Erosion and its rate on an accumulative Polish dune coast: the effects of the January 2012 storm surge

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Abstract

The Polish coast is a non-tidal area; its shores are affected mainly by autumn-winter storm surges. Those of 6 and 14 January 2012 are representative of the forces driving the erosion of normally accumulative sections of coastal dunes, monitored by the author since 1997. The sea level maximum during these two storm surges reached 1.2 to 1.5 m amsl along the Polish coast. Land forms up to 3 m amsl were inundated. Beaches and low parts of the coast up to this height were rebuilt by sea waves attacking the coast for almost 12 days. Quantitative analyses of the morphological dynamics of the coastal dunes are presented for 57 profiles located along the coast. Only those accumulative sections of the Polish coast are analysed where sand accumulation did occur and led to new foredune development. The mean rate of dune erosion was 2.5 m^3 per square metre with an average toe retreat of 1.4 m. Erosion understood as dune retreat was greater when a beach was lower (correlation coefficient 0.8). Dune erosion did not occur on coasts with beaches higher than 3.2 m or on lower ones covered by embryo dunes.

1. Introduction

The Polish coast is 500 km long and is mainly exposed to the north. A coast is understood as the first land forms in areas adjacent to the sea and affected by it. Polish coastal forms are composed mainly of loose sand, till and peat. Over 80% of the Polish coast consists of dune systems developing on sandbars. Only 15% of them are in a more or less accumulative state and 35% are eroded after every storm surge (Łabuz 2013). Because the Polish coast has a low durability, it is under constant threat from storm surges.

In the non-tidal Baltic, short-term sea level variations are caused mainly by meteorologically forced storm surges (Heyen et al. 1996, Samuelsson & Stigebrandt 1996, Wróblewski 1998, Cyberski & Wróblewski 1999, Johansson et al. 2001, Suursaar et al. 2003, Kont et al. 2008). Nowadays, the highest water levels during storm surges exceed 2–2.7 m amsl (above mean sea level), and have been recorded in the majority of countries around the Baltic, causing serious coastal erosion (Eberhards et al. 2005, Pruszak & Zawadzka 2005, Dailidienė et al. 2006, Suursaar et al. 2006, Tönisson et al. 2006, Chubarenko et al. 2009, Koltsova & Belakova 2009, Sorensen et al. 2009, Furmańczyk et al. 2011, Łabuz & Kowalewska-Kalkowska 2011, Ryabchuk et al. 2011).

The objective of this study is to describe the changes to the accumulative sandy dune coast caused by the storm surge in January 2012 and to estimate the volume of sand removed from the coastal dune. I analyse only accumulative sections of the Polish coast, i.e. those sections where sand accumulation (both marine and aeolian) usually prevails, leading to new dune growth. These areas were selected on the basis of the field studies I have been carrying out since 1997.

2. Storm surges in January 2012

Storm surges on the southern Baltic coast (the coasts of Germany, Poland and Lithuania) are associated with the passage of low-pressure systems over the Baltic Sea from south-west to north-west, which produce north-westerly to north-easterly onshore winds. The most dangerous storms occur during the passage of deep, intensive low pressure systems near the southern Baltic coast, with an extensive system of winds from the northern sector (Majewski et al. 1983, Zeidler et al. 1995, Sztobryn et al. 2005).

Sztobryn et al. (2005) estimated that in the period 1976–2000 about half of all storm surge events on the southern Baltic coast were caused by a strong northerly air flow over the Baltic, with high atmospheric pressure over Scandinavia and a depression shifting southwards. About 55% of the storm surges resulted from gale-force winds developing at the rear of depressions moving eastwards across southern Sweden, the southern basins of the Baltic Sea, or across the land close to the southern coast.

The number of storm surges (sea levels higher than 0.6 m amsl) along the southern Baltic coast differs from year to year (Zeidler et al. 1995). Most surges are recorded in November–February. During the last 10 years (2001–2012) there have been 17 such events when the water level was higher than 1 m amsl (at Świnoujście). Coastal erosion is worse when two or more storm surges occur in succession during a single season. Those of 6 and 14 January 2012, with maximum sea levels of 1.2–1.5 m amsl, caused serious coastal erosion. These surges were produced by northwesterly onshore winds related to the passage of a low-pressure system over the Baltic Sea. The first surge occurred on 5–6 January and the second one on 13–15 January 2012. The second surge was longer and produced a higher water level. Both were separated by drops in sea level ranging from 10 to 20 cm below the average sea level (Figure 1). On the western Polish coast these events started on 5 January. The alarm sea level in the port of Świnoujście was exceeded at 21:00 hrs on that day and remained relatively steady until 20:00 hrs on 15 January (according to the records of the Świnoujście Harbour Office of the Polish Maritime Bureau, prepared by Osóch & Łabuz, unpublished). At Świnoujście the maximum water level during these events was 1.42 m amsl (14 January 2012). The level of 1.0 m amsl persisted for 12 hours during the first storm episode on 6 January and for 30 hours during the second one on 14 January. Eastward surge development along the coast was delayed for several hours. Both surges hit the whole Polish coast, starting from the Pomeranian Bay in the west to the Gulf of Gdańsk in the east. The maximum sea levels during both storms

