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# Coastal erosion caused by the heavy storm surge of November 2004 in the southern Baltic Sea

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ABSTRACT: The Świna Gate Sandbar (southern Baltic Sea) is affected by storm surges caused by passages of deep low-pressure systems over the Baltic Sea. The storm surge of 22–25 November 2004, with a maximum sea level of 1.35 m above mean sea level (MSL) as measured at the Świnoujście gauging station, was one of the most severe storm events in 1993–2007. It produced changes in the coastal relief by inducing significant erosion of the dune shore in the western and eastern subsections of the sandbar area examined. Seawater flooded the beach and flowed over the low ridges, up to 3 m above MSL. As a result, all relief forms below the 3 m level were eroded, and the dunes retreated by an average of 2 to 6 m. The maximum amount of sediment that eroded away amounted to 22 m$^3$ per 1 m of coastline. This study showed that the magnitude of coastal erosion and retreat is dependent both on the height and the duration of the sea surge.

KEY WORDS: Storm surge · Coastal erosion · Sand volume changes · Pomeranian Bay · Świna Gate

## 1. INTRODUCTION

The sea level in the Baltic Sea varies substantially during the year due to joint effects of numerous meteorological and hydrological factors. One of the most important of these, the water exchange between the North and the Baltic Seas, which is largely controlled by the mean sea level (MSL) of the North Sea and atmospheric pressure patterns over the North Atlantic, strongly influences the volume of water in the Baltic. In the almost non-tidal Baltic, short-term sea level variations are, to a large extent, due to meteorological forcing (Heyen et al. 1996, Samuelsson & Stigebrandt 1996, Wróblewski 1998, Cyberski & Wróblewski 1999, Johansson et al. 2001, Suursaar et al. 2003, Jasińska & Massel 2007, Kont et al. 2008).

As shown by archived data, the most severe storm surges in the Baltic were recorded in the north-east and south-west. St. Petersburg (Russia) experienced 3 floods higher than 3 m and 1 higher than 4 m. The highest storm surge (4.21 m) was recorded in November 1824 (Suursaar et al. 2006, Averkiev & Klevanny 2007). In Estonia, the heaviest storm surge along the coasts of the Gulf of Riga occurred in January 2005. As a result of the passage of a fast and intensive low-pressure system known as Gudrun, the sea level in Pärnu was 2.75 m higher than the Baltic Mean Level. In the Bothnian Bay (Kemi), the maximum sea level, recorded in 1982, was 2.01 m above MSL (Suursaar et al. 2006, Tõnisson et al. 2008). At the southern Baltic coast, the largest storm surge occurred in 1872 when the sea level at the coast of Schleswig-Holstein (Germany) exceeded MSL by 3.2 to 3.7 m. The highest sea level rise at the Polish coast was recorded in February 1874, with water levels in Kołobrzeg and Świnoujście rising to 2.17 m and 1.96 m above MSL, respectively (Zeidler et al. 1995).

The Polish coast is a non-tidal area; its shores are affected by wind, wave action, and nearshore currents. Research on coastal dunes is gaining in importance at present because threats such as storm surges and human impact have been growing. Quantitative analysis of morphological evolution of the coast plays an essential part in integrated coastal zone management.

The objectives of this study were: (1) to present a meteorological and hydrodynamic analysis of a typical storm surge, (2) to describe the effects of storms on coastal morphology, and (3) to estimate the volume of sand removed and/or displaced by the storm.

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### 1.1. Storm surges at the Pomeranian Bay coast

Storm surges at the Pomeranian Bay coast are associated with the passages of low-pressure systems entering the Baltic Sea from south-west to north-west, which produce northwesterly to northeasterly onshore winds. When the surges overlap with an already high sea level (induced by large inflows from the North Sea caused by prolonged westerlies), the resulting sea level may be extremely high (Majewski et al. 1983, Zeidler et al. 1995, Sztobryn et al. 2005, Wiśniewski & Kowalewska-Kalkowska 2007). Sztobryn et al. (2005) estimated that in 1976–2000, about 40% of all storm surge events at the Pomeranian Bay coast were caused by a strong northerly air flow over the Baltic, with high — or rising — atmospheric pressure over Scandinavia and a depression moving southwards near the eastern boundary of the Baltic. About 55% of the storm surges resulted from gale-force winds developing at the rear of atmospheric depressions moving eastwards across southern Sweden, the southern basins of the Baltic Sea, or across the land close to the southern coast. Only about 5% of all storm surge events were due to a strong eastern air flow over the southern Baltic along the southern edge of an anticyclone over northern Russia and Scandinavia. During some of the easterly storm surge situations, cyclonic circulation was caused by a low over the mainland which, when travelling slowly northwards, was blocked by high pressure over the Baltic.

Kowalewska-Kalkowska & Wiśniewski (2009) demonstrated that at the Pomeranian Bay coast, deep lows moving at high velocity produced high and short-term (ensuing within a few to several hours) storm surges caused by the atmospheric pressure effect. Wind-induced storm surges prevailed during the passage of shallow and slow low-pressure systems. The most dangerous storm surges at the Pomeranian Bay coast occurred during passages of deep and intensive low pressure systems near the coast of the southern Baltic, with an extensive system of winds from the northern sector.

