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FREQUENCY AND STRENGTH OF STORM SURGES IN THE ODER RIVER MOUTH AREA

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ABSTRACT

The aim of the study was to estimate the frequency and strength of storm surges in the Oder River mouth area during the 1993/94–2016/17 seasons. The analyses involved water level readings recorded at gauges located in the Oder River mouth area, including the coasts of the Pomeranian Bay (Zatoka Pomorska) and the Szczecin Lagoon (Zalew Szczeciński), as well as the downstream reach of the Oder. Recognition of temporal and spatial water level variations in the region under investigation revealed significant irregularities in storm surge occurrence; periods with an increased frequency of surges followed long periods with their scant occurrence. During the year, most of the storm events were observed between November and January. In the period discussed, the most severe and extensive storm surge in the Oder River mouth area was observed in October 2009. Very high surges were recorded in November 1995, January 2012, and January 2017. The long-lasting and extensive high water events in the downstream reach of Oder River resulted from the progressive and prolonged increase in sea level in the Pomeranian Bay. Long-term persistence of high water levels in the Oder River mouth area were also registered when storm surges limited the outflow of the Oder River during snow-melt events, ice jams developing on the lower Oder at the same time. Finally, severe storm events were observed under the condition of the increased water volume in the Baltic Sea.

Keywords: storm surges, water level, water regime, Oder River mouth area

INTRODUCTION

The Pomeranian Bay, with its small depths and a varied shoreline, belongs to those Baltic coastal water bodies that are particularly vulnerable to storm surges (Majewski et al. 1983). The main factors affecting the character of these storm events include the vector wind field, the distribution of atmospheric pressure over the sea, and the filling of the Baltic Sea (Hünicke et al. 2015, Wiśniewska 1979). The most dangerous surge events of the 20th century at the southern coasts of the Pomeranian Bay were associated with low-pressure systems shifting over the Baltic Sea from the Norwegian Sea towards the south-east (Sztobryn et al. 2005). The highest water level was recorded during the storm surge on 9–10 February 1874, when the sea level in Świnoujście reached 696 cm, that is 196 cm above the mean sea level (MSL) (Richter in. 2012). The sea level changes occurring during storm surges entail an increase in the water level of the Szczecin Lagoon, and then in the river network of the lower course of the Oder River. The highest storm event on the Szczecin Lagoon was recorded on 30–31 December 1913, when the level of 637 cm was registered in Trzebież (Majewski 1980). In Szczecin, the maximum water level of 680 cm was recorded on 7 March 1850 during a storm surge, which occurred during an increased supply from the Oder River catchment (Borówka 2002).

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Due to the low capacity of the straits connecting the Szczecin Lagoon with the Pomeranian Bay, changes in the water level during storm surges occur with some delay in time, depending largely on the dynamics of sea level changes (Majewski 1980, Robakiewicz 1993, Kowalewska-Kalkowska 2012). In the river network of the lower Oder, the pace of upward surge wave movement and intensity of storm event depend largely on the atmospheric conditions, specifically wind speed and direction, and on the changes in the atmospheric pressure (Buchholz 1990, 1991, Ewertowski 2000, Kowalewska-Kalkowska and Wiśniewski 2009). The flow rate in the Oder River also influences the degree of surge wave suppression; the higher the flow, the lower the wave height reaching the Oder (Ewertowski 1992, Kowalewska-Kalkowska 2012). The aim of the research presented in this work was to estimate the frequency and intensity of storm surges in the Oder River mouth area in the seasons between 1993/94 and 2016/17.

MATERIAL AND METHODS

The analysis of storm surges was carried out based on water level readings from water level gauges located in the Oder River mouth area (see: Fig. 1) in the seasons from 1993/94 to 2016/17, designated after Sztobryn et al. (2005) from August to July of the following year. The collected material included daily water level readings in the lower Oder River (in Gozdowice, Bielinek, Widuchowa, Gryfino, Podjuchy (Szczecin Podjuchy) and Szczecin (Szczecin Most Długi), obtained from the IMGW-PIB website (https://dane.imgw.pl) and the RZGW in Szczecin. Information about water levels in the Szczecin Lagoon (in Trzebież) and at the coast of the Pomeranian Bay (in Świnoujście) was provided courtesy of the Maritime Office in Szczecin. In the Port Logs in Świnoujście, hydrological data were recorded every hour, while in Szczecin and Trzebież, it was recorded every four hours. Since May 2010, it has been possible to obtain hourly information on water levels from the entire Oder River mouth area from the IMGW-PIB website (http://monitor.pogodynka.pl).

