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Storm-Surge Induced Water Level Changes in the Odra River Mouth Area (Southern Baltic Coast)

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Abstract: The Odra River mouth area is a region of the Southern Baltic coastal zone especially prone to the influence of storm surges. In the present study, the height and extent of the Baltic storm surges, and temporal offsets of the respective maximum water level occurrences in the Odra River mouth area were explored using cross-correlation, cluster analysis and principal component analysis. The analyses were based on hourly water level readings retrieved from water gauging stations located along the lower Odra reaches and at the coasts of the Szczecin Lagoon and the Pomeranian Bay during storm surge years 2008/2009–2019/2020. The analysis of mutual relationships between water levels during storm surges indicated that the extent of marine influence on the lower Odra River and within the Szczecin Lagoon was variable during the studied surge events, and dependent on meteorological conditions (the strongest during the sustained occurrence of wind blowing from the northern sector), discharge from the Odra River catchment (the strongest at low discharge), ice conditions on the lower Odra (suppressing the storm surge propagation upstream), and general sea level in the Pomeranian Bay (stronger at high sea levels). The strongest correlation between sea levels at Świnoujście and water levels in the Szczecin Lagoon and the lower Odra was found at a 6–7 h offset. The extent of storm surges usually reached 100 km up the lower Odra channels, less frequently reaching 130 km away from the sea.

Keywords: storm surges; water level; wind-driven backflow; cluster analysis; principal component analysis; Odra River mouth; Southern Baltic Sea

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1. Introduction

Storm surges generated by tropical cyclones and mid-latitude low-pressure areas [1] are potentially hazardous natural phenomena, as they carry a risk of flooding, and pose an ecological threat to numerous coastal areas of the world. They also cause enormous material losses and cause large numbers of casualties. A storm surge is generated due to the impact exerted by strong winds, or strong winds in conjunction with atmospheric pressure drops, on the sea surface [2–5]. In areas adjacent to river mouths, surges reduce or obstruct the free discharge of river waters to the sea, generate a backflow of marine waters into the outlet stretches of rivers, and cause swells that may move up the river, flooding areas adjacent to the river, even at substantial distances away from the sea [6–10]. Unusually dangerous storm surges occur in the deltas of Ganges and Brahmaputra, where surges may penetrate up to 160 km inland [1,6]. Within the Hooghly Estuary (east coast of India), surge penetration reaches 120 km inland [10]. In Europe, within the mouths of the Ems, Jade, Weser and Elbe rivers, all of which flow into the North Sea, surges may be amplified by high tides [11]. Within the Elbe estuary, surges penetrate as far as Hamburg [1,7]. Storm surges are recorded also in estuaries and coastal lagoons of the nearly tideless Baltic Sea, for instance on the Neva River [12], the Curonian Lagoon, and the Nemunas River [13], on Vistula Lagoon [14], and in the Vistula River delta [15,16], as well as on the Szczecin Lagoon, and within the lower reaches of the Odra River [8,15,17–20].

In recent years, cluster analysis (CA) and principal component analysis (PCA) were found to be powerful tools in environmental research. Nakajo et al. [21] applied these techniques to develop a global stochastic tropical cyclone model, whereas Kim and Seo [22] applied CA to study tropical cyclone tracks over the Western North Pacific Ocean. Ward's method was applied to study cyclone tracks promoting extreme surge events at Brest in France [23]. You and Seo [24] used a centroid linkage method of hierarchical clustering to divide the Korean coast into sections according to regional similarities in storm surge height during typhoons. CA and PCA were found useful in studies on skew surge and storm tides of tropical cyclones in Delaware and Chesapeake Bays [25]. They were also employed to identify sections with similar rates of sea level rise within the Northwest Pacific Ocean marginal seas [26]. Various agglomerative techniques, such as Ward's method, were applied to study regional sea level variability at the coasts of the North Atlantic Ocean [27] and the Baltic Sea [8,28–31]. Moreover, PCA has proved successful in studies on regional sea level variability based on satellite altimetry data and tide gauge readings [32], tidal range changes in the North Sea [33], typhoon-induced waves in the Western North Pacific Ocean [34] and the evolution of storm surge threats along the southeastern coastline of China [35].

This study adopts the following hypothesis: storm surges at the Pomeranian Bay coast (Southern Baltic) determine the water level variability in the Odra River mouth area, involving the Lower Odra River network and the Szczecin Lagoon, and the height and extent of each surge, as well as the temporal offset of the maximum water level occurrence in this region, depends mostly on the character of sea level changes, determined by meteorological conditions, the overall Baltic Sea level, discharge from the Odra River catchment, and ice conditions on the lower Odra. Section 2 describes the study area and the data used for storm surge detection; it also summarizes the methods used for the statistical treatment of the data. Section 3 presents the results of multivariate analysis of storm surge impacts on the water level in the Odra mouth through the period 2008/2009−2019/2020. Moreover, Section 3 includes a detailed description of storm surge transformation in the Szczecin Lagoon and the lower Odra, and mutual relationships between water levels during three surges in October 2009, February 2011 and January 2019. Discussion and conclusions bring the paper to a close.

2. Materials and Methods

2.1. Study Area

The Baltic Sea (Figure 1) is a shallow, land-locked sea located in northern Europe. It occupies an area of 393×10^3 km^2 and has an average depth of 54 m [36]. Its location on the route of migration of low-pressure systems from the west to the east favors the occurrence of storm surges in this region. The most dangerous storm surges were noted along the southwestern and eastern Baltic coasts [3,37–39]. The coast of the shallow Pomeranian Bay is also prone to storm surges. It is an unsheltered, coastal basin of the Southern Baltic, with an average depth of 13 m, constrained on the northern side by the 20 m isobath [40]. Tides are noted here, but only within a range of several centimeters [15]. Relatively shallow depths, a highly diverse coastline, a peculiar seabed configuration, made even more shallow by the occurrence of shoals, all contribute to the occurrence of storm surges during periods characterized by sufficiently strong landward wind, i.e., from the NW-NE sector [41]. Such directions of air mass movement occur in low-pressure systems arriving over the Baltic Sea mostly from the N-W sector, considerably less frequently from the W-SW sector, and in low-pressure areas moving along tracks located away from the Baltic Sea, i.e., north of the Gulf of Bothnia, or over Central and Eastern Europe [42]. In the case of interference of sea level rise during a storm surge with an already high general Baltic Sea level, the observed culmination may be very high [3,41]. At the southern Pomeranian Bay coast, the highest storm surge was recorded in February 1874, when sea level in Świnoujście rose to 196 cm above mean sea level (amsl) [39].

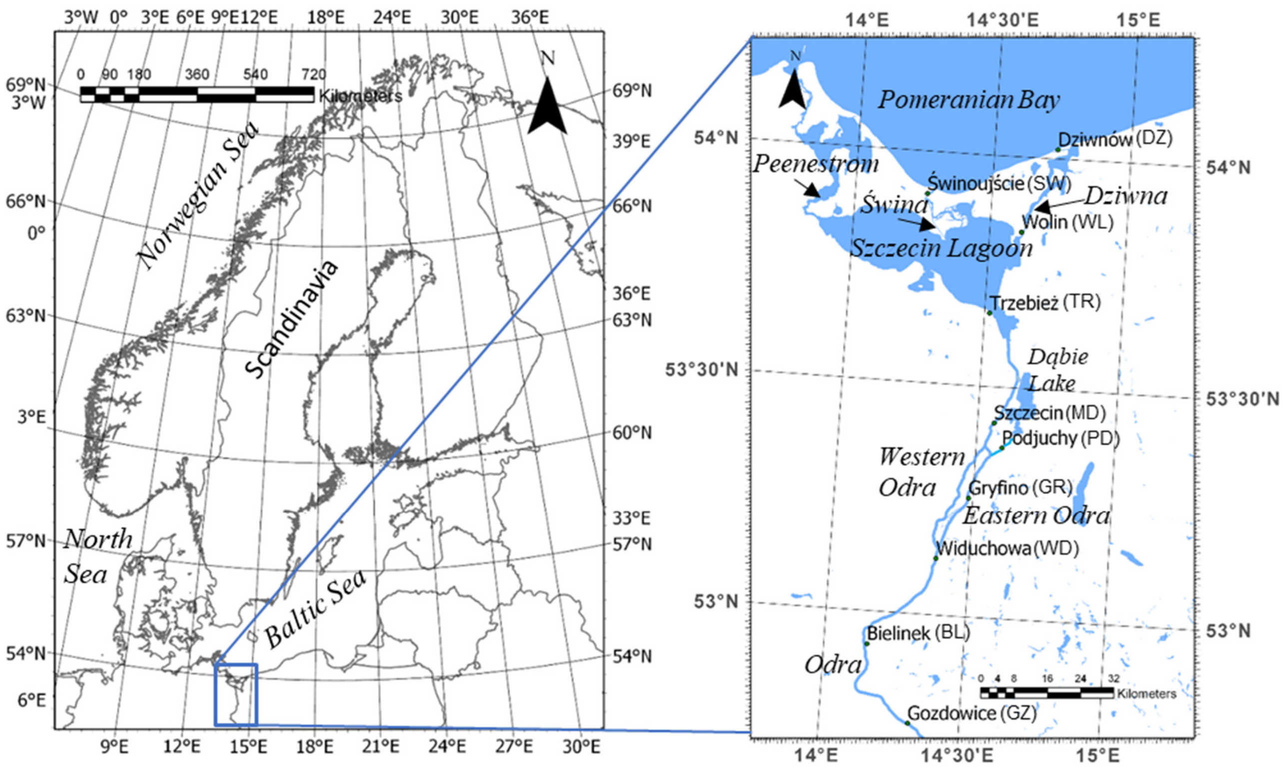


Figure 1. The Odra River mouth area, with the location of water level stations.

The Odra River is among the largest rivers of the Baltic Sea basin, both with respect to the catchment area, and runoff magnitude. Of the 250 rivers draining into the Baltic Sea, the Odra is the third with respect to the catchment area (118,840 km^2), the fourth with respect to the length (854 km), and the fifth with respect to runoff value (574 m^{3}s^{-1}) [43]. In its lower reaches, downstream from Widuchowa water gauge (ca. 100 km from the Baltic coast), the Odra River bifurcates into the Eastern Odra and the Western Odra (Figure 1). The Eastern Odra carries most of the water volume. The Western Odra discharge, regulated by a weir, amounts to 16–38% of the total Odra River discharge [44]. The eastern branch of the Odra River drains to a deltaic, flow-through Lake Dąbie, which occupies an area of 56.5 km^2 [18]. Lake Dąbie, which has multiple links with the Western Odra, plays the part of a natural retention basin, influencing both the discharge from the Odra River to the sea and the storm surge transformation within the Lower Odra River network [45]. Downstream from Lake Dąbie, the Eastern Odra joins the Western Odra. In the vicinity of Trzebież, the Odra River empties into the Szczecin Lagoon, a coastal semi-enclosed water body that occupies an area of 686.9 km^2, with an average depth of 3.8 m. The Szczecin Lagoon is further subdivided into the Large Lagoon in the east (409.7 km^2 surface area, and slightly deeper, up to 6 m deep in the central part), and the Small Lagoon in the west (shallower, with a surface area of 277.2 km^2) [46]. The Szczecin Lagoon is traversed by the 10.5 m deep Świnoujście-Szczecin Fairway. Waters from the Szczecin Lagoon reach the Pomeranian Bay via three straits: Świna, Dziwna and Peenestrom. Świna Strait is the main link between the Szczecin Lagoon and the Pomeranian Bay, comprised of multiple channels. Over its 16.3 km length, Świna Strait is part of the Świnoujście-Szczecin Fairway, passing along the artificially dredged Piastowski Channel (200 m broad), Mieliński Channel (200 m broad), and Zbiorczy Channel (300 m broad). The 30 km-long Dziwna connects the Large Lagoon with the Pomeranian Bay. At its outlet to the Pomeranian Bay, Dziwna is 100–150 m broad. Peenestrom is 46 km long and connects the Small Lagoon with the Pomeranian Bay. The Krumminer Wiek and Achterwasser bays, both of which cut deep into Usedom Island, are branches of Peenestrom. At its outlet to the Pomeranian Bay, Peenestrom is 350 m broad [46]. Water exchange between the bay and the lagoon depends on the current meteorological conditions (wind and atmospheric pressure), sea level, and discharge from the Odra catchment [15]. 60–70% of water exchange occurs via Świna, while Peenestrom and Dziwna each contribute 15–20% to water exchange [47].

The lower Odra River, from the confluence with Warta at 617.6 km to its mouth, is a lowland river, with a minor average slope of free surface water, ranging from 0.15‰ within the section between Gozdowice and Bielinek to less than 0.002‰ within the section between Szczecin and Trzebież [8]. As a result, water levels in the Szczecin Lagoon and in the lower Odra River network are strongly affected by sea level fluctuations. The extent of sea level-induced impact in the lower Odra River depends on a number of meteorological and hydrological factors, in extreme cases reaching as far upstream as Gozdowice [18]. Due to the low capacity of the straits linking the Szczecin Lagoon with the Pomeranian Bay, water level changes within the lagoon during storm surges are somewhat delayed, largely dependent on the sea level fluctuations [8,46]. Within the lower Odra River network, the pace of the upstream motion of the surge, and surge intensity are both largely dependent on atmospheric conditions, i.e., wind velocity and direction, and atmospheric pressure changes [17,19,48]. The degree of surge suppression is further influenced by the Odra River discharge magnitude. The higher the discharge, the lower the height of the wave traveling up the Odra River [8,44]. Additional important factors controlling the water level increase in the lower Odra reaches during storm surges are ice phenomena occurring on the river and the degree of filling in the Baltic Sea [29].

2.2. Data

The storm surge analysis was performed based on hourly water level readings from sea level stations located along the coast of the Pomeranian Bay (Southern Baltic), and water gauging stations within the outlet stretch of the Odra River (Figure 1, Table S1), during storm surge years 2008/2009−2019/2020. Storm surge years were determined following Sztobryn et al. [41] as spanning August through July of the subsequent year (number of data in each series N = 105,192). The Pomeranian Bay was represented by sea level stations at Świnoujście (SW) and Dziwnów (DZ), and the Szczecin Lagoon was represented by water level stations at Trzebież (TR) and Wolin (WL). The water level stations at Szczecin (Long Bridge (MD)) on the Western Odra, and at Podjuchy (PD) on the Eastern Odra, Gryfino (GR, Eastern Odra), Widuchowa (WD), Bielinek (BL) and Gozdowice (GZ) were considered representative for water levels along the lower Odra reaches. Each data set was referenced against the Normall-Null ordnance datum (Table S1).

