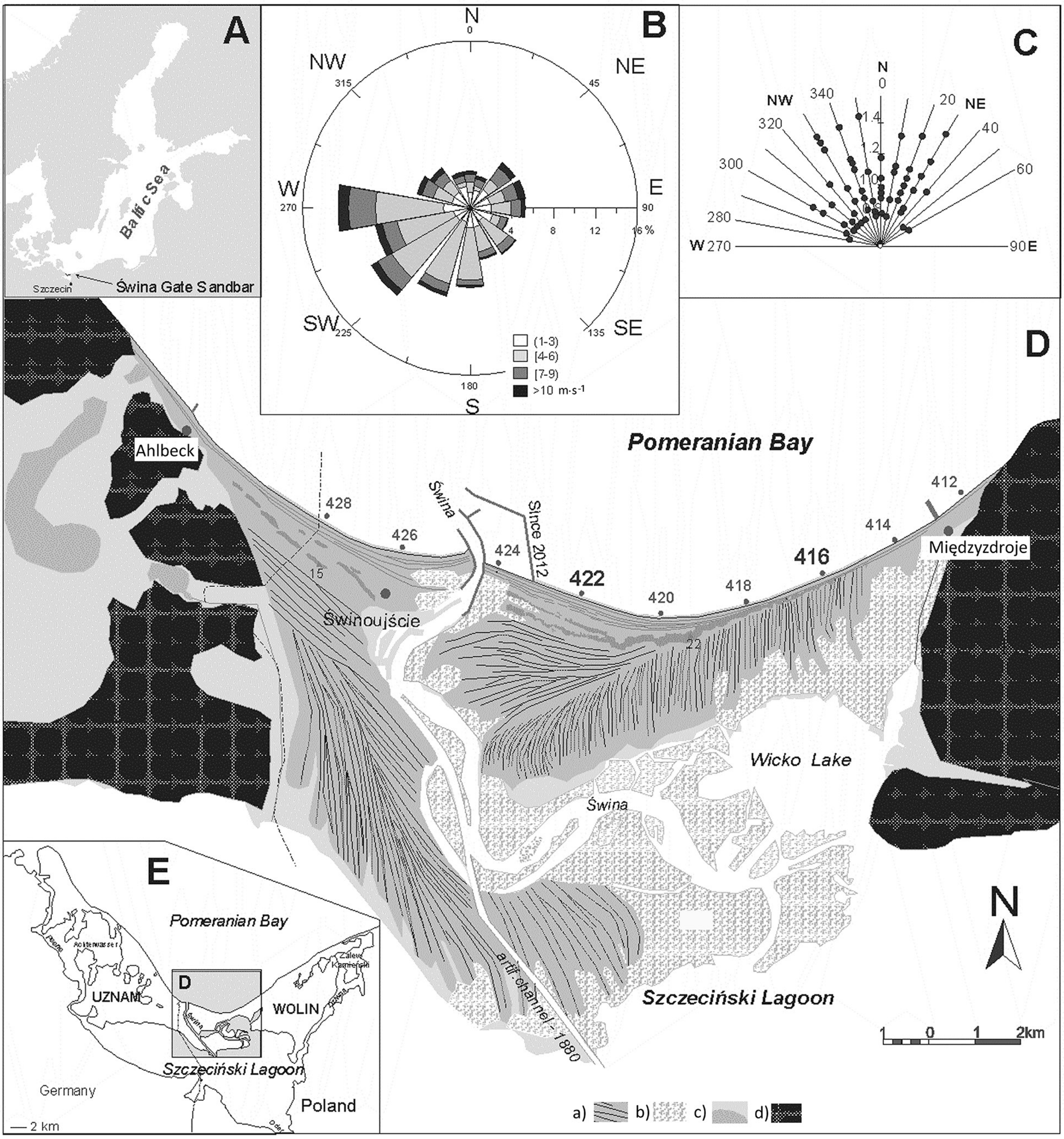

Fig. 1. Geographic characteristics of the study area.
A – location in the Baltic Sea coast, B – wind rose at station Świnoujście, 2000-2020, C – storm surge height and level in Świnoujście harbour, 2000-2020, D – coast exposure and morphology of the Świna Gate Sandbar (location of shore profile studied on kilometres 422 and 416); a) sandbar dune ridges, b) wetlands, c) lowlands and lakes, d) moriane.
E – sandbar location in the Pomeranian Bay.

over a short period of time (Sztobryn et al. 2005, Dailidienė et al. 2006, Hünicke et al. 2015). The most important factor for causing the water level to rise is the inflow of water from the North Sea, which occurs when the wind changes direction from SW to NW. This is why storm surges on the southern Baltic coast are more frequent with W to NW winds, the surge incidence being lower with NE winds. However, a probability of the very high SL increases in the latter case, with the water being pushed south from the northern part of the Baltic Proper (Johansson et al. 2001, Sztobryn et al. 2005, Surkova et al. 2015, Weisse, Weidemann 2017).

The number of storm surges [i.e. SLs higher than 0.8 m above the mean sea level (AMSL)] on the southern Baltic coast differs from year to year, indicating the irregular nature of storm surge occurrence there (Zeidler et al. 1995, Sztobryn et al. 2005, Wolski, Wiśniewski 2020). Surges at the southern Baltic coast are most frequent during winter (November–February) (Sztobryn et al. 2005, Dailidienė et al. 2006, Surkova et al. 2015). At present, the highest water levels during storm surges on the Baltic Sea coast exceed 1.5 m AMSL and have been observed in most Baltic countries, with a resultant heavy shore erosion (Suursaar et al. 2003, Dailidienė et al. 2006, Eberhards et al. 2006, Pruszak, Zawadzka 2008, Tõnisson et al. 2008, Koltsova, Belakova 2009, Furmańczyk et al. 2011, Łabuz, Kowalewska-Kalkowska 2011, Ryabchuk et al. 2011, Łabuz 2015, MacPherson et al. 2019, Wolski, Wisniewski 2020).

The scale of the shore erosion and coastal retreat depends on both the surge height and duration (Van de Graaff 1977, Tõnisson et al. 2008, Furmańczyk et al. 2011, Kelpšaite, Dailidienė 2011, Ryabchuk et al. 2011, Jarmalavicius et al. 2016). The average retreat rate along the Polish Baltic coast was 0.1 m · year^{-1} over the last 100 years, and 0.5 m · year^{-1} from 1960 to 1983 (Zawadzka-Kahlau 1999, Pruszak, Zawadzka 2008). At present, the average retreat in the western part of the Polish coast is 0.9 m · year^{-1}; following a heavy storm surge, it can and be as high as 5–8 m (Łabuz 2009, Łabuz, Kowalewska-Kalkowska 2011). With the on-going climate change, the average SL in the southern Baltic is showing an increasing trend; an increase has been also observed in the incidence of smaller surges (Zeidler et al. 1995, Samuelsson, Stigebrandt 1996, Johansson et al. 2001, Suursaar et al. 2003, Sztobryn et al. 2005, Gräwe, Burchard 2012, Richter et al. 2012, Jaagus, Suursaar 2013, Hünicke et al. 2015, Weisse and Weidemann 2017, MacPherson et al. 2019, Wolski, Wisniewski 2020). This increases the risk of coastal erosion, the potential scale of which should be assessed in relation to the magnitude of storm surges.

Storm surge-related dune erosion has been studied, both in the field and using numerical modelling, by several authors (Van de Graaff 1977, 1986, Vellinga 1982, Basiński 1995, Orviku et al. 2007, Tõnisson et al. 2008, 2013, Roelvink et al. 2009, Van Thiel de Vries 2009, Furmańczyk et al. 2011, Kelpšaite, Dailidienė 2011, Łabuz, Kowalewska-Kalkowska 2011, Kortekaas et al. 2013, Łabuz 2014, Bobykina, Stront 2015). Quantitative analysis of morphological changes of a surge-threatened shore plays an essential part in the integrated coastal zone management. And yet, no data on a single section of the coast affected by erosion caused by various storm surges have been published.

This study is aimed at describing and comparing changes, associated with recorded storm surges, in accumulative and erosive sandy dune coast sections. The data were collected over 21 years (between 2000 and 2020) of field observations. The objectives of this study are: 1) to present a hydrodynamic analysis of the heaviest storm surges which primarily produce the foredune erosion, 2) to describe the rate of beach and foredune erosion caused by each surge, 3) to estimate the volume of sand removed and/or displaced by the storm, and 4) to explore the relationships between storm parameters and the shore erosion rate.

Study area, material and methods

Study area

The study area extends along a 16-km long stretch of the shoreline of the Usedom and Wolin Islands (southern Baltic Sea, Pomeranian Bay), forming a sandbar (Fig. 1A, E). The Pomeranian Bay in its southern part is shallow, with depths of up to 2–5 m close to the shore, and displays a system of 2–3 bars near the shore. The Świna Gate Sandbar consists of two sand spits between the moraine plateaus of the two islands (Fig. 1D). The sandbar is located between Polish coast kilometres 412 and 424 (shown in Fig. 1D); kilometre 0 is at the border between Poland and the Russian Federation's Kaliningrad Region on the Vistula Spit, while kilometre 424 marks the border between Poland and Germany on the Świna Gate Sandbar; the coast kilometrage is used to locate the measurement points as well as for the location and management of threats along the coast. The two Świna Gate Sandbar spits emerged as a result of accumulation of the marine sand eroded from the Wolin and Usedom moraines (Łabuz 2009). The dunes and beaches are built by medium and fine sand. The annual sea level rise (SL) in Świnoujście exceeds 1.1–1.3 mm (Zeidler et al. 1995, Richter et al. 2012). The highest surge in the Pomeranian Bay recorded in recent years exceeded 1.86 m AMSL (Sztobryn et al. 2005). The concave shoreline of the Pomeranian Bay is exposed to NE or NW storms, for which reason coastal erosion is observed in the eastern or western part of the shore, depending on the main direction of waves advancing onto the shore and into the near-shore zone (Łabuz 2009). Long-term observations showed the shore in the eastern part of the sandbar, exposed to NW storm surges, is more prone to erosion, compared with the western part, affected by the NE winds. However, due to the accumulative nature of the sandbar in-between surges, the beach and dunes are usually rebuilt to their former state or to a new one (up to progradation of new dunes).

Hydro-meteorological data

The hourly wind information (velocity, force, direction) for each surge was extracted from data of the Polish Maritime Bureau and readings at the Institute of Meteorology and Water Management (IMGW 2022) weather station at Świnoujście, a town located in the southern part of the Pomeranian Bay. The wind force associated with the low-pressure system is responsible for waves from a specific direction, which is important for a shore with an opposite exposure. Information on the occurrence of storm surges and their characteristics was collected, for the

Table 1. The parameters of the highest storm surges observed on Świna Gate Sandbar in 2000–2022 (source of raw data: Maritime Office and IMGW station in Świnoujście (IMGW 2022) and Wetterzentrale (2022)).

Year	Days, month	Max. sea level	Sea waving	Wind-waves direction	Wind velocity	Time with sea level H_{SL}>1m	Storm name
		[m AMSL]	[Bft]	[–]	[m $\cdot$ s^{-1}]	[h]	[–]
2000	17–20 Jan	1.01	5–6	NE–NW	10–12	2	Gilda
2001	21–24 Nov	1.04	7–8	NW–NNE	14–16	3	Janika
2002	19–22 Feb	1.44	7	NNW–NNE	13–15	11	Wisia
2003	21–23Dec	1.04	6	NW–N	16–18	3	Jan
2004	22–24 Nov	1.37	10–12	NW–NNE	17–20	15	Pia
2005	21–26 Jan	1.12	7	NNW	12–15	2	Lutz
2006	1–4 Nov	1.48	8–12	NW–N	16–20	18	Britta
2007	18–21 Jan	1.38	10	WNW–NW	15–19	24	Kyrill
2008	21–23 Mar	1.06	7	NE–N	12–15	6	–
2009	12–16 Oct	1.33	7	NNE–NE	12–15	30	Wimar
2010	14–15 Dec	1.02	6	NNE	14–16	3	Xynthia
2011	16–19 Dec	1.08	6–7	NW–NNE	14–16	3	Joachim
2012	13–16 Jan	1.42	7–9	WNW–N	14–17	32	Andrea
2013	6–9 Dec	1.04	10	W–WNW	16–24	4	Xavier
2014	20–21 Dec	0.85	9	W–NW	13–17	0	Aleksandra
2015	7–8 Feb	1.09	6–8	W–NNW	10–15	2	Ole
2016	4–6 Oct	1.13	6–8	NE–NNE	14–18	6	Angus
2017	4–6 Jan	1.42	7–11	NW–NE	16–20	28	Axel
2018	23–24 Oct	0.80	6	W–NW	14–16	0	Siglinde
2019	1–3 Jan	1.33	8–10	W–NNE	12–17	15	Zeetje
2020	14–15 Oct	1.10	8	NE	17–18	11	Gisela
2021	4–5 Nov	0.93	6–7	NE–NW	13–17	0	Wanda
2022	29–31 Jan	0.99	7–9	WSW–NNW	14–18	0	Nadine

21-year period of study, from the Polish Maritime Bureau and the Harbour Master's Office in Świnoujście. In relation to the Amsterdam level, the zero level of the tide gauges in Poland and in Świnoujście is PN = NN-500 cm (Sztobryn et al. 2005). For this study, were selected surges producing an SL higher than 0.8 m above NN and AMSL. Such surges cause the state of alert for the town of Świnoujście. The temporal resolution of the data was 1 h. The main descriptors of the storm magnitude included the highest storm sea level (H_{SL}), the main wave direction (and possibly its change), and the duration (hours; T_{SL}) of a surge higher than 1 m (T_{SL} with $H_{SL} > 1$ m); the runup resulting in the SLr was also taken into account (see below). The storm surges were named after those used in media coverage in the Baltic countries, and were cross-checked against the lowpressure system names used in the Institute of Meteorology of the Free University of Berlin (FU 2000–2022, Wetterzentrale 2022). However, not every surge could be named as not every low-pressure system observed during the on-going storm was named. A total of 62 significant storm surges with SL higher than 0.8 AMSL ($H_{SL} > 0.8$ m) were observed. To examine the storm impact on the shore, the highest surges that appeared in each year were selected (Table 1).

Field measurements of shore morphology

Changes in the relief of coastal forms were determined based on the analysis of cross-shore profiles (transects) from the waterline to the stable dune. More than 80 profiles from two contrasting locations, exposed to different surge directions, were analysed (Fig. 1D). One location (at kilometre 422) is exposed to NE storm surges, the other one (kilometre 416) being exposed to NW surges. The transects extended from the fixed and stable parts of the dunes to the waterline. Measurements along the transects were before and after each selected storm surge, within 2000–2020. The dynamics of the shore relief could be followed this way as well (Fig. 2). The field measurements involved the use of geodesic tools, including a cross-shore linear levelling (Ni-20) and a 3D levelling using the GPS RTK base Hiper II and Hiper SR made by TOPCON. Some observations were also made with a TLS ground laser scanning device TLS-1500 made by TOPCON (Fig. 3). Field observations on the presence of a storm surge and its impact on the shore morphology involved the measurement of the highest surge range, called the run-up or swash (SLr); it is marked by erosional cuts, as well as the presence of debris on the beach or in the runnel behind the eroded dune (Figs 6 and 7).