Storm surges were analysed, during which the alarm level (H ≥ 580 cm) was exceeded at the southern coast of the Pomeranian Bay in Świnoujście. In the first stage of the analysis, the general characterization of surge events was developed in terms of the frequency of their occurrence in the annual cycle and over the multi-year period, their extreme values and their duration, and then the transformation upstream of the lower Oder River. In the second stage, based on hourly information on water levels in the seasons from 2010/11 to 2016/17, the impact of water inflow from the Oder River catchment and the degree of filling of the Baltic Sea on the height, range and duration of selected storm surges in the Szczecin Lagoon and in the lower Oder was examined. In order to detect the relationships between water levels read on water level gauges located in the Oder River mouth region, correlation and cluster analyses were applied. In cluster analysis, the grouping procedure was performed using

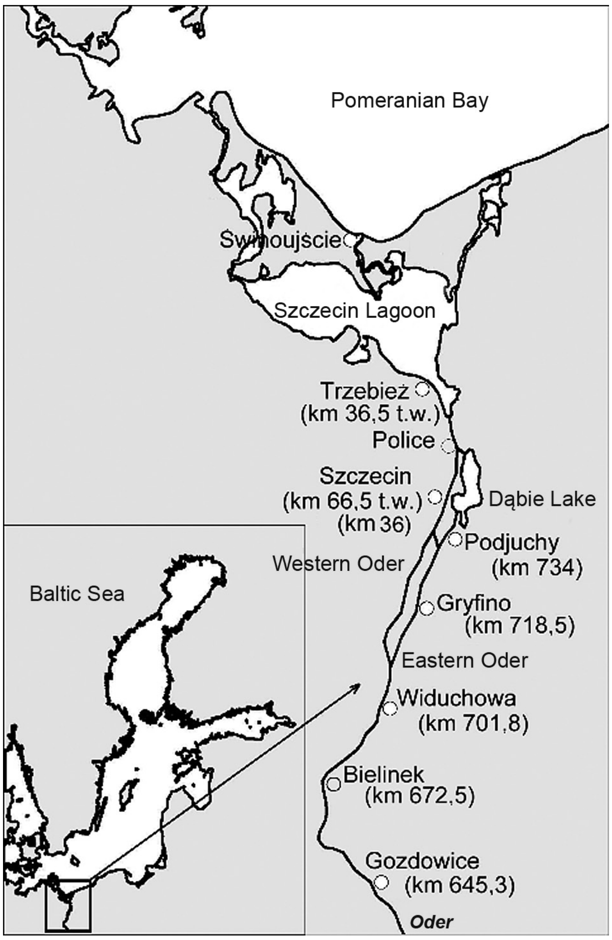

Fig. 1. The Oder River mouth area with the marked locations of water level stations

the Ward method, whereas the measure $d(x, y) = 1 - R$ was adopted as a measure of distance, where R is the Pearson correlation coefficient (Stanisz 2007). In order to present the variability of water levels in the Oder River mouth area, the graphs used standardized values (Z), showing the deviation of x variable from its expected value of μ, expressed in units of standard deviation σ (Balicki and Makać 2000).

RESULTS AND DISCUSSION

Characteristics of storm surges at the coast of the Pomeranian Bay

In the seasons from 1993/94 to 2016/17, at the coast of the Pomeranian Bay, there were 72 storm surges, during which the sea level in Świnoujście reached or exceeded the alarm level ($H \geq 580$ cm). During 32 events, the sea level reached at least 600 cm. The highest surge was registered on 3–4 November 1995, when the level of 683 cm was recorded in the Port Log in Świnoujście. According to the IMGW data, the culmination of this surge in Świnoujście amounted to 669 cm (Sztobryn et al. 2005). The second highest surge was the flood of 4–6 January 2017, during which the sea level in Świnoujście reached 653 cm. During both events, the sea level exceeded the level of 643 cm, that is, the water level with the exceedance probability of $p = 1\%$, estimated by Buchholz (1991) according to Pearson distribution type III.

In particular years, the storm surge events at the coast of the Pomeranian Bay were recorded irregularly. After long periods of time with a low frequency of surges, the period of intensified occurrence was recorded, for instance in the 2006/07 season, when 11 storm events were recorded during which the sea level in Świnoujście exceeded the alarm level. Among those surges, 7 cases were characterized by water levels of at least 600 cm. A large number of surges were also recorded in the 2001/02 season – during the 9 cases at that time, the alarm level was exceeded, and during 5 events, the sea level reached at least 600 cm. On the other hand, in the 2000/01 and 2005/06 seasons, the alarm level was not exceeded. The analysis of the frequency of occurrence of exceeding the alarm level in Świnoujście demonstrated similar regularities. The 2006/07 season, apart from the highest number of storm surges, was also characterized by the highest percentage of water levels equal or higher than 580 cm (1.6%). The high share of such levels was also recorded in the 2016/17 season (0.9%), as well as 1995/96 and 2001/02 (0.8%), and 2011/12 seasons (0.7%). As a result of correlating average annual water levels in Świnoujście with the frequency of water levels equal to or above 580 cm, a statistically significant correlation was obtained: $\alpha = 0.002$ with the correlation coefficient $R = 0.60$, indicating that the annual water levels would explain 36% of the variation in the frequency of water levels equal to or higher than 580 cm.

