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# Storm surges in the Odra mouth area during the 1997–2006 decade

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The 1997–2006 storm surges in the Odra River mouth area (a complex structure encompassing the terminal section of the Odra split into two branches, the Szczecin Lagoon, and the inshore Pomeranian Bay in the southern Baltic Sea) were analysed to assess the impact of wind action and changes in atmospheric pressure during passages of low-pressure systems over the Baltic on the magnitude, duration, and extent of the surges. The study revealed three types of storm surges differing with respect to the dominant causative factor (baric wave, wind, and wind and baric wave combined). The baric wave-induced storm surges, recorded only at the Pomeranian Bay coast, were associated with the passage of deep and fast cyclones. The wind- and baric wave-caused storm surges coupled with an extensive system of northerly and north-westerly winds resulted in wind-driven backflow in the Odra branches. Most of the surges were recorded within November–February.

## Introduction

The water level of the Baltic Sea varies substantially within a year as a result of overlap of a number of meteorological and hydrological factors. Due to the sea's fjordlike shape, the peripheral parts of the Baltic may show the maximum sea level variations of up to 5.7–5.8 m. In the central part of the Baltic the range covers 2–3 metres (Suursaar *et al*. 2003). The main factors affecting the sea level include the wind and weather systems over the Baltic Sea and the North Atlantic, the water exchange between the North and Baltic Seas, the mean sea level of the North Sea as well as the riverine runoff into the Baltic. Precipitation, evaporation, seasonal water density changes, and seiches as well as bathymetry and type of the coastline are other factors affecting the sea level (Heyen *et al*. 1996, Samuelsson and Stigebrandt 1996, Carlsson 1998, Cyberski and Wróblewski 1999). Tidal effects on the sea level are negligible along the Baltic Sea coast (Suurssar *et al*. 2003, Jasińska and Massel 2007).

Frequent passages of low pressure weather systems over the Baltic Sea generate considerable sea-level fluctuations. Suursaar *et al*. (2003) pointed out that the highest surge events at the west Estonian coast are associated with deep cyclones producing strong SW and W winds in the suitably oriented bays such as the Pärnu Bay. As reported by Suursaar *et al*. (2006), the cyclone Gudrun that occurred in January 2005 caused the heaviest storm surge along the coasts of the Gulf of Riga. The sea level in Pärnu was by 2.75 m higher than the mean level there. In the Gulf of

Finland, new records of sea level increase were measured as well, e.g., in Helsinki (1.51 m).

Skriptunov and Gorelits (2001) showed that significant wind-induced variations in the water level near the Neva River as well as their magnitude and duration result from wind regime and the morphology of the near-mouth offshore zone. In a recent study, Averkiev and Klevanny (2007) — who analysed the impact of wind direction, wind speed, and air pressure on the sea level in the Gulf of Finland — showed the cyclone trajectory to be of great importance in generating particularly dangerous storm surges in St. Petersburg (Russia). It should be mentioned that in St. Petersburg, the highest sea level increase of 4.23 m was recorded in 1824 (Suursaar *et al.* 2006).

Storm surges at the southern Baltic coast are associated with cyclonic circulation having its centre within the Baltic Sea or in its vicinity, when NW, N or NE onshore winds blow onto land. Those winds are associated with passages of lows entering the Baltic Sea from SW to NW (Majewski *et al.* 1983, Zeidler *et al.* 1995, Sztobryn *et al.* 2005). According to Zeidler *et al.* (1995), the greatest storm surge observed along the southern Baltic coast occurred in 1872 when the sea level at the coast of Schleswig-Holstein exceeded the mean level by 3.2–3.7 m. At the Polish coast, the highest sea level was recorded in 1874 in Kołobrzeg and exceeded the mean level by 2.17 m.

Explanation of storm surge-related changes in the sea level invokes also sea level deformation by the prevailing pressure system. As in the case of a tropical cyclone, a sea level deformation caused by a fast moving, concentric low with its positive phase inside the low and its negative phases outside it (the so-called baric wave) may be analysed. The wave is like a cushion of water under a depression that moves together with it. A static increase in the sea level underneath the atmospheric low is described (Wiśniewski and Holec 1983) by:

$$\Delta H_{\mathrm{s}} = \frac{\Delta p}{\rho g} \qquad (1)$$

where $\Delta H_{\mathrm{s}}$ is the static increase or decrease of the sea level, $\Delta p$ is the increase or decrease of the air pressure relative to the mean pressure, $\rho$ is mean water density, and $g$ is acceleration of gravity. The equation shows that a 1 hPa change in air pressure results in 0.01 m change in the sea level. However, the progressive movement of the low-pressure system results in a dynamic deformation of the sea level, described (Wiśniewski and Holec 1983) by:

$$\Delta H_{\mathrm{d}} = \frac{\Delta H_{\mathrm{s}}}{1 - \frac{v^2}{gH}} \qquad (2)$$

where $\Delta H_{\mathrm{d}}$ is the dynamic increase in the sea level, $v$ is the velocity of the air pressure system movement, and $H$ is an average sea depth. Consequently, the resultant water level changes in different parts of the coast depend not only on the characteristics of the atmospheric low, but also on those of the shallow water inshore zone; and may 2–4 times exceed the increase that could be a result of static conditions. It should be mentioned that, at the Polish coast, dynamic effects of the wave caused by changes in air pressure are more evident in the eastern part of the low, whereas increasing wind speeds are observed in the western part (Wiśniewski and Kowalewska-Kalkowska 2007).

The Odra River mouth area, an estuarine water body in the southern Baltic Sea, features a complex hydrodynamic regime (Fig. 1). In its downstream reach, the Odra opens into the Szczecin Lagoon, a coastal semi-enclosed water body of about 680 km$^2$ surface area and 3.8 m in mean depth. Then it drains into the Pomeranian Bay coastal zone via three narrow straits: the Świna, the Dziwna, and the Peenestrom. Water circulation within the Odra mouth is greatly affected by the shipping channel (about 66 km long, 10–11 m deep, and 250 m wide), extending from Szczecin along the western Odra, intersecting the Szczecin Lagoon and, along the Świna Strait, reaching the Pomeranian Bay. The Bay is a shallow basin with a mean depth of about 13 m, bordered to the south by a highly diversified coastline (Majewski 1980).

Gradients within the whole Odra mouth area are very low. As reported by Buchholz (1990), they range from 0.013% and 0.007% between Gozdowice and Widuchowa and decrease to ca. 0.0003% between Widuchowa and Szczecin and to 0.00015% between Szczecin and Trzebież. Consequently, water levels in the Szczecin Lagoon and in the downstream Odra reach are strongly affected by changes in the sea level. During heavy storm surges associated with strong winds from northern sector, when the sea level in the Bay is higher than that in the Lagoon, the Bay's brackish water enters the Lagoon and raises the water level both there and in the Lower Odra channels. The resultant wind-driven water backflow into the Odra River may penetrate as high up the river as Gozdowice (160 km south from the sea). As found by Ewertowski (1998), water level rise in that section may, in addition to the wind effect, be a result of air pressure changes during the passage of a cyclone over the Baltic Sea. In contrast, effect of the instantaneous Odra discharge on water levels in the river's mouth area is of less importance because, even during Odra flood events, the water level increases by only a few centimetres as the flood wave enters the Szczecin Lagoon. However, Ewertowski (2000) pointed to a possible flood threat in the Odra mouth resulting from combined effects of an active cyclone-induced storm surge and a flood event in the Odra River.

The present study analyses storm surges in the Odra mouth area in 1997–2006 to estimate the impact of characteristics of low pressure systems travelling across the Baltic Sea on the magnitude, duration, and extent of storm surges. First, a general characteristics of water level fluctuations in the Odra mouth area is presented. Then a detailed analysis of typical storm surge patterns in the area of study, resulting from the characteristics of a corresponding atmospheric low, is provided.