A detailed analysis was performed on those storm surges during which alarm sea level of H $\geq$ 80 cm amsl was exceeded in Świnoujście, at the southern coast of the Pomeranian Bay. Alarm level exceedance indicates a flood hazard. Mean sea level (msl) is defined as present-day normal average water level along the Southern Baltic coast and equals 500 cm at the tide gauge [41,49]. Sea level fluctuations during the surge events were analyzed in the first stage, and their propagation within the Szczecin Lagoon and up the lower Odra reaches were analyzed in the second stage. The Odra River discharge magnitude, and mean sea level within the Pomeranian Bay (average level from 7 and 30 days) were both considered in the analysis of height and extent of storm surges, as well as the temporal offset of the maximum water level occurrence in the Odra outlet stretch.

Data on wind velocity and direction from routine readings at the IMGW weather station at Świnoujście (No. 12200) were utilized in order to identify the impact of meteorological factors on generating storm surges along the southern coast of the Pomeranian Bay, as well as their features and propagation within the Szczecin Lagoon and up the outlet stretch of Odra River. Special attention was paid to the time over which wind blew from a given direction. The water level and wind velocity and direction time series used for statistical analyses in the present study were retrieved from the website of Institute of Meteorology and Water Management—National Research Institute (IMGW-PIB) in Poland (https://danepubliczne.imgw.pl/, accessed on 10 November 2021).

Six hourly Analysis Surface Synoptic Charts (ASXX), available from the United Kingdom Met Office website: https://digital.nmla.metoffice.gov.uk/SO_4d70038f-c03f-4cb2-818e-7bc3aec7cfb0/ (accessed on 10 November 2021) were utilized for the analysis of the atmospheric pressure field over Europe and North Atlantic. These were used in particular for estimating the tracks of low-pressure systems impacting the sea level in the study area.

2.3. Methods

In order to identify and describe statistical patterns in the spatial and temporal changes of water levels recorded at gauging stations located in the Odra River mouth and the Pomeranian Bay coast area, the basic measures of assemblage structure description were computed [50]. The analysis of mutual relationships between the analyzed water level data series was preceded by correlation analysis, performed based on Pearson's linear correlation coefficient R [51]. Its statistical significance at α = 0.05 level was verified using Student's *t*-test. The analysis of mutual relationships between water level data series representing storm surge events was expanded to include the temporal offset, by computing the correlation coefficient between data series temporally offset relative to one another by k hours (where k = 0, 1, 2, . . . , n) [52].

Cluster analysis was employed in order to detect groups of features characterized by a similar variability rhythm. The clustering procedure was based on Ward's method [53]. This method clusters together such elements that yield the least squared deviation sums for all elements relative to the balance point of a cluster. The objective function, error sum of squares (*ESS*) is formulated as [54]:

$$ESS = \sum_{i=1}^{n} d_{xi}^2 - \frac{1}{n}\left(\sum_{i=1}^{n} d_{xi}\right)^2 \quad (1)$$

where d_{xi} represents the deviation of the *i*-th object from the balance point of the cluster. This method is regarded as highly effective, although it tends to form small clusters.

The expression 1-R, where R is Pearson's correlation coefficient, was assumed as the measure of distance. The resultant dendrogram plots clusters. The shorter the taxonomic distance, the stronger the links between the variables. The *X*-axis unit is percent, resulting from standardization of the dendrogram scale, achieved by dividing the node distance (D_{link}) by maximum distance (D_{max}), and multiplying the result by 100.

The detected patterns and relationships were verified by principal component analysis [55]. PCA is another exploratory multivariate technique used in environmental research to discover, i.e., structure in relationships between data series. It creates new, unobservable variables that are linear combinations of the original variables. The new variables, termed principal components (PCs), are orthogonal (mutually uncorrelated) and are identified in order of decreasing importance. They are extracted based on a correlation matrix. The obtained eigenvalues of the PCs are a measure of their variance, whereas the contribution of the original variables to the PCs is expressed by the loadings [56]. Bartlett's sphericity test [57], which tests the degree of correlation between the variables selected for analysis, was employed to assess whether PCA application was justified. The appropriate number of components was chosen based on Cattell's criterion [58]. This criterion is based on a so-called scree plot, which is a linear plot showing the successive eigenvalues. The point from which eigenvalues display a gentle decrease toward the right-hand side indicates the number of PCs explaining the highest variance percentage (i.e., the largest part of the variability in the original variables).

Regardless of absolute values (recorded water levels *H* expressed as cm), standardized values Z were used in statistical analyses. These represent the momentary deviation of water level (x_i) from its mean value ($\overline{x}$), divided by the standard deviation of the data series (s):

$$Z_i = \frac{x_i - \overline{x}}{s} \quad (2)$$

Standardization eliminated the possible interference of various gauge null datums in the Odra River outlet stretch with the obtained results and facilitated a comparison of water level time series [8].

3. Results

3.1. Water Levels at the Lower Odra River Outlet Stretch Versus the Pomeranian Bay Sea Level—Variability Rhythm Disparity

The Odra River water levels along the section between Gozdowice and Bielinek were largely a reflection of river discharge. Through the period 2008/2009−2019/2020, mean discharge at Gozdowice equaled 457 m^3s^{-1}. Mean water levels from January to April were higher than multi-year mean annual water level, pointing to the dominance of thaw high water in shaping the water levels along this section of the river (Figure 2). High waters resulting from rainfall or ice phenomena occurrences were less frequent in the Odra River. Through the study period, 12 high water events were recorded on the Odra River, including four multi-peak events. The highest water level at Gozdowice, equal to 617 cm, i.e., 301 cm above the Odra River mean level was noted during a rainfall high water event in May 2010 (Table S1). This event was above the water level characterized by p = 5% exceedance probability, estimated by Buchholz [48] using Pearson's type III distribution. The corresponding discharge was 2180 m^3s^{-1}. In the period from May to December, mean monthly Odra River water levels were lower than the multi-year mean annual water level. At Gozdowice, during the period of the lowest Odra River water levels in September 2015, a water level of 171 cm was recorded, i.e., 145 cm below mean. The corresponding discharge was just 123 m^3s^{-1}.

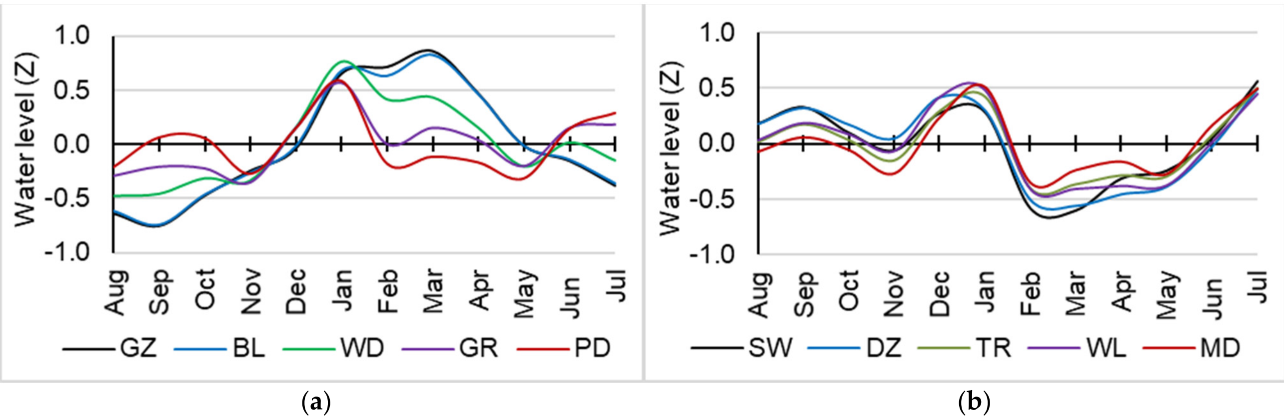


Figure 2. Average monthly water levels at: (**a**) GZ, BL, WD, GR, and PD and (**b**) SW, DZ, TR, WL, and MD in years 2008/09−2019/20 (Z—standardized water level values).

At the southern coast of the Pomeranian Bay, in Świnoujście and Dziwnów, the rhythm of annual sea level variability (Figure 2) was consistent with seasonal changes in the Baltic Sea level [59]. From February to May, monthly sea levels were lower than the mean annual sea level for the study period, which equaled 6 cm amsl. Higher sea level values were noted for the second half of the year, with a peak in July; 28 storm surge events were recorded through the study period, during which sea level at Świnoujście reached or exceeded alarm sea level (a total of 360 h with an H $\geq$ 80 cm amsl). These events were noted from September to March, most frequently from October to January (21 surges). The highest storm surge was recorded on 4 January 2017 (Table 1), when sea level rose to 142 cm amsl, i.e., approximately a sea level value characterized by a p = 1% exceedance probability (following Buchholz [48]). This was driven by the passage of the deep and extensive low-pressure system Axel over the Baltic Sea. Sea level values >120 cm amsl were recorded for the further three storm surge events, i.e., in October 2009, and in January 2012 and 2019. At Świnoujście, alarm sea level remained exceeded for the longest time during the two surge events in January 2012 and 2017 (38 h). On average, during a surge event during which alarm sea level was exceeded, sea level rose by 100 cm. The highest sea level rises were noted during a storm surge event associated with the migration of the low-pressure system Zeetje in January 2019 (190 cm), and the low-pressure system Xaver in December 2013 (171 cm). The average sea level values from the last 30 and 7 days preceding the surge event equaled 12 cm amsl. These were the highest during the January 2012 surge event: 31 and 48 cm amsl, respectively.

Table 1. The highest storm surges at the coast of the Pomeranian Bay in Świnoujście in years 2008/2009−2019/2020.

No.	Low Pressure System [1]	Date	Maximum Sea Level (cm amsl)	Number of Hours with Alarm Level Exceeded [2]	Relative Sea Level Rise (cm)	Average Sea Level over 30 Days Preceding a Surge (cm amsl)	Average Sea Level over 7 Days Preceding a Surge (cm amsl)
1	Yulietta	30 October 2008	101	10	105	−4	4
2	Wimar	15 October 2009	122	34	80	12	32
3	Olaf	11 February 2011	120	8	120	4	8
4	Joahim	17 December 2011	107	11	109	−6	3
5	Elfriede	14 January 2012	132	38	149	31	48
6	Xaver	7 December 2013	100	18	171	17	11
7	Zofia	5 October 2016	105	20	79	9	−5
8	Axel	4 January 2017	142	38	124	14	26
9	Herwart	30 October 2017	112	37	122	10	15
10	Zeetje	2 January 2019	133	19	190	−3	−1

[1] source: [60]; [2] alarm sea level at Świnoujście—H = 80 cm amsl.

The analysis of correlation between maximum sea level during a surge event, and the number of hours with an exceeded alarm sea level indicated a statistically significant relationship between the studied features ($\alpha < 0.01$). R equaled 0.768. A weaker relationship was observed between the maximum value and sea level rise during a surge event ($R = 0.587$, $\alpha < 0.01$). No statistically significant relationship was detected between storm surge height and mean sea level for the 30 and 7 day periods preceding a surge. The influence of the average sea level from the last 7 days, however, made an impact on how long the alarm sea level remained exceeded ($R = 0.431$, $\alpha < 0.05$).

3.2. Water Level Variability within the Lower Odra River Network and the Szczecin Lagoon

Water level variability within the lower Odra River network downstream from Bielinek to the outlet of the Odra River to the Szczecin Lagoon was due to a seasonal rhythm of discharge from the Odra catchment, and the Baltic Sea level variability. At Widuchowa, water levels displayed a seasonal rhythm of changes characteristic for the fluvial section of the lower Odra, with a minor influence of the sea. The highest water level, associated with the occurrence of ice phenomena on the Odra River, was noted in December 2010. On both the eastern and western branches of the Odra River, marine-type fluctuations were superimposed on fluvial-type fluctuations. High water levels on the Odra River were due to both enhanced discharge from the Odra catchment, and ice cover occurrence or storm surges on the sea. At Gryfino, the highest water levels were noted during a high water event on the Odra River in the winter of 2010/2011, and also during a storm surge event in October 2009. On both the Western and the Eastern Odra at Szczecin (MD and PD data series), the highest water levels were recorded during the October 2009 storm surge. The rhythm of water level changes in the Szczecin Lagoon was mostly due to sea level variability. The October 2009 surge proved to be the highest storm surge on the Szczecin Lagoon.

The correlation analysis indicated statistically significant (at $\alpha < 0.05$ level) relationships between the studied water level data series, characterized by a varying degree of mutual correlation (Table 2). The SW and DZ series correlated the strongest with TR and WL series ($0.846 < R < 0.902$), slightly weaker with MD and PD series ($0.752 < R < 0.844$).

Correlation between SW and DZ series, and GR and WD series was weaker but statistically significant. The analysis indicated that the sea level influence on the water level within the lower Odra River network and the Szczecin Lagoon decreases away from the sea. Whereas sea level variability (SW series) can explain 72% of the water level variability in the Szczecin Lagoon and 57−66% of water level variability at Szczecin water gauge, at Widuchowa it explains only 9% of water level variability. Furthermore, the analysis indicated that the influence of discharge from the Odra catchment on water level variability diminishes downstream toward the Odra outlet to the Szczecin Lagoon.

Table 2. Triangular matrix of correlation of water levels in the Odra River mouth area in years 2008/09 to 2019/20.

	SW	DZ	TR	WL	MD	PD	GR	WD	BL	GZ
SW	1.000									
DZ	0.955	1.000								
TR	0.849	0.886	1.000							
WL	0.846	0.902	0.979	1.000						
MD	0.815	0.844	0.976	0.952	1.000					
PD	0.752	0.778	0.924	0.900	0.964	1.000				
GR	0.621	0.637	0.805	0.774	0.882	0.927	1.000			
WD	0.300	0.297	0.461	0.435	0.570	0.672	0.847	1.000		
BL	−0.091	−0.115	−0.008	−0.015	0.099	0.228	0.462	0.772	1.000	
GZ	−0.106	−0.129	−0.027	−0.031	0.077	0.207	0.434	0.736	0.981	1.000

The cluster analysis yielded two basic clusters (Figure 3a). The first cluster comprises water levels along the typically fluvial section of the lower Odra (BL and GZ), slightly less strongly linked with WD and GR series. The rest of the studied measurement series formed a separate cluster, indicating a strong marine influence within the Szczecin Lagoon and the Szczecin Water Area (cluster of SW and DZ series, closely linked with TR, WL, MD and PD series).