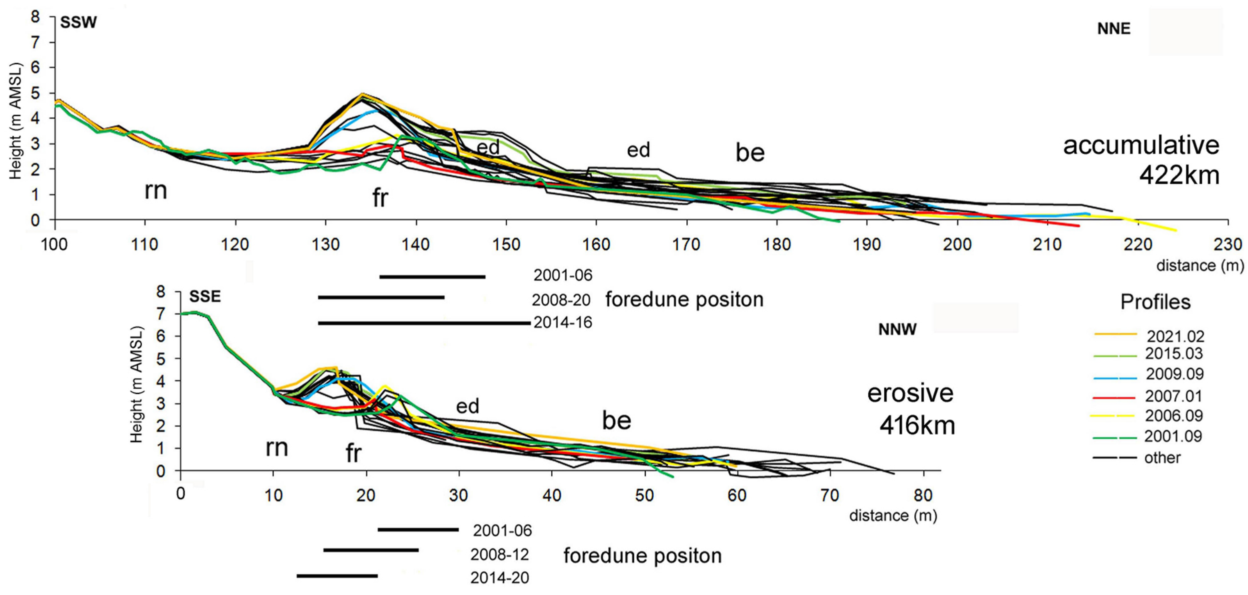

Fig. 2. Relief dynamics across the shore in 2001-2021 at two selected shore profiles (location on fig. 1D). Selected phases in colour, changes of foredune position caused by erosion marked below graphs. rn – runnel, fr – foredune, ed – embryo dune, be – beach.

Fig. 3. Field measurements.
A – dune levelling, B – beach with embryo form levelling, C – relief measurements using GPS-RTK tool, D – observation of dune retreat during a surge.

Numerical analyses

The transect measurements were processed, using a range of software products (Microsoft Office Excel 97, Grapher and Surfer by Golden Software, Grab it!, Statistica and Quantum GIS), to determine changes in the beach and dune height and width, followed by calculation of the sediment volume displaced from every square metre of the shore. This way, changes in the sediment volume were determined for individual coast morphology features, i.e. the lower beach, the upper beach and mainly the foredune. The range of shore relief change-related variables used in subsequent analyses included the movements of the foredune base and ridge or edge, the foredune height and the dune base width, and the beach width and height, as well as the height and dynamics of embryo dunes on the beach. The plotted dynamics layer shows short-time changes in the shore relief surface (Fig. 4). The changes are subsequently used to calculate the sand volume per metre in a 1 m^2 cell surface. The variables associated with changes in the beach morphological forms (x) reflected the present, seasonal, annual and post-storm surge state and included:

- wind: maximum velocity (V_w), time (T_w) $V_w > 10\ m \cdot s^{-1}$ and azimuth (Az_w),
- sea: sea level (H_{SL}), $H_{SL} > 1$ m AMSL surge duration in hours (T_{SL}) and, water run-up (H_{SLr}),
- beach (be): width (W_{be}), height (H_{be}), volume (Q_{be}) and changes in those variables (ΔX_{be}),
- foredune (fr): width (W_{fr}), height (H_{fr}), foot (P_{fr}) and top (K_{fr}), volume (Q_{fr}) and changes in those variables (ΔX_{fr}),
- embryo dune on the beach (ed): height (H_{ed}), volume change (ΔQ_{ed}), width (W_{ed}) and changes in those variables (ΔX_{be}).

Data for these variables were calculated based on transect data entered in Excel spreadsheets.

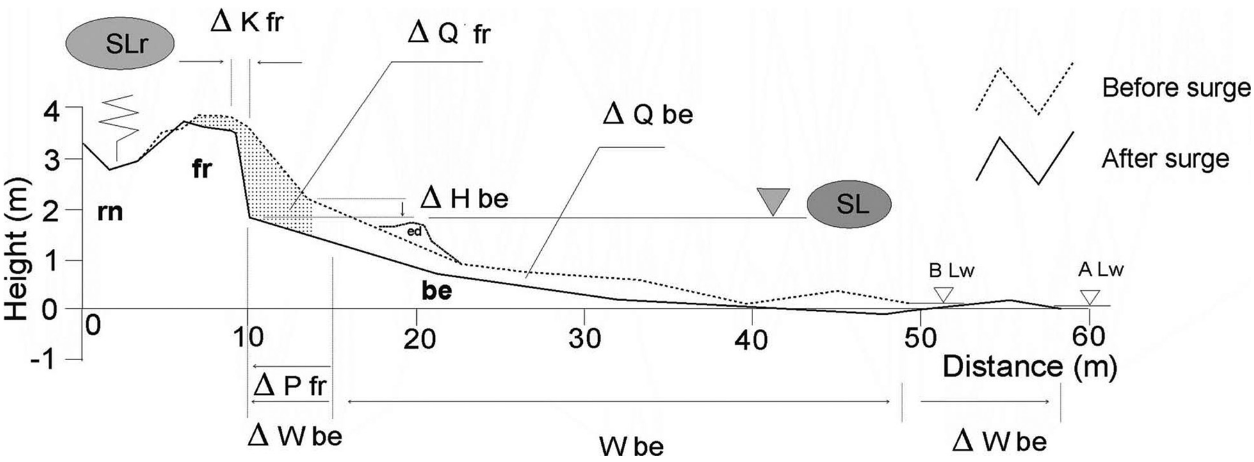

Fig. 4. Forms measured along the profile and indicators of their dynamics (B – before the surge, A – after the surge).
ΔH_{be} – beach height change, W_{be} – beach width, ΔW_{be} – beach width change, ΔQ_{be} – beach sand volume change, ΔP_{fr} – foredune foot change, ΔK_{fr} – foredune top/edge change, ΔQ_{fr} – foredune sand volume change, BLw – water line before the surge, ALw – water line after the surge, SL – max. sea level, SLr– water run-up.

Morphological changes were calculated for every square metre of each beach form (x) from the state determined before (B_{xi}) and after (A_{xi}) a measurement/storm surge (where *i* is the length of a form/profile in metres). The data were calculated mainly for the foredune (fr) and the beach (be). Further comparisons involved the following selected indicators: the foredune foot retreat (ΔP_{fr}) in metres; the foredune volume change (ΔQ_{fr}) in cubic metres; and dune width and beach sand volume changes ($\Delta Q_{fr/1m}$ and ΔQ_{be}, respectively) for each metre. Additionally, the beach height (before and after surge) and its change (ΔH_{be}) were analysed in relation to the SL and the run-up (SLr). The sand volume (Q_x) for the shore morphological form (*x*) was calculated using formulas developed earlier, where the change in sand volume is calculated per square metre surface (*d*) of each shore form (*x*i) as a sum of values derived from the profile (transect) width:

$$Q_x = \Sigma H_{xi} \cdot d$$

and added up to obtain the total volume change between the pre- and post-storm surge events (A and B, respectively):

$$\Delta\Sigma Q_x = \Delta Q A_{xi} - \Delta Q B_{xi}.$$

Changes in the beach and foredune width (ΔW_x), the foredune foot (ΔP_{fr}) and the position of the dune top (ΔPK_{fr}) were calculated in a similar manner.

The final step involved exploration of relationships between the field measurements and storm surge parameters. This was done using the correlation analysis by calculating appropriate Pearson's correlation coefficients (Table 2).

Results

Within 2000–2020, a total of 62 surges with H_{SL} > 0.8 m were observed in Świnoujście (Fig. 5A). The highest surges, with H_{SL} > 1.3 m AMSL, occurred in 2002, 2004, 2006, 2007, 2009, 2012, 2017 and 2019. During most storms, a surge with H_{SL} > 1 m lasted 3–5 h, the longest surges taking 15–40 h (as recorded in 2004, 2006, 2007, 2009, 2012, 2017 and 2019) (Fig. 5B, Table 1). Those surges were the most severe and showed the highest run-up (Fig. 5C). Morphological changes on the shore studied are described below. Changes in erosional and accumulative shore fragments following the same selected surge events are illustrated in Figures 6 and 7, respectively.

Characteristics of the storm surge impact at the coast stretch examined (2000–2020)

In 2000, there was one surge associated with a storm named Gilda, with the SL rising to H_{SL} = 1.01 m AMSL in the Świnoujście harbour.

Table 2. Coefficients correlation between the main input and output parameters of storm surge impact to the shore (B – parameters before the surge, A – parameters after the surge). Statistically significant correlations on the $p < 0.05$ value are typed in bold.

Input (B) and output (A) parameters [HSL, m AMSL]		Max. sea level H	Sea level T	Run-up	Max. wind velocity	Wind-wave azimuth NW	Wind-wave azimuth NE	Wind-wave azimuth NW–NE	Beach width before	Beach height before
		[TSL, hours HSL> 1m]	[HSLr, m AMSL]	[V, m · s^{-1}]	[degree]			[Wbe B, m]	[Hbe B, m]	
Main storm parameters	Max. sea level [HSL, m AMSL]	1.00	**0.87**	**0.92**	0.31	0.12	0.24	0.40	×	×
	Sea level time [TSL, hours H>1m]	0.87	1.00	**0.75**	0.29	−0.03	0.10	0.09	×	×
	Run-up [HSLr, m AMSL]	**0.92**	**0.80**	1.00	**0.49**	0.34	0.08	0.40	×	×
Average morphometric indicators	Beach width [ΔWbe, m]	0.01	0.10	−0.03	−0.06	0.24	0.16	0.32	**0.85**	**0.45**
	Beach height [ΔHbe, m]	**0.64**	**0.50**	**0.67**	0.20	**−0.45**	−0.06	**0.52**	0.26	0.35
	Beach volume [ΔQbe, m^3]	**0.66**	**0.49**	**0.70**	**0.59**	0.32	0.06	**0.48**	0.15	**0.46**
	Dune foot [ΔPfr, m]	**0.74**	**0.59**	**0.85**	**0.47**	−0.03	−0.17	0.43	0.26	**0.52**
	Dune volume [ΔQfr, m^3]	**0.71**	**0.57**	**0.71**	0.41	−0.20	−0.22	0.42	0.29	**0.49**
	Dune volume [ΔQfr, m^3/m^2]	**0.65**	**0.54**	**0.64**	0.36	0.18	0.21	**0.47**	0.21	**0.53**
Indicators for accumulative shore, 422 km	Beach volume [ΔQ be, m^3]	**0.55**	0.13	**0.64**	**0.65**	0.42	−0.12	0.31	0.19	−0.08
	Dune foot [ΔPfe, m]	**0.64**	0.34	**0.85**	**0.45**	0.31	0.28	**0.59**	0.33	**0.48**
	Dune volume [ΔQfr, m^3/m^2]	**0.63**	0.29	**0.69**	**0.47**	0.30	0.22	**0.51**	0.08	0.30
Indicators for erosive shore, 416 km	Beach volume [ΔQbe, m^3/m^2]	**0.79**	**0.57**	**0.83**	**0.54**	0.32	0.06	**0.45**	0.30	0.30
	Dune foot [ΔP fe, m]	**0.86**	**0.77**	**0.90**	**0.51**	0.29	−0.07	0.29	0.10	**0.62**
	Dune volume [ΔQfr, m^3/m^2]	**0.79**	**0.72**	**0.75**	0.38	0.28	0.20	**0.67**	−0.06	0.35

The surge produced no significant beach and dune erosion on the Świna Gate Sandbar, except for the lower part of the beach being flooded because of a higher upper beach. The water run-up on the shore exceeded 1.4 m AMSL.