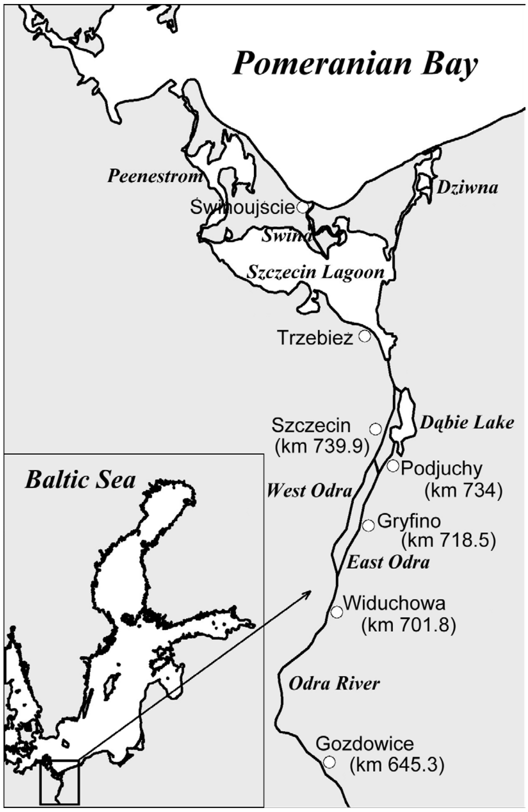


**Fig. 1**. The Odra River mouth area, with the location of gauging stations.

## Materials and methods

The analysis of storm surges in the Odra mouth area in 1997–2006 was based on 114 episodes of a dynamic rise of water level in the Pomeranian Bay and/or Szczecin Lagoon, above the warning or alarm states, during the passage of a low pressure system over the Baltic Sea. In addition, the analysis took note of rapid storm-caused falls in the sea level. First, selected storm events were analyzed in relation to characteristics (trajectory, velocity of passage, pressure in the centre) of a corresponding atmospheric low and local wind conditions (direction and velocity). The effect of instantaneous water level in the lower Odra branches was taken into consideration as well. Subsequently, an impact of the wind action and an air pressure effect on the amplitude, duration, and extent of each storm surge in the Pomeranian Bay, Szczecin Lagoon, and the downstream Odra branches were estimated. On that basis, three typical patterns of the storm events in the Odra mouth area were identified.

The analyses involved data obtained from routine readings collected at gauges located in the Odra mouth area, including the southern part of the Pomeranian Bay, the Szczecin Lagoon, and the downstream reach of the Odra. The Pomeranian Bay was represented by the gauging station at Świnoujście, the Szczecin Lagoon being represented by the Trzebież gauge. The gauges in Szczecin, Podjuchy, Gryfino, Widuchowa, and Gozdowice were considered representative for the water levels along the downstream channels of the Odra River (Fig. 1).

The water level readings taken in Świnoujście, Trzebież, and Szczecin as well as the weather conditions data at those locations (4-h resolution) were collected by the Harbour Master's Office in Szczecin within the framework of the Vessel Traffic System, in operation from the 1990s. Daily water level data in the downstream reach of the Odra were made available by the Regional Board of Water Management in Szczecin. In the analysis, all the water level series data were referred to the mean sea level (MSL = −5.00 m N.N.$_{55}$, the land survey datum of Poland). In Świnoujście and Szczecin, the warning and alarm states are 0.6 m and 0.8 m above MSL, respectively; the respective levels in Trzebież are 0.4 m and 0.6 m above MSL. Daily Earth surface air pressure distributions were provided by the National Meteorological Archive, Met Office in Exeter and the German Weather Service (http://www.wetterzentrale.de/topkarten/fsfaxsem.html).

## Results and discussion

### Characteristics of water level fluctuations in the decade 1997–2006

In 1997–2006, sea levels ranged from 1.3 m below MSL to 1.49 m above MSL in Świnoujście (the range of 2.79 m) and from 0.52 m below MSL to 0.96 m above MSL in Trzebież (the range of 1.48 m). Warning levels occurred during 1.65% of the total number of observations in Świnoujście, the corresponding frequency at Trzebież being 6.83%; the respective alarm levels frequencies were 0.34% and 1.21%.

The largest sea level changes were observed at the Pomeranian Bay coast. The maximum drop in the sea level amounted to 0.21 m an hour, the highest rise being 0.25 m. Because of strong suppression of sea level fluctuations in the straits connecting the Pomeranian Bay with the Szczecin Lagoon, water level fluctuations in the Lagoon and in the Odra channels were weaker. In Trzebież, the maximum drop and the highest rise amounted to 0.09 m and 0.1 m an hour, respectively.

Although the mean free surface gradient between the Szczecin Lagoon (Trzebież) and the Pomeranian Bay (Świnoujście) amounts to a few centimetres only, during storm surges the gradients were observed to oscillate within a substantial range, a reversed slope of free surface of water being occasionally observed (from −1.13 m to +1.30 m). Differences in the water level between the tide gauges in the lower Odra channels were less significant; those between Szczecin and Trzebież ranged from −0.43 m to +0.44 m.