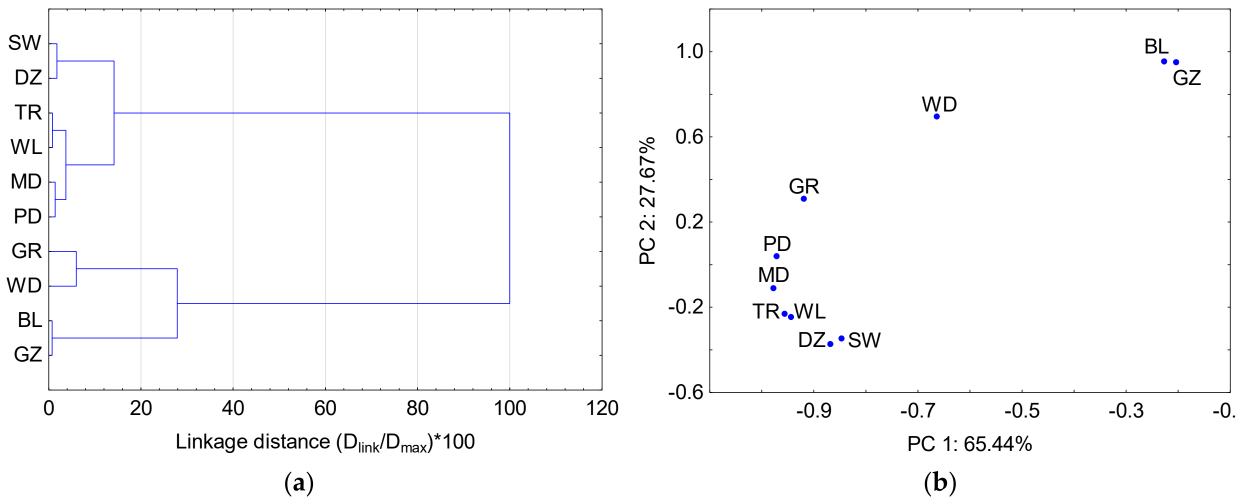


Figure 3. Relationships between water levels in the Odra River mouth area in years 2008/2009–2019/2020: (**a**) dendrogram and (**b**) loading scatter plot for PC1 (principal component 1) versus PC2 (principal component 2), along with percentage of total variance explained by PC1 and PC2.

Analysis of correlations between water level series in the Odra mouth area showed all the variables to be correlated (Table 2). Bartlett's sphericity test showed the value χ^2 (2348636) to be higher than the critical value χ^2 = 61.66 (α = 0.05 and 45 degrees of freedom), thus proving that the PCA was capable of detecting and describing the data set structure. The analysis performed here identified principal components, of which the two most significant components explained 93.1% of the total variance (Table S2). A resultant 2D scatter plot indicated that SW, DZ, TR, WL, MD, PD and GR series are strongly correlated with the first component (PC loadings from −0.85 to −0.98), which points to a clear sea level-induced influence as high upstream as Gryfino (Figure 3b). The fluvial-type GZ, BL and WD series are more strongly correlated with the second component (PC loadings from 0.69 to 0.95). The slightly weaker correlation of the WD series with the second component may be due to the presence of marine influence at Widuchowa.

3.3. Water Level Variability in the Odra Mouth Area during Storm Surge Events

Through the study period, on the Szczecin Lagoon and within the lower Odra reaches, four storm surge events were noted during which water level at Trzebież exceeded 100 cm amsl, i.e., 40 cm above alarm water level (Table 3). Due to sea level fluctuation suppression within the straits linking the Szczecin Lagoon with the Pomeranian Bay, the relative water level rises in the Szczecin Lagoon and within the lower Odra were lower than in the sea. During the 28 storm surge events studies here, relative water level increases in the Szczecin Lagoon and upstream Odra River up to Widuchowa usually equaled 51−60 cm. It was thus 43% lower than in the sea. The highest water level rise in the Odra mouth area was recorded during the October 2009 surge event, when the water level rose by 90−106 cm. 80 cm water level rises were noted during surge events in early January 2012, in October 2017, and in early January 2019. On the other hand, during several surge events, water level rises in the Odra mouth area were of the order of 30 cm (e.g., in March 2009 or in December 2010). At Bielinek, a 25−40 cm water level rise on the Odra River was noted only during the most extensive storm surge events (in October 2009 and 2016, and in January 2019).

Table 3. The highest storm surges at the coast of the Szczecin Lagoon in Trzebież in years 2008/2009−2019/2020.

No.	Date	Maximum Water Level (cm amsl)	Number of Hours with Alarm Level Exceeded [1]	Relative Water Level Rise (cm)
1	15 October 2009	126	146	90
2	14 January 2012	110	91	74
3	5 October 2016	92	68	69
4	4 January 2017	107	63	71
5	30 October 2017	106	62	82

[1] alarm water level at Trzebież—H = 60 cm amsl.

During the examined surge events, the temporal offset of the maximum water level occurrence in the Szczecin Lagoon at Trzebież relative to its occurrence at Świnoujście in 24 cases (86% of the studied surge events) ranged from 6 to 20 h, while on the Odra River in Widuchowa (100 km from the Baltic coast), in 86% of surges, it ranged from 6 to 25 h.

The analysis of the correlation between maximum sea level values at the coast of the Pomeranian Bay during storm surges, and the corresponding water level values in the Szczecin Lagoon and upstream lower Odra reaches indicates a positive correlation up to Gryfino (Table 4). Statistically significant correlation coefficient values equaled 0.60–0.76 for the TR, WL, MD and PD series, and 0.44–0.47 for the GR series. Moreover, statistically significant relationships were detected between maximum Szczecin Lagoon and lower Odra River water level values and the duration of alarm sea level exceedance at Świnoujście (R ranged from 0.55 to 0.84 for TR, WL, MD, PD and GR series), and mean sea level from 7 days preceding the surge event (R ranged from 0.47 to 0.63 for TR, WL, MD and PD series).

Table 4. Variability of correlation coefficients (R) between variables characterizing storm surges at the coast of the Pomeranian Bay and maximum water levels in the Odra mouth area.

	Max (SW)	Max (DZ)	Ave7	Alarm (SW)
Max (TR)	**0.685**	**0.690**	**0.533**	**0.832**
Max (WL)	**0.630**	**0.761**	**0.626**	**0.784**
Max (MD)	**0.697**	**0.642**	**0.519**	**0.843**
Max (PD)	**0.668**	**0.605**	**0.469**	**0.770**
Max (GR)	**0.470**	**0.442**	0.340	**0.550**
Max (WD)	0.105	0.149	0.083	0.109

Note: bold font denotes statistically significant R values at $\alpha \leq 0.05$; Abbreviations: Max (SW, . . . ,WD)—maximum water level at a specific station; Ave7—Average sea level over 7 days preceding a surge; Alarm (SW)—Number of hours with alarm level exceeded at Świnoujście (H $\geq$ 80 cm amsl).

The analysis of the correlation between the studied data series indicated that during the periods with exceeded alarm sea level at Świnoujście, the relationships between sea levels in the Pomeranian Bay and water levels in the Szczecin Lagoon and within the lower Odra are considerably weaker than those computed based on the data series from the entire 12-yearlong study period (Table 5). Statistically significant (at $\alpha \leq 0.05$ level) relationships with sea levels at Świnoujście were obtained only for sea levels in Dziwnów (R = 0.535), water levels in the Szczecin Lagoon and water levels up the Odra River to Gryfino (0.250 < R < 0.305). Weaker correlations were due to suppression of sea level fluctuations within the straits linking the lagoon with the bay. The strongest relationships were detected between the Szczecin Lagoon water levels (TR, WL) and water levels upstream of the lower Odra River up to Widuchowa (MD, PD, GR and WD). Statistically significant correlation coefficients ranged from 0.70 to 0.98. Strong correlations were due to the high similarity of storm surge course along this section. Moreover, the analysis indicated a progressively weaker role of discharge from the Odra catchment in shaping water levels downstream toward the Odra outlet into the Szczecin Lagoon (statistically significant relationships for the GZ series were obtained only for WD and GR series).

Table 5. Triangular matrix of correlation of water levels in the Odra River mouth area during periods with exceeded alarm sea level at Świnoujście in years 2008/09 to 2019/20.

	SW	DZ	TR	WL	MD	PD	GR	WD	BL	GZ
SW	1.000									
DZ	**0.535**	1.000								
TR	**0.304**	**0.521**	1.000							
WL	**0.283**	**0.618**	**0.971**	1.000						
MD	**0.305**	**0.514**	**0.982**	**0.948**	1.000					
PD	**0.290**	**0.489**	**0.964**	**0.929**	**0.977**	1.000				
GR	**0.250**	**0.472**	**0.947**	**0.914**	**0.974**	**0.960**	1.000			
WD	0.099	**0.351**	**0.709**	**0.701**	**0.744**	**0.748**	**0.863**	1.000		
BL	−0.080	**0.154**	−0.016	0.044	0.030	0.005	**0.186**	**0.526**	1.000	
GZ	−0.070	**0.162**	−0.089	−0.020	−0.044	−0.067	**0.108**	**0.448**	0.991	1.000

Note: N = 360, bold font denotes statistically significant R values at $\alpha \leq 0.05$.

The analysis of the dendrogram showing periods with alarm water level exceeded at Świnoujście indicated an increased role of the Pomeranian Bay sea level variability in shaping the lower Odra water level variability. The closest relationships occurred between the lower Odra water level between Widuchowa and Szczecin (MD, PD, GR and WD series) and the Szczecin Lagoon water levels (TR and WL series). Due to sea level fluctuation suppression within the straits linking the Szczecin Lagoon with the Pomeranian Bay, water level values between Widuchowa and Trzebież clustered together with the Pomeranian Bay water level values, with a lower degree of mutual correlation (Figure 4a). BL and GZ series formed a separate cluster with a high degree of mutual correlation, not correlated with the water levels at gauging stations located further downstream.

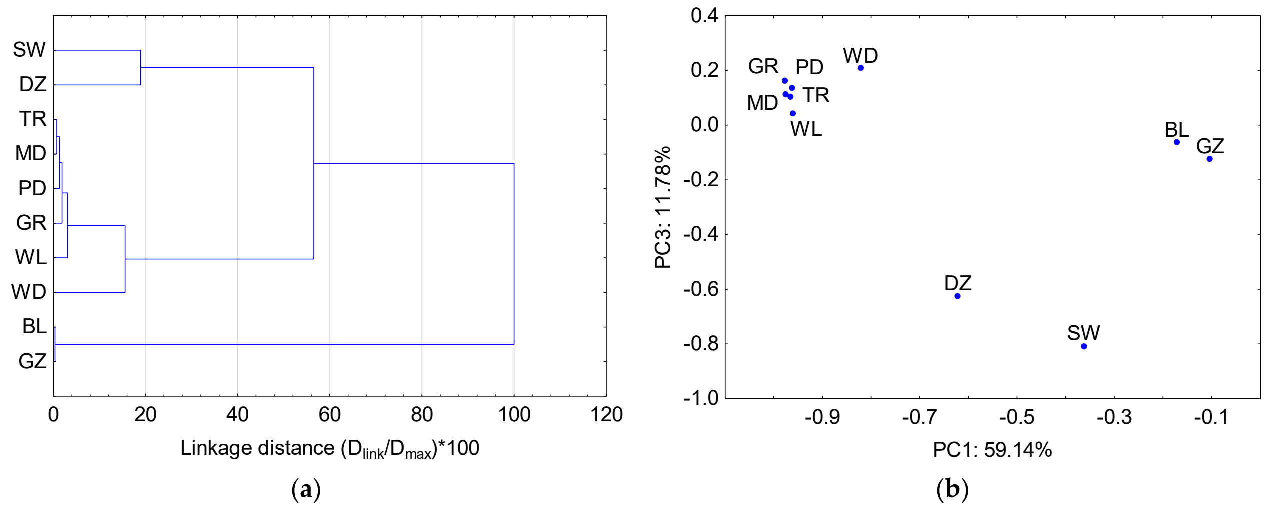


Figure 4. Relationships between water levels in the Odra River mouth area during periods with exceeded alarm sea level at Świnoujście: (**a**) dendrogram and (**b**) loading scatter plot for PC1 (principal component 1) versus PC3 (principal component 3), along with a percentage of total variance explained by PC1 and PC3.

The PCA analysis performed here corroborated the results obtained from cluster analysis. Three principal components with eigenvalues >1 were identified by PCA, which explained 93.3% of the total variance (Table S3). TR, WL, MD, PD, GR and WD series are strongly correlated with the first component (PC loadings from −0.82 to −0.97). The fluvial-type GZ and BL series are more strongly correlated with the second component (PC loadings equal to 0.98). SW and DZ series is most strongly correlated with the third component (PC loadings from −0.63 to −0.81). Figure 4b shows a scatter plot for water levels in the Odra mouth area during storm surges (PC1 versus PC3).

The analysis of cross-correlation between sea level values at Świnoujście and water levels in the Szczecin Lagoon and up the lower Odra reaches up to Widuchowa during periods with exceeded alarm sea level at Świnoujście indicated a positive correlation of the parameters used for computations both synchronously, and when involving an offset of several hours (Table 6). Maximum, statistically significant cross-correlation coefficient values were obtained at 6–7 h offset. On the other hand, the strongest correlation between the Szczecin Lagoon (TR and WL series) and lower Odra (MD, PD, GR and WD series) water levels was detected for synchronous timing (k = 0 h). TR and WL series were the most strongly correlated with MD, PD and GR series (R > 0.9). A slightly weaker correlation was obtained for the WD series (R = 0.71).

Table 6. Values of coefficients of maximum correlation between sea levels in Świnoujście and the Szczecin Lagoon and lower Odra water levels during periods with exceeded alarm sea level at Świnoujście.

Station	$R(k_0)$	$R(k_{max})$	k_{max}(hours)	ΔR
TR	**0.304**	**0.495**	7	0.191
WL	**0.283**	**0.499**	7	0.216
MD	**0.305**	**0.486**	7	0.180
PD	**0.290**	**0.455**	6	0.165
GR	**0.250**	**0.422**	7	0.172
WD	0.099	**0.217**	6	0.118

Note: bold font denotes R statistically significant at $\alpha \leq 0.05$. Abbreviations: $R(k_0)$—correlation coefficient at synchronous timing (k = 0 h); $R(k_{max})$—coefficient of maximum correlation; kmax—offset of maximum correlation (hours); R = $R(k_{max})$—$R(k_0)$.

