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Probabilistic Assessment of Correlations of Water Levels in Polish Coastal Lakes with Sea Water Level with the Application of Archimedean Copulas

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Received: 29 May 2019; Accepted: 18 June 2019; Published: 20 June 2019

Abstract: The hydrology of coastal lakes differs significantly from that of inland water bodies due to the influence of the neighboring sea. Observed climatic changes are expected to enhance the effect of the sea on coastal lake ecosystems, which makes research on sea–lake interactions even more significant. In this study, on the basis of maximum annual and monthly values of water level, dependencies among the water levels of six lakes located along the southern coast of the Baltic Sea in Poland, and the Baltic Sea water levels were analyzed. First, the Spearman rank correlation and the linear regression method were applied. Then, selected copulas were used to find joint distributions of the studied time series. In the next stage, the degrees of synchronous and asynchronous occurrences of maximum water levels in lakes and the sea were calculated. The study revealed that correlations between the maximum annual water levels in coastal lakes and in the Baltic Sea in the selected gauge stations were very strong and statistically significant. These results were confirmed by a synchronicity analysis carried out with the help of a copula function. The highest relationship was detected in the case of Lake Resko Przymorskie (correlation coefficient 0.86, synchronicity 75.18%), while the lowest were observed in Lakes Jamno (0.62 and 58.20%, respectively) and Bukowo (0.60 and 56.82%, respectively). The relation strength between maximum water levels of the sea and coastal lakes may increase in the future due to sea level rises caused by climate warming.

Keywords: time series analysis; coastal lakes; Baltic Sea; water level; Poland; copula; surface water

1. Introduction

A total of 7081 Polish lakes have a surface area of more than one hectare [1]. A large group of those are coastal lakes characterized by complex water circulation due to the intensive supply of river waters from inland areas and the impact of sea waters [2].

Unlike in the case of the remaining parts of Poland, lakes in the coastal zone in the north of the country are characterized by the occurrence of hydrological phenomena and processes that do not occur in inland areas, e.g., the phenomenon of backwater and sea water intrusion, wind-induced blocking of lake water outflows, and the phenomenon of water rise, which are particularly observed on the Baltic coast in the period of winter storms [3].

Lakes located at the interface of land and sea, i.e., areas different in terms of both physical and chemical properties, develop a specific geoecosystem in which the direction of physical, chemical, and biological processes depends on which of the two environments has a stronger impact at a given moment [4]. A study of the coastal zone carried out by Rotnicki [5] confirmed that changes in the sea level determine the existence of the coastal lakes. The maximum Baltic Sea levels in the years 1889–2006 grew both on the Swedish and Polish coasts. The trend of the maximum water levels has increased in the last 60 years [6].

Coastal lakes are characterized by complex water circulation related to their location at the interface of two "environments", sea and land, and they supply marine waters and river waters from inland areas. Research on coastal lakes in Poland and in the world has covered issues concerning, among other things, the chemistry/quality of water (including its salinity) [7–13], the development of lakes in the Holocene [14], the trophic status of lakes in the Holocene [15], biodiversity [16–20], sea water intrusions [4,21,22], and ice phenomena [23]. All of these said studies have confirmed the effect of the sea on the aforementioned properties of lakes.

Water level fluctuations in lakes have various characteristics and causes. Water level changes, their scale, dynamics, and change tendencies depend on natural [24–26] and anthropogenic [27,28] factors [29]. In the case of coastal lakes, more dynamic changes in water levels are observed than in the remaining lakes. This is related to the effect of the Baltic Sea [30–34]. Research on the water level regime in lakes in North Poland has shown that coastal lakes constitute a separate type [35–37]. They are lakes with considerable mean annual amplitudes exceeding 100 cm [35], and according to Reference [36], they show a four-period rhythm of seasonal water level variability determined by atmospheric circulation and the hydrodynamic state of the Baltic Sea. In a classification of lakes through values of pentad water level coefficients in an average annual cycle, lakes are included in a separate group with the smallest range of the parameter. The lakes are the only ones to be characterized by a period of higher water levels in the winter (December, January) and in the summer–autumn period (July–September) and by a period of low water levels in spring (March–May) [37].

The observed strong effect of the sea on changes in the ecosystem of coastal lakes co-occurs with modern climatic changes. Changes in the thermal regime and water levels of the sea will undoubtedly affect lake ecosystems even more strongly, increasing the importance of this research. The possibility of forecasting and the accuracy of forecasts of one variable (water level in lakes) by means of another variable (sea water levels) depends on the degree of dependency between them. The dependency between variables is usually analyzed by means of the Pearson linear correlation coefficient, as well as Spearman and Kendall rank correlation coefficients. These correlation measures have their drawbacks, however, which in the case of analyses of correlations between variables may affect their credibility. According to literature on the subject, linear correlation is not a resistant measure [38]. This means that untypical observations (so-called outliers) can significantly affect the value of the correlation coefficient. The correlation also shows no invariance toward nonlinear transformations. Copulas and related measures of correlation strength have no such drawbacks. They are exceptionally useful and practical approaches in studies on correlations between random variables. The copula theory has already been applied in limnological research, e.g., in the determination of the probability of occurrence of hydrological draught in Lake Poyang and the Yangtse River system [39], in the determination of correlations between extreme water levels in Lake Ontario and the Saint Lawrence River [40], in the determination of correlations of water levels in the Great Lakes and the Saint Lawrence River [41], and in an analysis of the quantity of water supplied to dam reservoirs in the context of forecasting the occurrence of draught [42]. This paper points to the possibility of obtaining new information resulting from the applied new research approach. It concerns, for example, separate and combined probabilities of the occurrence of maximum water levels in lakes and the sea (probabilistic assessment of correlations of maximum water levels in lakes and the sea).