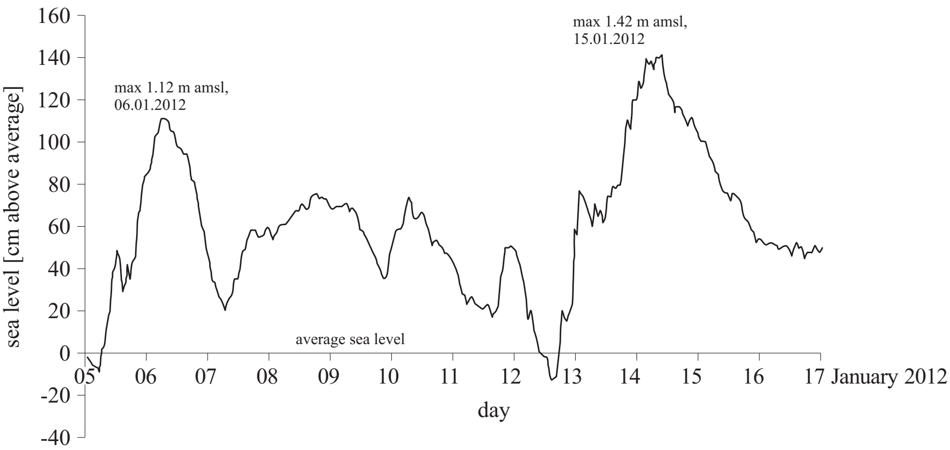

Figure 1. Hourly water levels during storm surges on January 2012 (data from Świnoujście Harbour Office, prepared by Osóch & Łabuz)

Table 1. Maximum sea levels recorded at harbour offices and water overflow on land [m]

Harbour	Coastal section	Investigated sandbar (No. of area, Table 2)	Max. sea level, harbour offices [m]	Water range on coast, on basis of field measurements [m]
Świnoujście	West, Pomeranian Bay (middle part)	Świna Gate Sandbar/ west coast (8)	1.42	3.4
Kołobrzeg	West	West coast sandbars (Lake Resko)/ west coast (7)	1.32	3.2
Ustka	Middle	Gardno-Łebsko Sandbar/ central coast (6)	1.28	3.2
Łeba	Middle	Kaszubska and Sarbska Sandbars/central coast (5) Gardno-Łebsko Sandbar/ central coast (6)	1.33	3.3
Władysławowo	East	Karwia Sandbar/ east coast (4)	1.28	3.2
Hel	East	Hel Spit/ east coast (3)	1.40	3.8

Table 1. (*continued*)

Harbour	Coast section	Investigated sandbar (No. of area, Table 2)	Max. sea level, harbour offices [m]	Water range on coast, on basis of field measurements [m]
Gdańsk	East, Gulf of Gdańsk (western part)	Vistula mouth/ east coast (2)	1.30	3.5
Baltiysk (Russia)	East, Gulf of Gdańsk (eastern part)	Vistula Sandbar proper/ east coast (1)	1.40	4.0

Data source of storm surges: German Weather Service and Harbour Offices of the Polish Maritime Bureau based along the coast. Water range determined on the basis of field research.

at coastal stations exceeded 1.40 m amsl (Table 1). The wind strength accompanying both events exceeded 17–19 m s^{-1} and blew in from the sea. Its strength was also responsible for aeolian movements of sand from beaches to foredunes.

3. Material and methods

The results presented here are part of a study of coastal morphodynamics and geo- and biodiversity (www.fomobi.pl) carried out along the whole Polish dune coast and financed by the National Centre for Research and Development (NCBiR). This study covers almost 20% of dunes on the Polish coast. This article contains an analysis of the effect of the January 2012 storm surges on the accumulative part of the Polish coast, where dune erosion occurs only after strong storm surges.

The field research methods are: (i) field levelling as profiles across coastal forms, (ii) surface measurements in plots of 50×70 m as 3D levelling using a GPS RTK base. Fieldwork relief profiling is a cheaper and faster method that has proved helpful in determining short-term coastal changes. Digital terrain models (DTM) give more accurate data, especially in built-up areas.

More than 110 profiles along the whole Polish coast were investigated in this project. Located on every accumulative part of every Polish sandbar (Figure 2a–c), these profiles were established by means of geodesic tools (a leveller and a GPS RTK). They extended from the fixed and stable parts of the dunes across beaches to the water line. Their length on each sandbar ranged from 0.3 m to 2 km. There were from 6 to 10 profiles on each sandbar. Over 60 of them were analysed in this study, representing 8 coastal areas (Table 1, Figure 2d). Surface analyses were done on the mostly accumulative coastal parts of the Świna Gate Sandbar (2 areas), the Lakes Gardno-Łebsko Sandbar (2 areas) and the Vistula mouth on the Vistula Sandbar (2 areas) and in other places, where there are wide beaches and foredunes (Table 2). Profiles and 3D surface measurements were carried out twice a year – in winter and autumn, starting from 2010. Laboratory computations were based on the measurement of changes in the dune relief and quantifying sand volumes with the aid of the Excel, Grapher, Surfer, Grab it, Winkalk, Statistica and Quantum GIS programs. I used such indicators of coastal relief changes as (Figure 3): movements of the foredune base, ridge or edge; foredune height and dune base width; beach width and height; height and dynamics of embryo dunes on the beach. The dynamic layer is a graph showing surface relief changes over short periods of time. Their comparison yields changes in height that can be used for computing sand volume.