In the course of the year, storm surges, during which the sea level in Świnoujście exceeded the alarm state, were recorded from September to April (see: Fig. 2). The exception was the surge at the turn of August and September 1995. Most storm surges were recorded between November and January (48 events). Most often, the surges appeared in January (22 cases of which 11 were observed at the level of at least 600 cm). In the month of January, the incidence of water levels equal to or above 580 cm reached 1.5%, and those of at least 600 cm, 0.6%. The second month in terms of the incidence of surges was November. In that month, there were 14 cases, during which the sea level reached at least 580 cm, including 7 events with the level of 600 cm. The frequency of the occurrence of exceeding the alarm level was 1.0%.

The duration of the levels equal to or higher than 580 cm in Świnoujście ranged from 1 hour to 47 hours. Exceeding the alarm level for more than half a day was recorded during 28 surges, and for over a day, during 5 surges. The longest exceedance of the alarm level took place on 13–15 October 2009 (last-

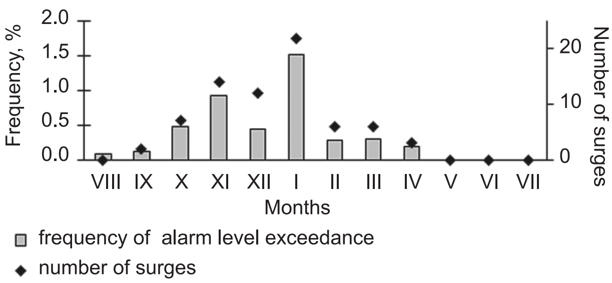

Fig. 2. The number of surges and seasonal frequency of sea levels reaching or exceeding the alarm level at Świnoujście in the 1993/94–2016/17 seasons

ing for 47 hours, including states equal to or higher that 600 cm lasting for 31 hours), on 13–15 January 2012 (for 41 hours, including 32 hours of water levels reaching at least 600 cm), 4–6 January 2017 (for 40 hours, including 28 hours with levels of at least 600 cm), and 3–5 November 1995 (for 33 hours, including the level of 600 cm, registered for the duration of 17 hours). Comparison of the number of hours with water levels of at least 580 cm in the seasons from 1993/94 to 2004/05 (322 hours), and from 2005/06 to 2016/17 (510 hours) showed a much higher number of such high levels in the second half of the analysed period (see: Fig. 3). Similarly, the number of hours increased, at which the sea level reached at least 600 cm (76 and 188 hours in the first and second half, respectively), which indicates the increasing threat of storm floods in recent years. Similar trends at the coasts of the Pomeranian Bay were reported by Sztobryn et al. (2005) and Wolski (2017).

15 October 2009. It was 9 cm higher than the water level with a probability of exceeding $p = 1\%$ (616 cm, according to Buchholz (1991)). The next highest in terms of high surges were the storm events noted: in mid-January 2012 (on 15 January, the water level in Trzebież reached 610 cm); at the beginning of November 1995 (on 4 November, the level of 608 cm was reached), and at the beginning of January 2017 (on 5 January, the level of 604 cm was recorded). The highest frequency of surges during which the alarm level was exceeded in Trzebież ($H \geq 560$ cm) was observed during the seasons of: 2006/07 (4.4% of all readings), 2001/02 (4.0% of all observations), and 2011/12 (3.1% of all recorded data). Similarly as at the coast of the Pomeranian Bay, in the 2000/01 and 2005/06 seasons no exceedance of the alarm level was recorded.

In the course of the year, from October to March, over 1.5% of all observations in Trzebież indicated

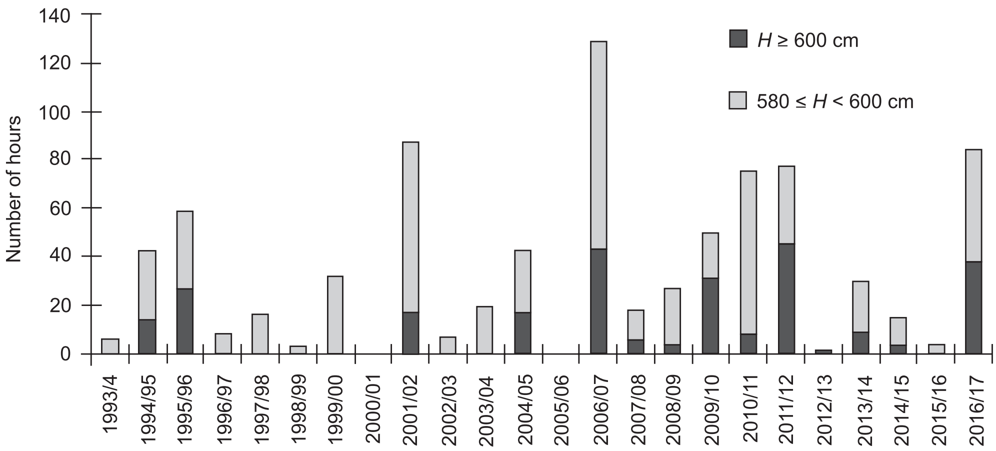

Fig. 3. The number of hours with sea level reaching or exceeding 580 cm and 600 cm at Świnoujście in the 1993/94–2016/17 seasons