The analysis performed here indicated that due to the low capacity of the straits linking the Szczecin Lagoon and the Pomeranian Bay, during storm surges, the water level rise in the lagoon resulting from the elevated sea level occurred with an apparent delay. Also following the culmination of the surge, the water level in the lagoon decreased considerably slower than in the bay. The examination of the time lag of the maximum correlation between SW and TR series during the 28 surge events studied here indicated a 6–10 h offset for 20 cases, most frequently 7 h (5 surge events).

3.4. Transformation of Storm Surge in the Szczecin Lagoon and the Lower Odra River

3.4.1. October 2009 Storm Surge

The storm surge that took place from 13 to 16 October 2009 was preceded by a storm surge associated with an eastward migration of a shallow baric depression over northern Poland on 12 October, moving from over the northern part of Germany toward the east. A 41-cm sea level rise was noted then, causing alarm sea level exceedance for an 18-h period. This was caused by a strong wind blowing from the NNE-NNW sector, with gusts of up to 15 ms^{-1}. The sea level subsequently dropped by only 33 cm, because a northern wind persisted at the coast of the Pomeranian Bay. This wind was supported by an expansion of a high-pressure area over the Norwegian Sea and the British Isles, and by migrations of another low-pressure system from over the Adriatic coast (995 hPa in the center) toward Ukraine. On 14 October, the low-pressure system Wimar deepened to 989 hPa, and moved toward Belarus. From there, it moved very slowly (at 5 ms^{-1} velocity) over eastern Poland, where it was blocked by a high-pressure area above Scandinavia, and remained there until 16 October, slowly dissipating (Figure 5).

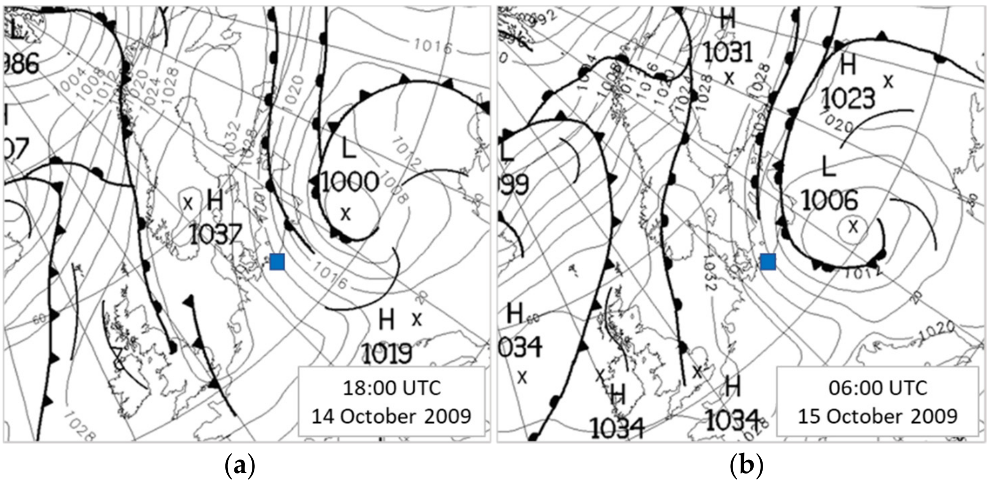
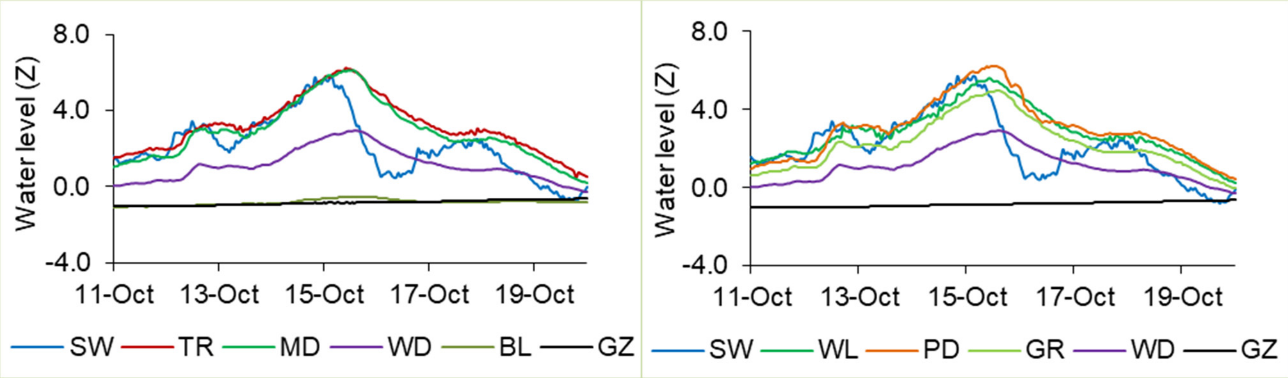


Figure 5. Synoptic situation during the October 2009 storm surge on: (**a**) 14 October, 18:00 UTC; (**b**) 15 October, 6:00 UTC (published with permission, ©British Crown copyright 2009, the Met Office) (blue square: study area).

From 13 October, the sea level at Świnoujście started rising gradually in response to the strong northern wind (Figure 6). A maximum sea level of 122 cm amsl, i.e., 42 cm above alarm sea level, was recorded on 15 October, at 3:00 a.m. At Dziwnów, a maximum sea level equal to 107 cm amsl was recorded an hour later. Following the peak of the surge, sea level started dropping, but due to the influence of very strong northern wind, the alarm sea level remained exceeded until 1:00 p.m. in Świnoujście and until 2:00 p.m. in Dziwnów. After wind strength decreased and wind direction changed to W and WSW, the sea level decreased. A wind direction change to N again on the evening of 16 October influenced another sea level rise. Due to a considerably lower strength of the wind from the northern sector, however, sea level rose in Świnoujście only by 40 cm. The northern wind blew until noon on 18 October. Only on 19 October, an expansion of a high-pressure system over Western and Central Europe, which caused an SW and subsequently S wind at the Pomeranian Bay coast, caused the sea level to drop to a mean level.



(**a**) (**b**)

Figure 6. Water level changes in the Odra River mouth area on 11–19 October 2009: (**a**) the western track, (**b**) the eastern track (water level readings were converted to standardized values—Z).

The mid-October 2009 storm surge was caused by a prolonged period of sustained wind blowing from the northern sector, mostly from the north. The wind blew from this sector for over 6 days, and on the evening of 14 October, gusts of wind reached velocities of 21 ms^{-1}. This wind caused an 80-cm sea level rise. This surge event was preceded by a storm surge on 12 October, which increased the overall Pomeranian Bay sea level. Thus, the mean sea level over the 7 days preceding the surge equaled 32 cm amsl. Due to the extended period of northerly wind influence, as well as the high Baltic sea level, the alarm sea level remained exceeded for 34 h at Świnoujście and for 23 h at Dziwnów.

In the Szczecin Lagoon and within the lower Odra reaches, an increase in water levels was noted from 11 October (Figure 6). This was due to the inflow of marine waters from the Pomeranian Bay, and the influence of wind blowing from the northern sector. In the Szczecin Lagoon at Trzebież, water level rose by 90 cm and reached 126 cm amsl at 10:00 a.m. on 15 October. This was recorded 7 h after the maximum observed at Świnoujście. The maximum, which rose above the level characterized by p = 1% exceedance probability (according to Buchholz [48] estimate), was only 11 cm lower than the highest-ever water level noted during the December 1913 storm surge [39]. At Wolin, the water level reached 111 cm amsl. High water levels caused flooding of low-lying areas adjacent to the lagoon. Following the high water culmination, the lagoon water level started slowly decreasing, but due to the influence of northern wind, water levels remained elevated for an extended period. Overall, the warning water level remained exceeded for 194 h, including 146 h of alarm water level exceedance.

During the surge event, water level increases within the lower Odra reaches up to Widuchowa were slightly higher than in the sea. In Szczecin, the water level rose by 98 cm on the Western Odra (MD) and by 106 cm on the Eastern Odra (PD), causing a two day-long alarm water level exceedance. Maximum water levels were recorded at 8 and 6 h, respectively, after the maximum observed at Świnoujście. Water level increase at Gryfino and Widuchowa equaled 100 cm, causing an alarm water level exceedance in Gryfino, and warning water level exceedance in Widuchowa. At Bielinek, a 47 cm water level rise was noted on the Odra River. Maximum water levels were recorded with a 10 h delay at Gryfino, 11 h delay at Widuchowa and 13 h delay at Bielinek, relative to the maximum recorded at Świnoujście. At Gozdowice, water levels oscillated at the boundary between low and mean water, with a slightly increasing trend due to an increased discharge from the Odra catchment.

The analysis of the correlation between water level readings from the period 11–19 October 2019 indicated an important part played by the Pomeranian Bay sea level variability in shaping the Odra mouth area water level variability (Table 7). The sea level values were the most strongly correlated with water levels in the Szczecin Lagoon and within Szczecin Water Area (0.59 < R < 0.77). Only a slightly weaker correlation was observed between sea level at Świnoujście and water levels at Gryfino and Widuchowa (0.53 < R < 0.71). Additionally, a weak, but statistically significant at $\alpha = 0.05$ level positive correlation was detected between sea level variability and water level variability at Bielinek. The strongest correlations were observed between water levels in the Szczecin Lagoon and those upstream the lower Odra reaches up to Widuchowa (0.98 < R < 0.99). As the October 2009 storm surge was marked by slow and progressive water level changes within the Odra mouth area, correlations calculated for water levels between 11 and 18 October were much stronger than correlations calculated for periods with exceeded alarm sea level in Świnoujście (Table 5).

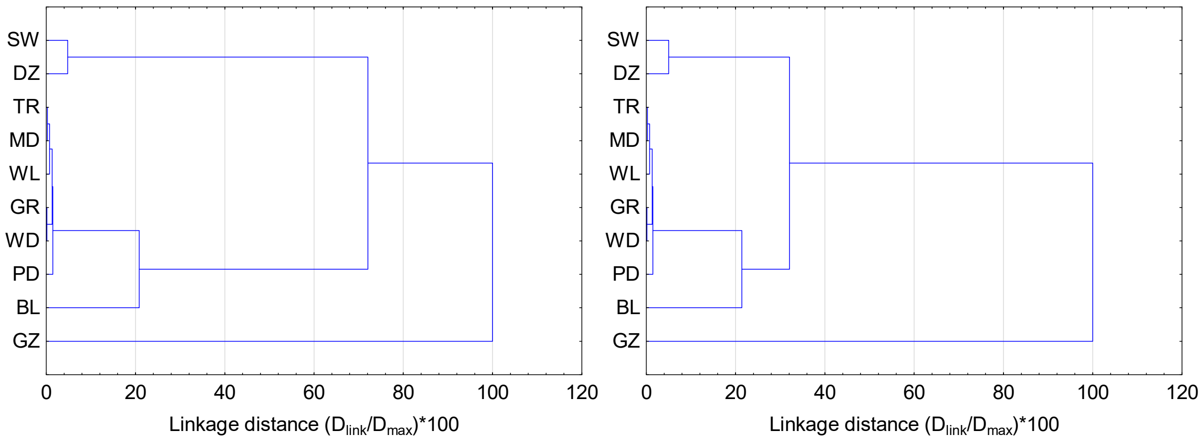
Table 7. Triangular matrix of correlation of water levels in the Odra River mouth area during the October 2009 storm surge.

	SW	DZ	TR	WL	MD	PD	GR	WD	BL	GZ
SW	1.000									
DZ	**0.929**	1.000								
TR	**0.630**	**0.762**	1.000							
WL	**0.589**	**0.742**	**0.993**	1.000						
MD	**0.639**	**0.766**	**0.996**	**0.989**	1.000					
PD	**0.648**	**0.770**	**0.985**	**0.975**	**0.990**	1.000				
GR	**0.573**	**0.713**	**0.993**	**0.989**	**0.995**	**0.986**	1.000			
WD	**0.534**	**0.681**	**0.986**	**0.983**	**0.988**	**0.981**	**0.998**	1.000		
BL	**0.200**	**0.364**	**0.794**	**0.799**	**0.796**	**0.812**	**0.835**	**0.862**	1.000	
GZ	**−0.258**	**−0.209**	0.088	0.081	0.093	**0.156**	0.139	**0.183**	**0.611**	1.000

Note: N = 192, bold font denotes R statistically significant at $\alpha \leq 0.05$.

The analysis of cross-correlation between the Pomeranian Bay sea levels (SW and DZ series) and the Szczecin Lagoon water levels (TR series) yielded statistically significant maximum values of cross-correlation coefficient for SW series at k = 10 h temporal offset, and for DZ series at k = 5 h offset. The analysis of the correlation between SW series at k = 10 h and water levels within the Odra mouth area indicated an increase in the correlation coefficient value by 0.20–0.35, the strongest increase concerning the BL series. An increase in the coefficient of correlation between DZ series at k = 5 h and the remaining studied series was weaker and equaled 0.08–0.14.

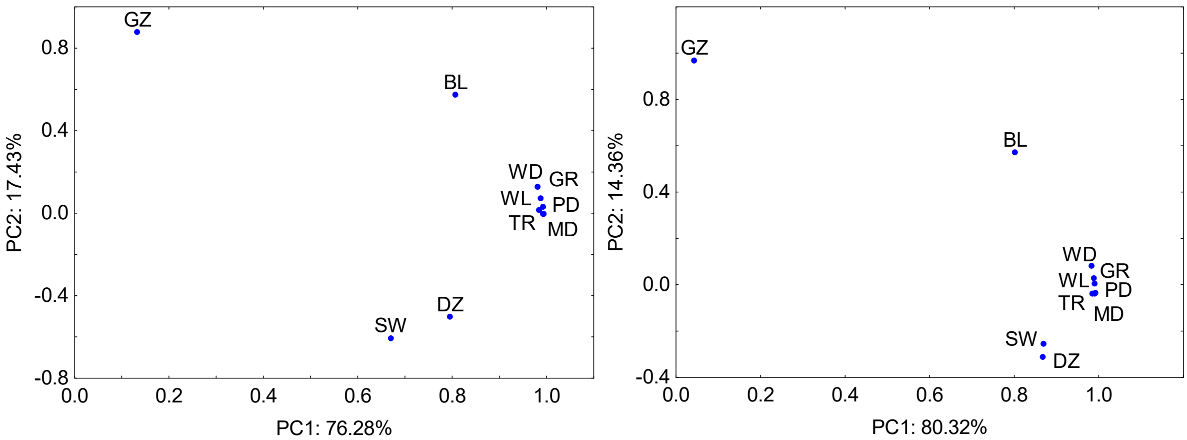
The analysis of the dendrogram clustering water level readings from the Odra River mouth area gauging stations between 11 and 19 October 2009 indicates sea level-induced influence was propagated far inland, reaching as high upstream Odra River as Bielinek (Figure 7a). Water levels from Trzebież to Widuchowa cluster together with a high degree of mutual correlation. In contrast to the dendrogram showing the periods with alarm water level exceeded at Świnoujście (Figure 4a), they are further closely linked to water levels at Bielinek. Water levels from Trzebież to Bielinek are further linked to the Pomeranian Bay sea levels. A cluster analysis of water levels including k = 10 h offset for SW series and k = 5 h for DZ series indicated a considerable increase in similarity of the variability rhythms displayed by the Pomeranian Bay sea levels and the Szczecin Lagoon and the lower Odra River water levels up to Bielinek (Figure 7b).