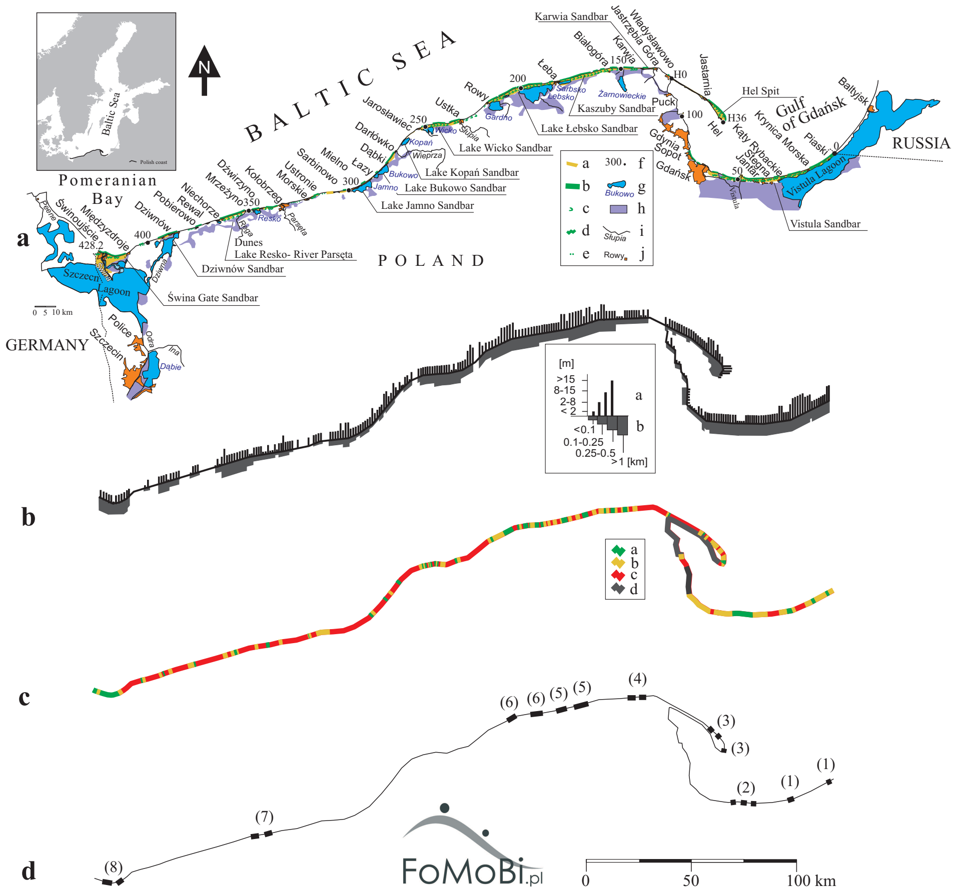

Figure 2. Polish Baltic Sea coast. **a)** Coast map, a – sandbars, b – foredunes, c – formerly shifting parabolic and barchan dunes, d – formerly shifting transverse ridges, e – dunes on moraine coast, f – coastal kilometrage, g – lakes, h – wetlands, swamps, i – rivers, j – settlement. **b)** Dune coast location, a – dune coast height, b – sand barrier width (Łabuz 2005). **c)** Coastal dynamics between 2002–2012, dune coast changes, a – accumulation, b – stable, c – erosion, d – no data. **d)** Study areas 1–8, see Table 2, (Łabuz 2013, simplified)

The data collected during the project from autumn 2011 to spring 2012 were used for quantifying the erosion resulting from the January 2012 storm surge. The effects of water dynamics on the transect profile were recorded, and sites featuring erosion-caused depressions and gutters were identified. The results of coastal profiling and 3D GPS RTK measurements served to calculate the volume of sediment displaced from every square metre of the foredune in the measured areas. Information on storm surge development was taken from the German Weather Service

Table 2. Relationship between foredune erosion on an accumulative coast and beach height, and exposure to the January 2012 storm surges on the Polish coast (numbers of sandbars: locations on Figure 2)