In 1993–2007, the sea level in Świnoujście (the Pomeranian Bay coast), as recorded by the Harbour Master's Office, ranged from 1.33 m below MSL to 1.83 m above MSL (a range of 3.16 m). The highest sea level (1.83 m above MSL) was observed on 4 November 1995. The number of storm surges (sea levels higher than 0.6 m above MSL) differed greatly from year to year, from 4 (1994) to 18 (2007), confirming the irregularity of storm surge occurrence along the southern Baltic coast reported by Zeidler et al. (1995). Most of the surges were recorded within November–February. In January, warning levels (0.6 m above MSL) occurred during 5.9% of the total number of observations, with the alarm state (0.8 m above MSL) recorded during 1.9% of observations. Usually, the first storm surges appeared in September, and the last surge events occurred in April. The period of May–August was usually free of storm events. Occasionally, the warning level was exceeded as a result of strong winds from the northern sector.

Alarm levels in Świnoujście were exceeded during 53 storm events; the level of 1.0 m above MSL was exceeded during 20 of them (Table 1). The largest sea level change of 0.56 m $h^{-1}$ was recorded on 1 November 2006. The storm surge duration depended mostly on characteristics of the corresponding low-pressure system passing over the Baltic. During the strongest November 1995 storm event, the alarm level was exceeded for 33 h.

Wave action in the Pomeranian Bay is strongly related to wind-generated surface waves or post-storm swell. On the basis of their observations in the second half of the 1990s and results of modelling with the WAM4 model, Pruszak et al. (2000) reported that the maximum single wave height in the bay was 6.5 m, and the maximum significant wave heights in the bay's inshore zone amounted to 3.3 m. Due to the largest fetch produced by the north and north-east winds, those winds also produce the highest and most dangerous waves and storm surges. Similar findings were reported by Paplińska (1999).

## 2. MATERIALS AND METHODS

### 2.1. Study area

The study area extends along a 16 km long stretch of the shoreline of the Uznam (Usedom) and Wolin Islands (southern Baltic) forming a sandbar. The sandbar consists of 2 sand spits between the morainic plateaus of the 2 islands (Fig. 1). Both spits emerged as a result of accumulation of sea sand eroded from the Wolin and Usedom moraines (Keilhack 1912).

At present, the entire barrier created by the 2 spits is covered by dune ridges formed during various accumulation stages since the Atlantic period (5000 yr BP). The youngest dunes — white dunes I (large with transvers) — developed in the 17th century. Following the construction of jetties protecting the River Świna outlet in the 18th century, the adjacent stretch of the coast was observed to accumulate sandy sediment (Keilhack 1912). Since the beginning of the 19th century, 11 dune ridges — white dunes II (up to 7 m high; Łabuz 2009a) — have developed in the most accumulation-prone central part of the sandbar. The dune shape and between-ridge distance evidence intensive progradation, accelerated due to the presence of the jetties. The

Table 1. Characteristics of extreme storm surges (≥1 m above mean sea level, MSL) in Świnoujście in 1993–2007 (data from the Harbour Master's Office in Świnoujście). Bft: Beaufort scale

| No. | Year | Date of occurrence | Maximum sea level (cm above MSL) | Maximum sea level change (cm h$^{-1}$) | Duration (h) of alarm levels (≥80 cm above MSL) | Maximum wind force (Bft) | Wind speed (m s$^{-1}$) | Wind direction | Maximum sea state (WMO scale) | Minimum air pressure (hPa) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1993 | 21–22 Feb | 150 | 55 | 17 | 9 | 20.8–24.4 | N | 7 | 984 |
| 2 | 1995 | 1–5 Jan | 124 | 15 | 13 | 7 | 13.9–17.1 | N-NE | 4 | 988 |
| 3 | 1995 | 7–9 Apr | 105 | 17 | 21 | 10 | 24.5–28.4 | NW | 6 | 1000 |
| 4 | 1995 | 31 Aug – 2 Sep | 115 | 15 | 18 | 10 | 24.5–28.4 | N-NE | 7 | 1006 |
| 5 | 1995 | 2–6 Nov | 183 | 49 | 33 | 11 | 28.5–32.6 | NW-NE | 7 | 991 |
| 6 | 2001 | 8–11 Nov | 102 | 13 | 16 | 7 | 13.9–17.1 | NW-NE | 5 | 984 |
| 7 | 2001 | 15–17 Nov | 102 | 40 | 7 | 7 | 13.9–17.1 | NW-N | 4 | 1021 |
| 8 | 2001 | 22–25 Nov | 100 | 25 | 14 | 9 | 20.8–24.4 | NW-N | 4 | 996 |
| 9 | 2002 | 1–3 Jan | 109 | 34 | 15 | 9 | 20.8–24.4 | NW-NE | 6 | 1010 |
| 10 | 2002 | 19–22 Feb | 140 | 39 | 12 | 12 | >32.6 | NE | 7 | 985 |
| 11 | 2003 | 6–7 Dec | 102 | 43 | 8 | 10 | 24.5–28.4 | N-NE | 6 | 999 |
| 12 | 2004 | 22–25 Nov | 135 | 30 | 19 | 10 | 24.5–28.4 | N | 5 | 994 |
| 13 | 2005 | 23–26 Jan | 112 | 15 | 22 | 7 | 13.9–17.1 | NE | 5 | 1001 |
| 14 | 2006 | 31 Oct – 4 Nov | 143 | 56 | 21 | 11 | 28.5–32.6 | N | 7 | 989 |
| 15 | 2007 | 18–19 Jan | 138 | 44 | 10 | 10 | 24.5–28.4 | NW | 7 | 962 |
| 16 | 2007 | 21–23 Jan | 109 | 19 | 19 | 8 | 17.2–20.7 | NW | 4 | 993 |
| 17 | 2007 | 24–26 Jan | 119 | 11 | 20 | 10 | 24.5–28.4 | NE | 4 | 1006 |
| 18 | 2007 | 26–28 Jan | 106 | 49 | 20 | 8 | 17.2–20.7 | NW | 5 | 998 |
| 19 | 2007 | 28–30 Jan | 122 | 28 | 5 | 10 | 24.5–28.4 | N | 6 | 993 |
| 20 | 2007 | 31 Jan – 2 Feb | 102 | 21 | 8 | 10 | 24.5–28.4 | NW-N | 6 | 998 |