In the period discussed, 114 events of a dynamic water level rise above the warning or alarm states, during the passage of a low pressure system over the Baltic Sea, were recorded in the Pomeranian Bay and/or in the Szczecin Lagoon. The alarm levels, as recorded in Świnoujście, were exceeded during 23 storm events; the level of 1.0 m above MSL was exceeded during six of them. The highest sea level of 1.49 m above MSL was observed on 1 November 2006. In Trzebież, the alarm level was exceeded during 34 storm surges. The highest level (0.96 m above MSL) was observed on 21 February 2002. In Szczecin, the highest level (1.0 m above MSL) was observed on 21 February 2002 as well. It should be mentioned that the highest level ever recorded in Świnoujście was 1.96 m above MSL (in 1874), whereas in Trzebież it was 1.37 m above MSL (in 1913) (Majewski 1980).

The number of storm surges differed greatly from year to year, from 8 (2003) to 16 (2001), 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. Usually, the first storms surges appeared in late September, the final surges occurring in April. The period of May–August was usually free of storm events. Occasionally, the warning level in the Szczecin Lagoon was exceeded as a result of strong northerly winds.

### Typical patterns of storm surges in the Odra mouth area

#### Storm surges induced mainly by atmospheric pressure changes

In 1997–2006, 11 deep lows travelling over the Baltic Sea at a high speed generated short-lived

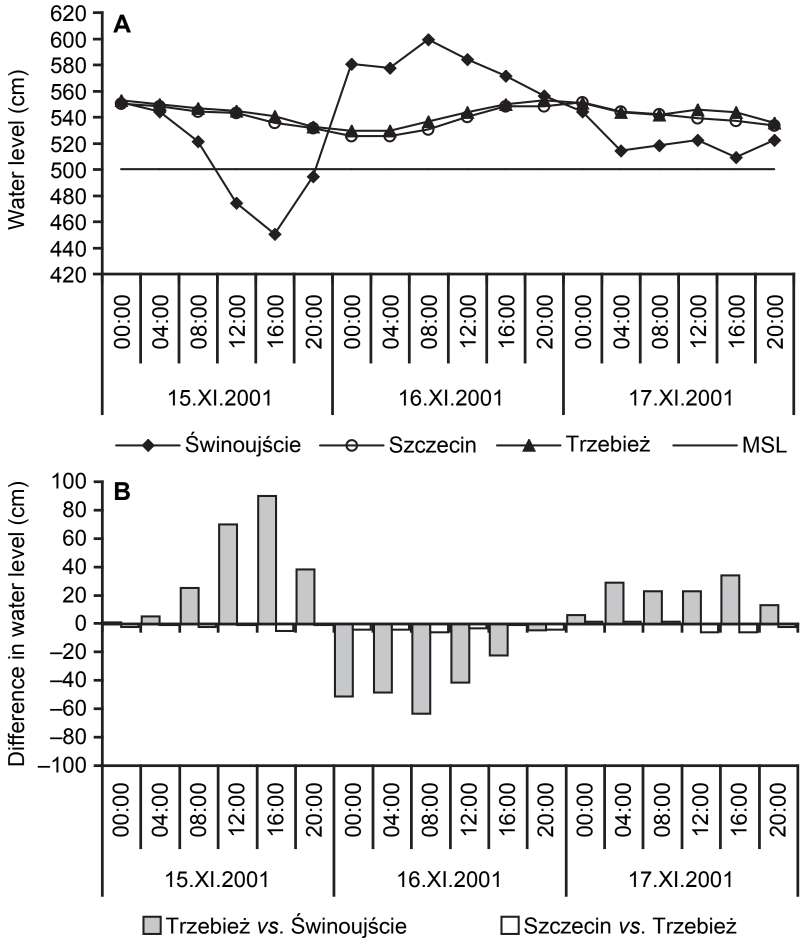


**Fig. 2**. (**A**) Water levels and (**B**) differences in water level in the Odra mouth during the 15–17 November 2001 storm surge. Note: mean sea level (MSL) = –5.00 m $NN_{55}$ (Amsterdam) = –5.08 m $H_{Kr}$ (Kronshtat).

storm surges, registered only at the Pomeranian Bay coasts. They resulted mainly from changes in the air pressure at the sea surface. The wind effect was less pronounced due to the relatively short duration of winds from individual directions. Effects of the low's shift were often negligible in the Szczecin Lagoon and in the downstream Odra reach because of a too low hydraulic capacity in the straits connecting the Lagoon with the Pomeranian Bay.