(**a**) (**b**)

Figure 7. Dendrograms of water levels in the Odra River mouth area during the October 2009 storm surge: (**a**) synchronous water level clustering (**b**) water level clustering with k = 10 h offset for SW series and k = 5 h offset for DZ series.

The PCA analysis corroborated the results obtained from cluster analysis. PCA identified two principal components that explained 93.7% of the total variance in water levels during the October 2009 storm surge (Table S4, Figure 8a). DZ, TR, WL, MD, PD, GR, WD and BL series were strongly correlated with the first component (PC loadings above 0.8), while the GZ series was strongly correlated with the second component (PC loadings = 0.88). The PCA analysis performed here incorporating a k = 10 h temporal offset for SW series and k = 5 h offset for DZ series enabled a distinction of two principal components that explained 94.7% of the total variance in water levels. All series, except for GZ, were strongly correlated with the first component (PC loadings from 0.80 to 0.99), which points to a clear impact of the storm surge event as far upstream as Bielinek. The fluvial-type GZ series was more strongly correlated with the second component (PC loadings = 0.97). Figure 8b shows a scatter plot for water levels in the Odra mouth area during the October 2009 storm surge, incorporating k = 10 h offset for SW series and k = 5 h offset for DZ series.



(**a**) (**b**)

Figure 8. Loading scatter plot (PC1 versus PC2) of water levels in the Odra River mouth area during the October 2009 storm surge, along with percentage of total variance explained by PC1 and PC2: (**a**) synchronous correlations (**b**) correlations incorporating k = 10 h offset for SW series and k = 5 h offset for DZ series.

3.4.2. February 2011 Storm Surge

In the Odra River mouth area, ice phenomena occurring in winter pose a high risk of flooding. In the vicinity of the Szczecin Lagoon, the ice occurrence period lasts on average from late December to early March. Ice phenomena occurs almost every year, on average for 51 days [61]. The ice cover formed in winter is broken by waves, water level changes, and shipping. In order to sustain shipping to and from Szczecin, the Świnoujście-Szczecin Fairway is kept ice-free.

On the Lower Odra River, the forms of ice phenomena occurring on individual sections of the river vary. On the Western Odra in Szczecin, the ice cover is disintegrated by intense shipping, while on the Eastern Odra downstream from Gryfino, the occurrence of permanent ice is hindered by the discharge of heated water from the "Dolna Odra" power plant. From Gozdowice to Widuchowa, there occurs both ice formed in situ, and ice carried from upstream. Here, ice season lasts usually from late December to late March (on average, 45 days with ice) [62].

One of the most hazardous winter surge events on the Odra River occurred in late 2010/early 2011 [29]. It was caused by ice jams followed by a thaw. The maximum water level at Gozdowice in January 2011 equaled 262 cm above the mean Odra River water level, and discharge equaled 1770 m^3s^{-1}. During this high water event, the maximum water level at Bielinek was higher than that recorded during the 2010 Odra rainfall flood, while maximum water levels at Widuchowa and Gryfino were higher than during the 1997 Odra rainfall flood. Flood hazard was further aggravated by the occurrence of five storm surges during this period.

The highest storm surge of winter 2010/2011 was noted from 11 to 13 February 2011. It was associated with the migration of the low-pressure system Olaf from over the North Atlantic (Figure 9) above the Central Baltic. On 11 February, the rapid migration of the low-pressure area over the Central Baltic (992 hPa at the center) toward Latvia and further toward the southeast caused a shift in wind direction at the Pomeranian Bay coast from SSW to W, and, later that day, to N. The wind velocity increased to 14 ms^{-1}, reaching up to 19 ms^{-1} in gusts. The situation outlined above caused the sea level to increase by 120 cm. At Świnoujście at midnight on 11/12 February, the sea level rose to 120 cm amsl (Figure 10). At Dziwnów, due to a 75 cm sea level rise, the culmination equaled 82 cm amsl. The wind weakened, and its direction subsequently changed to ESE on the evening of 12 February, which caused a rapid sea level drop. At Świnoujście on 13 February, the sea level equaled 9 cm amsl. Despite the considerable height of the storm surge, the alarm water level remained exceeded for only 8 h.

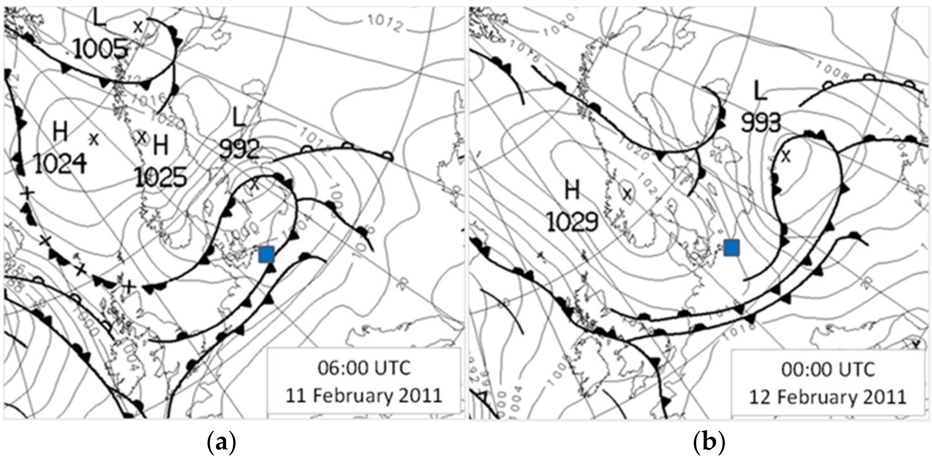
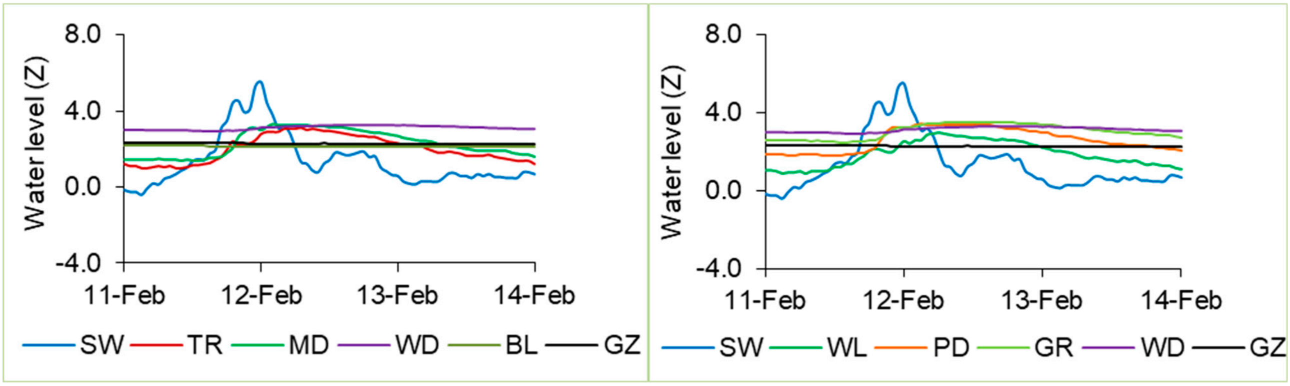


Figure 9. Synoptic situation during the February 2011 storm surge on: (**a**) 11 February, 6:00 UTC; (**b**) 12 February, 00:00 UTC (published with permission, ©British Crown copyright 2011, the Met Office) (blue square: study area).



(**a**) (**b**)

Figure 10. Water level changes in the Odra River mouth area on 11–13 February 2011: (**a**) the western track; (**b**) the eastern track (water level readings were converted to standardized values—Z).

Due to the short and rapid sea level rise along the Pomeranian Bay coast, and due to the occurrence of ice phenomena in the Odra mouth area, the water level rises in the study area were significantly lower than in the sea. Along the coast of the Szczecin Lagoon and within the Szczecin Water Area, these increases were 70% lower than the sea level rise at Świnoujście. At Trzebież, the maximum water level equal to 68 cm amsl was noted 8 h after the culmination at Świnoujście (Figure 10). The alarm water level remained exceeded for 19 h. At Gryfino and Widuchowa, water levels rose only by 24 and 13 cm, respectively, in response to the storm surge. Importantly, high water levels on the Lower Odra between Gryfino and Gozdowice occurring during the February 2011 surge, were associated mostly with a long-lasting winter Odra high water due to the occurrence of ice phenomena on the Lower Odra.

The analysis of the correlation between water levels from the period 11–13 February 2011 performed as part of this study showed a significantly smaller role of the Pomeranian Bay sea level variability in shaping the Odra mouth area water level variability (Table 8). Statistically significant correlations (at $\alpha = 0.05$ level) between sea levels (SW and DZ series) were found only with water levels in the Szczecin Lagoon and within Szczecin Water Area ($0.36 < R < 0.58$). Due to the occurrence of ice phenomena on the lower Odra River, the marine influence further up the Odra River was weaker than usual during periods with exceeded alarm sea level at Świnoujście (Table 5).

Table 8. Triangular matrix of correlation of water levels in the Odra River mouth area during the February 2011 storm surge.

	SW	DZ	TR	WL	MD	PD	GR	WD	BL	GZ
SW	1.000									
DZ	**0.944**	1.000								
TR	**0.465**	**0.567**	1.000							
WL	**0.452**	**0.578**	**0.988**	1.000						
MD	**0.443**	**0.518**	**0.974**	**0.951**	1.000					
PD	**0.365**	**0.443**	**0.963**	**0.940**	**0.994**	1.000				
GR	0.100	0.184	**0.882**	**0.866**	**0.910**	**0.946**	1.000			
WD	−0.166	−0.071	**0.724**	**0.716**	**0.741**	**0.799**	**0.945**	1.000		
BL	0.112	0.095	**−0.476**	**−0.456**	**−0.463**	**−0.516**	**−0.661**	**−0.724**	1.000	
GZ	0.034	0.073	**−0.348**	**−0.314**	**−0.361**	**−0.406**	**−0.514**	**−0.538**	**0.898**	1.000

Note: N = 70, bold font denotes R statistically significant at $\alpha \leq 0.05$.

The analysis of cross-correlation between the Pomeranian Bay sea levels (SW and DZ series) and the Szczecin Lagoon water levels (TR series) yielded statistically significant maximum values of cross-correlation coefficient for both SW and DZ series at k = 7 h temporal offset. The analysis of the correlation between SW and DZ series at k = 7 h and waters levels in the Szczecin Lagoon and up the Lower Odra to Widuchowa, indicated an increase in correlation coefficient by 0.31–0.54, the strongest increase concerning WD series.

The dendrogram showing clustering of water level readings from the Odra River mouth area gauging stations during the February 2011 storm surge indicated a high similarity of water level variability in the Szczecin Lagoon and within the Szczecin Water Area which clusters together with a high degree of mutual correlation (Figure 11a). This cluster is further linked to GR and WD series. In contrast to the dendrogram showing periods with alarm water level exceeded at Świnoujście (Figure 4a), water level values between Widuchowa and Trzebież did not cluster together with the Pomeranian Bay sea level values. The cluster analysis incorporating a k = 7 h offset for SW and DZ series, however, showed a close link between the Pomeranian Bay sea levels and water levels in the Szczecin Lagoon, and within Szczecin Water Area. SW, DZ, TR, WL, MD and PD series are further linked to GR and WD series, which indicates a marine influence reaching upstream as far as Widuchowa (Figure 11b).

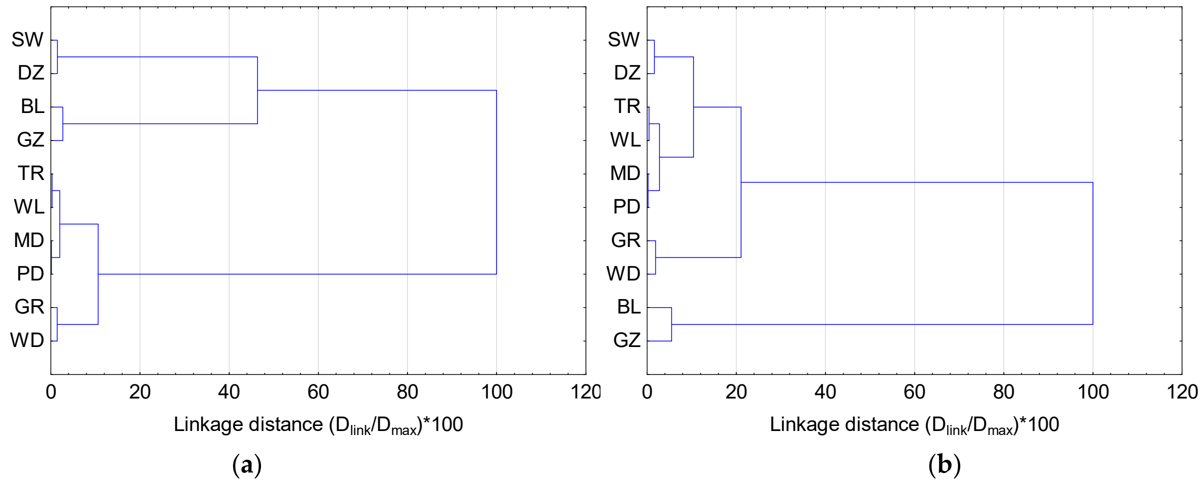
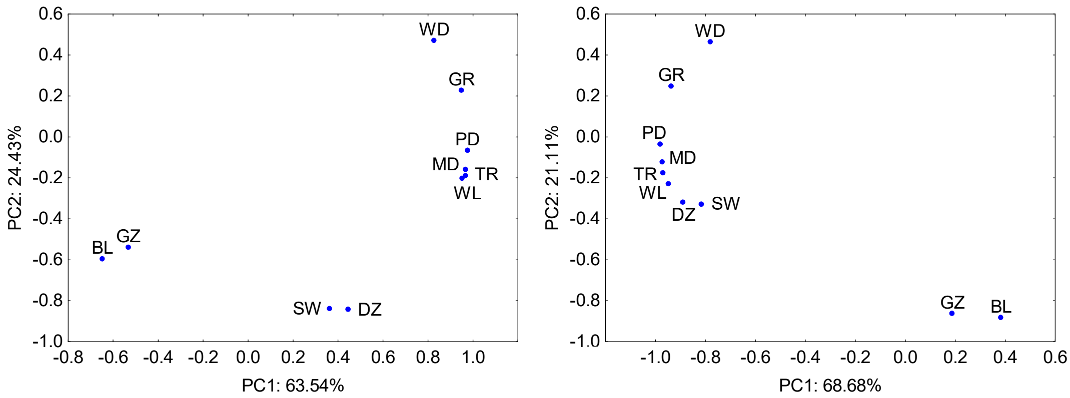


Figure 11. Dendrograms of water levels in the Odra River mouth area during the February 2011 storm surge: (**a**) synchronous water level clustering (**b**) water level clustering incorporating k = 7 h offsets for SW and DZ series.