Sandbar/ location	Profile area code	Polish coastal kilometrage classification	Beach height before surge	Dune foot retreat [m]	Erosion volume [m^3]	Erosion volume per square m [m^3 m^{-2}]	Exposure of coast to surge 2 – full, 1 half, 0 – none
	P1	3.00	1.60	−9.0	−28.00	−1.20	2
Vistula	P3	3.80	2.00	−7.0	−14.20	−1.30	2
Sandbar proper/	P5	23.50	2.60	−2.0	−3.80	−0.60	1
east coast (1)	P6	22.50	2.90	−0.5	−1.40	−0.25	1
	P7	22.25	2.80	−0.6	−3.60	−0.70	1
	JM0	42.45	3.10	−0.2	−0.15	−0.04	1
	JM1	42.80	2.80	−0.1	−0.04	−0.01	0
	JM2	43.45	2.60	−0.5	−0.70	−0.38	0
Vistula mouth/	M1	46.70	2.50	−0.1	−0.11	−0.06	0
east coast (2)	M2	46.30	2.70	0.0	0.00	0.00	0
	M3	46.00	2.90	0.0	0.00	0.00	0
	S2	50.70	2.80	0.0	0.00	0.00	0
	S3	50.00	2.75	−0.2	−1.00	−0.20	0
	H1	35.00	2.65	−0.2	−0.85	−0.14	0
	H2	35.70	2.40	−2.5	−3.40	−0.50	0
Hel Spit/	H3	33.00	2.50	−1.0	−0.50	−0.16	0
east coast (3)	H5	29.40	2.60	−5.0	−0.80	−0.85	1
	H6	30.50	2.20	−3.0	−2.00	−0.55	1
	H7	23.00	2.70	0.0	0.00	0.00	1
	H8	23.30	3.00	0.0	0.00	0.00	1

Table 2. (*continued*)

Sandbar/ location	Profile area code	Polish coastal kilomatrage classification	Beach height before surge	Dune foot retreat [m]	Erosion volume [m^3]	Erosion volume per square m [m^3 m^{-2}]	Exposure of coast to surge 2 – full, 1 half, 0 – none
Karwia Sandbar/ east coast (4)	KR1	138.1	2.6	−1.50	−2.30	−0.45	2
	KR2	140	3.1	0.00	0.00	0.00	2
	KR3	143	3.0	−0.10	−0.40	−0.08	2
	KR5	143.2	2.6	−2.00	−1.30	−0.27	2
	KR6	147.3	2.7	0.00	0.00	0.00	2
Kaszubska and Sarbska Sandbars/ central coast (5)	ST1	169	2.6	−2.00	−3.40	−0.48	0
	ST2	168	2.9	−0.10	−0.70	−0.18	1
	ST3	169.7	3.2	0.00	0.00	0.00	1
	ST5	179.6	2.9	−0.20	−1.50	−0.16	2
	ST6	180	2.8	−0.20	−0.30	−0.15	2
Gardno-Łebsko Sandbar/ central coast (6)	LP0	190	2.9	0.00	0.00	0.00	1
	LP1	191	2.7	−0.15	−0.40	−0.08	2
	LP2	192	2.0	−9.00	−11.50	−0.16	2
	LP3	193	1.9	−3.00	−4.00	−0.16	2
	LP4	194	2.1	−4.00	−3.00	−0.16	1
	LP5	195	2.6	−1.50	−2.00	−0.16	1
	CZ0	201	2.9	0.00	0.00	0.00	2
	CZ1	202.5	2.6	−0.70	−1.50	−0.37	1
	CZ2	203	2.4	−3.00	−6.60	−1.10	1
	CZ3	205	2.7	−0.20	−0.36	−0.12	1
	CZ4	206	2.7	−0.30	−0.50	−0.17	1

Table 2. (*continued*)

Sandbar/ location	Profile area code	Polish coastal kilomatrage classification	Beach height before surge	Dune foot retreat [m]	Erosion volume [m^3]	Erosion volume per square m [m^3 m^{-2}]	Exposure of coast to surge 2 – full, 1 half, 0 – none
	G1	338	2.50	−2.0	−3.50	−0.45	2
West coast sandbars	G2	340	3.00	0.0	0.00	0.00	1
(Lake Resko)/	G3	341	2.10	−3.5	−8.30	−1.40	1
west coast (7)	G5	346	2.10	−4.0	−9.90	−0.99	2
	G6	349	2.50	−1.5	−3.20	−0.46	2
	MBS A	412	2.50	−5.0	−8.50	−0.85	2
	MBS B	413	2.20	−2.4	−4.00	−0.80	2
	MBS C	414	2.80	0.0	0.00	0.00	2
	MBS 1	415	2.70	−0.3	−0.43	−0.07	2
Świna Gate Sandbar/	MBS 2	416	2.10	−2.5	−3.25	−0.93	2
west coast (8)	MBS 3	417	2.60	−0.2	−0.64	−0.06	1
	MBS 4	418	2.50	−0.5	−1.00	−0.11	1
	MBS 5	419	2.40	−1.0	−2.75	−0.15	1
	MBS 6	420	2.75	0.0	0.00	0.00	1
	MBS 7	421	2.80	0.0	0.00	0.00	1
	MBS 8	422	2.70	0.0	0.00	0.00	0