The objective of this paper was the determination of correlations of water levels in coastal lakes of the South Baltic with water levels in the sea (through the application of the correlation coefficient) and the consideration of the possibility of simultaneous modeling of correlations between the selected variables (with the application of copula theory), which provided more possibilities for interpretation of the detected relations than traditional statistical tools did.

The strength of the relationship between maximum water levels in lakes and the sea is presented in the form of the probability of occurrence of synchronous and asynchronous situations. This approach has so far been applied in research on, among other things, correlations between the volume of outflow and volume of supplied debris [43–45] and the volumes of outflow in rivers [46,47]. The results of this study provide a more precise view of connections between water levels in the Baltic Sea and the analyzed coastal lakes. This is particularly important in the context of projected climate warming, which through increased sea water levels may have an impact on coastal lakes, including fluctuations in their water levels, chemistry, and ecological status.

2. Materials and Methods

2.1. Materials and Study Area

The analysis of correlations of water levels in coastal lakes with water levels in the sea was based on the maximum annual and monthly values of water levels in lakes and the sea. They were calculated based on daily values of water levels from the years 1976–2015, which were obtained from the collections of the Institute of Meteorology and Water Management, National Research Institute. Due to the availability of measurement data, in the case of Lake Resko Przymorskie, the analysis covered the multiannual period 1981–2015. The analysis concerned 6 selected coastal lakes where observations of water levels are conducted, namely Resko Przymorskie (station Dźwirzyno), Jamno (station Unieście), Bukowo (station Bukowo Morskie), Gardno (station Gardna Wielka), Łebsko (station Izbica), Druzno (station Żukowo), and 4 water gauge stations in the Baltic Sea (Kołobrzeg, Ustka, Łeba, and Tolkmicko). The water gauge stations in the sea were assigned to lakes based on location. Each lake was ascribed to the nearest water gauge station on the sea (Figure 1).

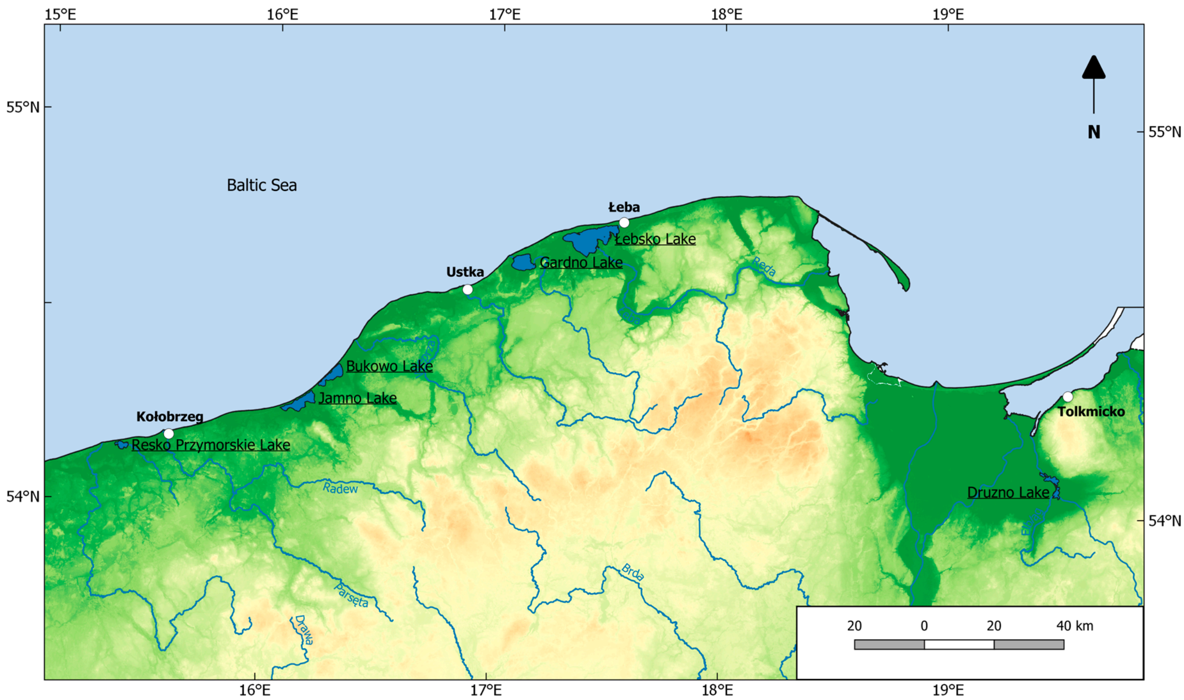

Figure 1. Location of lakes and water gauge stations in the Baltic Sea.

Lakes Resko Przymorskie, Jamno, Bukowo, Gardno, and Łebsko are connected to the sea by means of canals, simultaneously constituting the mouth sections of rivers. Lake Jamno is connected to the sea by means of the Jamno Canal, Bukowo through the Szczucza Canal, Gardno through the Łupawa Canal, Łebsko through the Łeba Canal [32], and Lake Resko Przymorskie through the Resko Canal [48]. Lake Druzno, located in the east of the study area, has a connection to the Baltic Sea through the Vistula Lagoon. The analyzed lakes are shallow, with a mean depth of 1.2 m to 1.8 m (Table 1), but belong to the group of the largest lakes in Poland in terms of surface area. They are characterized by high values of mean, maximum, and extreme annual water level amplitudes. Extreme annual amplitudes in the lakes in the analyzed multiannual period exceed 100 cm. They are the highest in Lake Resko Przymorskie (200 cm) and the lowest in Lake Łebsko (127 cm) (Table 2). The highest water level amplitudes are observed in Kołobrzeg (Table 2). The lowest mean and maximum annual amplitudes occur in Łeba (132 cm and 151 cm), and the most extreme amplitudes are in Ustka (188 cm).