beach is covered mostly by medium sand, but fresh aeolian deposits (the aeolian layer or ripples) are dominated (up to 80–90%) by fine sand. Fine and very fine sands are the major (up to 85%) component of the foredune ridge, and medium sand accounts for no more than 15% (Łabuz 2005). As a result of erosion along the eastern part of the spit near the town of Międzyzdroje, the older, yellow dunes are at present closest to the water line. Marine sediments are still being accumulated in the central and western parts of the sandbar, with the coastline shifting slowly northward (Łabuz 2005).

Coastal accretion is in progress, and new dune ridges are being formed. Since 1986, 3 new foredune ridges (up to 5.5 m high) have been evolving in the central part of the sandbar, at the Wolin coast. Accretion in the eastern part of the sandbar proceeds at a slower rate, as evidenced by the presence of only a single dune ridge being formed since 1986. Studies carried out since 1996 have revealed the development of new ridges in the central, accumulation-prone section of the sandbar, between km 421 and 419 of the Polish coast; the ridges took 5 to 6 yr to emerge (Łabuz 2005, 2009a). Until 2003, the youngest ridge, which formed in 2001, was repeatedly subjected to severe storm-caused damage along its entire length. As of 2004, the wave-driven erosion of the ridge in question, located in the central section of the sand bar, was observed to abate because of the increased level of the upper beach and the formation of embryo dunes 3 to 4 m above MSL. No penetration of water during the maximum storm surges was observed higher than 3.2 m above MSL. In contrast, storm surges eroded the previously accumulated deposits in the remaining sections of the sandbar (Łabuz 2009a).

## 2.2. Meteorological and sea level data

The meteorological and hydrological description of the November 2004 storm surge was based on the routine data provided by the Harbour Master's Office in Świnoujście, collected by the Vessel Traffic System, which has been in operation since the 1990s. The data sets included hourly readings of wind conditions (direction and speed) and atmospheric pressure as well as sea levels, relative to Normal Null (NN), the land survey datum of Poland). Hourly data used to describe the storm surge made it possible to accurately assess the impact of weather conditions on the storm surge parameters (in a previous study, Wiśniewski & Kowalewska-Kalkowska 2007 applied data collected with a lower resolution of 4 h). Daily Earth surface air pressure distributions, provided by the German Weather Service