The PCA analysis corroborated the results of the CA analysis. PCA identified 2 principal components that explained 88.0% of the total variance in water levels during the surge event in February 2011 (Table S5, Figure 12a). TR, WL, MD, PD, GR and WD series were strongly correlated with the first component (PC loadings above 0.8), while SW and DZ series were strongly correlated with the second component (PC loadings below −0.8). The PCA analysis incorporating a k = 7 h offset for SW and DZ series identified two principal components that explained 89.8% of the total variance in water levels. Unlike the previous analysis, however, all data series except BL and GZ were strongly correlated with the first component (PC loadings from −0.78 to −0.98), which indicates the marine influence reached as far inland as Widuchowa. BL and GZ series were strongly correlated with the second component (PC loadings below −0.86). Figure 12b shows a scatter plot for water levels in the Odra mouth area during the February 2011 storm surge, involving k = 7 h offset for SW and DZ series.

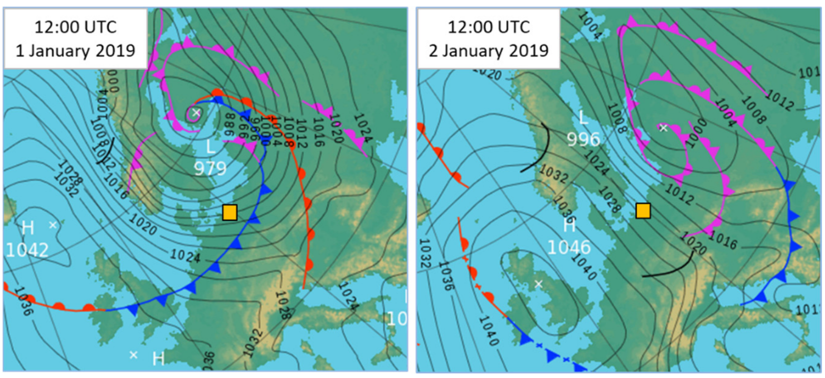


(**a**) (**b**)

Figure 12. Loading scatter plot (PC1 versus PC2) of water levels in the Odra River mouth area during the February 2011 storm surge, along with the percentage of total variance explained by PC1 and PC2: (**a**) synchronous correlations (**b**) correlations incorporating k = 7 h offsets for SW and DZ series.

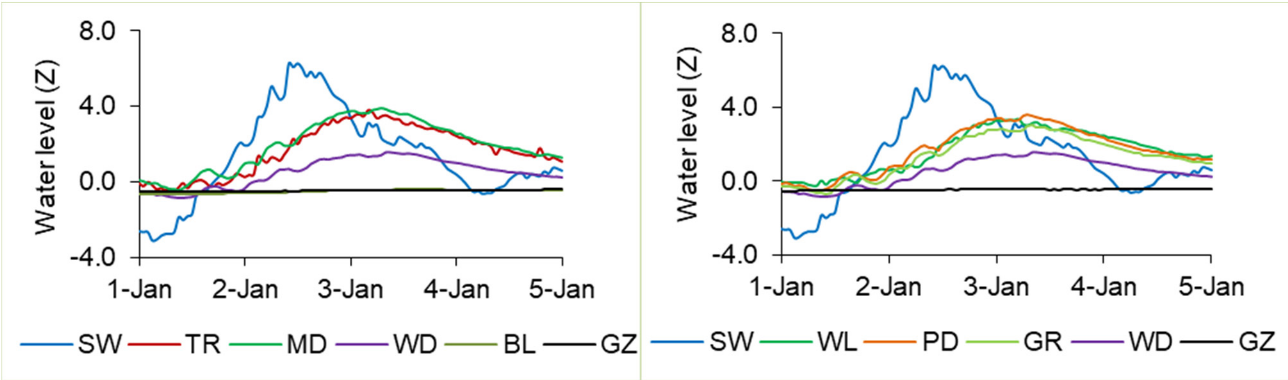
3.4.3. January 2019 Storm Surge

A very high and short-lasting storm surge was noted at the coast of the Pomeranian Bay in the period 1–3 January 2019. This was caused by rapid migration of the low-pressure system Zeetje from over Iceland through the Norwegian Sea, Gulf of Bothnia, over Estonia, and further toward the southeast (Figure 13). On 1 January, an extensive high-pressure area occurred over Western and Central Europe, with 1038 hPa in the center over the English Channel. A 978 hPa low-pressure system was moving at high velocity toward the Gulf of Bothnia and further over Estonia. On this day in Świnoujście, a strong wind (up to 18 ms^{-1}) was blowing from WSW and W. In the afternoon the wind velocity increased to 20 ms^{-1}, and the direction changed to WNW and subsequently NW. At the southern coast of the Pomeranian Bay, this situation led to a sea level lowering to 57 cm below mean sea level (bmsl) at 3:00 a.m., followed by a progressive sea level rise (Figure 14). On 2 January, an increase in wind velocity, and a change in wind direction, which now blew from the north, caused a further sea level rise, which reached 133 cm amsl (53 cm above alarm sea level) in Świnoujście at noon. Sea level remained exceeded until late at night on this day, sustained by a strong wind blowing from the north with an average velocity of 14 ms^{-1}. Wind strength decrease and a subsequent change to SW wind caused a sea level lowering. On 4 January at Świnoujście, the sea level dropped to 7 cm bmsl. During this surge event, sea level changes at Dziwnów were lower. The maximum level of 97 cm amsl was noted 5 h after the culmination at Świnoujście.



(**a**) (**b**)

Figure 13. Synoptic situation during the January 2019 storm surge on: (**a**) 1 January, 12:00 UTC; (**b**) 2 January, 12:00 UTC (published with permission, ©British Crown copyright 2019, the Met Office) (orange square: study area).



(**a**) (**b**)

Figure 14. Water level changes in the Odra River mouth area on 1–4 January 2019: (**a**) the western track; (**b**) the eastern track (water level readings were converted to standardized values—Z).

The January 2019 storm surge was caused by a rapid movement of a deep low-pressure system over the Baltic Sea, accompanied by a strong wind from the northern sector, mostly from the north. Wind from this sector blew incessantly for two days, and on the morning of 2 January, its velocity rose to 21 ms^{-1} in gusts. At Świnoujście, the wind caused the sea level to rise by 190 cm. Alarm sea level remained exceeded for 19 h in Świnoujście, and for 8 h in Dziwnów. The surge event culmination and the number of hours with alarm level exceedance were influenced by a relatively low sea level: its average value for the 7 days preceding the surge equaled 1 cm bmsl.

High, but short-lasting storm surges at the coast of the Pomeranian Bay caused a 79 cm water level rise in the Szczecin Lagoon at Trzebież, and >80 cm water level rise up the lower Odra reaches as far upstream as Widuchowa (Figure 14). These increases were over 55% lower than the sea level rise at Świnoujście. At Trzebież, the maximum water level equal to 81 cm amsl was noted 16 h after the culmination at Świnoujście. The alarm water level remained exceeded for 30 h. The surge event caused water levels to exceed warning levels in the Szczecin Lagoon at Wolin, and up the lower Odra reaches to Gryfino. On the lower Odra River, the surge culmination was noted 19–20 h after the maximum recorded at Świnoujście. At Gozdowice, the water level remained below the multi-year mean value.

The correlation analysis performed here indicated a statistically significant ($\alpha \leq 0.05$), positive correlation of water level values in the whole Odra River mouth area, resulting from a similar variability in the data series (Table 9). The strongest correlations were detected between waters levels in the Szczecin Lagoon and those up the Lower Odra reaches to Bielinek ($0.89 < R < 0.99$). More intensive sea level changes in the Pomeranian Bay and lower water level fluctuations in the Odra River mouth area resulted in a relatively weaker correlation between the examined data sets ($0.27 < R < 0.69$) in comparison to the October 2009 storm surge (Table 7). Nevertheless, the correlation was stronger than correlations calculated for periods with exceeded alarm sea level in Świnoujście (Table 5).

Table 9. Triangular matrix of correlation of water levels in the Odra River mouth area during the January 2019 storm surge.

	SW	DZ	TR	WL	MD	PD	GR	WD	BL	GZ
SW	1.000									
DZ	**0.962**	1.000								
TR	**0.570**	**0.640**	1.000							
WL	**0.494**	**0.579**	**0.986**	1.000						
MD	**0.612**	**0.688**	**0.982**	**0.970**	1.000					
PD	**0.611**	**0.685**	**0.981**	**0.968**	**0.999**	1.000				
GR	**0.576**	**0.654**	**0.980**	**0.970**	**0.994**	**0.995**	1.000			
WD	**0.548**	**0.622**	**0.976**	**0.971**	**0.984**	**0.987**	**0.996**	1.000		
BL	**0.268**	**0.349**	**0.891**	**0.922**	**0.868**	**0.870**	**0.897**	**0.918**	1.000	
GZ	**0.349**	**0.406**	**0.737**	**0.766**	**0.718**	**0.720**	**0.746**	**0.756**	**0.856**	1.000

Note: N = 88, bold font denotes R statistically significant at $\alpha \leq 0.05$.

The analysis of cross-correlation between the Pomeranian Bay sea levels (SW and DZ series) and the Szczecin Lagoon water levels (TR series) yielded statistically significant maximum values of cross-correlation coefficient for SW series at k = 11 h temporal offset, and for DZ series at k = 8 h offset. The analysis of the correlation between SW series at k = 11 h and waters levels in the Szczecin Lagoon and up the Odra River to Bielinek, indicated an increase in correlation coefficient by 0.33–0.42. Further up the Odra River to Widuchowa, these exceeded 0.9. An increase in the coefficient of correlation between DZ series at k = 8 h and the remaining studied data series was weaker and equaled on average 0.2.

The dendrogram showing clustering of water level readings from gauging stations located within the Odra River mouth area during the January 2019 surge event indicated a high similarity of water level variability from Trzebież to Widuchowa, which cluster together with a very high degree of mutual correlation (Figure 15a). In contrast to the dendrogram showing the periods with alarm water level exceeded at Świnoujście (Figure 4a), this cluster is further linked to typically fluvial-type water level series (BL and GZ). The cluster analysis incorporating a k = 11 h offset for SW series and k = 8 h offset for DZ series, however, showed a close link between water levels from Trzebież to Widuchowa with sea level fluctuations in the Pomeranian Bay, which shows a far-ranging impact of the storm surge event, reaching as far inland as Widuchowa (Figure 15b).

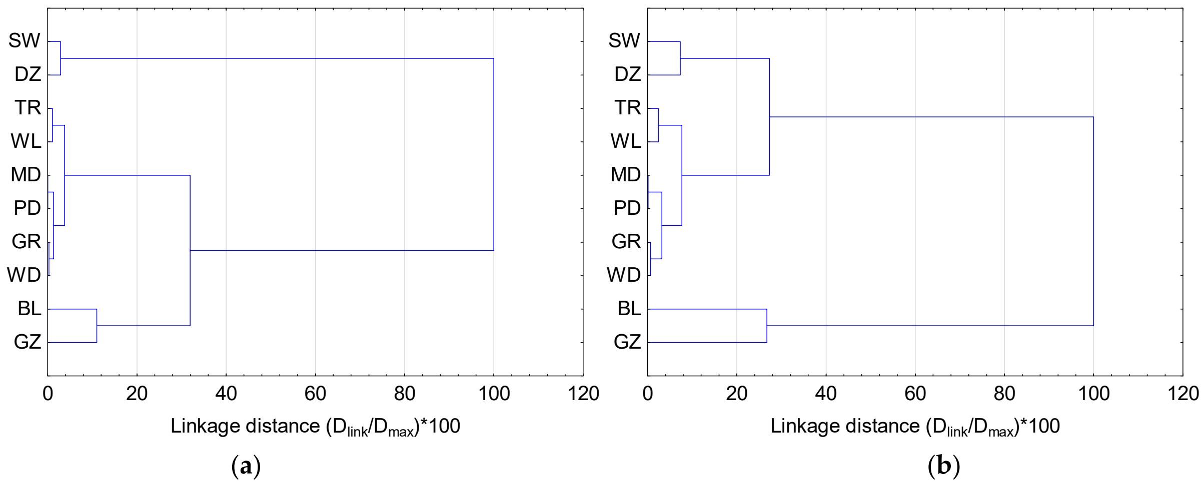


Figure 15. Dendrograms of water levels in the Odra River mouth area during the January 2019 storm surge: (**a**) synchronous water level clustering (**b**) water level clustering with k = 11 h offset for SW series and k = 8 h offset for DZ series.

The PCA analysis performed here identified two principal components that explained 94.8% of the total variance in water levels during the surge event in January 2019

(Table S6, Figure 16a). All data series, except SW, were strongly correlated with the first component (PC loadings below −0.7). The SW series was strongly correlated with the second component (PC loading = 0.75). The PCA analysis incorporating a k = 11 h offset for SW series, and k = 8 h for DZ series identified two principal components that explained 95.6% of the total variance in water levels. Unlike the previous analysis, however, all data series except GZ were strongly correlated with the first component (PC loadings from −0.86 to −0.99), which indicates the marine influence reaching as far inland as Bielinek. GZ series was strongly correlated with the second component (PC = −0.73). Figure 16b shows a scatter plot for water levels in the Odra mouth area during the January 2019 storm surge, involving k = 11 h offset for SW series, and k = 8 h offset for DZ series.