Characteristics of storm surges in the Szczecin Lagoon and downstream Oder river system

The occurrence of storm surges in the Szczecin Lagoon and in the river network of the lower Oder River is associated with their occurrence at the coast of the Pomeranian Bay. In the seasons between 1993/94 and 2016/17, the highest water level in Trzebież, amounting to 625 cm, was recorded during a storm surge flood at the coast of the Szczecin Lagoon on that the alarm level was exceeded. As in Świnoujście, the alarm level was most often exceeded in January (5.1% of the readings). Over 2% of the data indicated that the alarm level was exceeded also in November (2.4%) and in March (2.2%). Due to the low flow capacity of the straits connecting the Szczecin Lagoon with the Pomeranian Bay, the duration of the exceeded alarm level in Trzebież during storm surges was much longer than in Świnoujście. The prolonged, multi-day exceedance of the alarm level on the Szczecin Lagoon was usually accompanied by situations where several storm surges occurred one after the other at the coast of the Pomeranian Bay. Such a situation took place in January and February 2007, when the 9 storm surges, occurring one after the other, caused a multi-day storm surge on the Szczecin Lagoon (in total, the alarm level exceeded in Trzebież was recorded for 300 hours). Long-term persistence of very high water levels in the lagoon was also observed in January 2005, in October 2009, and in January 2012.

On the Western Oder River in Szczecin, near the Długi Most, and on the Eastern Oder River in Podjuchy and Gryfino, the largest surge, just like in the Szczecin Lagoon, was the one registered in October 2009. On 15 October, the level of 631 cm was registered in Szczecin at the Most Długi, while 644 cm was recorded in Podjuchy, and 638 cm in Gryfino. During the culmination of the flood in Szczecin near the Most Długi, the water level was exceeded with the 5% probability of exceedance, while in Gryfino the observed maximum state reached approximately the water level with a 10% probability of exceedance (620 cm and 640 cm respectively, according to Buchholz (1991)). The next highest surges on the lower Oder River were the storm events in November 1995, as well as in January 2012 and January 2017. On the water level gauges in Szczecin (near Długi Bridge and in Podjuchy) the exceeded alarm level during storm surges was recorded only 9 times. It lasted for up to two days. In Gryfino, its exceedance was recorded 21 times during storm surges, but sometimes very high water levels on this gauge resulted from the freshets in the Oder River, as during a storm surge in December 2010 when the water level in Gryfino reached 641 cm due to the formation of ice phenomena.

In Widuchowa, the influence of storm surges was manifested in the form of an increase in the water level in the Oder River, sometimes matching the relative sea level increase. Exceeding the alarm level most often resulted from the overlap of the high water level in the river, which was associated with increased supply from the Oder catchment and/or the emergence of ice phenomena (winter-spring freshet of the Oder River in 2002, and at the turn of 2010/11).

During the high storm surges, lasting several days each, the increase in the water level on the Szczecin Lagoon and on the lower Oder River up to Widuchowa remained within the range of several dozen centimetres, reaching 90 cm, including during surges at the turn of August and September 1995, in November 1995, and in October 2009. In Bielinek, the increase in water level in the Oder River did not usually exceed about a dozen centimetres. The exceptions were the events at the turn of August and September 1995, in October 2009, and in October 2016 (increase in the Oder River level by over 40 cm). In Gozdowice, the impact of storm surges on changes in water levels during the analysed situations was negligible.

The highest storm surges in the period covered by the analysis included an event recorded at the beginning of January 2017, related to the movement of the deep and extensive low-pressure system called *Axel* over the Baltic Sea, with the water level in the Pomeranian Bay being higher than usual at this time of year (average water level in Świnoujście in December 2016 amounted to 514 cm). At the coast of the Pomeranian Bay in Świnoujście, on 4 January, the sea level reached 653 cm, that is 73 cm above the alarm level. The surge in the sea caused a 60–70 cm increase in the water level on the Szczecin Lagoon and in the Oder River network up to Widuchowa (see: Fig. 4). In Bielinek, the water level has risen by 12 cm (see: Table 1).

The analysis of the obtained dendrogram of grouping the water level sequences in the Oder River mouth area on 3–7 January 2017 showed a distant influence of the sea impacts, reaching Bielinek (see: Fig. 5). The water levels from Trzebież to Widuchowa formed

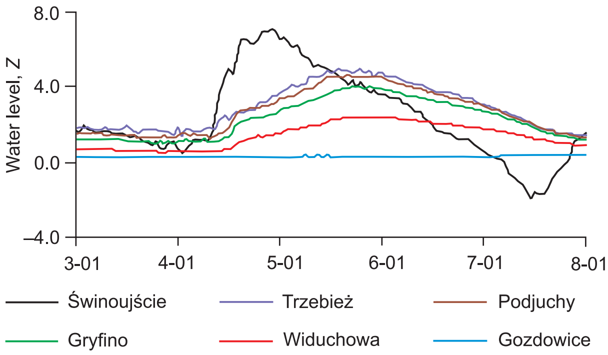

Fig. 4. Water level changes in the Oder River mouth area between 3 and 7 January 2017 (water level readings were converted to standardized values (Z))