The autumn-winter season of 2001/2002 witnessed five major surges of H_{SL} < 1 m AMSL. Each surge was produced by NW to NE or NE to NW winds and resulted in shore erosion along the entire sandbar. The two largest surges (H_{SL} of 1.44 m AMSL) occurred in January and February 2002 and washed away the young, 3–4 m high, foredunes formed on the upper beach between 1997 and 2001, following the sandbar erosion caused by a heavy storm in November 1995 (Łabuz 2009). The dune erosion was considerable because, in the first place, the beach was lowered and the foredune slopes were somewhat undercut by the first storm in November 2001 (Janika); in early 2002, the dune erosion reached major dimensions. In November 2001, the dune receded by 2–3.5 m (Fig. 7, 2001, Fig. 8). The February

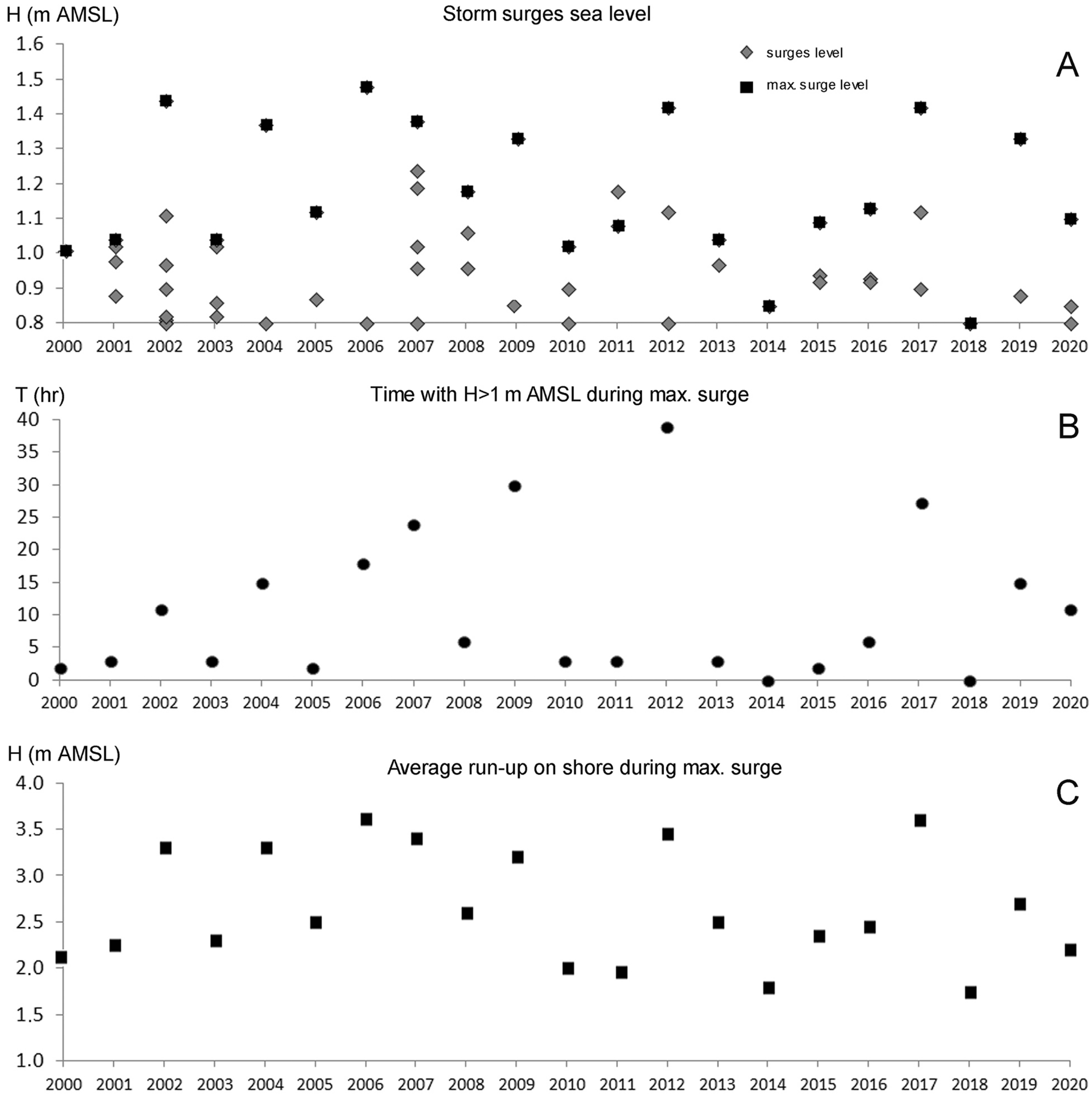

Fig. 5. Storm surge parameters in 2000-2020.
A – maximum surges and surges with H_{SL} of 0.8 m, B – duration (T_{SL}) of max. surges with H_{SL} > 1 m, C – run-up during maximum surges (H_{SLr}).

2002 storm (Wisia) (Fig. 10D), with H_{SL} = 1.44 m AMSL, caused the dune to recede by a further 6 m due to the presence of a low beach that had eroded in 2001. During the February 2002 storm, the SLr above 1 m was observed for 11 h. The water run-up reached 3.3 m AMSL. Along the spit section examined, three-fourths of the dune volume was washed away, the dune base receding by 8–9 m. Approximately 1.2–1.3 $m^3 \cdot m^{-2}$ of sediment was removed from the dune surface, the removal from both sandbar sections totalling 7–8 m^3. The beach erosion exceeded 13 $m^3 \cdot m^{-1}$ (per metre of shore width) (Fig. 8). As a result of aeolian accumulation, the foredune was rebuilt along the entire sandbar in 2002 and 2003, including the sections analysed here (Łabuz 2009). Two consecutive storms in December 2003 with H_{SL} > 1 m AMSL resulted in another retreat or partial washing-out of the foredune ridge (Fig. 6, 2003, Fig. 7, 2003). The foredune foot retreat did not exceed 1 m. In places where the beach was lower than 2 m above the SL, the ridges were broken (Łabuz 2009). The main surge, when the SL exceeded 1 m, lasted only 3 h.

The storm in November 2004 (surge Pia), induced by NW–NNE winds, produced a surge that resulted in erosion of the dunes in the area examined and reduced their volume by up to onethird (Łabuz, Kowalewska-Kalkowska 2011). The SL reached 1.37 m AMSL and remained above 1 m for 15 h. The water run-up was 3.3 m AMSL. The dune base in the western part was

Fig. 6. Photographic documentation of storm surge consequences on the foredune in the eastern part of Świna Gate Sandbar (kilometre 416).
2003 – fresh escarpments during the surge, 2004 – inundated beach and eroded foredune during heavy surge associated with storm Pia, 2006 – 2/3 of foredune eroded after surge associated with storm Britta, 2007 – remnants of foredune between 3 surges associated with storm Kyrill, 2009 – rebuilt foredune eroded by a heavy surge, 2012 – erosion after double heavy surge associated with storm Andrea, 2016 – small cut-off after 3 surges in autumn (including storms Angus and Barbara), 2017 – high escarpment of foredune eroded and beach washed by heavy surge associated with storm Axel, 2019 – foredune erosion during heavy surge associated with storm Zeetje.

subject to erosion by 6 m, the erosion in the eastern part – with NW waves – amounting up to 12 m (Figs 6 and 7, 2004). The eroded volume of dune and beach sediment exceeded 10 m^3. The following winter (2004/2005) brought no major storms (with H_{SL} > 1 m AMSL). In November 2006, however, a storm (surge Britta) produced a surge with the highest SL thus far, with a 1.48 m AMSL (described by Kettle 2015). The main surge came from NW, resulting in a larger erosion in the eastern part of the spit. In the foredune base, erosion reached 7–8.5 m. The beach erosion was one of the highest recorded in the preceding 20 years, ranging from 14 to 15.8 m^3. The water run-up, up to 3.6 m AMSL, washed away the foredune ridge almost completely (Figs 6–8). The water flooding through the storm gates produced erosion and accumulation of material in the interdune runnel (a washover fan).

Subsequent major surges (associated with storms, the main one among which was named Kyrill) occurred in January 2007, causing further erosion and retreat of the dune base. Between November 2006 and January 2007, there was no chance for the beach or dune to rebuild. Throughout the whole of January 2007, the SL exceeded 0.5 m AMSL. There were three storm surges with SLs of 1.19–1.38 m AMSL. As a result of the highest one, with WNW–NW winds, the water run-up reached 3.2 m. The dune base retreated by 4 m and 9.5 m in the western (kilometre 422) and eastern (kilometre 416) parts of

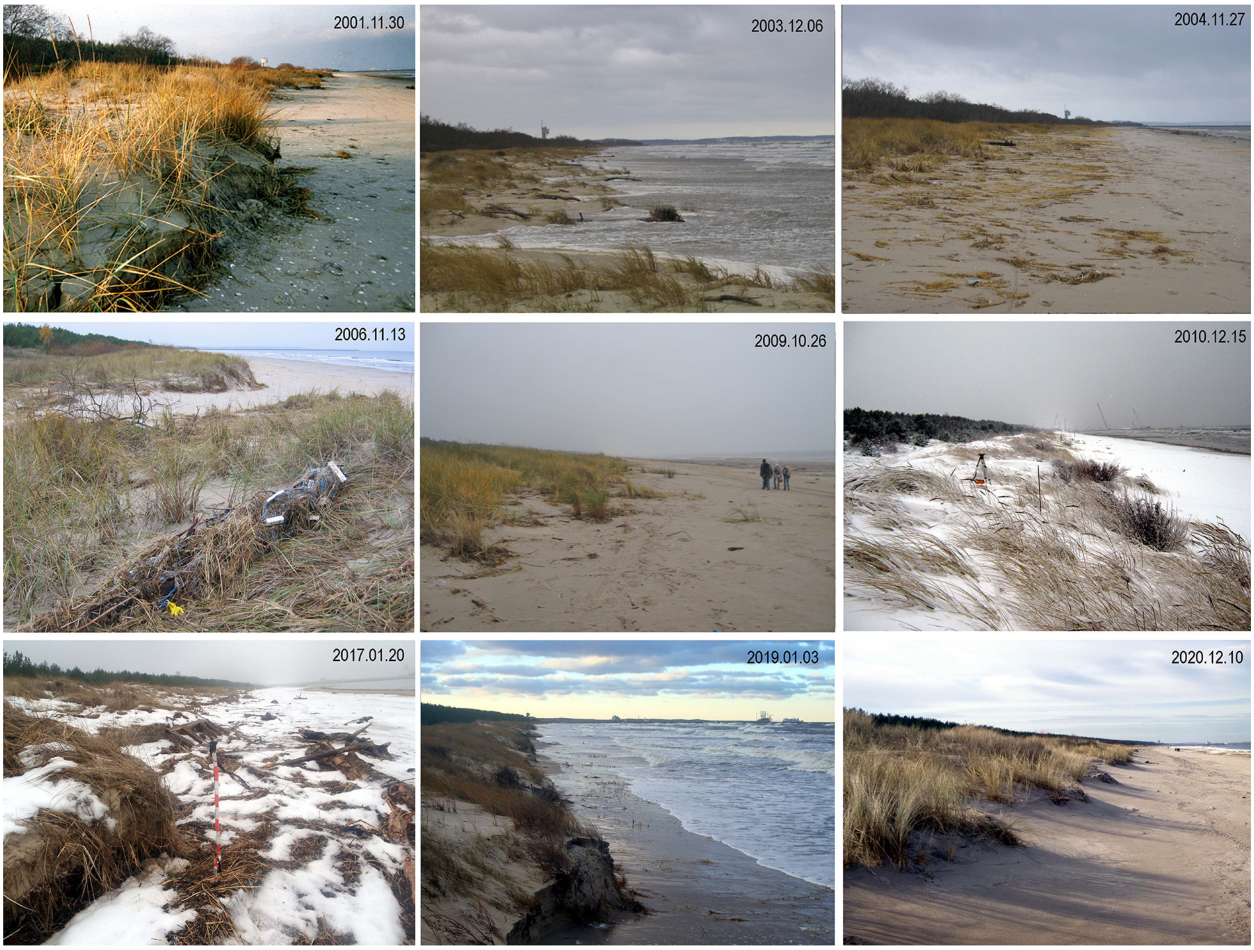

Fig. 7. Photographic documentation of storm surge consequences on the foredune in the western part of Świna Gate Sandbar (kilometre 422).
2001 – dune escarpment and flattened beach after 3 surges associated with storm Janika, 2003 – during surge, water entering low dune abraded in 2002, 2004 – eroded embryo dunes 3 days after surge associated with storm Pia, 2006 – washover fans and storm gates in foredune after surge associated with storm Britta, 2009 – dune protected by high beach, 10 days after heavy surge, 2010 – only lower beach eroded during storm Xynthia, 2017 – organic debris slipped on partly eroded foredune by heavy storm Axel, 2019 – abrasion of foredune during surge associated with storm Zeetje, 2020 – small escarpments just after surge associated with October storm Gisela.

the sandbar, respectively. The beach sediment volume was reduced by 8.9–9.4 m^3. Along the entire length of the sandbar, the foredune was completely eroded in both sections examined, whereas a somewhat less severe erosion was observed in the middle section (kilometre 420). The water flooded the eroded foredune ridge into the interdune space to create new washover fans.

The dune was rebuilt again in mid-2008, but retreated several metres into the interdune runnel. The process of dune ridge retreat and rebuilding higher up on the shore is typical of abrasive shores (e.g. Carter et al. 1990). In the meantime, small storm surges were recorded in March and October 2008; these, however, lowered the beach surface only. By autumn 2009, the sediment volume and dune height had increased. In October 2009, a prolonged and strong surge, elicited by a low-pressure system Wimar, eroded the dunes again. As a result of NNE–NE winds, the SL rose to 1.33 m AMSL and the run-up amounted to 3.2 m AMSL. The SL exceeding 1 m prevailed for 30 h. This was one of the longer storms, and produced a double surge (one surge after another in a short period of time). A shore section with a low beach profile in the eastern part of

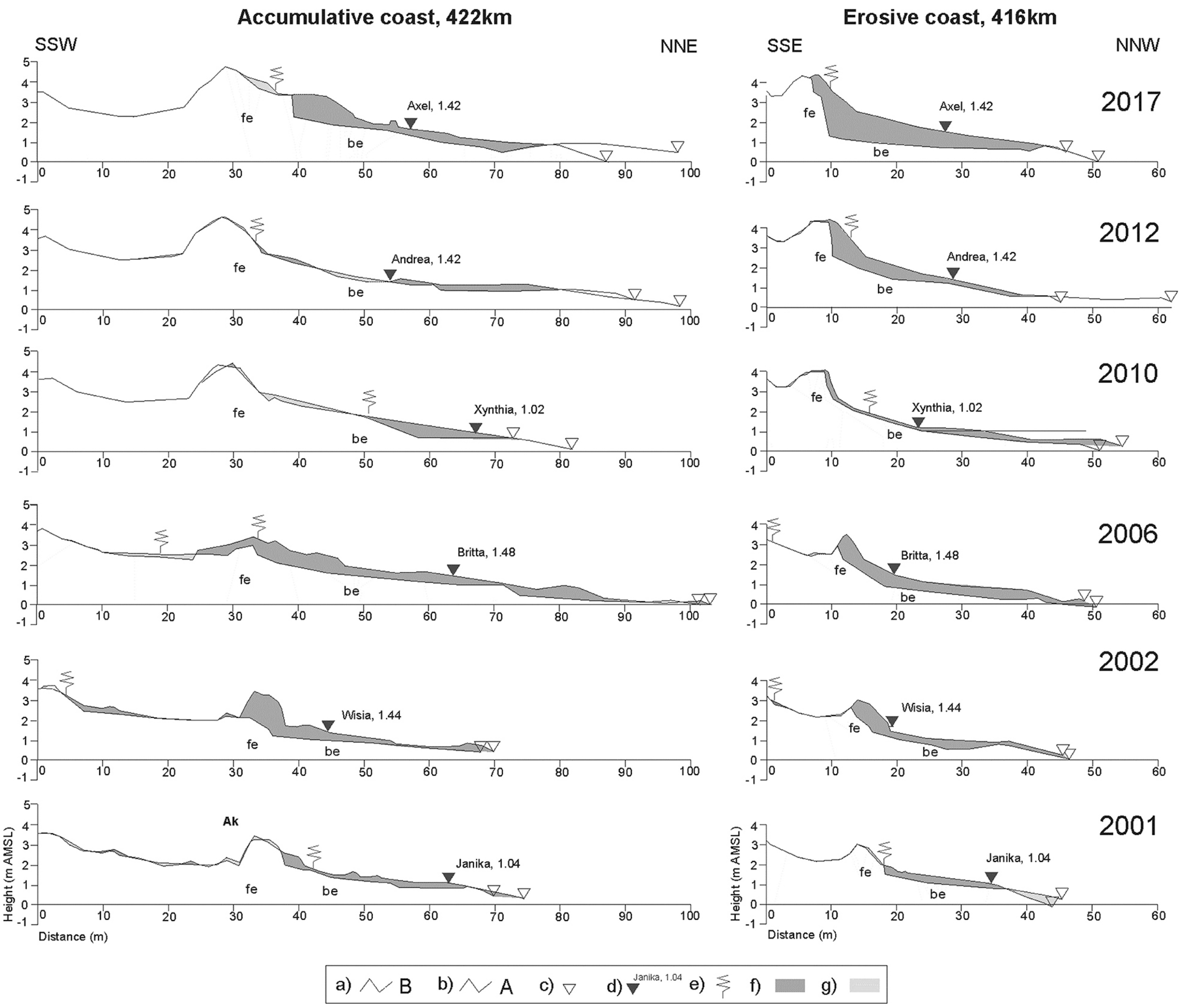

Fig. 8. Examples of shore erosion on accumulative and erosive shore section of Świna Gate Sandbar due to storm surges (substantial sea level and water run-up).
2001 – low sea level and low beach, 2002 – high sea level and low beach, 2006 – high sea level and low beach, 2010 – low sea level and high beach, 2012 – high sea level and high beach, 2017 – high sea level and high beach but heavy surge.
a) relief before surge (B), b) relief after surge (A), c) sea level on profile, d) max. sea level and storm name, e) run-up during surge, f) erosion layer, g) accumulation layer.

the area (kilometre 416) suffered major erosion. The dune in the section with the beach rising to 2.1 m AMSL retreated by 5.3 m, while that in the section where the beach was up to 2.8 m high retreated by as little as 1.5 m (Figs 6, 7). Beach erosion was less severe in the accumulated section (up to 2.3 m^3) and heavier on the eroded section with a lower beach (9.2 m^3). The marine and aeolian accumulation resulted in rebuilding of the beach and the foredune in spring 2010.