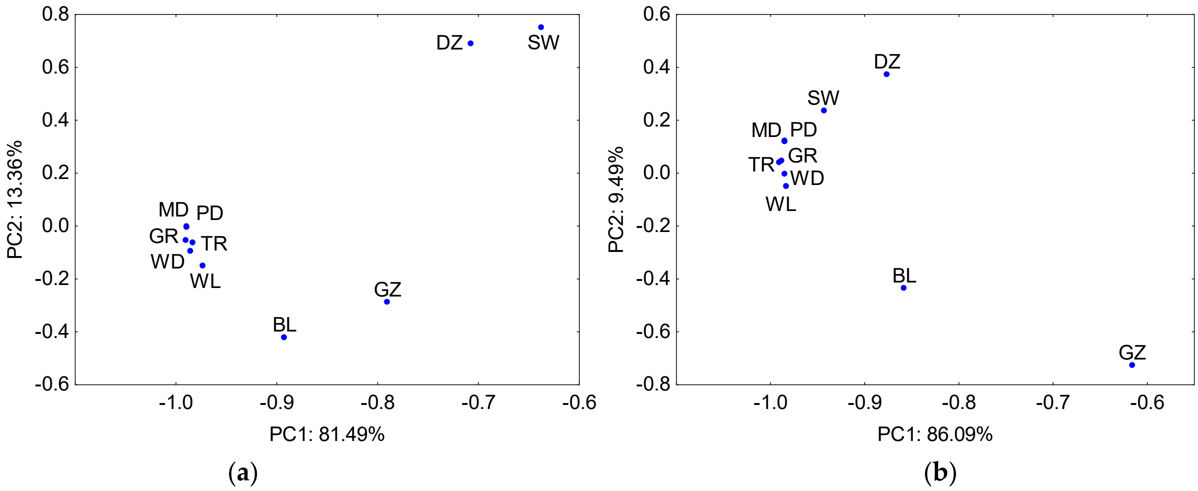


Figure 16. Loading scatter plot (PC1 versus PC2) of water levels in the Odra River mouth area during the January 2019 storm surge, along with the percentage of total variance explained by PC1 and PC2: (**a**) synchronous correlations (**b**) correlations incorporating k = 11 h offset for SW series and k = 8 h offset for DZ series.

4. Discussion

In areas adjacent to river mouths, the hazard of flooding caused by compound floods may be due to interference of a storm surge with enhanced discharge from a river catchment [9,63–66]. Through the period 2008/2009–2019/2020 in the Odra River mouth area, only a few storm surge events coincided with elevated discharge from the Odra catchment, e.g., in the winter of 2010/2011. The influence of storm surges estimated based on CA and PCA analyses, was basically restricted at that time to the Szczecin Lagoon and Szczecin Water Area (ca. 65 km from the Baltic coast). During storm surge events, relative water lever rises decreased upstream from the Odra River mouth. On the other hand, the influence of surges was detected as far as Bielinek (ca. 130 km from the Baltic coast), especially so during periods of decreased discharge from the Odra catchment (e.g., in October 2009 and 2016, January 2019). The results of the present study corroborate the results of modeling and expand our understanding of the suppressing impact of the Odra catchment discharge on the height of the surge being propagated upstream [44]. On the other hand, the present study shows a lack of significant water level increases along the lower Odra River downstream from Gryfino (due to elevated discharge from the Odra catchment), as previously reported by Buchholz [48]. During the rainfall high water event on the Odra River in 2010, a sea level increase to 72 cm amsl caused only a 50–60 cm water level increase in the Odra mouth and acted to extend the time of river water discharge to the sea. Despite the low probability of synchronous occurrence of a high storm surge and high river discharge, modeling results [66,67] point to a possible increase in flooding hazard in the Odra River mouth area due to an interference of a strong storm surge and discharge of floodwater of the Odra River. Studies [7,11] describe a similar impact of river discharge on the propagation of a storm surge in the estuaries of rivers draining into the tidal North Sea.

The results obtained here indicate that high water events in the Szczecin Lagoon and on the lower Odra River, lasting up to several days, and sometimes leading to storm flooding, were observed mostly when multiple successive storm surges were recorded at the Pomeranian Bay coast. Such surge events were usually associated with an elevated mean sea level. In the period 2008/2009 to 2019/2020, during the most extensive surge in October 2009, alarm sea level at Trzebież remained exceeded continuously for 146 h, and during the January 2012 surges for 198 h. Notably, in winter 2006/2007, nine successive storm surges resulted in the Szczecin Lagoon alarm water level remaining exceeded for 300 h [8]. On the other hand, the occurrence of storm surges during periods of elevated discharge from the Odra catchment and/or the presence of ice phenomena (the February 2011 surge event) caused an interference of the storm surge with an already high water level in the Odra River mouth, which suppressed the discharge of fluvial waters into the sea. In such cases, even a slight additional water level increase on the Lower Odra, caused by the occurrence of a storm surge in the Baltic Sea, posed a flooding risk to the low-lying areas within the Odra mouth area.

At the southern coast of the Pomeranian Bay, storm surges are generated mostly by low-pressure systems migrating from above the North Sea or the Norwegian Sea toward the east or southeast. Sztobryn et al. [41] showed that through the period 1976–2000, only 5% of storm surges were noted during the intense inflow of air masses from the east, along the southern periphery of a strong high-pressure system over Scandinavia and northern Russia, or when a baric low approaching from the south became obstructed by a high-pressure system over the Baltic Sea. At the coast of the Pomeranian Bay, through the study period, six surge events were noted during which the sea level at Świnoujście reached at least 80 cm amsl, and that resulted from the approach of a low-pressure area from the south or southeast. These surges, recorded between September and December, caused water levels in the Szczecin Lagoon to rise by 50–90 cm. These surges penetrated far inland within the lower Odra River network: in two cases as far as Widuchowa, and in three cases to Bielinek. All three surges that reached Bielinek were noted in October (2008, 2009 and 2016), and coincided with a decreased discharge from the Odra catchment. The storm surge in mid-October 2009 caused storm flooding on a scale unseen for many decades. The flooding covered areas adjacent to the Szczecin Lagoon and Lake Dąbie, but also those along the Eastern and the Western Odra. Relative water level increases up the lower Odra reaches, up to 100 km inland from the Baltic coast, matched, or even exceeded the relative increase in sea level, and maximum Szczecin Lagoon and Eastern and Western Odra water levels were among the highest levels ever recorded there.

Previous studies on the height and temporal offset of the surge culmination occurrence in the Szczecin Lagoon and within the lower Odra River were based on data series characterized by lower temporal and spatial resolution [8,19,46,48,62]. The statistical analyses included in the present paper are based on up-to-date 12-year-long series of high-resolution (hourly) water level readings from a dense network of sites (10 water gauging stations). This enabled a detailed analysis of the impact that storm surges make on the water level variability in the Odra River mouth area. Specifically, this allowed for an analysis of the height and delay of the surge culmination occurrence on the the Szczecin Lagoon and on the lower Odra River.

Due to the complex character of hydrodynamic processes taking place in the Odra River mouth area, for many years emphasis has been placed on mathematical methods for modeling water level variations in the Szczecin Lagoon [15,68,69], and in the lower Odra River [17,20,44,48,66]. The determined disparity between water level variability rhythm in the lower Odra River and the sea level, enabled a successful application of statistical analyses, such as cluster analysis and principal component analysis, in order to estimate storm surge-induced water level changes in the Odra mouth area. The obtained results have confirmed the applicability of CA to describing regional water level variability, previously utilized in the studies [8,27–31]. Future studies may expand the study by utilizing longer data series, and by examining additional hydrological and meteorological parameters. This will enable analyses to target a precise assessment of the influence of climatic changes on the occurrence of storm floods in the areas adjacent to the lower Odra River and the Szczecin Lagoon. Moreover, it will be possible to study the impact of surge suppression within Peenestrom on water level changes in the Szczecin Lagoon and in the lower Odra River network. Such expanded studies will also broaden our current knowledge derived from flood frequency modeling [5,41,48,70,71], which is of crucial importance for works associated with the protection of low-lying coastal areas and managing the adjacent land areas.

5. Conclusions

The analysis of mutual relationships occurring between water levels during storm surges in years 2008/2009 to 2019/2020 showed that storm surges along the Pomeranian Bay coast (Southern Baltic) determine the water level variability in the Odra River mouth area, involving the Lower Odra River network and the Szczecin Lagoon, and the height and extent of the surge, as well as the temporal offset of the maximum water level occurrence in this region, depend mostly on the character of the sea level changes driven by meteorological conditions, but also on the overall Baltic Sea level, discharge from the Odra River catchment, and ice conditions on the lower Odra:

(1) The extent of storm-surge induced water level changes within the lower Odra River and in the Szczecin Lagoon depended not only on the distance from the sea (the strongest in the lagoon) but varied during the studied surge events and depended on the meteorological conditions (the strongest during the sustained occurrence of wind blowing from the northern sector), discharge from the Odra River catchment (the farthest-reaching at low discharge), ice conditions on the lower Odra (suppressing surge propagation upstream) and generalized sea level in the Pomeranian Bay (stronger at high sea levels). In most cases (during 13 out of 28 studied surges), the extent of marine influence reached 100 km upstream the lower Odra reaches. Less frequently, during surges characterized by an extended sea level rise, or during a transformation of successive storm surges at the Pomeranian Bay coast into one extended surge event in the Odra mouth area, the influence reached 130 km away from the sea. Such surges were noted mostly when the mean sea level in the Pomeranian Bay was elevated.

(2) The low capacity of the straits connecting the Pomeranian Bay to the Szczecin Lagoon, and the very small slope of free surface water in the lower Odra River has influenced the strongest correlation between sea levels at Świnoujście with water levels in the Szczecin Lagoon and the lower Odra, at a k = 6–7 h offset. On the other hand, the strongest correlation between water levels in the Szczecin Lagoon and the lower Odra River network was obtained while incorporating synchronous timing.

(3) As a result of sea level fluctuation suppression within the straits linking the Szczecin Lagoon with the Pomeranian Bay, the relative water level rises in the Szczecin Lagoon and within the lower Odra during storm surges were lower than in the sea (on average 43% lower than in the sea). Nonetheless, in exceptional cases (i.e., when sea level rose gradually for several days and remained high for an extended period), the relative water level rises equaled the magnitude of the sea level rise, or even exceeded it, as far as 100 km inland.

(4) The analysis of causes of storm surges at the coast of the Pomeranian Bay pointed to a threat of storm flooding posed to low-lying areas adjacent to the Szczecin Lagoon and the lower Odra River in the case of the influence of low-pressure systems approaching the Baltic Sea region from the south or southeast, generating long-lasting occurrence of very strong northern winds over the study area.

The hydrologic relations shown here generally appear to reflect the hydrologic patterns that may occur in outlet stretches of rivers draining to tideless seas and characterized by a very low slope of free surface water, and located in areas prone to the occurrence of storm surges caused by mid-latitude low-pressure systems.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/atmos12121559/s1, Table S1: Water level stations in the Odra River mouth area and their specific long-term water levels over the period 2008/2009–2019/2020, Table S2: Principal component loadings (PC), eigenvalues and percentage of explained variance for water levels in the Odra River mouth area, Table S3: Principal component loadings (PC), eigenvalues and percentage of explained variance for water levels in the Odra River mouth area during the periods with exceeded alarm level at Świnoujście, Table S4: Principal component loadings (PC), eigenvalues and percentage of explained variance for water levels in the Odra River mouth area during the October 2009 storm surge, Table S5: Principal component loadings (PC), eigenvalues and percentage of explained variance for water levels in the Odra River mouth area during the February 2011 storm surge, Table S6: Principal component loadings (PC), eigenvalues and percentage of explained variance for water levels in the Odra River mouth area during the January 2019 storm surge.

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References

1. Gönnert, G.; Dube, S.K.; Murty, T.; Seifert, W. Global storm surges. Theory, observations and applications. *Die Küste* **2001**, *63*, 1–623.
2. Feng, L.H.; Hong, W. A quantitative expression for the magnitude and intensity of disaster of storm surges. *Nat. Hazards* **2008**, *45*, 11–18. [CrossRef]
3. Jensen, J.; Müller-Navarra, S.H. Storm surges on the German Coast. *Die Küste* **2008**, *74*, 92–124.
4. Weisse, R.; von Storch, H. *Marine Climate and Climate Change. Storms, Wind Waves, and Storm Surges*; Springer Praxis Books/Environmental Sciences, Praxis Publishing: Chichester, UK, 2010; pp. 1–219.
5. Wolski, T.; Wiśniewski, B.; Musielak, S. Baltic Sea datums and their unification as a basis for coastal and seabed studies. *Oceanol. Hydrobiol. Stud.* **2016**, *45*, 239–258. [CrossRef]
6. Ali, A.; Rahman, H.; Chowdhury, S.S.H.; Begum, Q.N. Back water effect of tides and storm surges on fresh water discharge through the Meghna estuary. *J. Remote Sens. Environ.* **1997**, *1*, 85–95.
7. Mikhailova, M.V. Interaction of Tides and Storm Surges at the Elbe River Mouth. *Water Resour.* **2011**, *38*, 284–297. [CrossRef]
8. Kowalewska-Kalkowska, H. *Impacts Of Storm Surges on the Water Level in the System of Downstream Reaches of the Odra River and the Szczecin Lagoon*; WNUS: Szczecin, Poland, 2012; pp. 1–258. ISBN 978-83-7241-882-1.
9. Paprotny, D.; Vousdoukas, M.I.; Morales-Nápoles, O.; Jonkman, S.N.; Feyen, L. Pan-European hydrodynamic models and their ability to identify compound floods. *Nat. Hazards* **2020**, *101*, 933–957. [CrossRef]
10. Gayathri, R.; Bhaskaran, P.K.; Murty, P.L.N. River-tide-storm surge interaction characteristics for the Hooghly estuary, East coast of India. *ISH J. Hydraul. Eng.* **2019**. [CrossRef]
11. Plüß, A.; Rudolph, E.; Schrödter, D. Characteristics of storm surges in German estuaries. *Clim. Res.* **2001**, *18*, 71–76. [CrossRef]
12. Skriptunov, N.A.; Gorelits, O.V. Wind-induced variations in water level in river mouths. *Water Resour.* **2001**, *28*, 174–179. [CrossRef]
13. Mikhailova, M.V.; Žaromskis, R. Hydrological processes in the mouth area of the Nemunas (Neman) River. *Water Resour.* **2013**, *40*, 97–110. [CrossRef]
14. Szydłowski, M.; Kolerski, T.; Zima, P. Impact of the Artificial Strait in the Vistula Spit on the Hydrodynamics of the Vistula Lagoon (Baltic Sea). *Water* **2019**, *11*, 990. [CrossRef]