The variability coefficient of daily water levels varies from 0.036 in Lake Łebsko to 0.044 in Lake Bukowo. In the case of the Baltic Sea, the variability coefficient in all stations is 0.041 (Table 2).

Table 1. Morphometric data of the studied lakes.

No.	Lake	Area (ha)	Volume (thousand m^3)	Average Depth (m)	Max Depth (m)
1	Resko Przymorskie (P.)	559.0	7703.4	1.3	2.5
2	Jamno	2231.5	31,528.0	1.4	3.9
3	Bukowo	1644.0	32,071.7	1.8	2.8
4	Gardno	2337.5	30,950.5	1.3	2.6
5	Łebsko	7020.0	117,521.0	1.6	6.3
6	Druzno	1147.5	17,352.0	1.2	2.5

Source: Reference [49].

Table 2. Water levels and their amplitudes in the analyzed lakes and in the Baltic Sea.

Lake/Gauge Station	Water Level (m)			Amplitudes of Water Level (m)			Coefficient of Variation (C_v)
	Annual Mean	Max	Min	Annual Max	Annual Mean	Extreme Multiyear	
Lakes							
Resko P.	502	571	460	175	111	200	0.043
Jamno	533	578	506	104	73	131	0.039
Bukowo	529	577	494	126	82	158	0.044
Gardno	520	573	485	122	88	134	0.040
Łebsko	509	561	475	120	86	127	0.036
Druzno	520	576	479	138	97	176	0.041
Baltic Sea							
Kołobrzeg	503	579	436	181	132	220	0.041
Ustka	505	573	443	161	119	188	0.041
Łeba	505	570	446	151	114	196	0.041
Tolkmicko	509	581	456	168	124	201	0.041

2.2. *Methods*

2.2.1. Mann–Kendall Test

The first stage of the analysis involved the analysis of tendencies of fluctuations of mean annual and maximum annual water levels both in lakes and in the sea in particular stations. This involved the application of the nonparametric Mann–Kendall test, which detects trends in temporal sequences. The Mann–Kendall test was employed in the MAKESENS stencil in Microsoft Excel software. This is a Mann–Kendall test that was extended by scientists from the Finnish Meteorological Institute [50].

2.2.2. Correlation

Next, the Spearman rank correlation and the linear regression method were applied in the analysis of correlations of water levels in the lakes with water levels in the sea (similarly to the case of Pearson's correlation coefficient). Spearman's rank correlation test is a nonparametric test applied in analyses of correlations between quantitative parameters in the case of a low number of observations or a statistic distribution deviating from normal. Then, statistical significance was analyzed at a level of $p = 0.05$,

$p = 0.01$, and $p = 0.001$. A statistical assessment of significance of correlation coefficients was performed by means of statistic t:

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \quad (1)$$

Statistic t has a Student distribution with $n-2$ degrees of freedom.

2.2.3. Application of the Copula Theory

The concept of copula was introduced by Reference [51], which defined copula as a joint distribution function of standard uniform random variables. Modeling joint distribution using copula relaxes the restriction of traditional flood frequency analysis by selecting marginals from different families of probability distribution functions for flood characteristics [52].

First, the best matching statistical distributions were selected for the analyzed data series. The following distributions reflect the maximum values in series of hydrological data: Weibull, Gamm, Gumbel, and log-normal [53]. Parameters of the distributions were estimated by means of the highest probability method [54]. For the purpose of an assessment of the goodness of fit of a given distribution in the data series, the Akaike information criterion (AIC) was applied [55], which was calculated from the following formulas:

$$\text{AIC} = \text{Nlog (MSE)} + 2(\text{no. of fitted parameters}), \quad (2)$$

where MSE is the mean square error, and N is the sample size, or

$$\text{AIC} = -2\log(\text{maximum likelihood for model}) + 2(\text{no. of fitted parameters}). \quad (3)$$

The best model is the one that has the minimum AIC value [55].

In the next step, the copula method was used to construct the joint distribution of lake and sea stages. In general, a bivariate Archimedean copula can be defined as [56]

$$C_\theta(u, v) = \phi^{-1}\{\phi(u) + \phi(v)\}, \quad (4)$$

where the θ subscript of copula C is the parameter hidden in the generating function ϕ, and ϕ is a continuous function called a generator that strictly decreases and is convex from $I = [0,1]$ to $[0, \phi(0)]$.

The Archimedean copula family is often applied in hydrological studies, for example in flood frequency analyses. It was found in References [57] and [58] that a copula-based flood frequency analysis performs better than a conventional flood frequency analysis, as joint distribution based on a copula fits the empirical joint distribution (i.e., from observed data using a plotting position formula) better than the established standard joint parametric distribution. Numerous successful applications of copula modeling have been achieved, most notably in survival analysis, actuarial science, and finance [52].

A large variety of copulas belong to the Archimedean copula family and can be applied when the correlation between hydrologic variables is positive or negative. The proofs of these properties have been reported by References [59] and [60]. For this reason, one-parameter Archimedean copulas, including the Clayton family, the Gumbel–Hougaard family, and the Frank family, were used in this study. The Gumbel–Hougaard and Clayton copula families are appropriate only for positively correlated variables, while the Frank family is appropriate for both negatively and positively correlated variables (Table 3).

Table 3. Copula function, parameter space, generating function $\phi(t)$, and functional relationship of Kendall's τ_θ with a copula parameter for selected single-parameter bivariate Archimedean copulas.