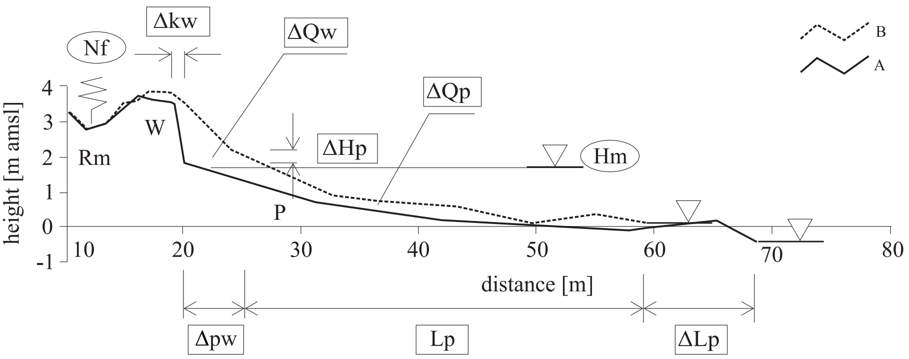

Figure 3. Measured parameters of the coastal profile; Rm – interdune runnel, W – foredune, P – beach, B – profile before storm, A – profile after storm, Δpw – foredune foot changes, Δkw – foredune ridge edge changes, ΔHp – beach height changes, ΔLp – beach width changes, Lp – beach width, ΔQw – sand volume changes in foredune (per 1 m wide profile), ΔQp – sand volume changes in beach (per 1 m wide profile), Hm – storm sea level, Nf – wave run-up (max. 3.5 m)

(www.wetterzentrale.de/topkarten/fsfaxsem.html) and the Harbour Offices of the Polish Maritime Bureau based along the coast. Data on the highest water levels on each part of the coast were marked on the profiles and DTMs. Also, the limit of wave run-up on land was marked during the field studies as indicated by the position of the washover fan (exceeding 3–4 m amsl).

4. Results – erosion of normally accumulative sections of the Polish dune coast

All the Polish dune coast sections exposed to the west were threatened by the events described above. Coastal sections exposed indirectly to surge waves were not so badly affected. The dataset analysed here contains only profiles representing the dune coast with permanent accumulative tendencies that were found during field measurements since 2010 within the framework of the FoMoBi project or in the course of earlier research during the ANDDY project (Łabuz 2005, www.polishdunes.szc.pl).

During the maximum of both storm surges, land (beach) higher than 3.2 m amsl was not inundated. On such a coast aeolian accumulation took place on the foredune. This demonstrates that storm surges may be a factor impacting on the development of the foredune ridge achieved by beach erosion understood as early deflation prior to the surge overflow on the beach. Dunes protected by a beach or embryo dunes higher than the water overflow were not eroded (Figure 4). On beaches lower than 2.5 m, every embryo dune that had developed since 2010 was eroded. The higher the form, the greater the volume of sand that was removed. Only

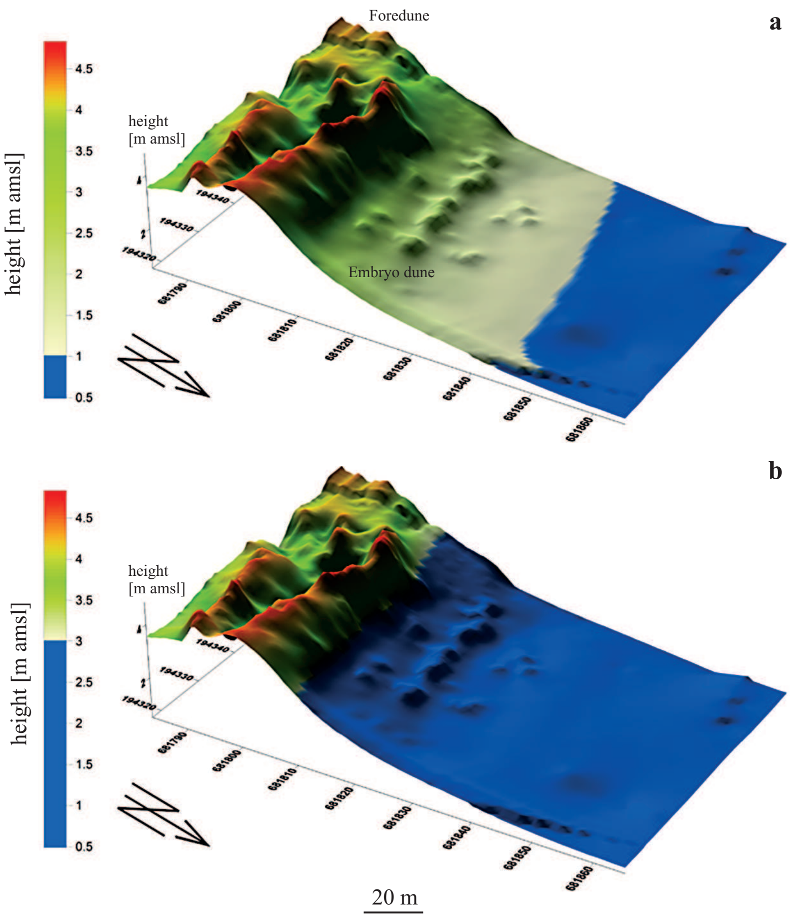

Figure 4. Scenario of beach and embryo dune overflow by a storm surge (Świna Gate Sandbar); a) water level 1 m above amsl, typical annual situation, b) water level 3 m amsl, catastrophic surge based on DTM produced from RTK GPS measurements (Łabuz 2013)