Table 1. Maximum water levels and water level changes in the Oder River mouth area on 3–7 January 2017

No.	Water level gauge	Maximum water level (cm)	Value of exceedance (above alarm level) (cm)	Increment of water level (cm)	Number of hours with alarm level exceeded (hours)
1	Świnoujście	653	73	138	40
2	Trzebież	604	44	67	64
3	Szczecin	615	15	69	23
4	Podjuchy	622	12	68	22
5	Gryfino	620	20	69	34
6	Widuchowa	627	–23	62	
7	Bielinek	371	–179	12	
8	Gozdowice	350	–150	4	

Source: item 1 – data from the Maritime Office (Urząd Morski) in Szczecin, items 2–8 – data from the IMGW-BIP

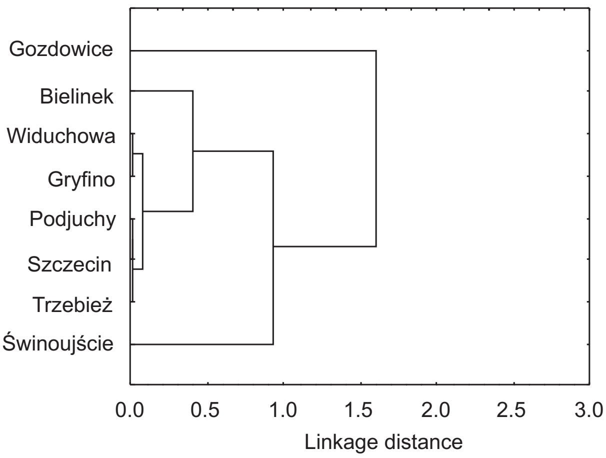

Fig. 5. Dendrogram grouping the water levels in the Oder River mouth area between 3 and 7 January 2017

a cluster with a very high degree of mutual correlation, which was then closely related to the water levels in Bielinek (at linkage distance of 0.4). The water levels from Trzebież to Widuchowa were then related to the water levels in Świnoujście (at linkage distance of 0.9).

STORM SURGES IN CASE OF HIGH DEGREE OF FILLING OF THE BALTIC SEA

The occurrence of storm surges at the coast of the Pomeranian Bay one after the other, usually recorded in periods of increased cyclone activity and in case of high degree of filling of the Baltic Sea, causes a prolonged rise in the water level in the Szczecin Lagoon, and in the river network of the lower Oder River (Kowalewska-Kalkowska 2012). The increased mean water level of the Baltic Sea affected the height and duration of storm surges in the 2011/12 season. Already in December 2011, the mean sea level in Świnoujście was higher than the average (519 cm). At that time, a high storm surge was registered, during which, on 17 December, the sea level in Świnoujście reached the level of 623 cm. In January 2012, at a significantly higher than average mean sea level (539 cm), two events were recorded during which the sea level in Świnoujście exceeded the level of 600 cm. The first storm surge was recorded on 4–7 January. In Świnoujście, as a result of an increase in the sea level by 165 cm on 6 January, the level of 612 cm was recorded. The alarm level remained exceeded for 21 hours. The second storm surge, preceded by two storm storm events, during which the warning state was exceeded in Świnoujście, was recorded in mid-January. As a result of the increase in the sea level by 155 cm on 14 January, in Świnoujście, a level of 642 cm was recorded, i.e. approximately the water level with exceedance probability of $p = 1\%$ (according to Buchholz (1991)). The alarm level remained exceeded for 41 hours.

The occurrence of several storm surges one after the other in the period from 4 to 26 January 2012 at the coast of the Pomeranian Bay, at the simultaneous high mean sea level of the Baltic Sea, caused the inflow of water from the Pomeranian Bay to the Szczecin Lagoon, and significant inhibition of free outflow of inland waters to the sea. As a result, the water level in the Szczecin Lagoon and in the river network of the lower Oder River increased considerably, which led to a multi-day persistence of a very high water level in this area (see: Fig. 6). In total, on the Zalew Szczeciński, the alarm level remained exceeded for 204 hours. In Trzebież, the highest water level was recorded on 15 January and amounted to 610 cm, which means that the water level was exceeded with exceedance probability of p = 5% (602 cm, after Buchholz (1991)). On the lower Oder River, the maximum water levels were recorded on 14 January. The water level in the Oder River in Szczecin reached the level of 618 cm, in Podjuchy, 630 cm, and in Gryfino, 624 cm. Exceedance of the alarm level lasted between 40 and 53 hours. In Widuchowa, the warning level was exceeded. Water level increases on the Szczecin Lagoon and in the river network up to Widuchowa ranged between 77–90 cm during the surge on 4–7 January, and 67–80 cm during the surge on 12–18 January. The reach of both storm events extended to Bielinek (13 and 25 cm increase in the water level in the Oder River).