The surge in December 2010 (associated with an NNE storm named Xynthia) slightly undercut the lower part of the foredune slope and lowered the beach. The surge heightened the SL to H_{SL} = 1.02 m AMSL (Fig. 10B). The dunes were rebuilt in 2011 and were not eroded during the minor storm Joachim that took place in December 2011. Only the beaches at an SL of 1 m AMSL were lowered.

Two very strong surges in January 2012 (associated with the storms Andrea I and Andrea II) resulted in beach and dune erosion along the whole Polish coast (Łabuz 2014). The storm Andrea I occurred in early January and was followed 6 days later by Andrea II (or Elfriede, according to the Institute of Meteorology of the Free University of Berlin). The maximum SL exceeded 1.4 m AMSL (Fig. 10E). The SL of H_{SL} > 1 m persisted for as long as 39 h. These were the 21st century's two longest storm surge events at the southern coast of the Baltic Sea. The maximum water run-up reached 3.4 m AMSL. The water eroded the dunes where the beaches were lower than 2.5 m AMSL. This explains the large difference between the profiles analysed: there was virtually no dune erosion (as little as 0.3 m) in the accumulative section (kilometre 422), with a beach 3.2 m high, whereas there was a dune erosion of up to 6 m in the section (kilometre 416) with a beach height of 2.8 m AMSL, in the eastern part of the spit (Fig. 6, 2012). The Andrea storm surge was advancing from WSW to N, and thus erosion was more severe in the section exposed to waves from that direction (kilometre 416). The differences were also reflected in the magnitude of beach erosion, whereby up to 3.5 m^3 and 12.6 m^3 of sediment were lost in the western and eastern parts of the spit, respectively. The extent of erosion depended on wave direction and pre-surge beach height. The dunes were gradually rebuilt throughout 2012 and 2013, and embryo dunes 2.5–3.2 m AMSL high were formed in the upper beach.

In December 2013, a strong hurricane named Xavier, with very strong westerly winds, produced a fairly small surge with H_{SL} = 1.04 m AMSL, which flooded the beaches along the entire sandbar. The ensuing erosion was slight in the foredunes, but the embryo dunes in the upper beach were completely destroyed and the beach itself was considerably eroded. As the waves were advancing from W–WNW, the dune with a NW exposure in the eastern part of the sandbar (kilometre 416) was eroded, its base retreating by 4.2 m. Due to very strong (up to 21 $m \cdot s^{-1}$) winds, the surge affected mainly the beaches that had been subject to deflation and then abrasion (erosion of approximately 15–18 $m^3 \cdot m^{-1}$). Large amounts of the sediment from the beach in the western part of the sandbar were blown onto the foredune ridge and into the interdune runnel in the eastern part, enlarging them by the sediment load equivalent to the total annual accumulation.

The dunes were rebuilt in 2014. New embryo forms emerged and the upper beach began to rise again. A minor surge in December 2014 (associated with a storm named Alexandra) of H_{SL} = 0.85 m AMSL caused no dune erosion. The water run-up was 1.8 m AMSL, i.e. 1–1.4 m lower than the foredune base.

Surges associated with two storms in early 2015, Felix in January and Ole in February, eroded the dunes again. The maximum SL was 1.09 m AMSL. The NW waves eroded the eastern stretch of the shore (kilometre 416) and the dune retreated by 2 m.

By October 2016, the dunes and embryonic forms on the beach were rebuilt. The storm Angus in October 2016 and recurrent storms in November and December resulted in surges from different directions, with the SL rising to a maximum of 1.13 m AMSL (Fig. 6, 2016). As a result, the beaches were lowered and the embryo dunes eroded down to 3 m AMSL. As the beaches were lowered, further dune erosion ensued the January 2017 storm event (Axel).

The January 2017 storm surge associated with the Axel turned out to be one of the heaviest surges at the southern Baltic coast since November 1995. With NW to NE waves, it lasted 3 days. The maximum SL at Świnoujście was 1.42 m AMSL and the water run-up amounted to 3.6 m AMSL.

The beaches, even those as high as 3.2–3.4 m, failed to protect the dunes from erosion (Figs 6 and 7, 2017). The prolonged surge (over 36 h with H_{SL} > 0.8 m and 28 h with H_{SL} > 1 m AMSL) resulted in a significant erosion of the dunes in the shore sections analysed. It was the largest erosion in the 21st century, comparable to that caused by the high storm surges of 1983 and 1995 (Sztobryn et al. 2005). The erosion resulted in the dune base retreat by 6–8 m. The high ridge shrank by 12 m^3 and 7 m^3 in the eastern and western parts of the sandbar, respectively. The beach profile was lowered to 1 m AMSL. The beach erosion amounted to 12–16 $m^3 \cdot m^{-1}$ of the shore width. The autumn storms in 2017, with an SL of 1 m AMSL, caused no dune erosion despite the low profile of the beach. From spring 2018 onwards, the beach grew in height, and sand was accumulated at the foredune base along the shore. Similarly, no dune erosion followed the storm surge of October 2018; it was only the beach that was eroded to the height of 1.7 m AMSL.

In January 2019, a storm (named Zeetje) produced a surge with an SL of 1.33 m AMSL. The Zeetje developed in a manner similar to that observed in the previous storm (Axel), from W to NNE. The SL above 1 m was persisting for 15 h. The Zeetje-associated surge resulted in another erosion of the dune slopes that were in the process of rebuilding after the January 2017 storm. The dune base was eroded down to 1–4 m (Figs 6 and 7, 2019). The beaches were significantly eroded as well, with 8.5–15 m^3 sand being removed per metre of the shore width. The foredune slope in both sections (and along the entire sandbar) was being rebuilt throughout 2019 and 2020, the dune rebuilding process continuing without disturbance by numerous minor storm surges from January to late March 2020, with SLs usually up to 0.8 m AMSL (four with $H_{SL} \geq 0.8$ m). As larger surges were absent, embryo dunes could form on the beaches from May to September 2020. These were, however, eroded by the storm surge in October 2020 (Fig. 7, 2020). With NE wind and waves, the SL reached 1.1 m AMSL (H_{SL} > 1 m persisted for 11 h). In February 2021, the beaches in the shore section analysed were devoid of embryo dunes. In numerous places, the foredunes were still undercut by the October 2020 surge. They began rebuilding in April 2021.

Worth mentioning are 23 minor storm surges that occurred in autumn-winter 2021/2022 along the southern Baltic coast, including 9 with $H_{SL} \geq 0.8$ m at Świnoujście. It was the highest number of surges recorded so far, comparable to the 18 that took place in 2019/2020. The two most severe storms in late January 2022, Marie and Nadine, produced surges with an SLr as low as 0.99 m AMSL (including short surge Ida with H_{SL} > 1 m for 3 h in mid-January). The surges mentioned resulted in beach lowering only, but this effect is not covered in the present study.

Sea level, wind and water run-up

A storm surge in the part of the Baltic Sea coast examined here is regarded as major when the water level is higher than 0.8 m AMSL (after Zeidler et al. 1995, Sztobryn et al. 2005, Wolski et al. 2014). In the period covered by this study (2000–2020), there were 62 such surges, including 11 surges with H_{SL} > 1.2 m AMSL and 5 surges with H_{SL} > 1.4 m AMSL. The detailed analysis in this study concerned only the maximum surges in each year (Table 1, Fig. 5). The wind velocity (V_w, $m \cdot s^{-1}$) and direction (Az_w, 0^0–350^0) as well as the sea level (H_{SL}) during the storm surges analysed and the resulting water run-up (H_{SLr}) were subjected to a correlation analysis. The maximum wind velocity was fairly weakly correlated with the highest SL ($r = 0.29$) and the duration of a level higher than 1 m ($r = 0.31$). However, a higher wind velocity produced stronger waves that resulted in a higher water run-up ($r = 0.49$). During larger storm surges and at wind velocity above 15 $m \cdot s^{-1}$, the waves can reach 3–4 m.

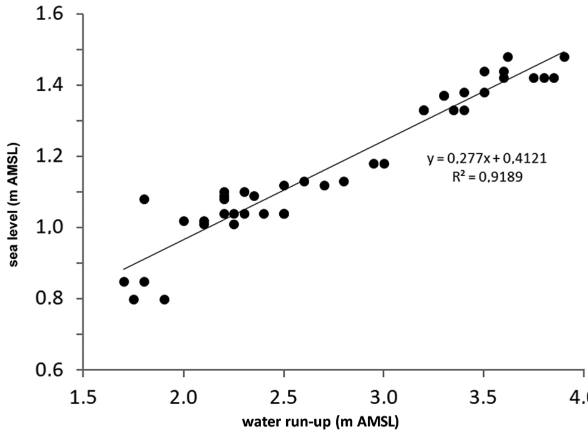

Fig. 9. Relationship between water run-up and the max. sea level on Świna Gate Sandbar.

A significant correlation (r = 0.92) was observed between the maximum SL during a storm and the water run-up (Fig. 9). During surges with H_{SL} = 0.8 m AMSL, the ascent of water onto the beach reached 1.6–1.8 m AMSL. With the SL up to 1 m, the usual wind speed of 15 m · s^{-1} generates, according to the Beaufort scale, waves up to 3 m high. The run-up of a subsiding wave at an SL of 1 m AMSL reaches 2–2.5 m AMSL. In the period analysed, such storm surges occurred at the Świna Gate sandbar at least once a year. The water run-up at H_{SL} = 1.2 m AMSL was up to 2.8 m AMSL. The largest surges observed, with $H_{SL>}$1.3 m AMSL, resulted in a run-up (SLr) of up to 3.8 m AMSL. These effects were recorded eight times, on average every 2 years (2002, 2004, 2006, 2007, 2009, 2012, 2017 and 2019). The shore-eroding surges analysed showed an average H_{SL} of 1.2 m AMSL, the maximum H_{SL} reaching 1.48 m AMSL (during the storm Britta in 2006). However, the SL at the gauging site (the Świnoujście harbour) is not necessarily identical with that at the sandbar section examined. Therefore, generally, the run-up is more important than the SL for assessing the extent of storm-surge-caused dune erosion. During each maximum surge, the run-up was up to 3.2–3.8 m AMSL, as could be inferred from the location of organic matter layer in the sediment as well as from a direct observation of the surge itself.

Storm surge duration and recurrence

The maximum SL during a storm and duration of H_{SL} > 1 m AMSL were strongly and significantly correlated (r = 0.87). During smaller and shorter surges, the duration was in the range of 2–5 h. With H_{SL} = 1.2 m, the duration of H_{SL} > 1 m AMSL averaged 10 h. During the period analysed, there were six storm surges with H_{SL} > 1 m AMSL lasting more than 15 h (with a maximum of 27–32 h). Typically, such surges were produced by storms lasting 2–3 days and resulted in the heaviest beach and dune erosion (2004, 2006, 2007, 2009, 2012 and 2017). Some surges were long-lasting (2004, 2006 and 2017), some were double (e.g. 2009 and 2012) and others were alternating (2007 and 2016). The period analysed also witnessed surges with lower SLs, which eroded the beach only (2001, 2011, 2015 and 2020). The longer the duration of a high-level surge (or the higher the number of their occurrences in a given period), the more extensive was the beach (ΔQ_{be}) and dune (ΔQ_{fr}) erosion (2006/2007, 2009, 2011/2012, 2016/2017). In November 2006 and January 2007, there were four surges with H_{SL} > 1 m AMSL. The high SLs persisted from November 2006 through the end of January 2007. These surges, owing to their occurring in a sequence, resulted in a more extensive erosion than that produced by a single large storm. As a result, the dunes retreated further inland and were rebuilt at a higher altitude (Fig. 2).

A single larger surge was capable of removing more than 10–12 m^3 of sediment from the beach. The erosion was weaker, 6–10 m^3, during shorter surges, even at a high SL (e.g. in January 2002, October 2020). One or several surges with a lower SL, H_{SL} < 1 m AMSL, could erode away 5–8 m^3 of the beach sediment. The recurrence of lower surges (January–February 2020 or November 2001) posed a weaker threat for the shore. There was no strong relationship (r = 0.24) between the number of surges and the beach erosion observed. The

Table 3. Average dune-beach parameters after surges with different water height on Świna Gate Sandbar.