embryo dunes located on beaches over 3 m amsl were safe. Erosion was the strongest on beaches lower than 2 m. Erosion understood as dune retreat was greater when a beach was lower (coefficient 0.8). Foredune sections of the coast that had hitherto been accumulative witnessed dune foot erosion at a rate of 2–9 m after described storm surges (Table 2), i.e. from 2 to 4 times more than the annual rate of retreat of the Polish coast (1 m per year). Figure 5 presents selected profiles representing different types of foredune erosion forced by the beach height during the events described. The mean rate of dune erosion was 2.5 m^3 with an average toe retreat of 1.4 m. The volumetric erosion of sand per square

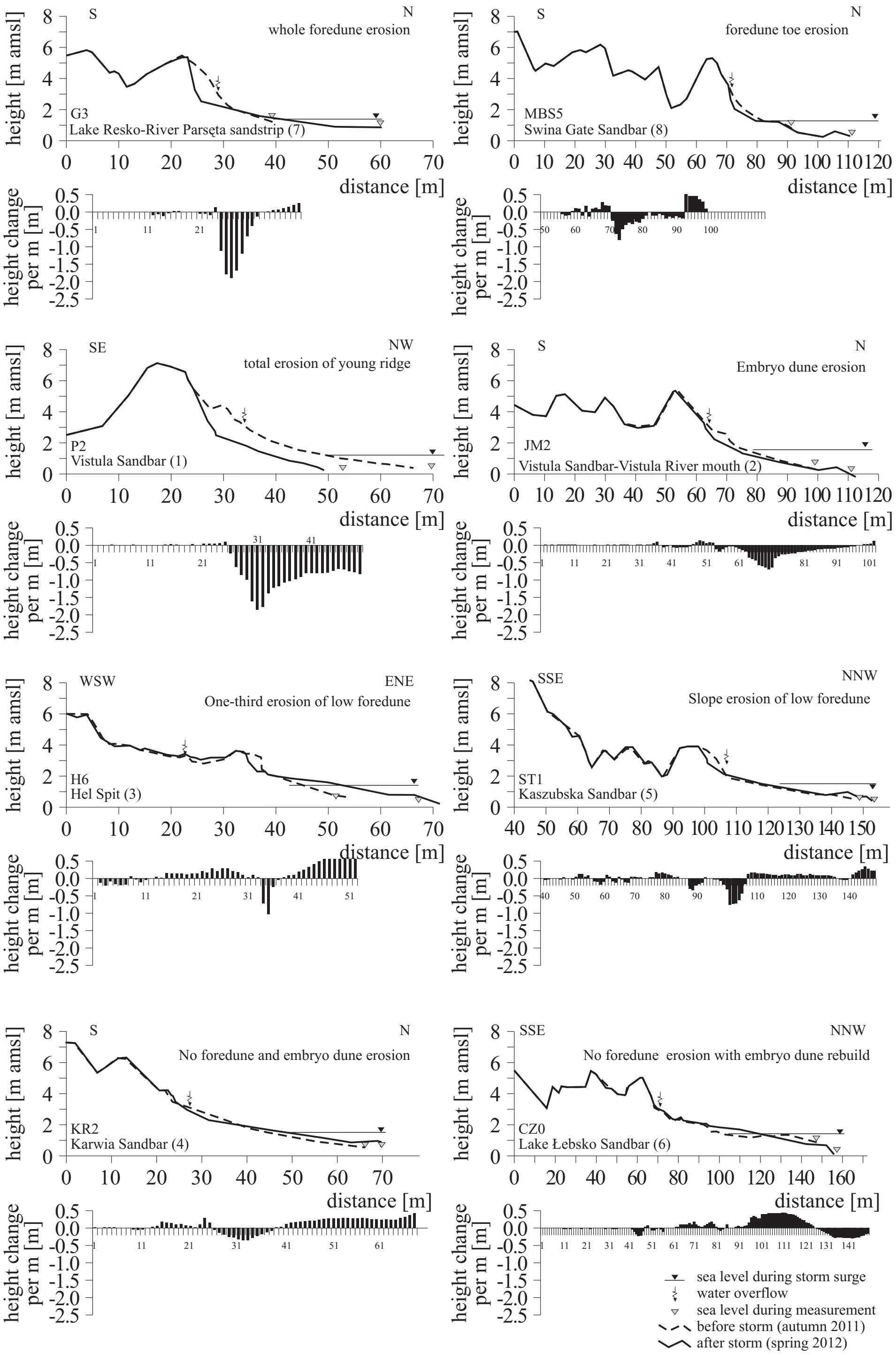

Figure 5. Selected coastal profile reliefs before and (*continued on next page*)

(Figure 5, *continued***)** after storm surge on 14 January 2012; with height changes as relief pillars for each metre (dynamic layer). Solid line – November 2011 research (before the surge), dashed line – March/April research (after the surge)