Copula Family	$C_\theta(u,v)$	Generator $\phi(t)$	Parameter $\theta\in$	Kendall's τ_θ	
Clayton	$max\left(\left(u^{-\theta}+v^{-\theta}-1\right)^{-\frac{1}{\theta}},0\right)$	$\frac{1}{\theta}\left(t^{-\theta}-1\right)$	$[-1,\infty)\backslash\{0\}$	$\tau=\theta/(2+\theta)$	(5)
Gumbel–Hougaard	$exp\left\{-\left[(-ln\ u)^{\theta}+(-ln\ v)^{\theta}\right]^{\frac{1}{\theta}}\right\}$	$(-\ln t)^{\theta}$	$[1,\infty)$	$(\theta-1)/\theta$	
Frank	$\frac{-1}{\theta}ln\left[1+\frac{(e^{-\theta u}-1)(e^{-\theta v}-1)}{e^{-\theta}-1}\right]$	$-ln\frac{e^{-\theta t}-1}{e^{-\theta}-1}$	$(-\infty,\infty)\backslash\{0\}$	$1+4[D_1(\theta)-1]/\theta$	

where $D_k(x)$ is Debye function, for any positive integer k,

$$D_k(x)=\frac{k}{k^x}\int_0^x\frac{t^k}{e^t-1}dt. \quad (6)$$

The best fitted joint distribution was selected through comparison to the empirical joint distribution using the Akaike information criterion (AIC), as mentioned earlier.

For each compared pairs of series, based on previously calculated parameters of statistical distribution, 5000 hypothetical points were generated. They were used for the selection of the best fitted family of copulas for a given pair of series and then for the development of an appropriate copula. Based on empirical pairs of values for particular years and generated hypothetical points, graphs with probability curves (expressed in return periods) were developed (Figure 2).

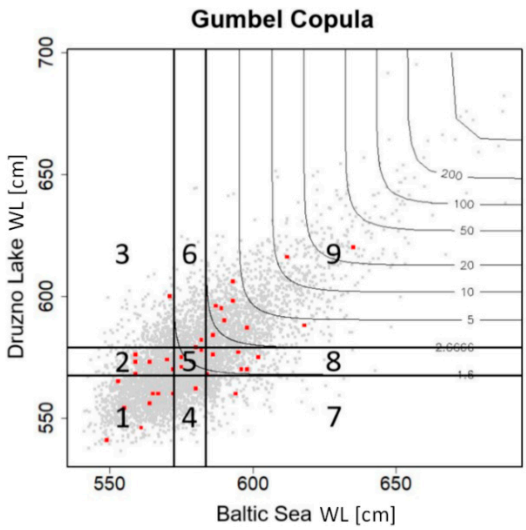

Figure 2. Example of combined accumulated curves of the probability of exceedance of maximum water levels and the determination of sectors with various degrees of synchronicity or asynchronicity of maximum water levels.

The next stage involved a calculation of the degree of synchronicity (synchronous occurrence) and asynchronicity (asynchronous occurrence) of maximum water levels in lakes and the sea. For each pair of stations, probability curves at a level of 62.5% (once in 1.6 years), 37.5% (once in approximately 2.7 years), 20% (once in 5 years), 10% (once in 10 years), 2% (once in 50 years), 1% (once in 100 years), 0.5% (once in 200 years), and 0.2% (once in 500 years) are presented (Figure 2).

The obtained data were then analyzed based on probabilities of 62.5% and 37.5% [44]. Nine sectors were designated, representing different relations between probable maximum water levels. Based on generated points with a distribution imitating the shared distribution of values from comparable water gauge stations and their participation in particular sectors (Figure 2), 3 sectors with synchronous occurrences of maximum water levels were designated:

- Sector 1: $LHWL_S$–$LHWL_L$ ($X \leq S_{62.5\%}$, $Y \leq L_{62.5\%}$);
- Sector 5: $MHWL_S$–$MHWL_L$ ($S_{62.5\%} < X \leq S_{37.5\%}$, $L_{62.5\%} < Y \leq L_{37.5\%}$);
- Sector 9: $HHWL_S$–$HHWL_L$ ($X > S_{37.5\%}$, $Y > L_{37.5\%}$);

as well as 6 sectors with asynchronous occurrence:

- Sector 2: $LHWL_S$–$MHWL_L$ ($X \leq S_{62.5\%}$, $L_{62.5\%} < Y \leq L_{37.5\%}$);
- Sector 3: $LHWL_S$–$HHWL_L$ ($X \leq S_{62.5\%}$, $Y > L_{37.5\%}$);
- Sector 4: $MHWL_S$–$LHWL_L$ ($S_{62.5\%} < X \leq S_{37.5\%}$, $Y \leq L_{62.5\%}$);
- Sector 6: $MHWL_S$–$HHWL_L$ ($S_{62.5\%} < X \leq S_{37.5\%}$, $Y > L_{37.5\%}$);
- Sector 7: $HHWL_S$–$LHWL_L$ ($X > S_{37.5\%}$, $Y \leq L_{62.5\%}$);
- Sector 8: $HHWL_S$–$MHWL_L$ ($X > S_{37.5\%}$, $L_{62.5\%} < Y \leq L_{37.5\%}$);

where X = the values of x coordinates of generated points, Y = the values of y coordinates of generated points, $S_{62.5\%}$ = the value of the maximum sea water level with a probability of exceedance of 62.5%, $S_{37.5\%}$ = the value of the maximum sea water level with a probability of exceedance of 37.5%, $L_{62.5\%}$ = the value of the maximum sea water level with a probability of exceedance of 62.5%, $L_{37.5\%}$ is the value of the maximum sea water level with a probability of exceedance of 37.5%, *WL* = water level, *LH* = "low high", *MH* = "mean high", and *HH* = "high high".

The percent contribution of points included in sectors 1, 5, and 9 permitted a determination of the degree of synchronicity of maximum water levels between the two analyzed water bodies in a given time unit.