The analysis of the correlation between water levels read on 4–26 January 2012 showed a significant role of variability of the sea level in the Pomeranian Bay in shaping the variability of the water level of the Oder River mouth area (see: Table 2). The water levels in Świnoujście were most strongly correlated with water levels in the Szczecin Lagoon, and within the Szczecin Water Node (Szczeciński Węzeł Wodny) at $R \approx 0.7$. Slightly weaker correlation was obtained between water levels in Świnoujście and water levels in Gryfino (R = 0.65) and Widuchowa (R = 0.54). The influence of sea level on the water level in the lower reaches of the Oder River decreased gradually along

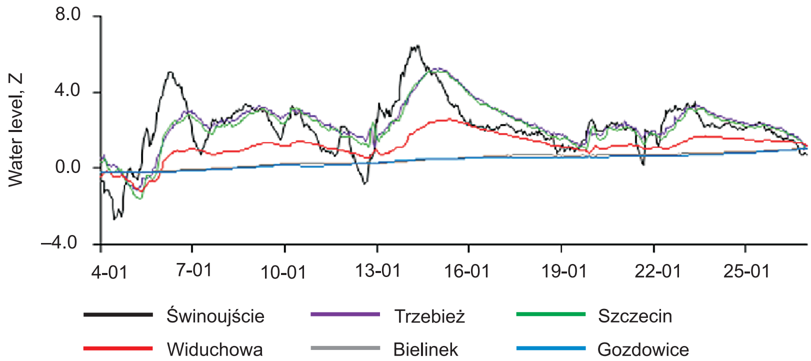

Fig. 6. Water level changes in the Oder River mouth area between 4 and 26 January 2012 (water level readings were converted to standardized values (Z))

Table 2. Triangular matrix of the correlation of water levels in the Oder River mouth area between 4 and 26 January 2012 (bold font denotes statistically significant correlation coefficients at the level of $\alpha = 0.05$)

	Gozdowice	Bielinek	Widuchowa	Gryfino	Podjuchy	Szczecin	Trzebież	Świnoujście
Gozdowice	1.000							
Bielinek	**0.993**	1.000						
Widuchowa	**0.635**	**0.629**	1.000					
Gryfino	**0.432**	**0.418**	**0.964**	1.000				
Podjuchy	**0.342**	**0.324**	**0.924**	**0.990**	1.000			
Szczecin	**0.317**	**0.298**	**0.909**	**0.984**	**0.999**	1.000		
Trzebież	**0.306**	**0.288**	**0.898**	**0.971**	**0.987**	**0.989**	1.000	
Świnoujście	**0.132**	**0.101**	**0.541**	**0.647**	**0.700**	**0.716**	**0.712**	1.000

with the distance from the sea. While the variability of water levels in Świnoujście could explain 50% of the variability of water levels at the Szczecin Lagoon and within the Szczecin Water Node, in this way it was possible to explain only 29% of the variability of the water levels in Widuchowa. The sea impact on the water levels in Bielinek and Gozdowice was negligible.

The analysis of the dendrogram of grouping of the sequences of water levels recorded at the water level gauges in the Oder River mouth area on 4 – 26 January 2012 confirmed the important role of the sea impacts in shaping the variability of water levels in the Oder River's lower network up till Widuchowa (see: Fig. 7). The strongest correlations were obtained between water levels from Trzebież to Gryfino. They formed the cluster which was closely linked to water levels in Widuchowa. The water levels from Trzebież to Widuchowa were then related to the water levels in Świnoujście (at linkage distance of 0.5). The construction of the dendrogram indicated the lack of significant correlations between the water levels in Świnoujście and those in Bielinek and Gozdowice, which formed a separate cluster with a high degree of mutual correlation.

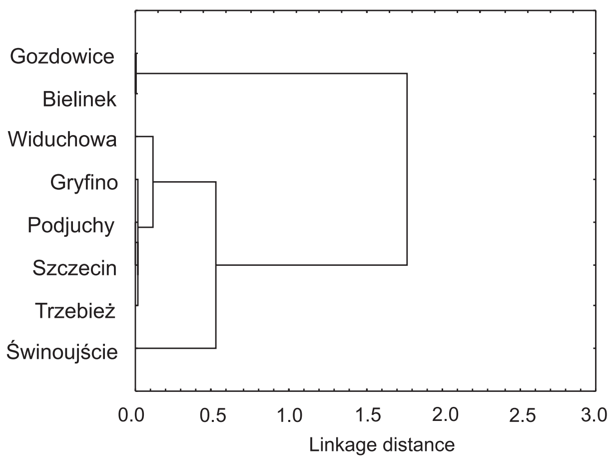

Fig. 7. Dendrogram grouping the water levels in the Oder River mouth area between 4 and 26 January 2012