Figure 6. Photographic documentation of foredune erosion caused by the January 2012 storm. a) removed embryo dunes, Hel Spit, b) eroded slope of low foredune ridge, Lake Łebsko Sandbar, c) undercutting of high foredune ridge, Vistula Sandbar

metre of dune exceeded 0.3 m^3. On seriously threatened sections of the coast, the volume of sand washed off the dune ridge was larger than 1.0 m^3 per square metre. This was a typical situation on the coastal section where the beach was lower than 2.5 m. The rate of sand washout was higher when a foredune was higher than 6 m. Throughout the study area, the largest loss of sediment from a dune was estimated at 1.2–1.4 m^3 per square metre. Figure 6 illustrates examples of dune damage on the monitored sections of the coast. On the lower sections of the coast washover fans were formed that encroached on to the land up to 200 m from the beach, for example, on the Hel Peninsula and the Karwia Sandbar. The mouths of the channels connecting lakes with the sea were reformed and enlarged by waves flowing back into the lakes. After the storm, beaches were narrower by 10 to 20 m.

5. Discussion

The strongest storms, with force 10–12 winds, are produced by NE winds (after Zeidler et al. 1995). All autumn-winter storms have caused erosion and a southward retreat of the coast at an average rate of 0.1 m $year^{-1}$ over the last 100 years and 0.5 m $year^{-1}$ from 1960 to 1983 (Zawadzka-Kahlau 1999, 2012). On the southern Baltic coast the sea level during a storm may rise to 1.5–2 m amsl (Zeidler 1995); water flows on to the land, however, can reach 3.5 m amsl (Łabuz 2009, 2013), and such events can cause flooding in these areas. The lower the beach, the greater the dune erosion (Figure 7). The retreat of a dune foot is also related to the beach height (Table 3). Water overflows low dune ridges, artificial paths and depressions up to 3.5 m amsl, causing washover fan development (Łabuz 2009). All relief forms below this level are abraded, and dune ridges in the beach hinterland are subject to regression. The extent of coastline erosion and retreat depends on both the sea surge height and its duration (Suursaar et al. 2006, Tönisson et al. 2006). There is a definite relationship between storm surge height and the rate of dune retreat (Łabuz & Kowalewska-Kalkowska 2010, 2011, Łabuz 2011). The January 2012 storm surges with high water levels also caused erosion on the hitherto accumulative part of the Polish coast. The calculated changes in sand volume indicated that the greatest decrease in sediment on the dunes and beaches occurred on coastal sections with an exposure perpendicular to the direction of the storm surges. The dune sand balance was negative owing to the considerable lowering of the beach, caused firstly by deflation (strong onshore winds of 12–16 m s^{-1}) and secondly by abrasion. In places where the beach was lower than 2 m amsl, erosion was worse than elsewhere. An additional factor causing annual erosion was the negative sand balance on the beach caused by deflation. Low and narrow beaches did not protect dune dykes from erosion. The observed

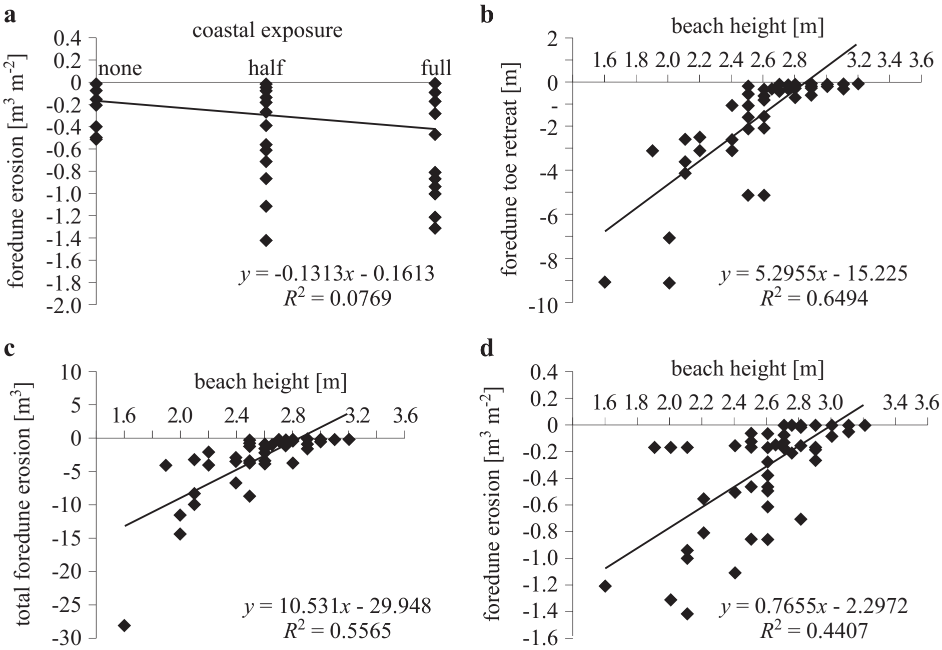

Figure 7. Correlation of selected parameters of dune relief changes for whole data sets (57 profiles); a) foredune erosion per square m to coastal exposure, b) retreat of foredune toe to beach height, c) foredune erosion to beach height, d) foredune erosion per square m to beach height