That pattern of water level fluctuations in the Odra mouth was followed during the storm surge that occurred within 15–17 November 2001. A fast low pressure system from the Norwegian Sea passed over the central part of Scandinavia and progressed further east over the Gulf of Finland, inducing a storm surge at the southern coast of the Baltic. On 15 November, the residence of the low (974 hPa in the centre) over the Norwegian Sea and the development of a high pressure system (1040 hPA in the centre) over western Europe resulted in strong (6 Bft) WSW winds along the Pomeranian Bay coast and in a water level drop down to 0.5 m below MSL at 16:00 (Świnoujście) (Fig. 2A). Next day, the fast movement of the low (at an average speed of 16.8 m $s^{-1}$) over the Gulf of Finland (978 hPa) and a change in the wind direction (NW–NNE) resulted in a fast rise of the water level. The highest rise (by 1.3 m) was recorded in the afternoon and evening on 15 November. In Świnoujście, the maximum sea level reached 0.99 m above MSL (recorded at 8:00 on 16 November). Later on, the eastward shift of the low (at an average speed of 10.3 m $s^{-1}$) and the further development of a high (1042 hPa in the centre) over the western and central Europe generated the system of WSW winds and resulted in a fast drop of the sea level by 0.9m (negative phase of the baric wave). The sea level reached 0.09 m above MSL at 16:00 on 17 November.

During the November 2001 storm, effects of the fast shift of the low were negligible in the Szczecin Lagoon and in the lower Odra channels. The Szczecin Lagoon water level changes were only within a few centimetres. The high water levels both in the Lagoon (the warning level) and along the downstream Odra reach (the warning levels in Podjuchy and Gryfino) resulted from accumulation of water during an earlier wind-driven backflow, observed in the first half of November 2001.

As a result of different responses of free water surface to the fast movement of deep depression in the Pomeranian Bay and in the Szczecin Lagoon, the water levels in those areas differed substantially. Initially, on 15 November, the Szczecin Lagoon water level was much higher than that in the Pomeranian Bay (Fig. 2B). The difference between the water levels in Trzebież and Świnoujście was even as high as 0.9 m. On 16 November, the reversed slope of free surface between the Pomeranian Bay and the Szczecin Lagoon was observed and the sea level in the Bay was higher than the water level in the Lagoon by more than 0.6 m. Again on 17 November, a fast drop of the sea level in the Bay resulted in the Lagoon's water level being higher, even by more than 0.3 m.

## Storm surges caused mainly by wind activity

In 1997–2006, 62.3% of all the surges resulted mainly from strong winds. They were caused mostly by the passage of shallow and slow low-pressure systems over the Baltic Sea. Under such circumstances the pressure effect was imperceptible. In such surges, both the rising and dropping phases of the water level change were slow and gentle. Raised water levels were observed both in the Pomeranian Bay and in the Szczecin Lagoon as well as along the downstream reach of the Odra. Whenever water accumulated in the Odra mouth, a wind-caused storm surge was more intensive, resulting in a prolonged rise of the water levels in the Lagoon and in the lower Odra channels.

Such situation is aptly exemplified by a shallow storm surge that occurred between 4 and 10 April 2003. The surge resulted from the passage of a low pressure system (988 hPa in the centre) from the Norwegian Sea over the Gulf of Bothnia and further east over Finland (994 hPa in the centre) at 13.4 m $s^{-1}$. As of the evening of 4 April, a subsequent slow sea level rise, from 0.29 m below MSL up to the maximum of 0.88 m above MSL on at 4:00 on 6 April was observed in Świnoujście (Fig. 3A). The sea level rose by a few centimetres an hour, up to 0.1 m only. The alarm level was exceeded throughout the day on 6 April as a result of the low's slow shift south and further east (at an average speed of the depression of 6.4 m $s^{-1}$ only) as well as due to strong northerly and north-easterly winds (7–9 Bft). Over the following days, the Pomeranian Bay coast experienced a slow and gentle drop of the sea level (averaging a few centimetres an hour).

During the storm surge discussed, the Szczecin Lagoon water level fluctuations followed, with a time lag, the sea level changes. On 5 April, under the prevailing north-westerly and then northerly winds, the water level began to rise up to 0.81 m above MSL in Trzebież. The maximum water level, recorded at 8:00 on 7 April, was observed 28 h after the sea level maximum in Świnoujście. The alarm levels were being exceeded throughout the day on 7 April. Subsequently, the water level was observed to continually drop; however, the level was remaining at the warning state until 10 April.

Raised water levels were observed in the lower Odra channels as well. In Szczecin, the alarm level was exceeded on 6 April. The maximum of 0.89 m above MSL occurred at 8:00 on 7 April as a result of strong (6 Bft) northerly wind. Other gauges in the downstream Odra reach showed a rise in water level of about 0.6 m. At Podjuchy and Gryfino, the alarm levels were exceeded by 0.3 m; in Widuchowa the levels exceeded the warning state. The maximum levels were observed on 7 April. On the other hand, the effect of the storm surge was negligible at Gozdowice, the water level there remaining 0.4 m below the warning level.