15. Jasińska, E.; Massel, S.R. Water dynamics in estuaries along the Polish Baltic coast. *Oceanol. Hydrobiol. Stud.* **2007**, *36*, 101–133. [CrossRef]
16. Różyński, G.; Ostrowski, R.; Pruszak, Z.; Szmytkiewicz, M.; Skaja, M. Data-driven analysis of joint coastal extremes near a large non-tidal estuary in North Europe. *Estuar. Coast. Shelf Sci.* **2006**, *68*, 317–327. [CrossRef]
17. Ewertowski, R. Unsteady flow in Odra River outlet generated during the passage of strong cyclones. In *Advances in Hydro-Science and-Engineering, Volume III, Proceedings of 3rd International Conference Hydro- Science and–Engineering, Cottbus/Berlin, Germany, 31 August–3 September 1998*; Holz, K.P., Bechteler, W., Wang, S.S.Y., Kawahara, M., Eds.; University Mississippi: Oxford, MS, USA, 1998; ISBN 0-937099-09-0.
18. Buchholz, W. The Oder Estuary-hydrological, hydraulic and developmental considerations. *Pol. J. Environ. Stud.* **2009**, *18*, 26–34.
19. Kowalewska-Kalkowska, H.; Wiśniewski, B. Storm surges in the Odra mouth area during the 1997–2006 decade. *Boreal Environ. Res.* **2009**, *14*, 183–192.
20. Mańko, R. Ranges of Backwater Curves in Lower Odra. *Civ. Environ. Eng. Rep.* **2018**, *28*, 25–35. [CrossRef]
21. Nakajo, S.; Mori, N.; Yasudo, T.; Mase, H. Global Stochastic Tropical Cyclone Model Based on Principal Component Analysis and Cluster Analysis. *J. Appl. Meteorol. Climatol.* **2014**, *53*, 1547–1577. [CrossRef]
22. Kim, H.K.; Seo, K.H. Cluster analysis of tropical cyclone tracks over the western North Pacific using a self-organizing map. *J. Clim.* **2016**, *29*, 3731–3750. [CrossRef]
23. Betts, N.L.; Orford, J.D.; White, D.; Graham, C.J. Storminess and surges in the South-Western Approaches of the eastern North Atlantic: The synoptic climatology of recent extreme coastal storms. *Mar. Geol.* **2004**, *210*, 227–246. [CrossRef]
24. You, S.H.; Seo, J.W. Storm surge prediction using an artificial neural network model and cluster analysis. *Nat. Hazards* **2009**, *51*, 97–114. [CrossRef]
25. Callahan, J.A.; Leathers, D.J.; Callahan, C.L. Skew Surge and Storm Tides of Tropical Cyclones in the Delaware and Chesapeake Bays for 1980–2019. *Front. Clim.* **2021**, *3*, 610062. [CrossRef]
26. Luo, W.; Yuan, L.; Yu, Z.; Yi, L.; Xie, Z. Regional sea level change in Northwest Pacific: Process, characteristic and prediction. *J. Geogr. Sci.* **2011**, *21*, 387–400. [CrossRef]
27. Scotto, M.G.; Alonso, A.M.; Barbosa, S.M. Clustering time series of sea levels: Extreme value approach. *J. Waterw. Port Coast. Ocean Eng.* **2010**, *136*, 215–225. [CrossRef]
28. Scotto, M.G.; Barbosa, S.M.; Alonso, A.M. Model-based clustering of Baltic sea-level. *Appl. Ocean Res.* **2009**, *31*, 4–11. [CrossRef]
29. Kowalewska-Kalkowska, H. Frequency and strength of storm surges in the Oder River mouth area. *Acta Sci. Pol. Form. Cir.* **2018**, *17*, 55–65. [CrossRef]
30. Barbosa, S.M.; Gouveia, S.; Scotto, M.G.; Alonso, A.M. Wavelet-based clustering of sea level records. *Math. Geosci.* **2016**, *48*, 149–162. [CrossRef]
31. Wolski, T.; Wiśniewski, B. Geographical diversity in the occurrence of extreme sea levels on the coasts of the Baltic Sea. *J. Sea Res.* **2020**, *159*, 101890. [CrossRef]
32. Church, J.A.; White, N.J. Estimates of the regional distribution of sea level rise over the 1950–2000 period. *J. Clim.* **2004**, *17*, 2609–2625. [CrossRef]
33. Jänicke, L.; Ebener, A.; Dangendorf, S.; Arns, A.; Schindelegger, M.; Niehüser, S.; Haigh, I.D.; Woodworth, P.; Jensen, J. Assessment of tidal range changes in the North Sea from 1958 to 2014. *J. Geophys. Res. Oceans* **2021**, *126*, e2020JC016456. [CrossRef]
34. Hu, Y.; Shao, W.; Wei, Y.; Zuo, J. Analysis of Typhoon-Induced Waves along Typhoon Tracks in the Western North Pacific Ocean, 1998–2017. *J. Mar. Sci. Eng.* **2020**, *8*, 521. [CrossRef]
35. Zhang, Y.; Li, G.; Guo, T. Spatiotemporal Patterns and Evolution of Storm Surge Threats along the Southeastern Coastline of China. *Atmosphere* **2019**, *10*, 61. [CrossRef]
36. Leppäranta, M.; Myrberg, K. *Physical Oceanography of the Baltic Sea*; Springer: Berlin/Heidelberg, Germany, 2009; pp. 1–423.
37. Suursaar, Ü.; Kullas, T.; Otsmann, M.; Saaremäe, I.; Kuik, J.; Merilain, M. Cyclone Gudrun in January 2005 and modelling its hydrodynamic consequences in the Estonian coastal waters. *Boreal Environ. Res.* **2006**, *11*, 143–159.
38. Averkiev, A.S.; Klevanny, K.A. A case study of the impact of cyclonic trajectories on sea-level extremes in the Gulf of Finland. *Cont. Shelf Res.* **2010**, *30*, 707–714. [CrossRef]
39. Richter, A.; Groh, A.; Dietrich, R. Geodetic observation of sea-level change and crustal deformation in the Baltic Sea region. *J. Phys. Chem. Earth* **2012**, *53–54*, 43–53. [CrossRef]
40. Lass, H.U.; Mohrholz, V.; Seifert, T. On the dynamics of the Pomeranian Bight. *Cont. Shelf Res.* **2001**, *21*, 1237–1261. [CrossRef]
41. Sztobryn, M.; Stigge, H.-J.; Wielbińska, D.; Weidig, B.; Stanisławczyk, I.; Kańska, A.; Krzysztofik, K.; Kowalska, B.; Letkiewicz, B.; Mykita, M. *Storm Surges in the Southern Baltic Sea (Western and Central Parts)*; BSH: Rostock, Germany; Hamburg, Germany, 2005; pp. 1–74.
42. Zeidler, R.B.; Wróblewski, A.; Miętus, M.; Dziadziuszko, Z.; Cyberski, J. Wind, wave, sea level and storm surge regime at the Polish Baltic coast. *J. Coastal Res.* **1995**, *22*, 33–54.
43. Helcom. Fifth Baltic Sea pollution load compilation (PLC5). In *Baltic Sea Environment Proceedings No. 128A*; Helsinki Commission: Helsinki, Finland, 2011; pp. 1–220.
44. Ewertowski, R. Modeling of hydrodynamics and pollution dispersion in the mouth of the Odra River. In Proceedings of the International Conference on Development of Lower Odra River Water Management, Szczecin, Poland, 6–7 November 1992; Wyd. IM: Szczecin, Poland, 1992; pp. 90–158.

45. Wolski, T.; Wiśniewski, B. The analysis of Dąbie Lake water balance. *Limnol. Rev.* **2005**, *5*, 263–270.
46. Majewski, A. (Ed.) *Szczecin Lagoon*; Wyd. Kom. i Łącz.: Warszawa, Poland, 1980; pp. 1–323.
47. Mohrholz, V.; Lass, H.U. Transports between Oderhaff and Pomeranian Bight—A Simple Barotropic Box Model. *Dtsch. Hydrogr. Z.* **1998**, *50*, 371–383. [CrossRef]
48. Buchholz, W. (Ed.) *Monograph of the Lower Odra River, Hydrology and Hydrodynamics*; Prace IBW PAN 25; Wyd. IBW PAN: Gdańsk, Poland, 1991; pp. 1–103.
49. Gurwell, B. Coastal protection along the Baltic Sea Coast—Mecklenburg-Vorpommern. *Die Küste* **2008**, *74*, 179–188.
50. Maity, R. Basic Statistical Properties of Data. In *Statistical Methods in Hydrology and Hydroclimatology. Springer Transactions in Civil and Environmental Engineering*; Springer Nature Singapore Pte Ltd.: Singapore, 2018; pp. 53–92. ISBN 978-981-10-8779-0.
51. Helsel, D.R.; Hirsch, R.M.; Ryberg, K.R.; Archfield, S.A.; Gilroy, E.J. Correlation. In *Statistical Methods in Water Resources. U.S. Geological Survey Techniques and Methods*; U.S. Geological Survey: Reston, VA, USA, 2020; Book 4, Chapter A3; pp. 209–221.
52. Mentzafou, A.; Varlas, G.; Papadopoulos, A.; Poulis, G.; Dimitriou, E. Assessment of Automatically Monitored Water Levels and Water Quality Indicators in Rivers with Different Hydromorphological Conditions and Pollution Levels in Greece. *Hydrology* **2021**, *8*, 86. [CrossRef]
53. Ward, J.H. Hierarchical grouping to optimize an objective function. *J. Am. Statist. Assoc.* **1963**, *58*, 236–244. [CrossRef]
54. Marek, T. *Cluster Analysis in Empirical Research: Sahn Methods*; PWN: Warszawa, Poland, 1989; pp. 1–170.
55. Abdi, H.; Williams, L.J. Principal component analysis. *Chemom. Intell. Lab. Syst.* **2010**, *2*, 433–459. [CrossRef]
56. Helena, B.; Pardo, R.; Vega, M.; Barrado, E.; Fernandez, J.M.; Fernandez, L. Temporal evolution of groundwater composition in an alluvial aquifer (Pisuerga River, Spain) by principal component analysis. *Wat. Res.* **2000**, *34*, 3.
57. Bartlett, M.S. A note on the multiplying factors for various chi square approximations. *J. R. Stat. Soc.* **1954**, *16*, 296–298.
58. Cattell, R.B. The scree test for the number of factors. *Multivar. Behav. Res.* **1966**, *1*, 245–276. [CrossRef]
59. Stramska, M.; Kowalewska-Kalkowska, H.; Świrgoń, M. Seasonal variability in the Baltic Sea level. *Oceanologia* **2013**, *55*, 787–807. [CrossRef]
60. Adopt a Vortex. Available online: http://www.met.fu-berlin.de/adopt-a-vortex/archiv/ (accessed on 9 September 2021).
61. Girjatowicz, J.P.; Świątek, M. Relationship between Air Temperature Change and Southern Baltic Coastal Lagoons Ice Conditions. *Atmosphere* **2021**, *12*, 931. [CrossRef]
62. Buchholz, W. (Ed.) *Materials for the Monograph of the Lower Odra River. Hydrological and Hydrodynamic Conditions*; Prace IBW 22; Wyd. IBW PAN: Gdańsk, Poland, 1990; pp. 1–117.
63. Khanal, S.; Ridder, N.; de Vries, H.; Terink, W.; van den Hurk, B. Storm surge and extreme river discharge: A compound event analysis using ensemble impact modeling. *Front. Earth Sci.* **2019**. [CrossRef]
64. Ward, P.J.; Couasnon, A.; Eilander, D.; Haigh, I.D.; Hendry, A.; Muis, S.; Veldkamp, T.I.; Winsemius, H.C.; Wahl, T. Dependence between high sea-level and high river discharge increases flood hazard in global deltas and estuaries. *Environ. Res. Lett.* **2018**, *13*, 084012. [CrossRef]
65. Zscheischler, J.; Westra, S.; van den Hurk, B.J.J.M.; Seneviratne, S.I.; Ward, P.J.; Pitman, A.; AghaKouchak, A.; Bresch, D.N.; Leonard, M.; Wahl, T.; et al. Future climate risk from compound events. *Nat. Clim. Chang.* **2018**, *8*, 469–477. [CrossRef]
66. Ewertowski, R. Assessment of flood threat in Lower Odra River caused by hypothetical influence of water levels in Szczecin Bay and atmospheric factors superposed on the flood of July 1997. In *Seminar on Problems of Environmental Engineering in the Odra River Mouth*; Technical University: Szczecin, Poland, 1999; pp. 123–153.
67. Mohrholz, V.; Pastuszak, M.; Sitek, S.; Nagel, K.; Lass, H.U. The exceptional Oder flood in summer 1997-riverine mass and nutrient transport into the Pomeranian Bight. *Dtsch. Hydrogr. Z.* **1998**, *50*, 129–143. [CrossRef]
68. Jasińska, E.; Robakiewicz, M.; Staśkiewicz, A. Hydrodynamic modeling in the Polish Zone of the Baltic Sea—An overview of Polish achievements. *Oceanologia* **2003**, *45*, 107–120.
69. Kowalewski, M.; Kowalewska-Kalkowska, H. Performance of operationally calculated hydrodynamic forecasts during storm surges in the Pomeranian Bay and the Szczecin Lagoon. *Boreal Environ. Res.* **2011**, *16A*, 27–41.
70. Markiewicz, I.; Bogdanowicz, E.; Kochanek, K. On the Uncertainty and Changeability of the Estimates of Seasonal Maximum Flows. *Water* **2020**, *12*, 704. [CrossRef]
71. Tylkowski, J.; Hojan, M. Threshold Values of Extreme Hydrometeorological Events on the Polish Baltic Coast. *Water* **2017**, *10*, 1337. [CrossRef]