Sea level	Time length with H > 1 m	Run-up	Accumulative coast, the western part				Erosive coast, the eastern part			
			Beach erosion volume	Dune foot retreat	Dune erosion volume	Dune erosion volume	Beach erosion volume	Dune foot retreat	Dune erosion volume	Dune erosion volume
HSL	TSL	HSLr	ΔQbe	ΔPe	ΔQfr	ΔQbe	ΔQbe	ΔPfe	ΔQfr	ΔQbe
[m AMSL]	[h]	[m AMSL]	[m^3]	[m]	[m^3]	[m^3/m^2]	[m^3]	[m]	[m^3]	[m^3/m^2]
Average surge H = 1.2	10	2.8	7.0	2.0	2.0	0.3	8.5	3.1	3.8	0.7
H > 0.8	0	1.6	2.6	0.0	0.0	0.0	2.2	0.3	0.1	0.2
H > 1.0	3	2.2	4.3	0.6	0.4	0.2	4.5	0.7	0.5	0.5
H > 1.3	20	3.3	7.5	4.9	4.0	0.7	11.2	6.6	5.4	1.3
H > 1.4	24	3.6	12.1	5.2	5.5	0.8	14.6	7.0	10.0	1.6

extent of erosion depends on a combination of factors: the SL and run-up, storm duration, wind effect and wave propagation angle with respect to the shore. The duration of storm surges with H_{SL} > 1 m AMSL was found to be strongly associated with the extent of shore erosion (r = 0.66 for the decrease in the beach volume, r = 0.71 for the decrease in the dune volume, ΔQ_{be}; the correlation coefficients are averages for the two shore sections examined). The longer the duration of a surge with H_{SL} > 1 m AMSL, the more extensive was the beach and dune erosion. Moreover, the higher the SL, the more extensive was the erosion of the beach and dune (Table 3).

The rate of erosion could be also related to the time during which the SL was rising to its maximum. A more rapid rise in the SL results in a more extensive erosion, as observed during the storm Axel in January 2017. The SLr to 1.4 m AMSL observed then was the fastest in the 21st century. The analysis of surge duration and the SL as well as their recurrences allowed the distinguishing of several types with respect to the shore erosion (Fig. 10):

- a very low surge (H_{SL} > 0.5 m AMSL) eroding the lower beach only,
- a low surge (H_{SL} > 0.8 m AMSL) or several surges of varying durations resulting in erosion of the beach (or its part) only,
- a medium-sized surge (H_{SL} > 1.0 m AMSL) eroding the beach but not the foredune (Fig. 10A),
- a medium-sized, but long-duration (sometimes double) surge (0.8 < H_{SL} < 1.0 m AMSL) eroding the beach and dune on a low beach shore (Fig. 10B),
- a high (H_{SL} > 1.0 m AMSL) but short-duration surge eroding the beach only (Fig. 10C),
- a high (H_{SL} > 1.0 m AMSL) and long-lasting surge eroding the foredune,
- a very high (H_{SL} > 1.2 m AMSL) but short-duration surge eroding the entire shore in a short time (Fig. 10D),
- a sequence of surges of various SLs (H_{SL} > 1.2–1.4 m AMSL), with at least one high-level one, heavily eroding the foredunes (Fig. 10E).

Directions of main wind and wave advance onto the shore

As already mentioned, the study involved surveying two opposite types of beach, one with

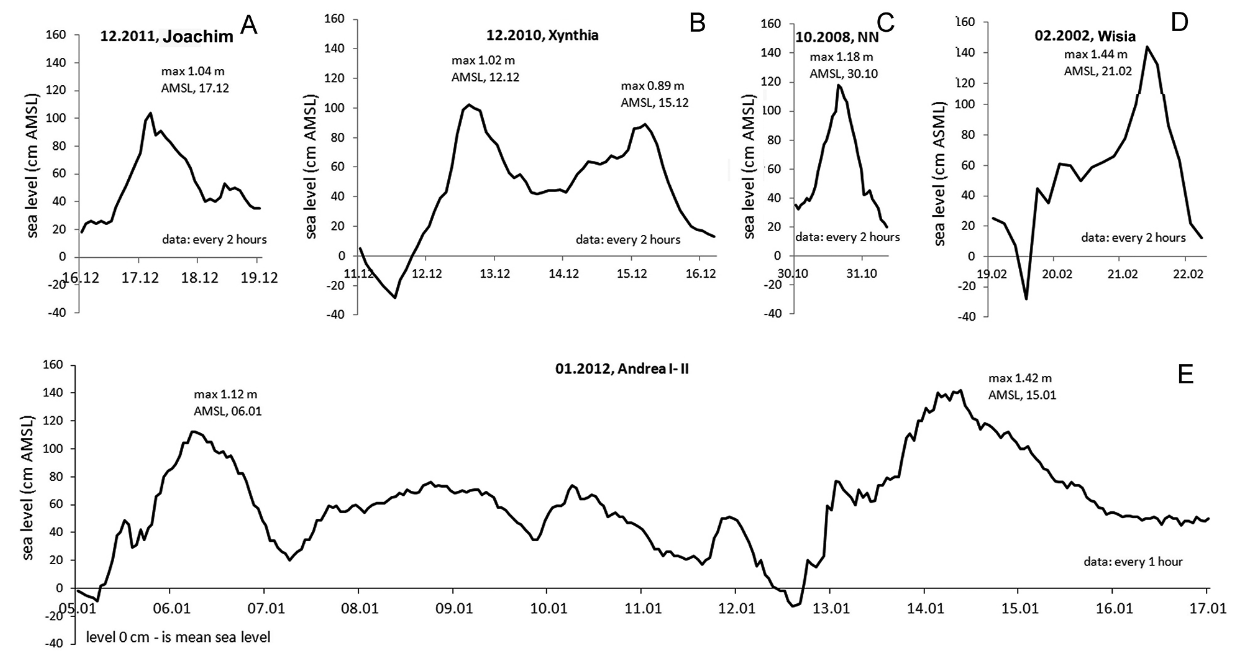

Fig. 10. Different storm surges with H_{SL} > 1m and sea-level changes (author's own graphs based on data from Świnoujście Maritime Office).

A – medium, single and long, no dune erosion, December 2011, storm Joachim, B – medium, double and long, no dune erosion, December 2010, storm Xynthia, C – high, single and short, no dune erosion, October 2008, D – very high, single and long, with large dune erosion, February 2002, storm Wisia, E – sequence of surges, with two high ones producing large dune erosion, January 2012, storm Andrea.

a NW and the other with a NE exposure. Based on previous measurements, it was assumed that a shoreline perpendicular to the incoming wind and wave would be more eroded. This was usually the case. However, due to the changing wave direction resulting from the change in wind direction, the correlation was not very strong. No significant correlation (r = −0.22 to 0.37) was found between the wind-wave direction and the extent of erosion. A greater correlation (r = 0.23–0.59) was observed with respect to the erosion extent, as against the wind and waves varying between NW and NE. The dune was eroded by waves hitting the shore at an angle, after the beach had been lowered. Erosion on the two opposite shore sections was mostly observed when the wave direction was perpendicular to the shore.

Impact of storm surges on beaches

Comparison of the beach morphology before and after a storm surge showed the beach to have been levelled off after the storm (Fig. 11A). The beach on both the accumulative and erosive sections was levelled by an average of 0.6–1.8 m. All the concave (beach lagoons) and convex (coastal banks, embryo dunes in the upper beach) forms were destroyed. Figure 12 illustrates the relationship between the change in beach parameters versus the SL and run-up. The correlations proved to be strong and significant (r = 0.66 for H_{SL} vs. ΔQ_{be}; r = 0.70 for H_{SLr} vs. ΔQ_{be}; the correlation coefficients shown are averages) (Tables 2 and 3). During storm surges with a lower SL, only the lower part of the beach was eroded, the erosion not exceeding 4 m^3 (Tables 3 and 4). The erosion affected the entire beach as well as the dune base where the beach was lower due to, for example, previous storm surges. During surges with H_{SL} < 1 m AMSL, the beach was lowered down to 1–1.3 m AMSL. The amount of the beach sediment removed then (ΔQ_{be}) reached 5–10 m^3 (Fig. 11C). During the heaviest storms with H_{SL} > 1.3 m AMSL, the water run-up was 3.6 m, the entire beach up to the foredune base being eroded. Such single surges resulted in a considerable removal of the beach sediment, 10–15 m^3 (ΔQ_{be}). The beach sand removal (ΔQ_{be}) was strongly and significantly correlated with the maximum SL (H_{SL}) and the run-up (H_{SLr}) (an average r = 0.66 for H_{SL} vs. ΔQ_{be}; r = 0.70 for H_{SLr} vs. ΔQ_{be} 0.70) (Fig. 12). A weaker erosion is observed on the accumulative part with a wider beach (r = 0.55 for H_{SL} vs. ΔQ_{be}), the erosive part showing a stronger sediment removal (r = 0.79 for H_{SL} vs. ΔQ_{be}). Although the beach width was observed to generally increase after surges, the beach width changes (ΔW_{be}) has a weak relationship (r = 0.01 to 0.10) with storm and surge parameters. The beach width was almost identical (r = 0.85) before (W_{be} B) and after (W_{be} A) the surge (Fig. 11B, C). After a few storms, the

Table 4. Dune-beach relief parameters change on accumulative and erosive shore after storm surges on Świna Gate Sandbar.

Shore profile type	Beach width	Beach height	Beach width change	Beach height change	Beach erosion	Beach erosion	Dune foot retreat	Dune erosion volume	Dune erosion volume
	Wbe B	Hbe B	ΔWbe	ΔHbe	ΔQbe	ΔQbe	ΔPfe	ΔQfr	ΔQbe
	[m]				[m^3]	[m^3 m^{-2}]	[m]	[m^3]	[m^3 m^{-2}]
Average: erosive, 416km	35.6	2.6	−1	−1.2	8.9	0.3	3.3	4.0	0.8
Average: accumulative, 422km	54.8	2.9	0	−1.3	7.4	0.1	2.2	2.1	0.3
Max.: erosive, 416km	23–45	1.7–3.0	−11 to 10	−1.8	16.6	0.6	9.5	12.3	2.0
Max.: accumulative, 422km	33–74	2.0–3.5	−15 to 14	−2.3	18.7	0.3	12.0	12.5	1.4

beach width was narrower by up to 9 m, whereas other storms resulted in the beach being wider by up to 8 m. Such small changes are typical of the Świna Gate Sandbar where the beach is usually wider and higher than in other sections of the Polish coast. When the SL decreases gradually, the water removes more sediment from the dune to form a new beach after the storm. The beach formed that way is wider, often with a deep lagoon and an extensive coastal bank, previously an underwater bar formed by near-shore currents.

The beach slope profile and the beach width after a storm are shaped by the rate at which the waves subside (the run-up). In addition, the post-storm beach width depends on the SL at which the beach width and slope were measured. It was 0.3 m to −0.2 m either above or below the mean, which influenced the measurement. For this reason, the post-storm beach width, especially in typical accumulative sections, is not a reliable indicator of shore erosion. It is usually related to the post-storm SL, and the height of the beach in its upper part is more important.

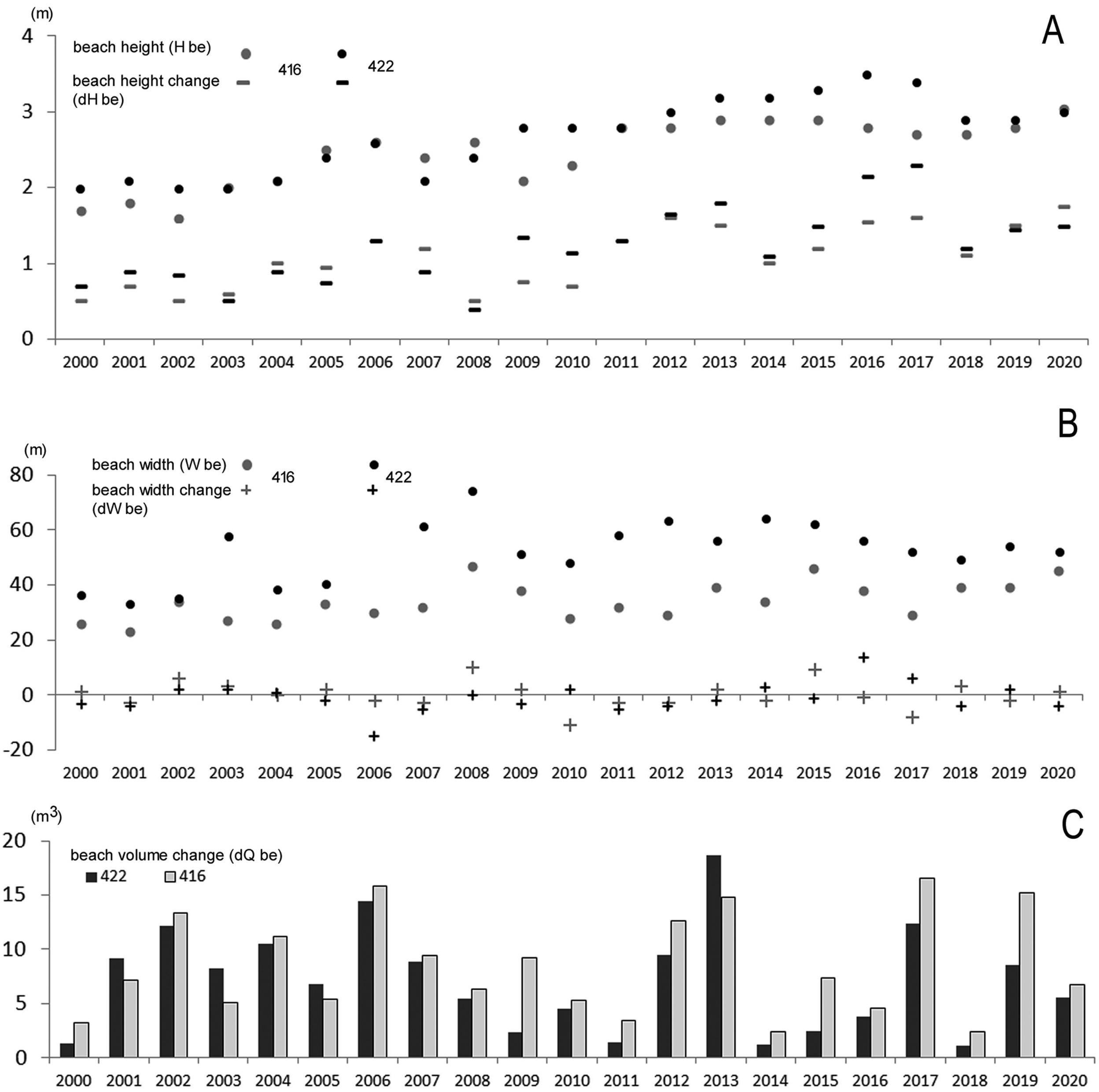

Fig. 11. Changes in beach characteristics after the heaviest surges (km 416 and 422).
A – pre-surge beach height (H_{be}) vs its post-surge change (ΔH_{be}), B – pre-surge beach width (W_{be}) vs its post-surge change (ΔW_{be}), C – the total volume of post-surge beach erosion (ΔQ_{be}).

When a storm was subsiding rapidly, i.e. there was a rapid decline in the wave height and SL, the beach was usually low, flat and slightly inclined. At a strong wave action, the water would wash away larger amounts of sediment from under the dune. The rapid sediment removal from the beach resulted in a significant decline of the beach height in its upper part. Then, after the storm, the beach height would not exceed 1 m AMSL, and the beach would be narrow and steeply inclined towards the sea. Also, the foredunes showed the formation of the highest abrasive slopes.