During the storm surge discussed, as of 5 April, the sea levels in the Pomeranian Bay

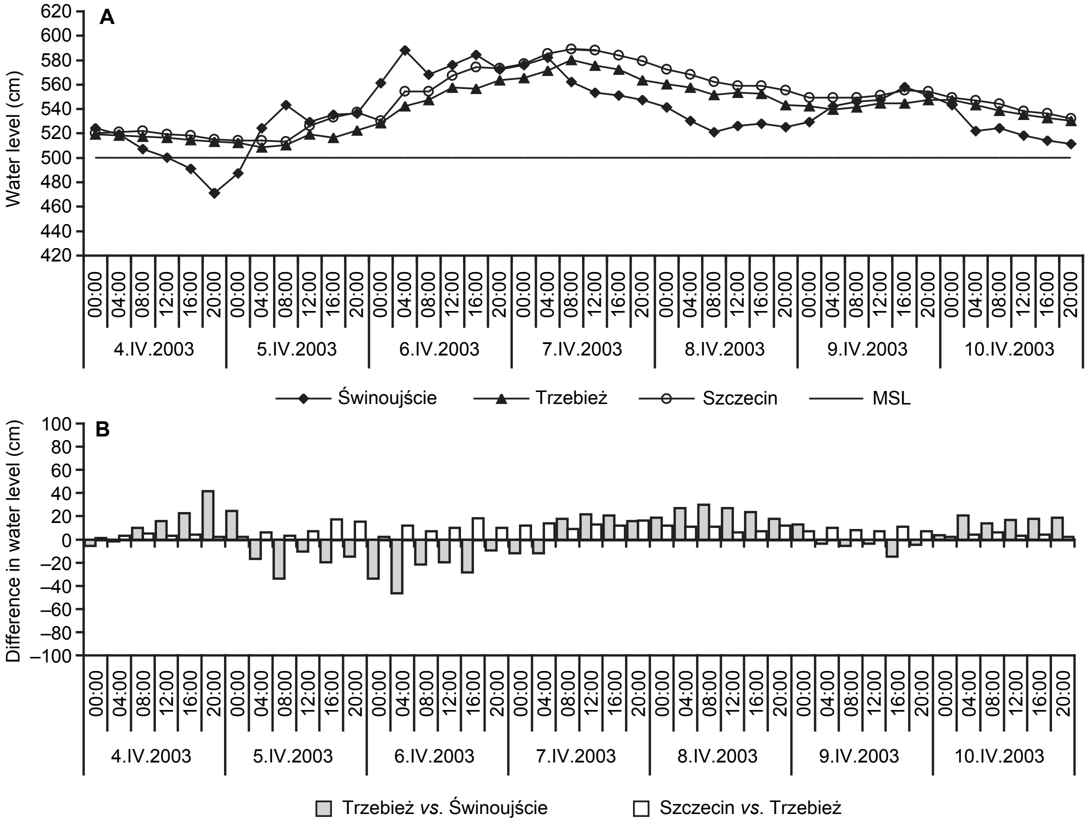


**Fig. 3**. (**A**) Water levels and (**B**) differences in water level in the Odra mouth during the 4–10 April 2003 storm surge.

were higher than those in the Szczecin Lagoon, about half a metre at the most (Fig. 3B). A reversed slope of free surface of water between the Pomeranian Bay and Szczecin Lagoon was maintained for two days. Over the next two days, the Lagoon's water level was higher than that in the Bay, by about 0.3 m at the maximum. Again on 9 April, a slight reversed slope of free surface of water was observed; as of 10 April, the Lagoon's level was higher than the sea level in the Bay.

## Storm surges induced by atmospheric pressure impact and wind activity

In 1997–2006, 32 storm events resulted from the additive effects of wind action and changes in atmospheric pressure on the sea surface during the passage of a deep low pressure system. In such cases, the sea level was observed to increase, at first at the Pomeranian Bay coasts, then in the Szczecin Lagoon, and finally in the lower Odra channels. As a result of the reversed slope of free water surface, a typical wind-driven backflow was observed in the Odra branches. The maximum level resulted from an overlap of the positive phase of the baric wave and winds from the northern sector. Subsequently, the water level was observed to drop as a result of the shift of the low outside the Baltic and an air pressure increase. The effect of the negative phase of the baric wave on the sea surface was very distinct. In the Szczecin Lagoon and along the downstream Odra reach, the water level fluctuations were weaker and followed, with a time lag, the changes in the sea level. During spring ice thaw or accumulation of water derived from a previous storm surge, the water level rises caused by the passage of a deep low pressure system over the Baltic Sea were stronger, resulting occasionally in flood events.