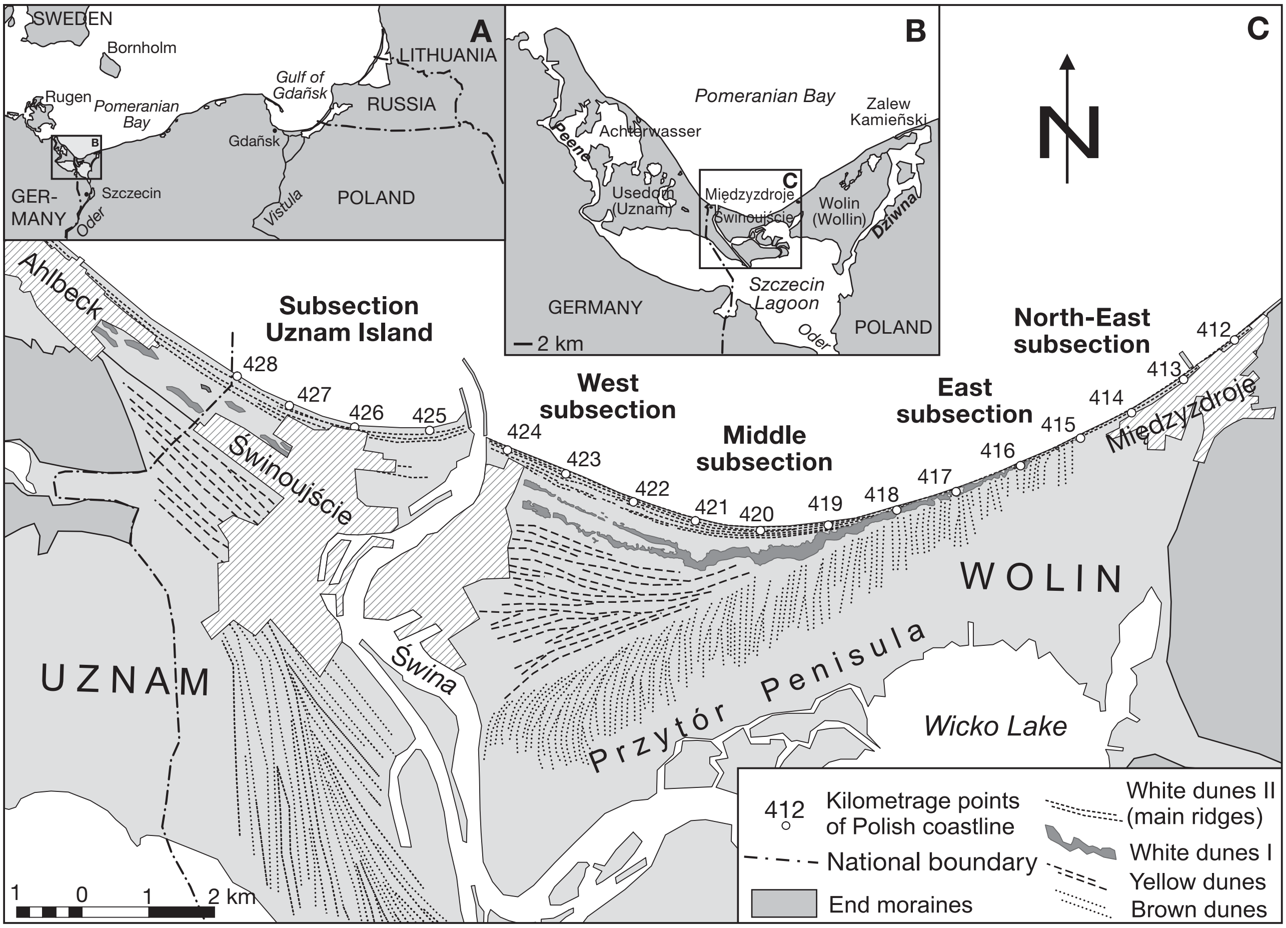

Fig. 1. Study area. (A) Location at the Polish Baltic coast; (B) location of the study site on the Usedom and Wolin Islands; (C) geomorphological map of the Świna Gate Sandbar (Łabuz 2005 after Keilhack 1912). Urban areas marked by single hatching

(www.wetterzentrale.de/topkarten/fsfaxsem.html), were used to characterise the features (trajectory, velocity of passage, pressure in the centre) of a corresponding atmospheric low-pressure system.

### 2.3. Field data

Changes in the relief of the coastal section examined were determined based on the analysis of beach profiles of transects established at 1 km intervals along the entire sandbar. Each transect was assigned a number (412 to 424), identical with the km classification of the Polish coastline. The transects extended from the fixed and stable parts of the dunes to the water line. The transects were established using geodesic tools (e.g. a leveller) and a measuring tape.

To quantify the changes caused by the storm surge, the transects surveyed on 26 and 27 November 2004, i.e. 3 d after the storm, were compared to those surveyed on 17 and 18 September 2004 (the last survey before the November storm surge).

On the morning of 23 November, additional levelling measurements were taken, and changes observed in the coastal relief were recorded. Sites with the strongest surge-caused beach and dune erosion along with washover fan development were identified. Effects of water dynamics on the transect profile were recorded, and sites featuring erosion-caused depressions and gutters were identified. The data thus obtained served to characterise the coastal relief 3 d after the storm.

Using Microsoft Office Excel and Golden Software Grapher, the transect profile data were used to determine changes in the height and width of the dunes and beach, which was then used to calculate the volume of sediment displaced from every square metre. This way, changes in the sediment volume were determined for individual coast morphology features, i.e. the lower beach, upper beach, foredune, depression behind the foredune, and the second dune ridge.

## 3. RESULTS

### 3.1. Storm surge description

The 22–25 November 2004 storm surge was caused by the passage of a deep low-pressure system moving from the North Sea over the central part of the Baltic and then over the Black Sea (Fig. 2). Initially, on 22 November, the residence of the low (991 hPa in the centre) over the North Sea and the development of a high-pressure system (1034 hPa) over central Europe generated a system of strong offshore southern and south-western winds (6 on the Beaufort scale [Bft], i.e. speed of 10.8–13.8 m s$^{-1}$) at the Pomeranian coast causing a drop in water level to 0.29 m below MSL at Świnoujście (11 am) (Fig. 3). The sea level at the southern Baltic coast was then observed to rapidly rise as as the centre of the low (984 hPa) shifted over the central Baltic, at an average speed of 13 m s$^{-1}$. At the southern Pomeranian Bay coast, the maximum sea levels were observed on 23 November, resulting from the combined effects of strong north-western and northern onshore winds up to 10°B, i.e. 24.5–28.4 m s$^{-1}$, and a drop in atmospheric pressure. In Świnoujście, the maximum level of 1.35 m above MSL occurred at 8 p.m. The highest rise in the sea level (by 1.12 m) was observed to occur between 07:00 and 16:00 h. Subsequently, the low moved to the south-east (at a velocity of 12 m s$^{-1}$) and a high developed over central Europe (1036 hPa), generating offshore south-western winds at the Pomeranian Bay coast, which resulted in a significant decrease in the water level at the Pomeranian