STORM SURGES IN CASE OF THE INCREASED WATER SUPPLY FROM THE ODER RIVER CATCHMENT

The Oder River is characterized by a snow-and-rain supply regime, with a clear predominance of the snow supply (Mikulski 1963). Occurrence of storm surges during the increased supply from the Oder River catchment hinders the outflow of river waters into the sea, and it causes the surge wave to overlap with the high water level on the lower stretch of the Oder. This situation results in long-term persistence of a very high water level in the Oder River mouth area, and in exceptional cases, it may lead to flooding of low-lying areas around the Szczecin Lagoon and the Dąbie Lake, and areas adjacent to the Eastern and Western Oder (Buchholz 1990, Ewertowski 2000, Kowalewska- Kalkowska 2012). A particular threat of flooding arises when ice phenomena are additionally observed. The latter take on different forms of icing in particular sections of the lower Oder (Buchholz 1990). One of the most dangerous events of this type was the period of high water on the lower Oder River at the turn of 2010/2011 (Fig. 8). It was caused by ice jams, and later by melt-water runoff from the Oder River catchment (Ocena ... 2010, 2011). The maximum levels recorded in Widuchowa and Gryfino during the analysed period (767 cm on 23 December 2010 and 657 cm on 9 January 2011, respectively) were higher than during the Oder River flood in the summer of 1997. They exceeded the water levels of 5% exceedance probability (749 cm in Widuchowa, and 653 cm in Gryfino, according to Buchholz (1991)). The appearance of 5 surges at the turn of 2010/2011 additionally resulted in an increase in the water level in the Szczecin Lagoon and on the lower Oder River (up to half a meter) for their duration. The highest storm surge was recorded on 11–13 February 2011, when the sea level reached 632 cm in Świnoujście.

Correlation analysis carried out between water levels in the period from 21 November 2010 to 26 February 2011 showed a significantly smaller role of variability of the sea level in the Pomeranian Bay in shaping the variability of the water level in the Oder River mouth area (see: Table 3). This impact was limited to the Szczecin Lagoon and the Szczecin Water Node. Water levels in Świnoujście were most strongly correlated with water levels in the Szczecin Lagoon (R = 0.76). With the increasing distance from the sea, the correlation between the water levels in Świnoujście and the water levels in the lower reaches of the Oder River declined significantly. Whereas in Szczecin, the correlation coefficient was 0.67 at the Most Długi, and 0.50 in Podjuchy, in Gryfino its val-

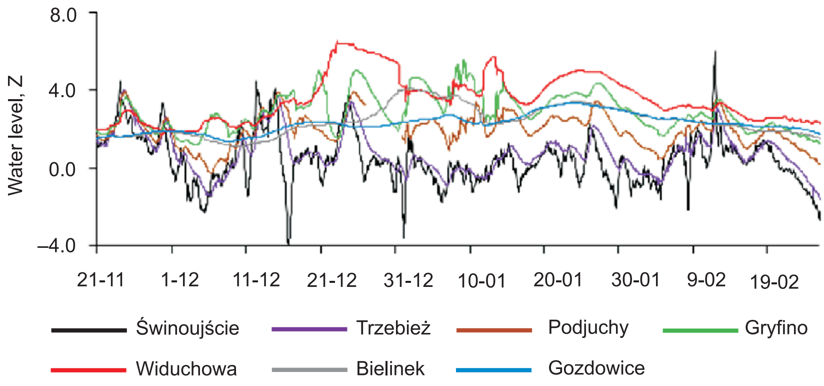

Fig. 8. Water level changes in the Oder River mouth area between 21 November 2010 and 26 February 2011 (water level readings were converted to standardized values (Z))

Table 3. Triangular matrix of the correlation of water levels in the Oder River mouth area between 21 November 2010 and 26 February 2011 (bold font denotes statistically significant correlation coefficients at α = 0.05 level)

	Gozdowice	Bielinek	Widuchowa	Gryfino	Podjuchy	Szczecin	Trzebież	Świnoujście
Gozdowice	1.000							
Bielinek	**0.824**	1.000						
Widuchowa	**0.631**	**0.606**	1.000					
Gryfino	**0.474**	**0.622**	**0.637**	1.000				
Podjuchy	**0.261**	**0.254**	**0.451**	**0.681**	1.000			
Szczecin	**0.077**	0.008	**0.256**	**0.458**	**0.913**	1.000		
Trzebież	**–0.109**	**–0.196**	**0.075**	**0.251**	**0.773**	**0.950**	1.000	
Świnoujście	**–0.169**	**–0.196**	0.033	**0.095**	**0.503**	**0.667**	**0.761**	1.000

ue decreased down to 0.095. Although the variability of water levels in Świnoujście could explain 58% of the variability of water levels in Trzebież, it would explain only 25–44% of the variability at water levels in Szczecin. The impact of the sea on the water levels in Gryfino was negligible.