The temporal water level variations during such storm events in the area may be visualized for a case involving the decade's heaviest storm surge that occurred in early November 2006. The storm surge was a result of a passage of a deep and intensive low pressure system over the Baltic Sea. Initially, the water level at the coastal stations was observed to drop on 31 October as a result of the low centre's fast shift over the North Sea (983 hPa in the centre). The lowest sea level of 0.31 m below MSL was recorded in Świnoujście at noon as a result of the negative phase of the baric wave and strong (6 Bft) south-westerly winds (Fig. 4A). Subsequently, the water level at the southern Baltic coast was observed to rapidly rise as a result of the low centre's shift over the southern part of Sweden and then eastward over the central Baltic, at a velocity of 14.75 m $s^{-1}$. At the southern Pomeranian Bay coast, the maximum levels were observed on 1 November, resulting from the overlap of the positive phase of the baric wave and strong northerly winds (8–9 Bft). In Świnoujście, the maximum level of 1.49 m above MSL occurred at 16:00. The highest rise in the sea level (by 1.5 m) was observed to occur between 8:00 and 16:00. From 12:00 to 16:00, hourly rises in the sea level were as high as 0.25 m. During the subsequent days, the low centre's intensity weakened and the low passed over the Gulf of Finland (986 hPa in the centre, an average speed of 9.1 m $s^{-1}$) and then moved northeast, resulting in the ensuing drop in the sea level at the southern Baltic coast.

During this storm surge, the Szczecin Lagoon water level began to rise on 1 November and exceeded the warning level at first, and then the alarm level. In Trzebież, the maximum water level reached 0.71 m above MSL at noon of 3 November and was observed 2 days after the sea level maximum in Świnoujście. As a result of the 3-day-long prevalence of winds from the northern sector, the warning levels were exceeded for more than three days, the alarm levels being exceeded for more than one day. As of the afternoon of 3 November, the water level was observed to drop slowly, down to 0.32 m above MSL on 6 November.

The effect of the passage of that low pressure system was also recorded by the gauges located in the downstream Odra reach. In Szczecin, the warning level was exceeded during three consecutive days. A maximum of 0.78 m above MSL occurred at 16:00 on 3 November. On 2 November, the 0.8 m water level rise at Podjuchy and Gryfino resulted in the alarm level being exceeded. At Widuchowa that day, the water level rose by ca. 0.8 m as well. In Gozdowice, the effect of the storm surge was negligible and the water level remained in the range of low states.

During the storm surge discussed, the slope of free surface of water between the Pomeranian Bay and the Szczecin Lagoon remained reversed for more than one day, and was as high as 1.13 m on 1 November (Fig. 4B). As of the afternoon of 3 November, accumulation of water in the Szczecin Lagoon resulted the Lagoon's level being higher (even by 0.44 m) than that of the Bay for about four days.

## Conclusions

In the decade 1997–2006, there were 114 events of a dynamic rise of the water level in the Pomeranian Bay and/or the Szczecin Lagoon, whereby the warning or alarm states were exceeded during passages of low pressure systems over the Baltic Sea. The baric wave-caused storm surges accounted for 9.6% of all the surges, the wind-induced surges made up 62.3%, whereas wind- and baric wave-caused storm surges accounted for 28.1% of all the surges. Although the surges occurred from September to April, most of the surges were recorded within November–February.

Deep (below 980 hPa) lows, with high energy vortices moving at high velocity produced significant fluctuations of the sea level. The changes were mainly a result of the atmospheric pressure effect; those changes varied within ±1.5m. The wind effect was then less pronounced because of a relatively short-lived wind activity from an individual direction. Such occasions were marked by high storm surges at the Pomeranian Bay coast only, ensuing within a few to several hours.