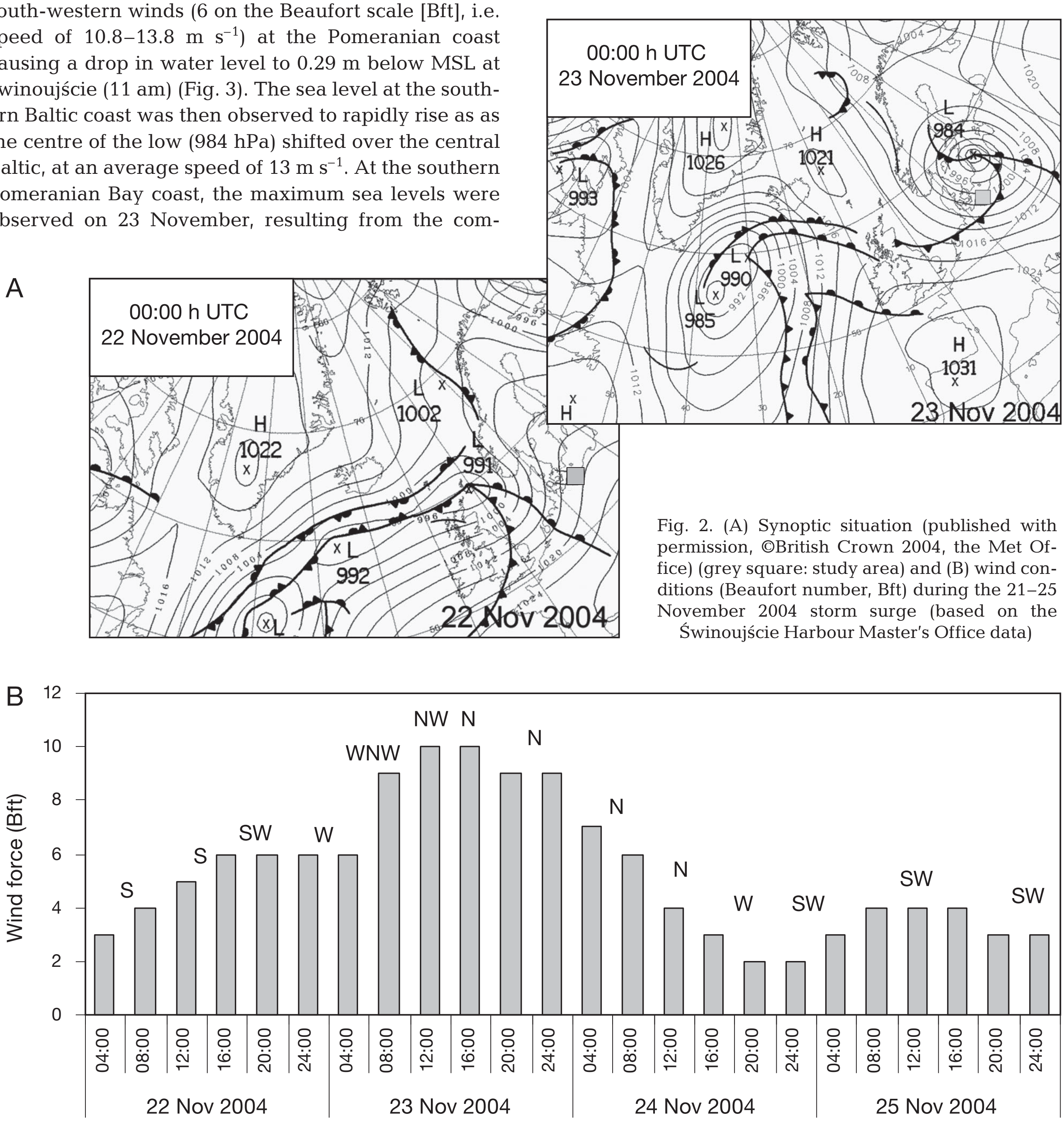

Fig. 2. (A) Synoptic situation (published with permission, ©British Crown 2004, the Met Office) (grey square: study area) and (B) wind conditions (Beaufort number, Bft) during the 21–25 November 2004 storm surge (based on the Świnoujście Harbour Master's Office data)

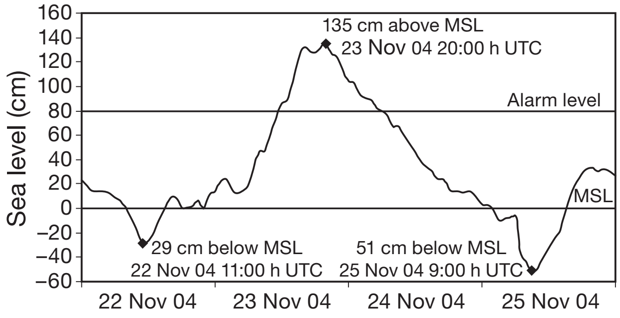

Fig. 3. Sea level changes at Świnoujście gauging station during the 21–25 November 2004 storm surge (based on the Świnoujście Harbour Master's Office data). Mean sea level (MSL) = 5.00 m at the tide gauge relative to NN, the land survey datum of Poland

Bay coast over the next 2 d. In Świnoujście, the minimum level of 0.51 m below MSL was observed on 25 November at 09:00 h. During the storm surge discussed, the levels remained at least at the warning state for 25 h. The alarm level was exceeded for 19 h, beginning at noon on 23 November until 06:00 h on 24 November. The level of 1.0 m above MSL persisted for a half day. The maximum sea state (5, i.e. wave height between 2.0 and 3.5 m) was observed to last for 16 h.