After the heaviest storms, the beach was widened seaward because of a large amount of sediment from the eroded dunes that was deposited to form a flat surface covered with ripplemarks, resembling a tidal plain. At a low SL, this post-storm plain was 10–30 m wide. Its formation on the shore was a result of long-term beach submergence during heavy storm surges and the post-storm recovery (as observed in 2002, 2007, 2012 and 2017). During a storm with a very high SL, the beach became shallow near the shore where ripplemarks and an underwater shoal were formed. After the storm, the shoal turned into a coastal bank. The sediment eroded from the dunes was accumulated at their foot and filled in any irregularity of the beach surface. Convex forms (embryo dunes) were eroded and depressions were filled with the sediment to form an even beach surface, inclined seaward. The beach width and height depended on the rate of the sea-level decline. A poststorm plain was formed where a large amount of sediment from the eroded dunes was deposited in the breaking wave zone during the rapid wave retreat and SL drop. This resulted in sediment accumulation, which translated into an increase of the beach width and the formation of a post-storm plain covered by wave ripplemarks. When the SL was rising again, the plain would be flooded, with a part of the beach being eroded and rebuilt. Table 3 shows the average and maximum values of beach erosion during surges with selected SLs in the accumulative and erosive shore section, while changes in beach parameters due to the storm surge-related erosion are detailed in Table 4.

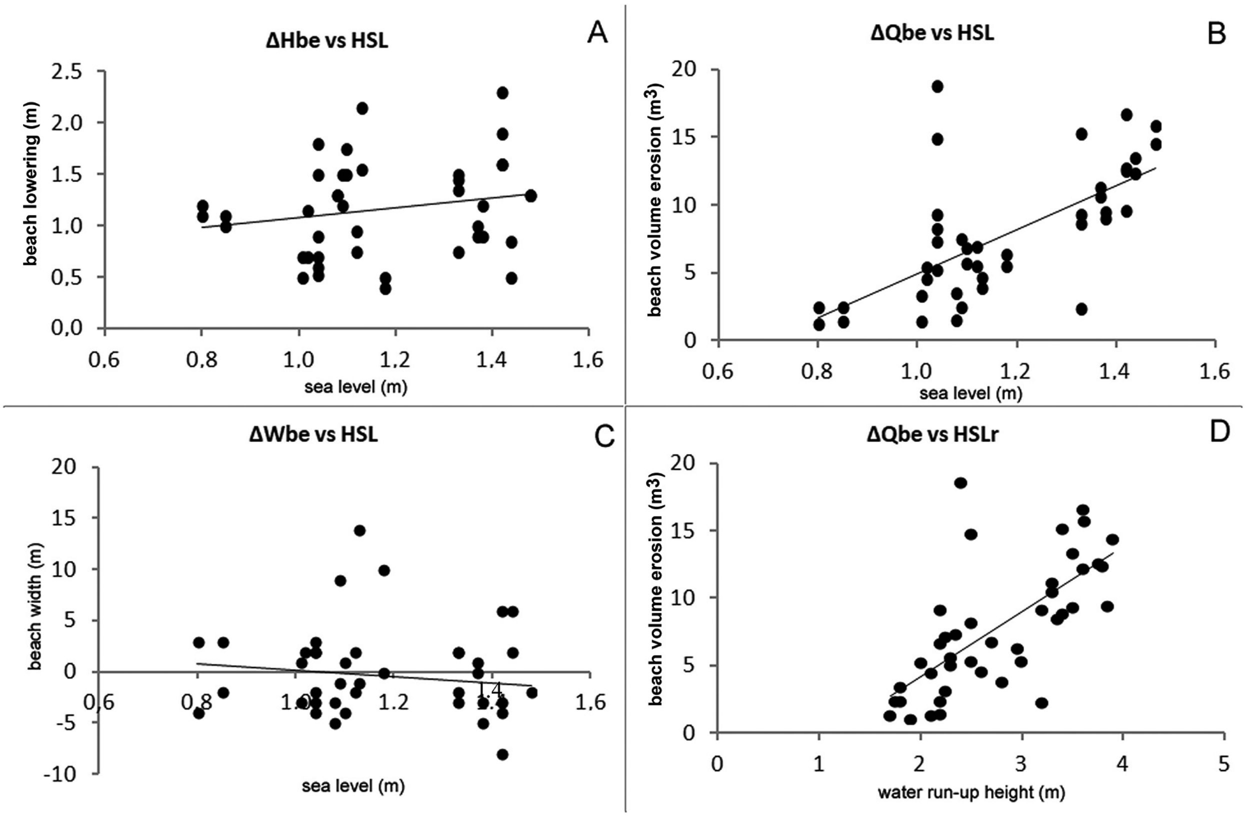

Fig. 12. Relationships between beach characteristics and surge level.
A – lowering of beach height (ΔH_{be}) vs sea level (H_{SL}), B – abrasion of beach in cubic meters (ΔQ_{be}) vs sea level (H_{SL}), C – width change (ΔW_{be}) vs sea level (H_{SL}), D – abrasion of beach in cubic meters (ΔQ_{be}) vs water run-up (H_{SLr}).

Storm surge impact on dunes

Figure 13 illustrates changes in dune parameters: dune retreat (Fig. 13A), sand volume removed (Fig. 13B) and erosion per square metre (Fig. 13C), over 21 years in a selected accumulative (kilometre 422) and erosive (kilometre 416) shore profile. Correlations between the magnitude of dune erosion, the retreat of dune foot (ΔP_{fr}) or crest (ΔK_{fr}) and the change in the volume of dune-building sediment (ΔQ_{fr}) on the one hand, and the SL (H_{SL}), storm surge duration, including duration of surges with H_{SL} > 1 m (T_{SL}), and the run-up (H_{SLr}) on the other, were explored (Tables 2 and 3; Fig. 14). The foredune retreat increased with the SLr (Fig. 14A). The largest removal of dune sediment occurred in both shore sections after the strongest surges in 2002, 2004, 2006 and 2007. In 2002 and 2004, a heavier erosion was related to the still insignificant beach height. The higher the beach prior to the surge (H_{be} B), the less likely dune erosion (ΔQ_{fr}, ΔP_{fr}) was to occur. This the reason why dune erosion in recent years, even during strong surges (2012, 2017, 2019), was weaker on accumulative shores. November 2006 and January 2007 saw some of the strongest storm surges with a maximum sea-level rise of almost 1.5 m AMSL. They resulted in a complete erosion of the foredune along the sandbar. For several days in January 2007, the sea water flowed through the foredune ridge that had been eroded and lowered earlier, in November 2006. Through

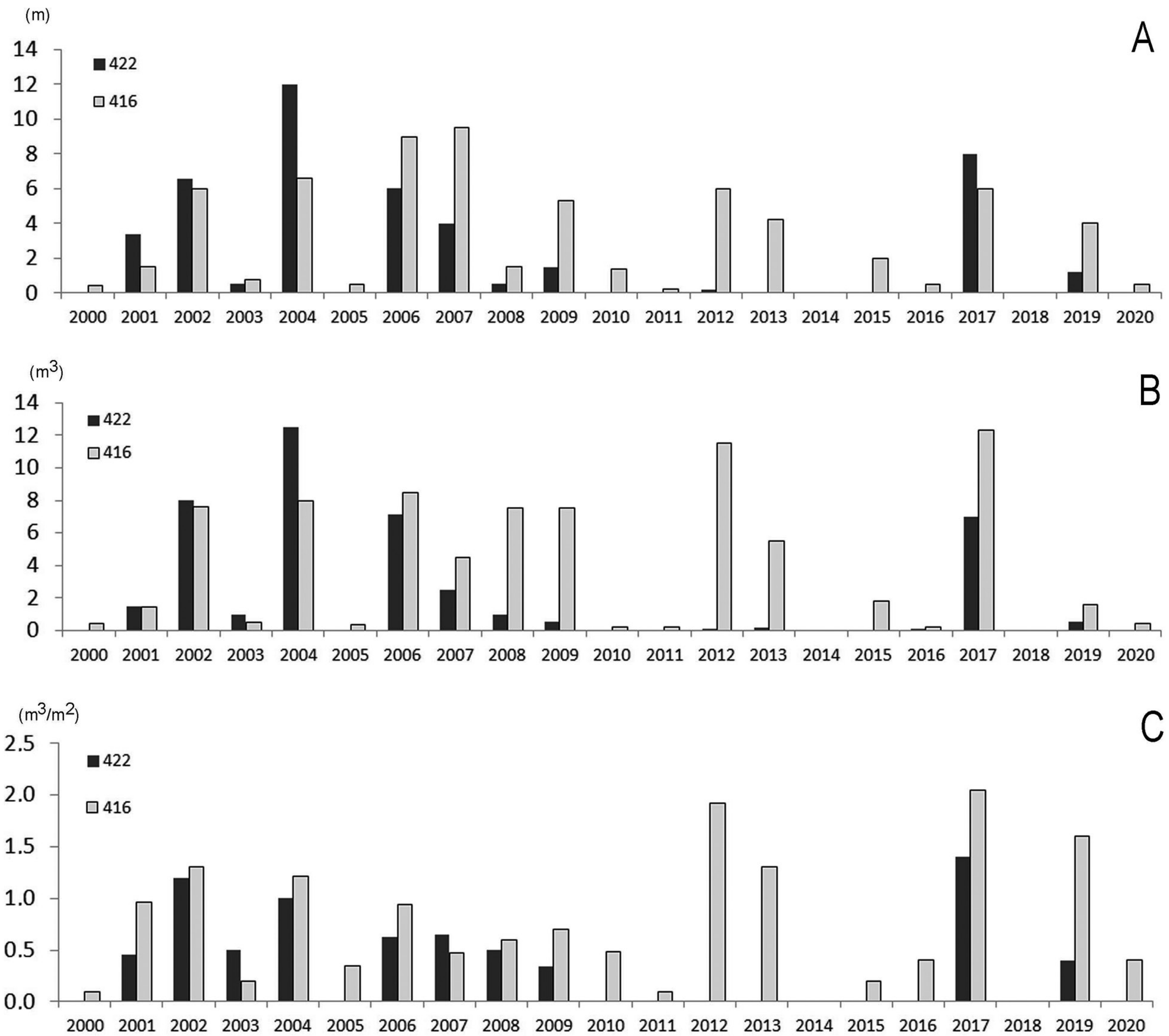

Fig. 13. Changes in foredune characteristics after the heaviest surges.
A – foredune retreat (ΔP_{fr}), B – foredune erosion in cubic meters (ΔQ_{fr}), C – foredune erosion per 1 squre meter ($\Delta Q_{fr/1m^2}$).

the wide storm gates, the water approached the older dune ridge, eroding the stabilised base of the interdune runnel. Washover fans were formed where the sediment was deposited in the runnel. Dune erosion was observed again on the accumulative shore during a long surge with a high water level (associated with the storm Axel in January 2017).

When an autumn–winter season witnessed only one surge event, the dunes were quickly reconstructed. This was also the case after a storm with a higher SL. When there were several surges during the storm season, dune erosion was larger (2001/2002, 2006/2007, 2016/2017). It took approximately 2 years for the dunes to be rebuilt. After a succession of strong surges occurring during a short period of time, the foredune was destroyed almost completely and was rebuilt deeper in the runnel, at a higher elevation (2002/2003 and 2007/2008). This exemplifies a foredune ridge retreat as a result of intense erosion, which was described by Carter et al. (1990). The intensely eroded or completely destroyed dune was rebuilt in the interdune runnel, which

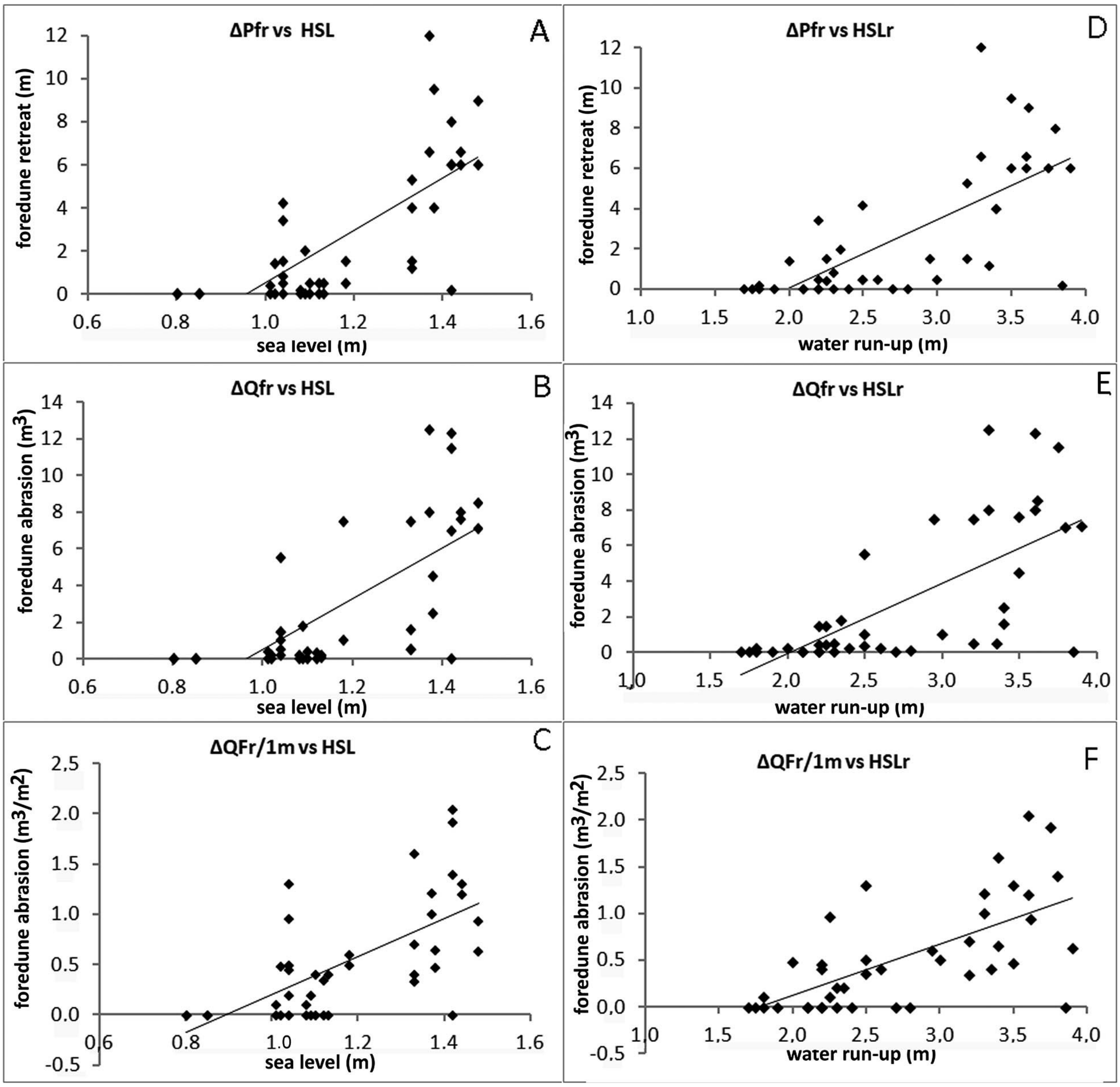

Fig. 14. Relationships between foredune characteristics and surge level.
A – foredune retreat (ΔP_{fe}) vs sea level (H_{SL}), B – foredune volume change (ΔQ_{fe}) vs sea level (H_{SL}), C – foredune volume change per each meter ($\Delta Q_{fe/1m}$) vs sea level (H_{SL}), D – foredune retreat (ΔP_{fe}) vs water run-up (H_{SLr}), E – foredune volume change (ΔQ_{fe}) vs sea level (H_{SLr}), F – foredune volume change per each meter ($\Delta Q_{fe/1m}$) vs sea level (H_{SLr}).

may happen only on the accumulative section of the shore.