Wind-induced storm surges prevailed during the passage of shallow (above 980 hPa in the centre) and slow (less than 8 m $s^{-1}$) low-pressure

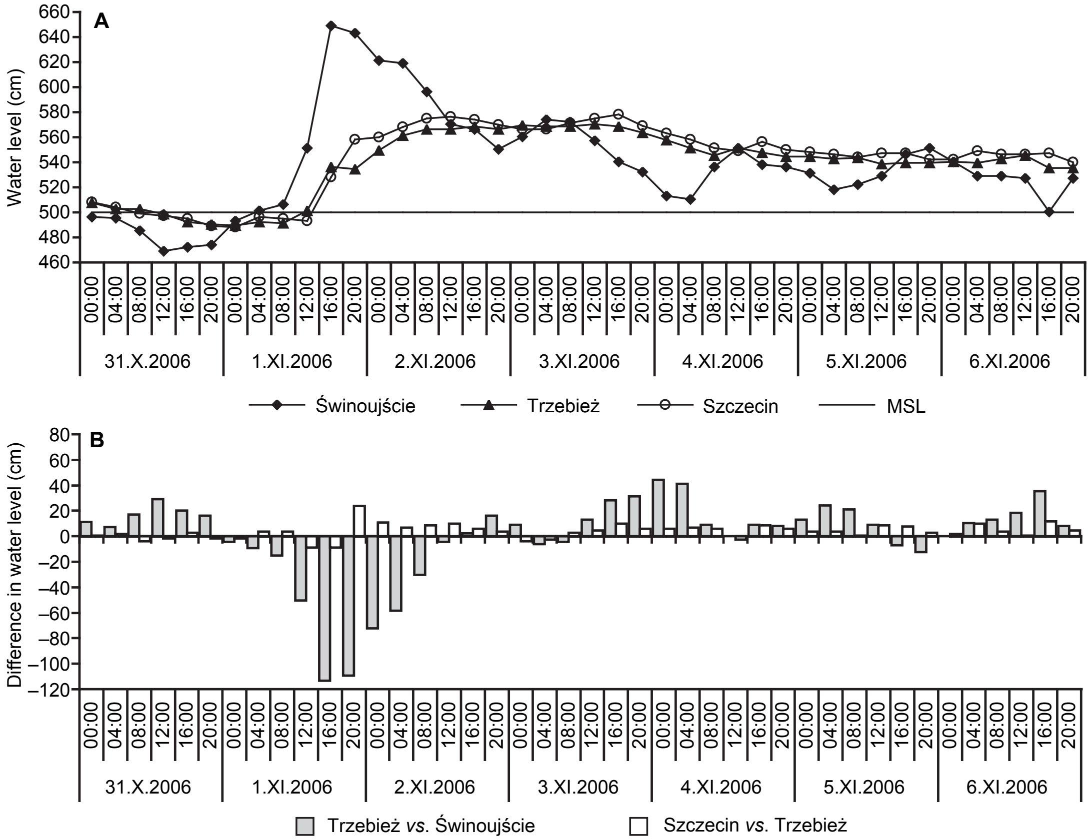

**Fig. 4**. (**A**) Water levels and (**B**) differences in water level in the Odra mouth during the 31 October–4 November 2006 storm surge.

systems or when the low's path was far outside the Baltic Sea. Under such circumstances and depending on wind velocity, duration, and direction, water level fluctuations in the Pomeranian Bay were within ±0.8 m. In the Szczecin Lagoon as well as along the downstream reach of the Odra, water level fluctuations followed, with a time lag, changes in the sea level. Such storm surges in the Odra mouth, with slow and gentle water level fluctuations, took from some days to one week.

The most dangerous storm surges occurred during passages of deep and intensive low pressure systems near the coast of the southern Baltic, with the extensive system of northerly and northwesterly winds. Under such circumstances, the sea level fluctuations in the Pomeranian Bay were the most extensive, sometimes — e.g. in November 2006 — resulting in flooding events. Moreover, during such events, the reversed slope of free surface of water caused the inflow of brackish water from the Pomeranian Bay into the Szczecin Lagoon and resulted in a water level rise not only in the Lagoon, but also in the lower Odra channels. Such surges pose a threat for the Odra mouth as they are capable of flooding coastal areas, polders, and areas adjacent to rivers; they affect shore and beach stability, produce coastal erosion, negatively affect port operations and navigation, and impinge on the coastal zone infrastructure.

The magnitude, extent, and duration of storm surges within the whole Odra mouth depended mostly on the features of a corresponding low pressure weather system passing over the Baltic Sea, i.e. trajectory, velocity of passage, pressure in the centre, and local wind conditions, i.e. direction and velocity. However, other factors such as water discharge of the Odra River, the degree of accumulation of water in the lower

Odra channels, and the amount of water in the Baltic Sea ('fill-up') modified the storm events.

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