Field measurements on 23 November showed that the sea level rose by 1 m between 07:00 to 16:00 h. At 07:00 h, the water reached only the lower beach, up to 1 m above MSL. The upper beach experienced intense aeolian transport. The wind speed, as determined with an anemometer, averaged 12.5 m $s^{-1}$ at the beach surface, 17.8 m $s^{-1}$ at 1 m, and 19 m $s^{-1}$ at 1.5 m above the surface.

Several minutes of rain halted aeolian transport for 40 min. At about 13:00 h, the wave runup reached the upper beach situated 2 m above MSL. Wave runup in the sections with a lower-lying beach reached the foot of the dune. By 14:00 h, the beaches situated 2 to 2.5 m above MSL were flooded and the water was eroding the foredune ridge. By 16:00 h, the water had removed up to one-third of the dune ridge in the lower sections of the beach. Insufficient light at dusk prevented further observations and measurements.

### 3.2. Coastal erosion

The storm surge affected the 4 subsections of the sandbar differently, with the severity of the damage related to differences in exposure and the initial height of the beach and the foredune. Where the beach was lower than the sum of the wave and surge height, i.e. lower than 2 to 2.5 m, parts of the coast (beach and foredune toe) were washed off by the storm. Where the dune ridge was <3 m above MSL, storm gates were formed and the water entered the slack (depression) behind the foredune to form washover fans. In the eastern and western part of the sandbar, a considerable wash-off affected both the beach and the foredune.

Where the surge did not manage to level off the beach relief (in the middle part of the sandbar), sand was observed to accumulate due to intense aeolian processes. No foredune erosion occurred in the middle section of the sandbar shore (e.g. km 421), which shows a tendency to accrete the sediment. Due to the high level of the upper beach, the aeolian forms at the foot of the foredune were not destroyed by the water, and it was only the lower beach relief that was levelled off.

Prior to the storm, the north-exposed middle subsection of the sandbar (transects 420 and 421), which had tended to accumulate sediment (Łabuz 2005), featured an upper beach (with embryo dunes) up to 3.5 m high. During the 1.3 m storm surge, the water flooded only the lower beach and reached the foredune ridge only through depressions in the upper beach where it left organic debris in washover fans. After the storm, the middle section of the beach became narrower by 15 to 19 m, while the beach height remained unchanged. It was only the lowest embryo dunes that were washed off and the beach surface levelled. In the upper part, aeolian accumulation induced the beach height to increase by 0.2 m at most. The dunes in this section were not affected by the storm (Fig. 4C).

The western subsection of the sandbar (NE exposure), with the beach rising up to 2 m above MSL (transects 422 to 424), showed that the entire beach had been flooded by wave runup within several hours during the storm surge. The waves reached the foot of the foredune ridge and gradually eroded it away. After the storm, the beach was narrower by 4 to 21 m, and the dune retreated by 17 m (e.g. transect 422). The beach height dropped by 0.2 to 0.6 m, and the foredune height was lowered by 0.6 to 1.5 m (Fig. 4D).

The eastern subsection of the sandbar (NNE exposure; transects 415 to 419) had a history of erosion in all of its upper beach aeolian forms; this erosion was associated with previous storm surges (Łabuz 2005). After the storm described in this paper, the beach in this section was wider by 1 to 15 m (Fig. 4B). In the western section, the beach height increased by up to 0.7 m. Further east, however, the beach lost 0.3 to 1 m of its height. The foredune ridge retreated by 4 and 8 m at km 418 and 415, respectively (Fig. 4A).

In the easternmost subsection of the sandbar (NW exposure; transects 412–414), the storm resulted in increased beach width, and beach height was reduced by an average of 0.6 m. The foredune was cut by 0.6 m only where the upper beach was lower than 2.5 m above MSL. Beach width was reduced only in the western and middle sections of the sandbar. This was caused by beach height reduction due to sediment