The dune sediment removal (ΔQ_{fr}) was primarily correlated with the dune heights (H_{fr}). The higher the eroded dune, the greater its negative sediment budget. The retreat of the dune base (ΔP_{fr}) and a change in dune volume per square metre ($\Delta Q_{fr} \cdot m^{-2}$) proved to be more important indicators of dune erosion; they were correlated with the beach height before the storm (r = 0.53 for $H_{be}B$ vs. $\Delta Q_{fr} \cdot m^{-2}$). It may be assumed that dunes on the southern Baltic shores featuring beaches higher than 3 m AMSL would be protected from erosion during typical storm surges. Such a correlation was evident when changes in the dune volume along the sandbar, caused by the same event, were compared. The beach height is a more important obstacle to erosion on the accumulative shore (r = 0.48 for $H_{be}B$ vs. $\Delta P_{fr,}$) than in the erosive part (r = 0.62 for $H_{be}B$ vs. ΔP_{fr}), where, during an average surge, the beach is mostly flooded. Where the beaches are still at least 3 m high as a result of aeolian accumulation (kilometre 420–421), the dunes are not eroded during a surge (except the heaviest events with a run-up H_{SLr} > 3.8 m AMSL). Embryo dunes are formed most often in such places. Their growth in height is accelerated by vegetation (growing out from root remnants left by the previous surge). Hills 3–3.5 m AMSL high are formed and protect the foredune from abrasion. During a major storm surge in January 2012 (associated with the storm Andrea), the dune in the accumulative shore section was protected from erosion by the beach with a height equal to the maximum water run-up (H_{SLr} = 3.5 m AMSL). Where the upper beach was lower than 2.5 m AMSL, the foredune ridge was eroded by most surges with H_{SL} > 1.2 m AMSL. On lower beaches, the surge water reached the dune slope faster, and thus it took longer for erosion to occur.

The dune retreat rate was also influenced by vegetation which stabilises the ground (this was observed during a surge, but not measured). At densely vegetated sites, plant roots inhibited erosion and thus the ridge retreat, whereas at other places, the ridge was washed away faster and to a greater extent. Sparsely vegetated dunes were prone to the formation of storm gates facilitating water advance into the interdune runnel. This effect was also observed, but not measured.

After the surge, loose sediment continues to be gravitationally removed from the disturbed dune slope. The so-called tension cracks are then formed, leading to the detachment of whole sediment lumps from the slope. Landslides on the slope decrease the sediment volume of the dune and increase the sediment volume of the beach. Table 3 presents average and maximum values of dune erosion during surges with various SLs in the accumulative and erosive sections of the shore. Table 4 shows changes in dune parameters after storm-surge-caused erosion.

Each storm surge in the area of study is triggered by strong (about 15–20 $m \cdot s^{-1}$) winds. Before the water starts flooding the beach, the sediment is blown away from it. Storms with winds advancing at an angle or perpendicularly to the shore blow the sediment off the beach onto the dune ridge and behind it. After each such surge, aeolian sediment accumulation can raise the dune and the runnel by up to 10 cm and 5–6 cm, respectively. This is important from the standpoint of dune formation dynamics. As a result, although the dune base is undercut by the incoming waves, the sediment budget on the dune crest can be positive. Accumulation on the foredune ridge was observed after the storms of 2003, 2004, 2009 and 2012 (mainly on the accumulative shore represented by the profile on kilometre 422). The largest accumulation occurring in a short period of time was observed during the storm Xavier of December 2013, with a wind velocity of up to 18–24 $m \cdot s^{-1}$. Such a westerly wind blowing along the shore produced sediment aeolian accumulation of 20–25 cm on the foredune in the eastern part of the area (kilometre 416). Usually, the accumulation is not higher than 10 cm on the dune top. Aeolian accumulation during (or just before) surges in the western part was larger because the source beach, from which the sand was blown away just before flooding, was wider. The accumulated fresh sand layer was more than 0.1–0.15 cm thick on the dune and behind it, which amounts to an average 0.4 m^3 of sand (maximum of 1.2 m^3). Accumulation occurs only before the surge and during low surges. In the latter case, aeolian deposition is observed on the windward slope. The stronger the wind, the higher the likelihood of accumulation on the lee slope. The correlation between the wind velocity (or direction) and the aeolian accumulation during surges proved to be weak (*r* = 0.14–0.36). Accumulation between grass shoots was accidental only and hardly visible on the profiles. In addition, some of the accumulated sediment was eroded by storms, and therefore such data are neither presented nor illustrated.

Discussion

The strongest storms along the Baltic coast are caused by spatially varying atmospheric pressure at the sea surface and by strong onshore wind (Zeidler et al. 1995, Sztobryn et al. 2005, Dailidienė et al. 2006, Eberhards et al. 2006, Fink et al. 2009, Hünicke 2010, Łabuz, Kowalewska-Kalkowska 2011, Stont et al. 2012, Jaagus, Suursaar 2013, Tõnisson et al. 2013, Kettle 2015, Jarmalavicius et al. 2016, Wolski, Wiśniewski 2020). The surge level is one of the most important variables in dune erosion (Van de Graaff 1986). At the southern Baltic coast, the SL during a storm may rise up to 1.5 m AMSL (Zeidler et al. 1995, Cyberski, Wróblewski 1999, Sztobryn et al. 2005, Wolski et al. 2014). In the last 21 years, the highest surges on the Świna Gate Sandbar exceeded 1.4 m AMSL four times (2002, 2006, 2012, 2017), surges with H_{SL} > 1.3 m AMSL occurring four times as well (2004, 2007, 2009, 2019). Wolski et al. (2014) determined that surges with such a water level would be recorded in Świnoujście every 6–10 years. However, during the period covered by this study (2000–2021), such surges were observed almost every other year or even each year (Table 1; Fig. 5A), i.e. a frequency higher than that found for the period 1960–2010 (Wolski, Wiśniewski 2020).

In recent years, similar extreme SLs have been reported from other Baltic countries (Dailidienė et al. 2006, Eberhards et al. 2006, Gräwe, Burchard 2012, Jaagus, Suursaar 2013, Jarmalavicius et al. 2016, Wolski, Wiśniewski 2020). On the Lithuanian coast, the maximum SL during surges is in the range of 1.4–1.5 m AMSL (Dailidienė et al. 2006), the ranges reported from the German Baltic coast and Latvia being 1.3–1.6 m (Sztobryn et al. 2005, Gräwe, Burchard 2012, Richter et al. 2012) and 1.4–1.6 m (Eberhards et al. 2009), respectively. However, the present study allows the conclusion that dune erosion was better correlated with the water run-up than with the SL (Table 2).

The observed frequency and intensity of shore erosion in the area of study was strongly associated with the autumn-winter storminess as well as with the high water level duration and the SL during the strongest surges. Lower surges, with the SL of 0.8 m AMSL, penetrated the shore up to an average height of 1.6 m, whereas a surge with the SL of 1 m AMSL produced a run-up of 2.2 m AMSL. Dune erosion was mainly observed during surges with H_{SL} > 1.2 m when the run-up exceeded the usual beach height (2.5 m AMSL). The wave height cannot play a direct role in erosion rate, the run-up being more important. During surges with H_{SL} > 1.4 m AMSL, the run-up exceeded, on the average, 3.6 m AMSL. All the relief forms below that level were abraded and the dune ridges in the beach hinterland were regressing. For this reason, the dune foot retreat was related also to the beach height: the lower the beach, the larger the dune erosion.

The extent of the shore erosion and coastal retreat depends on both the sea surge height and duration (Van de Graaff 1977, 1986, Suursaar et al. 2003, Tõnisson et al. 2006). This study showed a strong correlation (*r* = 0.74) between the storm surge height (H_{SL}) and the dune retreat rate (ΔP_{fr}). A similar strong relationship (overall *r* = 0.66) was found between the storm surge height (H_{SL}) and the beach volume eroded (ΔQ_{be}), but the correlation was stronger for the erosive that for the accumulative shore (*r* = 0.79 and *r* = 0.55, respectively). During the highest surges with H_{SL} > 1.2 m AMSL, the average dune retreat was 3–8 m. The changes observed were very similar to those reported from other parts of the Baltic Sea coast (Basiński 1995, Suursaar et al. 2003, Eberhards et al. 2006, Tõnisson et al. 2008, Koltsova, Belakova 2009, Ryabchuk et al. 2011, Kelpšaite-Rimkiene et al. 2021 and others).

The duration of surges with H_{SL} > 1 m AMSL correlated observably with the extent of dune erosion (dune base retreat, volume change) and with the beach erosion (volume change). The duration of high water exerted a stronger impact on the erosive shore, as well as on its beach and dune (*r* = 0.57–0.77), than on the accumulative stretch (*r* = 0.13–0.34). The differences were associated with the pre-surge beach height playing a protective role against erosion. During average storms with H_{SL} > 1.2 m AMSL and H_{SL} > 1.0 m AMSL, the dune on the sandbar retreated by 5–10 m and 1–5 m, respectively. No erosion was observed during storms with the SL 0.8 < H_{SL} > 1.0 m AMSL (or in areas with the beach height larger than maximum H_{SLr}). The longer the duration of surges with H_{SL} > 1 m, the stronger was the erosion of the beaches and dunes. Longer-lasting surges with a high SL produced an even heavier erosion, up to 10–12 m (e.g. surges associated with the storms Pia in 2004, Andrea in 2012, Kyrill in 2007 and Axel in 2017). In addition, the dune erosion was heavier on the accumulative shore during storm surges with waves arriving from opposite sectors at different times (r = 0.59). The erosion was stronger when the shore section was directly exposed to wave action. Storms advancing from NW to NE produced the largest dune erosion. The heaviest erosion was observed during the strongest surges with wind and waves changing their direction (2002, 2004, 2006, 2007, 2017 and 2019). In contrast, the erosion was lessened during heavy storms from one direction (e.g. the surge associated with the storm Wimar in 2009 advancing from NE, Andrea in 2012 approaching from WNW). A large number of small storms with the SL lower than the beach height (as in January–March 2020) did not result in dune erosion, but only lowered the beach (ΔQ_{be}).

Overall, the seasonal shore erosion is heavier when two or more high storm surges occur in succession during a single season (e.g. the surges associated with the storms Janika and Wisia in 2001/2002, Britta and Kyrill in 2006/2007, Angus and Axel in 2016/2017). Calculations of the sand volume changes showed that the greatest reduction in the dune and beach sediment occurred in the shore sections exposed to a storm surge advancing perpendicularly to the shore.

The beach height (the dune base) was found to play an important role in dune erosion. The lower the beach (erosive, reflective), the more prone it (and the adjacent dune) is to erosion. The height of the beach and the surge maximum are inter-correlated. At the southern Baltic coast (and probably also along the whole Baltic coast), if the beach is higher than 3.5 m AMSL, it may be able to withstand erosion and protect the inland forms from damage caused by high and average recurrent surges. It is only the strongest, hitherto rare storm surges with H_{SL} > 1.4 m AMSL that produce a run-up of up to 3.5–3.8 m AMSL. This was also observed in other sections of the Polish coast (Łabuz 2014). Nevertheless, the rise in the average annual SL of the Baltic Sea (and of the ocean) as well as the growing number of the heaviest surges pose an increasingly serious threat for coast safety (Kont et al. 2008, Pruszak, Zawadzka 2008, Fink et al. 2009, Koltsova, Belakova, 2009, Roelvink et al. 2009, Kelpšaite, Dailidienė 2011, Ryabchuk et al. 2011, Richter et al. 2012, Kettle 2015 and others).

The change in the dune or beach volume, expressed either as a total volume in cubic metre or referred to as the volume corresponding to one squared metre of the surface ($m^3 \cdot m^{-2}$), is correlated with the dune and beach height. The higher the eroded dune, the larger the sediment loss (a negative sand budget). This obvious correlation should be taken into account when comparing different locations with respect to changes in dune sediment volume after erosion. The sediment budget of the beach and the dune is also affected by the wind speed during the storm. The wind was also responsible for small accumulation on dunes during the surges observed. In periods between the highest surges, the beach and the foredune evolve and develop again in the accumulative shore sections (Jarmalavicius et al. 2016, Castelle et al. 2017, Kelpšaite-Rimkiene et al. 2021), as was observed during the 21 years of observations on the Świna Gate Sandbar shore.

Conclusions

The analyses revealed a number of correlations between the erosion extent in shore sections with various exposures on the one hand, and the direction of the maximum surge and waves during storms on the other.

The highest storm surges in 2002, 2004, 2006, 2007, 2009, 2012, 2017 and 2019 (with H_{SL} > 1.3 m AMSL) produced a heavy erosion of the dune shore at the Świna Gate Sandbar. Such storms occurred almost every other year. On the other hand, a succession of smaller surges in one autumn-winter storm period resulted in erosion of low beaches and dunes adjacent to them (2001, 2015, 2020).

The more rapid rise in the SL during surge causes a more extensive shore and coast erosion, as observed during the storm Axel in January 2017 in the studied area and along the Baltic Sea coast.

The duration of a high SL during a surge is the main factor responsible for beach and dune erosion. The heavier erosion was observed during longer surges, particularly those with $H_{SL} > 1.3$ m AMSL (2007, 2009, 2012 and 2017). A surge with $H_{SL} > 1.3$ m AMSL persisted over an average of 15 h. The longer the surge, the stronger was the beach and dune erosion in the erosive shore section with a low beach.

The SL and the run-up were significantly correlated, which should be taken into account during erosion parameterisation. Individual surges resulted in beach erosion, up to the maximum water run-up. A low SL (up to 1 m), induced by a shorter or weaker wind action, reached the beach height of up to 2.2 m. During such surges, dunes were eroded only in the erosive shore section with a low beach. The highest surges (with $H_{SL} > 1.4$ m AMSL) reached a height of 3.8 m and strongly eroded the dunes in the accumulative shore section with a high beach.