Analysis of the constructed dendrogram of grouping the water level series of the Oder River mouth area in the period from 21 November 2010 to 26 February 2011 confirmed the limited sea impact on water level variability in the lower Oder River system (see: Fig. 9). The strongest correlations were obtained between the water levels recorded in Trzebież and within the Szczecin Water Node. They formed a close cluster, which was related to the water evels in Świnoujście (at linkage distance of 0.5). On the other hand, the water

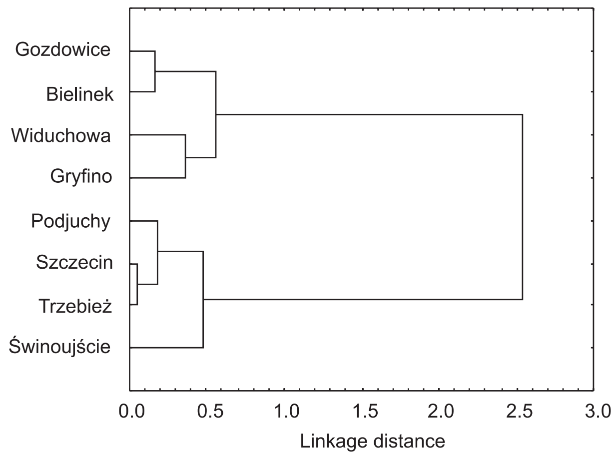

Fig. 9. Dendrogram grouping the water levels in the Oder River mouth area between 21 November 2010 and 26 February 2011

levels in Widuchowa and Gryfino also formed a close cluster, which was related to another cluster in which the water levels in Gozdowice and Bielinek were located (at linkage distance of 0.6). The construction of the dendrogram indicated the lack of significant correlations between the water levels in Świnoujście and the water levels upstream of the Oder River from Gryfino; the impact of the sea was limited to the Szczecin Water Node.

CONCLUSIONS

In the seasons from 1993/94 to 2016/17, storm surges at the coast of the Pomeranian Bay were characterized by a high irregularity of occurrence. Most of the registered 72 storm surges were observed between November and January. The highest water level of 683 cm was registered in November 1995. In the Zalew Szczeciński (Szczecin Lagoon), and in the downstream reach of the Oder, the largest surge was recorded in October 2009. The water level increases in the Oder River mouth area were 80–90 cm up to Widuchowa, and the water level in the Szczecin Lagoon reached 625 cm in Trzebież. Extreme surge events were also registered in November 1995, in January 2012, and in January 2017.

In the Oder River mouth area, high and long-term storm surges penetrating high up the lower Oder River occurred whenever high and several-day-long storm surges were observed at the coast of the Pomeranian Bay, with gradual rise of the sea level. Such situations were observed at the turn of August and September 1995, in October 2009, and in January 2017. The extent of this type of surge events reached as far as Bielinek.

Intensification of high water events in the Oder River mouth area was favoured by the occurrence of storm surges during increased supply from the Oder River catchment and/or the emergence of ice phenomena (the winter-spring freshet of the Oder in 2002, and at the turn of 2010/11). Long-lasting periods with very high water levels in the Szczecin Lagoon and on the lower Oder River were also noted in case of the high degree of filling of the Baltic Sea (in January and February 2007, and in January 2012).

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CZĘSTOŚĆ WYSTĘPOWANIA I INTENSYWNOŚĆ WEZBRAŃ SZTORMOWYCH W UJŚCIOWYM REJONIE ODRY

ABSTRAKT

W pracy oszacowano częstość występowania i intensywność wezbrań sztormowych w ujściowym rejonie Odry w sezonach 1993/94–2016/17. Analizę przeprowadzono w oparciu o serie pomiarowe stanów wody, odczytanych na stacjach położonych wzdłuż dolnego biegu Odry oraz u wybrzeży Zatoki Pomorskiej i Zalewu Szczecińskiego. Rozpoznanie czasowej i przestrzennej zmienności stanów wody w rejonie badań wykazało znaczną nieregularność występowania wezbrań sztormowych. Po długich okresach o znikomej częstotliwości wezbrań rejestrowano okresy o nasilonym ich występowaniu. W przebiegu rocznym wezbrania najczęściej notowano od listopada do stycznia. Najrozleglejsze wezbranie sztormowe w ujściowym rejonie Odry zaobserwowano w październiku 2009 r. Bardzo wysokimi wezbraniami okazały się wezbrania z listopada 1995 r., stycznia 2012 r. oraz stycznia 2017 r. Wysokim i długotrwałym wezbraniom, o dalekim zasięgu oddziaływania w górę dolnej Odry, sprzyjał stopniowy i długotrwały wzrost poziomu morza u wybrzeży Zatoki Pomorskiej. Intensyfikacji wezbrań w ujściowym rejonie Odry sprzyjało ponadto wystąpienie wezbrań sztormowych podczas zwiększonego zasilania ze zlewni Odry, w okresie występowania zjawisk lodowych na dolnej Odrze oraz przy podwyższonym poziomie Morza Bałtyckiego.

Słowa kluczowe: wezbrania sztormowe, stany wody, ustrój wodny, ujściowy rejon Odry