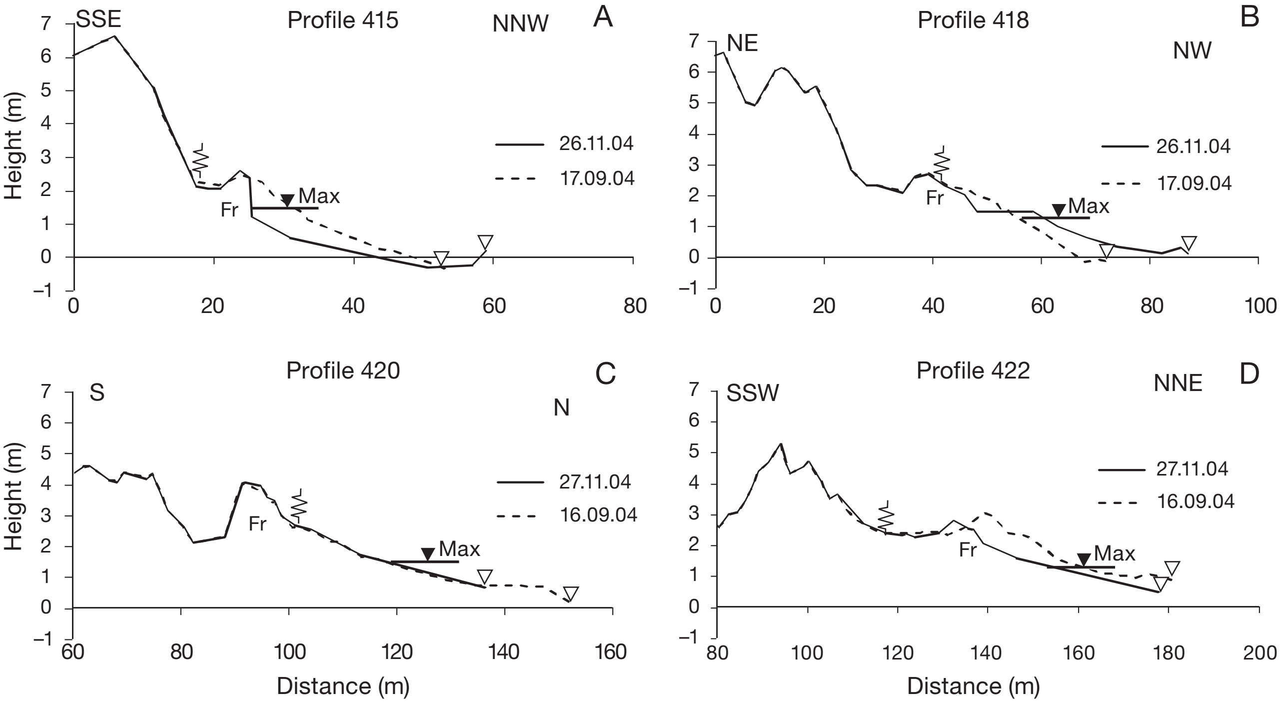

Fig. 4. Coastal changes after the storm surge along differently exposed transects. (A) Strong erosion in the eastern subsection; (B) erosion in the eastern subsection; (C) changes in the middle subsection; (D) erosion in the western subsection. ▼Max: maximum sea level during the storm; ∇: sea level during relief measurements; ≷: wave runup, washover fans; Fr: foredune

blowing off during heavy wind action before flooding. After that, water easily entered the lowered beach, causing its erosion.

The westerly wind exceeding 17 m $s^{-1}$ (as measured 1 m above the beach surface) blew away the sand from the western to the middle section of the sandbar. Erosion affected the beach and foredune ridges that lacked plant cover. In contrast, vegetation-covered sites experienced intense aeolian accumulation. Sediment from the beaches in the western subsection of the sandbar was transported to and accumulated on the foredune of the middle subsection of the study area. Aeolian processes resulted in accumulation of 0.02 and 0.15 m thick sediment layers on the second dune ridge and the foredune, respectively. In the eastern and north-eastern subsection of the sandbar, strong onshore winds resulted in a relatively low accumulation behind the foredune ridge.

### 3.3. Beach and dune sediment budget

Calculations of changes in the sand dunes showed that the largest losses in the dune and beach sediment volume occurred in the western and eastern sections of the sandbar, despite a post-storm increase in the beach width in the eastern subsection. The budget showed a net sediment loss as the beach was substantially lowered due to deflation (i.e. removal of sand by wind action) and erosion. The wind-borne sediment transport from the western subsection prevented the net sediment loss from becoming even larger in the 2 eastern subsections.

The dune sediment budget showed a loss of sediment in the western, eastern and north-eastern parts of the sandbar. The western section incurred a sediment loss because the strong wind first blew the sediment away from the beach, and then the sediment was washed by the storm from the lowered beach and the foredune. We estimate the sediment loss in the western section at 1.05 $m^3$ $m^{-2}$. The eastern and north-eastern sections also suffered sediment losses due to the beach and foredune wash-off. The highest loss, estimated at 1.19 $m^3$ $m^{-2}$, was observed at km 415. Throughout the study area , the average sediment loss was estimated at 0.57 $m^3$ $m^{-2}$ (Table 2). In the middle section, the sed-

Table 2. Examples of the balance of foredune erosion ($m^3$ $m^{-2}$) during the November 2004 storm surge on the Świna Gate sandbar. See Section 2.3 for explanation of profile numbers

| Profile (km); subsection | Mean | Max. | Sum |
|---|---|---|---|
| 415; eastern | 0.57 | 1.19 | 5.13 |
| 422; western | 0.39 | 1.05 | 6.98 |
| 421; middle | 0.04 | 0.26 | 0.79 |