Synchronous and asynchronous occurrences of maximum water levels were determined through a determination of threshold values of probability ranges:

- Probable maximum water levels with a probability of occurrence of <62.5% were designated as LHWL;
- Probable maximum water levels with a probability of occurrence in a range >62.5% and <37.5% were designated as MHWL; and
- Probable maximum water levels with a probability of occurrence >37.5% were designated as HHWL.

For example, the occurrence of LHWL in a given lake is a synchronous event if LHWL also occurs in the Baltic Sea in a given time unit, and it is asynchronous if MHWL or HHWL is recorded there.

The total contribution of synchronous and asynchronous events is always 100%.

The mathematical and statistical processing of analysis results employed statistical procedures included in the following software programs: Excel (Microsoft), Statistica (TIBCO Software Inc.), and RStudio. The implementation of the graphic form employed QGIS (3.6.2. Noosa) and Publisher (Microsoft) software.

3. Results

3.1. Mann–Kendall Test

The study revealed that multiannual fluctuations of maximum annual water levels in three lakes (Bukowo, Gardno, Łebsko) showed statistically nonsignificant decreasing trends (Table 4). In the remaining lakes, increasing trends were observed, whereas a statistically significant trend was only determined for maximum water levels in Lake Jamno ($p < 0.01$). Maximum annual sea water levels in all stations in the analyzed multiannual period showed an increase, although it was not statistically significant.

Table 4. Results of Mann–Kendall test for maximum annual and monthly water levels.

Lake/Gauges	Period	Year	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
							Lakes							
Resko P.	1981–2015	0.612	−0.724	−0.227	1.053	0.697	1.151	−0.442	1.010	1.096	0.355	−0.270	0.712	0.555
Jamno	1976–2015	3.032	2.937	**3.403**	2.005	2.342	**3.334**	**3.742**	**3.605**	**4.340**	3.207	**3.964**	3.183	2.682
Bukowo	1976–2015	−0.944	−0.723	−1.516	0.175	2.006	2.729	2.030	1.144	2.381	0.070	1.202	0.443	−0.816
Gardno	1976–2015	−0.642	−0.234	−1.353	−0.175	0.373	0.759	0.607	0.339	2.662	−0.233	−0.467	−1.295	−0.455
Łebsko	1976–2015	−0.082	0.233	−0.466	0.175	1.049	1.621	0.665	2.217	**3.918**	0.958	0.969	−0.058	0.793
Druzno	1976–2014	1.006	1.017	−0.218	1.065	2.325	2.470	1.273	2.967	**4.515**	1.977	2.315	0.654	0.921
							Baltic Sea							
Kołobrzeg	1981–2015	0.483	−0.639	0.241	−0.810	−0.142	1.364	−0.114	1.094	2.003	1.122	0.000	0.170	−0.156
Kołobrzeg	1976–2015	0.874	−0.350	0.606	−0.070	1.503	1.433	0.000	2.424	2.307	1.258	0.804	−0.023	0.466
Ustka	1976–2015	0.513	−0.152	0.396	0.128	1.213	1.271	0.338	2.450	1.995	1.450	0.945	−0.058	0.023
Łeba	1976–2015	0.000	−0.268	0.012	−0.035	0.875	1.270	0.385	1.902	1.890	0.058	0.187	−0.665	0.000
Tolkmicko	1976–2014	1.393	−0.061	0.048	0.436	1.634	1.659	−0.145	1.805	**3.445**	1.116	1.962	0.157	0.242

Statistically significant trends at levels of **$p < 0.001$**, $p < 0.01$, $p < 0.05$.

In the case of multiannual fluctuations of maximum monthly water levels in lakes, an increasing tendency was observed for a major part of the year. Only Lake Resko Przymorskie showed no statistically significant trends. Maximum water levels in Lake Jamno showed positive, statistically significant trends throughout the year ($p < 0.05$). In the case of Lakes Bukowo and Druzno, significant trends were observed for maximum water levels from February to June, in the case of Lake Łebsko in May and June, and for Lake Gardno in June.

Fluctuations of maximum monthly water levels in the Baltic Sea showed positive, statistically nonsignificant trends for a major part of the year. In June, however, in the case of all stations with the exception of Łeba, an increasing statistically significant trend was observed (Table 4). Statistically significant increasing trends were also recorded in Kołobrzeg (1976–2015) and Ustka in May, and in Tolkmicko in August ($p < 0.05$).

In the majority of cases, significant trends of maximum sea water were accompanied by significant trends of maximum water levels in lakes in June (with the exception of Resko) and in May (with the exception of Resko, Bukowo, and Gardno).

3.2. Correlation

3.2.1. Maximum Annual Water Levels

This paper determined correlation coefficients and degrees of synchronicity of the occurrence of maximum annual water levels in the analyzed lakes and the sea. The highest coefficient of correlation of water levels was observed for the pair Kołobrzeg–Resko Przymorskie (0.86) and the lowest for the pair Ustka–Bukowo (0.60).

According to the analyses, correlations between maximum annual water levels in coastal lakes and maximum annual water levels in the Baltic Sea in selected water gauge stations were very strong and statistically significant ($p < 0.001$) (Table 5, Figure 3). In the case of Lake Resko Przymorskie, as much as 68% of the variation in maximum water levels in the lake was accounted for by the variability in sea water levels. The weakest correlations were observed in the case of Lakes Jamno and Bukowo, where only (respectively) 30% and 39% of the variation in maximum water levels in the lakes was accounted for by the variance of water levels in the Baltic Sea.

Table 5. Results of analysis of correlation and synchronicity between the Baltic Sea and the analyzed lakes.