Table 3. Correlation of calculated morphological parameters of coastal erosion ($N = 57$)

Correlation	Beach height before surge	Dune foot retreat [m]	Dune erosion volume [m^3]	Dune erosion volume per square m [m^3 m^{-2}]
beach height before surge	1	0.805857	0.745969	0.663877
dune foot retreat [m]	0.805857	1	0.866921	0.703874
dune erosion volume [m^3]	0.745969	0.866921	1	0.721165
dune erosion volume per square m [m^3 m^{-2}]	0.663877	0.703874	0.721165	1

changes were very similar to those described in other Baltic coast studies (Eberhards et al. 2005, Dailidienė et al. 2006, Suursaar et al. 2006, Tõnisson et al. 2006, Chubarenko et al. 2009, Koltsova & Belakova 2009, Sorensen et al. 2009, Ryabchuk et al. 2011). Dune erosion reached 4 m and in some places, post-storm foredune accretion was also observed. In Poland the 2001–2009 storm surges resulted in a foredune retreat of 3–6 m, mostly on reflective beaches, i.e. where the beach was low and narrow (Łabuz 2009, Łabuz & Kowalewska-Kalkowska 2010, 2011). Such coasts are widespread along the Polish coast (Zawadzka-Kahlau 2012).

If a beach is higher than 3.5 m amsl (covered by incipient dunes), it may be able to withstand erosion and protect inland forms from damage. In such places after a storm, marine accumulation can be observed on the beach and aeolian accumulation on the dune ridge (Łabuz 2009). Thus, storm surges bringing sediment from eroded areas can increase the area of land; however, this normally occurs along only 15% of the Polish Baltic coast (Łabuz 2013). This type of coastal relief is called dissipative, where a high, wide beach and shallow water adjacent to it impacts on storm surge waves (Figure 8).

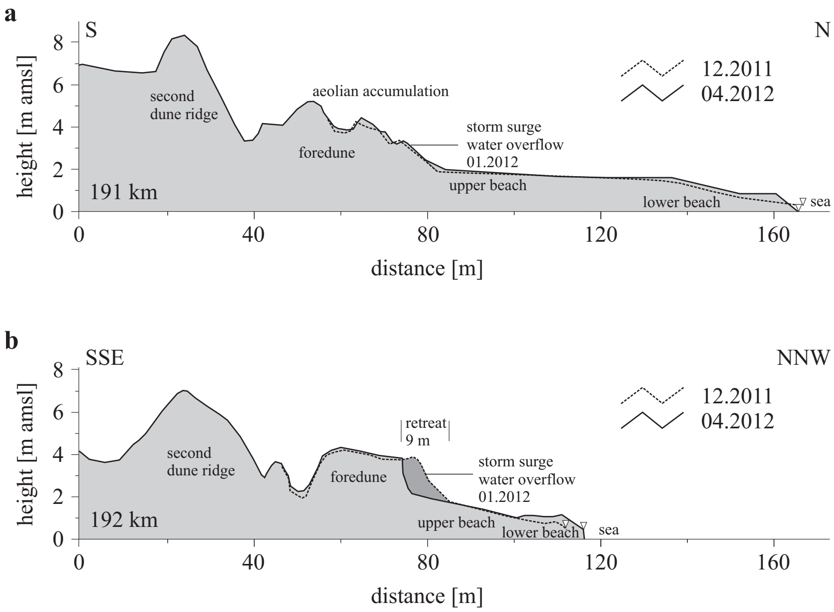

Figure 8. Influence of sea level rise during a storm surge (exemplified by the January 2012 storm) on dune relief, Lake Łebsko Sandbar; a) profile resembling a dissipative, low beach: considerable foredune abrasion (191 km), b) profile resembling a reflective, high beach: accumulation prevails (192 km)

6. Conclusions

Research into coastal dunes is gaining in importance because of the increasing levels of threats such as storm surges. Quantitative analysis of the morphological evolution of a coast plays an essential part in integrated coastal zone management. The strongest storm surges that affect the southern Baltic coast come from the north-easterly – north-westerly sector. The longer the fetch of a developing surge, the stronger the erosion of the coast. Storm surges with water levels of 1 to 1.4 m can erode beaches lower than 2.5 m amsl. On Polish coasts, water can inundate adjacent land during storm surges up to 3.5 m amsl. This is caused by sea level rise and permanent beach reduction resulting in a gradual retreat of the land. The extent of coastal erosion and retreat depends on both the sea surge height and its duration. Consequently, coastal retreat was more extensive on those parts of sandbars where the beaches are lower than 3.2 m amsl. The largest changes occurred where, prior to the storm, the beach was lower than the maximum wave run-up. The storm-caused changes in the coastal relief observed in the monitored areas did not break up the general tendency for foredune development. By 2013 the dunes had partly rebuilt themselves and new embryo dunes had appeared.

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