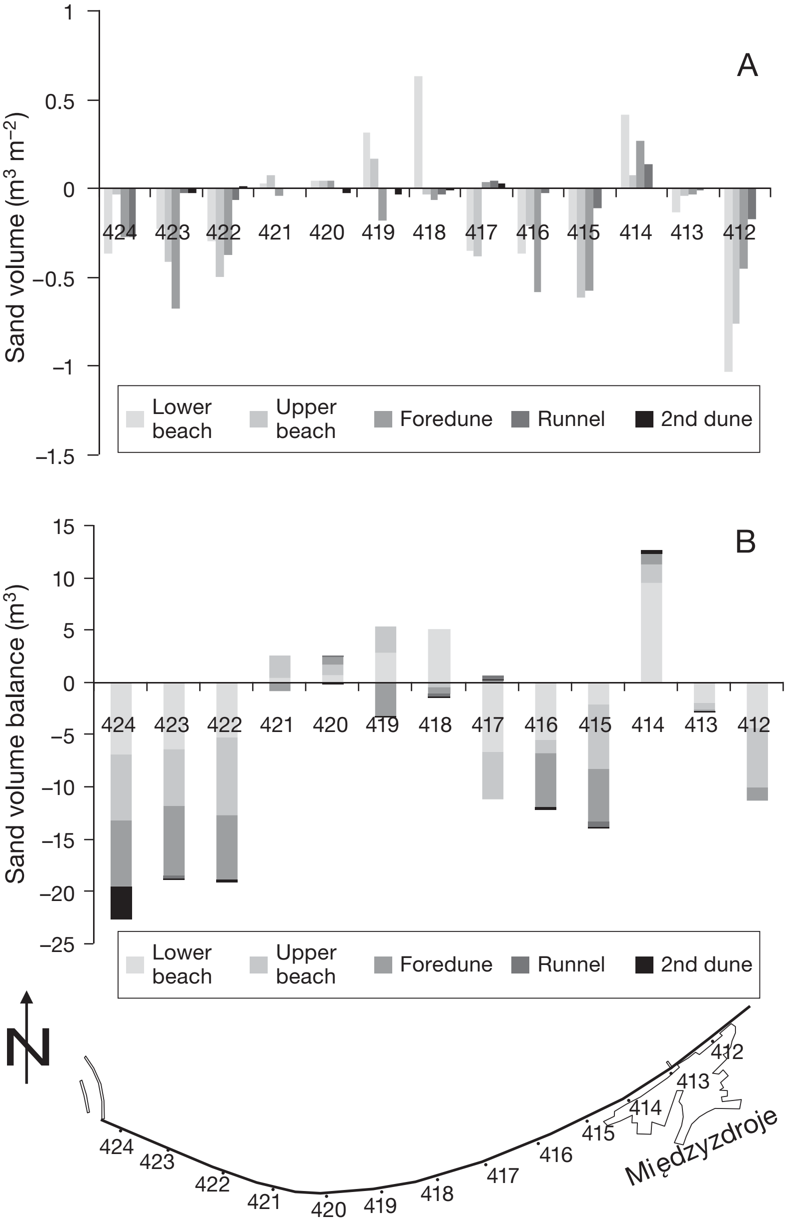

Fig. 5. Sand volume budget along a sandy spit after the storm surge. (A) Sand volume per square metre of transect length; (B) sum of sand volumes along transects

iment budget showed almost no change, with sediment accretion on the foredune and a small loss on the beach (Fig. 5).

## 4. CONCLUSIONS

The extent of coastal erosion and retreat depends on both the sea surge height and its duration. As shown by the levelling measurements taken in this study, the height of the coast reached by the storm surge was up to 3.2 m above MSL. Coastal retreat was consequently more extensive in that part of the sandbar which had beaches lower than 3.2 m above MSL. The storm resulted in a significant erosion of the dune shore in the western and eastern sections of the sandbar area examined. Even a short-lived surge that is 1 m higher than MSL erodes beaches up to 2.5 m high, as well as the dune ridges behind them. Wherever the ridges were lower than 3.2 m above MSL, the sea water would penetrate behind them. If there were only a single narrow ridge, the background area up to 3 m above MSL would be threatened by flooding.

The storm-caused changes in coastal relief observed over the area examined were consistent with general sandbar development tendencies as reported by Łabuz (2009a). Analysis of the results showed a pattern of relief changes that was related to the coastal exposure to storms. The largest changes occurred where, prior to the storm, the beach was lower than the maximum wave runup. At those sites, the dunes were also washed off. Where the beach was higher than 3 m, the water failed to wash off the foredune. Important in this analysis was the wind direction, as at certain locations the wind enhanced accretion and aeolian relief formation during the storm, with erosion enhanced elsewhere. During the storm, as the sand was being blown off by the strong wind, the beach was lowered and subsequently subject to wave runup.

The changes observed were very similar to those described by Tõnisson et al. (2008) after the storm surge in Estonia in January 2005. Dune erosion there reached 4 m, with the shoreline retreating up to 8 m. In some places, the post-storm foredune accretion was as high as 0.7 m. Data on storm surge-caused changes in other parts of the Polish coast show similarities to the consequences of the storm event described in this paper. Storm surges in 2001–2007 resulted in 3 to 6 m foredune retreat, mostly in reflective beaches, i.e. where the beach is low and narrow (Łabuz 2009b).

The 22–25 November 2004 storm surge was one of the most severe surges at the Pomeranian Bay coast over the period 1993–2007. The severity resulted from additive effects of very strong onshore northerly winds and changes in atmospheric pressure on the sea surface during the passage of a deep low-pressure system over the central part of the Baltic. The surge — which raised the sea level to a maximum of 1.35 m above MSL (only 0.61 m less than the highest level ever recorded in Świnoujście), and caused considerable sea level fluctuations — posed a threat to the Pomeranian Bay coast and affected shore and beach stability.

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