No.	Gauge stations (Sea–Lake)	Period	Annual Max Water Level		
			Correlation Coefficient	Synchronicity (%)	Asynchronicity (%)
1	Kołobrzeg–Resko P.	1981–2015	**0.86**	75.18	24.82
2	Kołobrzeg–Jamno	1976–2015	**0.62**	58.20	41.80
3	Ustka–Bukowo	1976–2015	**0.60**	56.82	43.18
4	Ustka–Gardno	1976–2015	**0.72**	65.92	34.08
5	Łeba–Łebsko	1976–2015	**0.76**	69.82	30.18
6	Tolkmicko–Druzno	1976–2014	**0.62**	60.42	39.58

Statistically significant correlation at a level of **$p < 0.001$**.

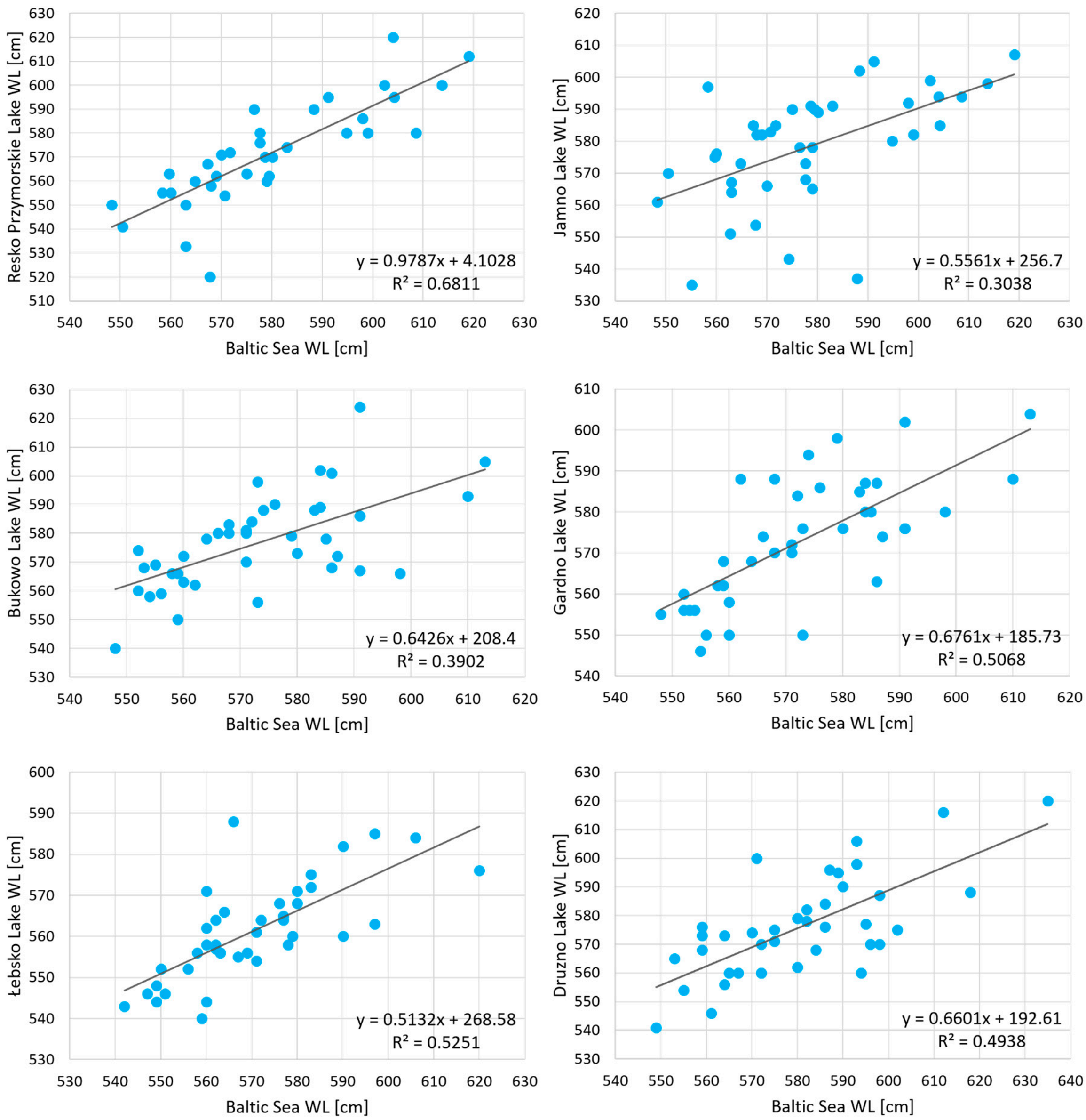

Figure 3. Correlations of maximum annual water levels of the analyzed lakes with maximum annual water levels in the Baltic Sea.

3.2.2. Maximum Monthly Water Levels

Coefficients of correlation between maximum monthly water levels in lakes and the sea were high and in the majority of cases statistically significant ($p < 0.001$) (Figure 4). The strongest and most statistically significant ($p < 0.001$) correlations with sea water levels were usually observed in the cool half-year, in the months from November to March. The highest coefficients of correlation between the analyzed lakes and the Baltic Sea (>0.90) were recorded in November, January (Gardno, Łebsko), and March (Resko Przymorskie, Łebsko). Water levels in three lakes, namely Gardno, Łebsko, and Resko Przymorskie, strongly correlated with sea water levels also in summer–autumn months. The weakest correlations of water levels in lakes with sea water levels were observed in April. Nonetheless, only the water levels in Lake Jamno correlated statistically nonsignificantly with sea water levels.