The pre-surge beach height is a key factor in dune protection against abrasion. The 3 m height is an effective protection against dune abrasion by storms with an SL averaging $H_{SL} = 1.2$ m AMSL. When the beach height was between 1.5 m and 2.0 m, the dunes were eroded during each surge with $H_{SL} > 0.8$ m AMSL.

The heaviest dune and beach erosion was observed when the strongest waves were advancing perpendicular to the shore during periods of the highest SL. Nevertheless, the most severe erosion of both the beach and the dune during a single storm event occurred when the wind and waves changed direction. Such storms were usually the longest lasting and showed the highest water level (2004, 2017, 2019).

The pre-storm beach width had no effect on the size of dune erosion. Erosion of a wider stretch of the beach resulted in a larger loss (negative budget) of beach volume. The volume of sediment removed due to beach erosion was similar in the accumulative and erosive shore sections (averaging 7.4–8.9 m^3), but was 2–3 times · m^{-2} higher on a narrower erosive shore. The volume of the removed beach sand declined sharply with the SLr. More important in this respect was the beach height, which was higher than the run-up. That was the reason why dunes on the accumulative shore were eroded less frequently and to a lower extent than those on the erosive shore with a lower beach.

Erosion of the dune can be assessed from the extent of its foot retreat, which is larger at higher surges. The average and maximum retreat were 2–3 m and 9–12 m, respectively, and were similar in erosive and accumulative shore sections during the heaviest surges. Nevertheless, a lower surge produced less or no damage to dunes on the accumulative shore.

The higher the SL (and run-up), the larger the dune erosion. A surge with $H_{SL} < 1$ m AMSL eroded 0.2–0.3 m^3 of the dune, with 2.0–3.8 m^3 being eroded at HSL = 1.2 m AMSL. The higher the eroded dune, the greater the sediment loss (negative sediment budget). The sand volume loss per square metre proved to be a better indicator of dune erosion, and ranged from 0 $m^3 \cdot m^{-2}$ on the accumulative shore to 1.6 $m^3 \cdot m^{-2}$ in the erosive section. The exponential change of this indicator was related to the SL during the surge.

After the storm surge abated, a further landslide from the disturbed and undercut dune slope would be initiated. A small dune accumulation observed during the surges was due also to the wind action. The sediment budget of the beach and the dune was also affected by the wind speed during the storm. In addition, the dune retreat was influenced by the vegetation that stabilises the ground, with plant roots inhibiting erosion at densely vegetated sites.

Acknowledgments

The presented material has been collected by the author during research since 1997, mainly in own financed project focused on the Polish dune coast titled Anthropogenic Natural Dunes Dynamics (ANDDY) and since 2011/14 in project Foredunes Morphodynamic and Biodiversity (FoMoBi 2.0). The author thanks the reviewers for their critical and helpful comments on the original version of the manuscript

References

Basiński T., 1995. Dune erosion during storm surges. *Journal of Coastal Research* 22 (Special Issue): 267–270.

Bobykina V.P., Stont Z.I., 2015. Winter storm activity in 2011–2012 and its consequences for the Southeastern Baltic coast. *Water Resource* 42: 371–377. DOI 10.1134/S0097807815030021.

Carter R.W.G., Hesp P.A., Nordstrom K.F., 1990. Erosional landforms in coastal dunes. In: Nordstrom K.F., Psuty N.P., Carter B. (eds), *Coastal dunes. Form and processes*, John Wiley & Sons, Chichester: 218–250.

Castelle B., Bujan S., Ferreira S., Dodet G., 2017. Foredune morphological changes and beach recovery from the extreme 2013/2014 winter at a high-energy sandy coast. *Marine Geology* 385: 41–55. DOI 10.1016/j.margeo.2016.12.006.

Cyberski J., Wróblewski A., 1999. Recent and forecast changes in sea level along the Polish coast during the period 1900–2011. *Quaternary Studies in Poland* 16 (Special Issue): 77–83.

Dailidienė I., Davulienė L., Tilickis B., Stankevicius A., Myrberg K., 2006. Sea level variability at the Lithuanian coast of the Baltic Sea. *Boreal Environment Research* 11: 109–121.

Eberhards G., Grīne I., Lapinskis J., Purgalis I., Saltupe B., Torklere A., 2009. Changes in Latvia's seacoast (1935–2007). *Baltica* 22(1): 11–22.

Eberhards G., Lapinskis J., Saltupe B., 2006. Hurricane Erwin 2005 coastal erosion in Latvia. *Baltica* 19: 10–19.

Fink A.H., Brucher T., Ermert V., Kruger A., Pinto J.G., 2009. The European storm Kyrill in January 2007. Synoptic evolution, meteorological impacts and some considerations with respect to climate change. *Natural Hazards and Earth System Science* 9: 405–423.

FU [Freie Universität Berlin], 2000–2022. Werden auch Sie Wetterpate! Online: https://www.met.fu-berlin.de/wetterpate/ (accessed 7 May 2022).

Furmańczyk K.K., Dudzińska-Nowak J., Furmańczyk K.A., Paplińska-Swerpel B., Brzezowska N., 2011. Dune erosion as a result of the significant storms at the western Polish coast (Dziwnow Spit example). *Journal of Coastal Research* 64(Special Issue): 756–759.

Gräwe U., Burchard H., 2012. Storm surges in the western Baltic Sea: The present and a possible future. *Climate Dynamics* 39(1–2): 165–183. DOI 10.1007/s00382-011-1185-z.

Hünicke B., 2010. Contribution of regional climate drivers to future winter sea-level changes in the Baltic Sea estimated by statistical methods and simulations of climate models. *International Journal of Earth Sciences* 99(8): 1721–1730. DOI 10.1007/S00531-009-0470-0.

Hünicke B., Zorita E., Soomere T., Madsen K.S., Johansson M., Suursaar Ü., 2015. Recent change – sea level and wind waves. In: *The BACC Author Team, Second assessment of climate change for the Baltic Sea Basin. Regional climate studies*. Springer: 155–185.

IMGW [Institute of Meteorology and Water Management (IMGW-PIB)]. Online: https://www.imgw.pl (accessed 7 May 2022).

Jaagus J., Suursaar Ü., 2013. Long-term storminess and sea level variations on the Estonian coast of the Baltic Sea in relation to large-scale atmospheric circulation. *Estonian Journal of Earth Sciences* 62(2): 73–92. DOI 10.3176/earth.2013.07.

Jarmalavicius D., Šmatas V., Stankunavicius G., Pupienis D., Žilinskas G., 2016. Factors controlling coastal erosion during storm events. *Journal of Coastal Research* 75 (Special Issue): 1112–1116. DOI 10.2112/SI75-223.1.

Johansson M., Boman H., Kahma K.K., Launiainen J., 2001. Trends in sea level variability in the Baltic Sea. *Boreal Environment Research* 6: 159–179.

Kelpšaite L., Dailidienė I., 2011. Influence of wind wave climate change to the coastal processes in the eastern part of the Baltic Proper. *Journal of Coastal Research* 64(Special Issue): 220–224.

Kelpšaite-Rimkiene L., Parnell K.E., Žaromskis R., Kondrat V., 2021. Cross-shore profile evolution after an extreme erosion event – Palanga, Lithuania. *Journal of Marine Science Engineering* 9(38): 1–15. DOI 10.3390/jmse9010038.

Kettle A.J., 2015. Storm Britta in 2006: offshore damage and large waves in the North Sea. *Natural Hazards Earth System Sciences Discussions* 3: 5493–5510. DOI 10.5194/nhessd-3-5493-2015.

Koltsova T., Belakova J., 2009. Storm surges on the southern coast of Gulf of Riga: Case study of the Lielupe River. Conference proceedings: Threats to Global Water Security, NATO Science for Peace and Security Series C: Environmental Security II: 91–97. DOI 10.1007/978-90-481-2344-5_10.

Kont A., Jaagus J., Aunap R., Ratas U., Rivis R., 2008. Implications of sea-level rise for Estonia. *Journal of Coastal Research* 24(Special Issues): 423–431.

Kortekaas S., Bagdanaviciute I., Gyssels P., Huerta J.M.A., Héquette A., 2013. Assessment of the effects of marine aggregate extraction on the coastline: an example from the German Baltic Sea coast. *Journal of Coastal Research* 51(Special Issue): 205–214. DOI 10.2307/40928832.

Łabuz T.A., 2009. The increase of the coastal dune area of the Świna Sandbar, West Polish coast. *Zeitschrift der Deutschen Gesellschaft für Geowissenschaften* 160(2): 123–135. DOI 10.1127/1860-1804/2009/0160-0123.

Łabuz T.A., 2014. Erosion and its rate on an accumulative Polish dune coast: the effects of the January 2012 storm surge. *Oceanologia* 56(2): 307–326. DOI 10.5697/oc.56-2.307.

Łabuz T.A., 2015. Environmental impacts – coastal erosion and coastline changes. In: *The BACC Author Team, Second assessment of climate change for the Baltic Sea Basin. Regional Climate Studies*. Springer: 381–396.

Łabuz T.A., Kowalewska-Kalkowska H., 2011. Coastal erosion caused by the heavy storm surge of November 2004 in the southern Baltic Sea. *Climate Research* 48(Special Issue): 93–101. DOI 10.3354/cr00927.

MacPherson L.R., Arns A., Dangendorf S., Vafeidis A.T., Jensen J., 2019. A stochastic extreme sea level model for the German Baltic Sea coast. *Journal of Geophysical Research: Oceans* 124: 2054–2071. DOI 10.1029/2018JC014718.

Orviku K., Suursaar Ü., Tõnisson H., Kullas, T., Rivis R., Kont A., 2007. Coastal changes in Saaremaa Island, Estonia, caused by winter storms in 1999, 2001, 2005 and 2007. *Journal of Coastal Research* 56(Special Issue): 1651–1655.

Pruszak Z., Zawadzka E., 2008. Potential implications of sea-level rise for Poland. *Journal of Coastal Research* 24(2): 410–422.

Richter A., Dietrich R., Liebsch G., 2012. Sea-level changes and crustal deformations at the southern Baltic Sea. In: Harff J., Lüth F., (eds). *Geosphere, Ecosphere and Anthroposphere of the Holocene Southern Baltic Sea*. Bericht der Römisch-Germanischen Kommission 88: 81–100.

Roelvink D., Reniers A., Van Dongeren A., Van Thiel de Vries J., McCall R., Lescinski J., 2009. Modelling storm impacts on beaches, dunes and barrier islands. *Coastal Engineering* 56(11–12): 1133–1152.

Ryabchuk D., Kolesov A., Chubarenko B., Spiridonov M., Kurennoy D., Soomere T., 2011. Coastal erosion processes in the eastern Gulf of Finland and their links with geological and hydrometeorological factors. *Boreal Environment Research* 16: 117–137.

Samuelsson M., Stigebrandt A., 1996. Main characteristics of the long-term sea level variability in the Baltic Sea. *Tellus A* 48: 672–683. DOI 10.1034/j.1600-0870.1996.t01-4-00006.x.

Stont Zh.I., Gushchin O.A., Dubravin V.F., 2012. Storm winds in the Southeastern Baltic Sea by data of automated meteorological station in 2004–2010, Izv. *RGO* 144(1): 51–58.

Surkova G., Arkhipkin V., Kislov A., 2015. Atmospheric circulation and storm events in the Baltic Sea. *Open Geosciences* 7(1): 332–341. DOI 10.1515/geo-2015-0030.

Suursaar Ü., Kullas T., Otsmann M., Kõuts T., 2003. Extreme sea level events in the coastal waters of western Estonia. *Journal of Sea Research* 49: 295–303.

Sztobryn M., Stigge H.J., Wielbińska D., Weidig B., Stanisławczyk I., Kańska A., Krzysztofik K., Kowalska B., Letkiewicz B., Mykita M., 2005. Storm surges in the southern Baltic (western and central parts), Report 39, Bundesamt für Seeschifffahrt und Hydrographie, Rostock/Hamburg: 1–73.

Tõnisson H., Orviku K., Jaagus J., Suursaar Ü., Kont A., Rivis R., Ratas U., 2006. Coastal damages in Estonia caused by Cyclone Gudrun. In: Tubilewicz A. (ed), *Coastal Dynamics, Geomorphology and Protection. Proceedings Littoral 2006, 8th International Conference "Coastal Innovations and Initiatives"*, 18–20 September 2006, University of Technology, Gdańsk: 18–26.

Tõnisson H., Orviku K., Jaagus J., Suursaar Ü., Kont A., Rivis R., 2008. Coastal damages on Saaremaa Island, Estonia, caused by the extreme storm and flooding on January 9, 2005. *Journal of Coastal Research* 24(3): 602–614.

Tõnisson H., Suursaar Ü., Rivis R., Kont A., Orviku K., 2013. Observation and analysis of coastal changes in the West Estonian Archipelago caused by storm Ulli (Emil) in January 2012. *Journal of Coastal Research* 65(Special Issue): 832–837. DOI 10.2112/SI65-141.1.

Trzeciak S., 2001. Storm winds on the Polish Baltic coast (in Polish). Wydawnictwa Wyższej Szkoły Morskiej nr 36, Szczecin: 1–78.

Van de Graaff J., 1977. Dune erosion during a storm surge. *Coastal Engineering* 1: 99–134.

Van de Graaff J., 1986. Probabilistic design of dunes, an example from Netherlands. *Coastal Engineering* 9: 479–500.

Van Thiel de Vries J.S.M., 2009. Dune erosion during storm surges. IOS Press Netherlands, Amsterdam: 1–202.

Vellinga P., 1982. Beach and dune erosion during storm surges. *Coastal Engineering* 6(4): 361–387.

Weisse R., Weidemann H., 2017. Baltic Sea extreme sea levels 1948–2011: Contributions from atmospheric forcing. *Procedia IUTAM* 25: 65–69. DOI 10.1016/j.piutam.2017.09.010.

Wetterzentrale, 2022. Top Karten. Online: www.wetterzentrale.de/topkarten/fsfaxsem.html (accessed 7 May 2022).

Wolski T., Wisniewski B., 2020. Geographical diversity in the occurrence of extreme sea levels on the coasts of the Baltic Sea. Journal of Sea Research 159: 101890. DOI 10.1016/j.seares.2020.101890.

Wolski T., Wiśniewski B., Giza A., Kowalewska-Kalkowska H., Boman H., Grabbi K., Hammarklint T., Holfort J., Lydeikaite Z., 2014. Extreme sea levels at selected stations on the Baltic sea coast. *Oceanologia* 56(2): 259–290. DOI 10.5697/oc.56-2.259.

Zawadzka-Kahlau E., 1999. Development trends of the Southern Polish Baltic coast (in Polish). IBW PAN, Gdańsk: 1–147.

Zeidler R.B., Wróblewski A., Miętus M., Dziadziuszko Z., Cyberski J., 1995. Wind, wave and storm surge regime at the Polish Baltic coast. *Journal of Coastal Research* 22(Special Issue): 33–55.