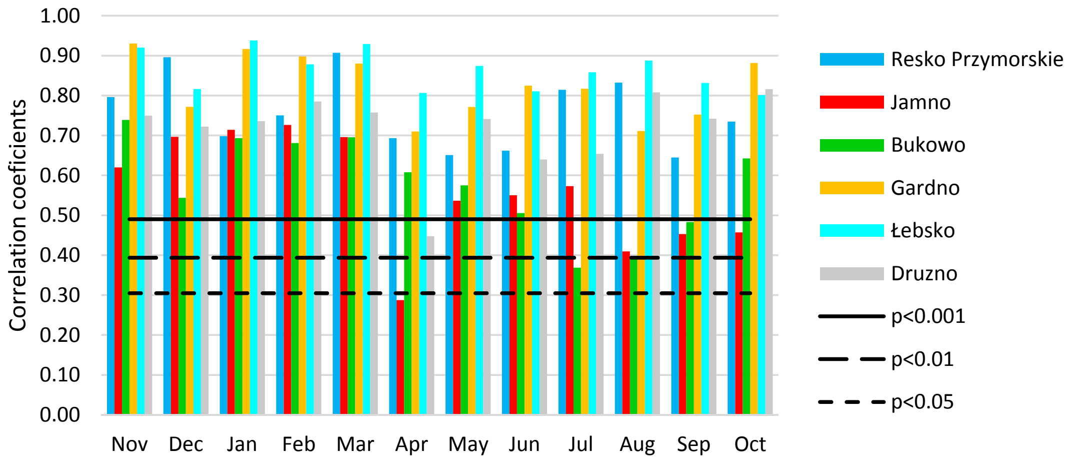

Figure 4. Coefficients of correlation of maximum water levels in the analyzed lakes and in the Baltic Sea and their levels of significance.

3.3. Synchronous–Asynchronous Encounter Probability

3.3.1. Maximum Annual Water Levels

Like the coefficient of correlation, modeling correlations by means of a copula function permitted the determination of the strength of correlations between water levels in lakes and the Baltic Sea. An additional advantage of the copula function was the possibility of quantifiable determination of the probability of occurrence of each analyzed variable separately and the probability of co-occurrence of maximum water levels in lakes and the sea, as well as the degree of their synchronicity.

The calculated synchronicity of maximum water levels in the lakes and the Baltic Sea oscillated between 56.82% and 75.18%, and asynchronicity between 24.82% and 43.18% (Tables 5 and 6). The patterns of relations of water levels in lakes with sea water levels resulting from the synchronicity analysis were in accordance with results obtained from the correlation analysis (Table 5). The highest degree of synchronicity concerned the occurrence of maximum annual water levels in the sea and Lake Resko Przymorskie (75.18%), and the lowest was in Lake Bukowo (56.82%). This means that the maximum water level in Lake Resko Przymorskie in a hydrological year is in the same range of probability of occurrence as the maximum sea water level (i.e., one of three possible synchronous situations occurs: $LHWL_S$–$LHWL_L$, $MHWL_S$–$MHWL_L$, or $HHWL_S$–$HHWL_L$), with a probability of approximately 75%. On the contrary, i.e., in asynchronous situations, the maximum water level in Lake Resko Przymorskie, being in a different range of probability than the maximum sea water level in the same hydrological year, occurs with a probability of once in four years (p = 25%).

Table 6. Synchronous and asynchronous occurrence of maximum annual water levels in lakes and the sea (division into nine sectors) (% share).

Sector	Kołobrzeg–Jamno	Ustka–Bukowo	Ustka–Gardno	Łeba–Łebsko	Tolkmicko–Druzno	Kołobrzeg–Resko
1	24.56	23.80	26.78	29.48	25.86	30.64
5	8.54	8.30	10.14	10.42	8.46	13.12
9	25.10	24.72	29.00	29.92	26.10	31.42
2	8.92	9.88	8.06	6.62	8.46	6.48
4	8.88	9.34	6.90	7.20	8.76	6.14
8	7.68	6.92	8.04	7.22	6.92	5.52
6	7.26	7.62	6.94	6.66	7.08	5.32
9	4.52	4.68	1.74	1.30	4.32	0.78
7	4.54	4.74	2.40	1.18	4.04	0.58
Syn.	58.20	56.82	65.92	69.82	60.42	75.18
Asyn.	41.80	43.18	34.08	30.18	39.58	24.82

Syn. = synchronicity, Asyn. = asynchronicity.

Next to Lake Resko Przymorskie, a relatively strong correlation (>65%) of maximum water levels was determined for Lakes Łebsko and Gardno, an average one (approximately 60%) for Lakes Druzno and Jamno, and a relatively low one (<60%) for Lakes Jamno and Bukowo. None of the lakes showed more than 50% asynchronicity. This means that the probability of occurrence of similar maximum water levels in a hydrological year in the sea and lakes is higher than the probability of occurrence of asynchronous events.

3.3.2. Maximum Monthly Water Levels

Synchronicity for maximum monthly water levels was calculated for Lake Jamno and stations in Kołobrzeg and for Lake Gardno and a station in Ustka (Table 7). The lakes were selected because the results of correlation and synchronicity pointed to their different relations with maximum annual sea water levels (Table 6).

The averaged synchronicity of maximum monthly water levels in Lake Jamno and the sea (55.56%) was inconsiderably lower than the synchronicity of maximum annual water levels in these water bodies (58.20%). Values above the average were obtained for the period from November to March. In the remaining months, they were below the average. In April, August, and October, the occurrence of asynchronous situations was more probable than synchronous ones. The highest synchronicity was characteristic of February and was slightly lower in December, and the lowest was in April. Concerning the correlation coefficient, the same pattern was observed (Figure 5).

The analysis of the results of synchronicity and asynchronicity for the pair Lake Jamno–station Kołobrzeg in particular sectors (Table 7; compare Figure 2) showed that the highest probability (approximately 10%) of occurrence of the situation $MHWL_S$–$MHWL_L$ occurred in February. The probability (approximately 28%) of occurrence of situation $HHWL_S$–$HHWL_L$ was in January, and $LHWL_S$–$LHWL_L$ was in December (approximately 27%).

Averaged synchronicity of maximum monthly water levels in Lake Gardno and the Baltic Sea (72.39%) was, unlike in the case of the correlations described earlier for Jamno, higher than the synchronicity of maximum annual water levels (65.92%, Table 7). The strongest correlations (>75% synchronicity) were determined for maximum water levels in November, January, February, March, and October (Table 7). Weaker correlations were particularly observed in the period from April to September, and the weakest, as in the case of Lake Jamno, was in April (62.00%). Unlike in the case of Lake Jamno, however, no month showed a prevalence of total shares in asynchronous sectors. In other months, the highest synchronicity values also occurred ($MHWL_S$–$MHWL_L$ and $HHWL_S$–$HHWL_L$) in November (17.28% and 33.92%, respectively), and $LHWL_S$–$LHWL_L$ in February (32.82%).

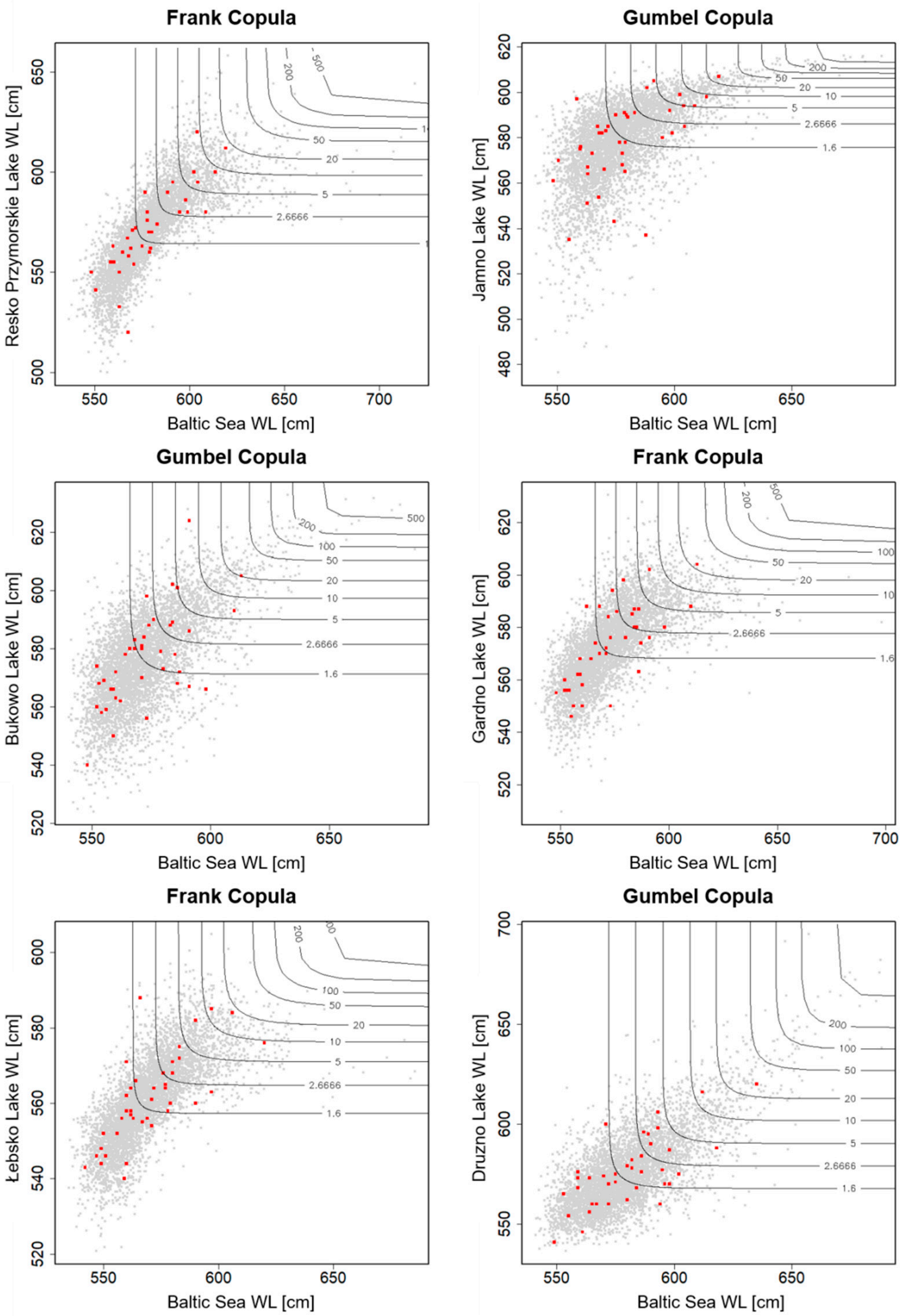

Figure 5. Total accumulated curves of probability of exceedance of maximum annual water levels for the correlation between water levels in the lakes and water level in the Baltic Sea. Red points are empirical pairs of values of maximum annual water levels. Gray points are generated theoretical points based on calculated parameters of joint distribution.

Table 7. Synchronicity and asynchronicity of maximum monthly water levels in Lake Jamno and the sea in Kołobrzeg and Lake Gardno and the sea in Ustka (division into nine sectors) (% share).

Sector	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
						Jamno–Kołobrzeg						
1	24.30	26.64	25.16	24.84	25.70	17.26	24.76	25.42	25.10	23.12	23.06	22.72
5	8.64	9.06	9.06	10.06	9.22	7.40	7.64	7.68	7.94	7.54	6.64	7.12
9	25.60	27.00	28.04	27.86	26.28	18.12	22.00	22.06	22.06	19.22	22.36	20.00
2	8.32	7.78	8.32	8.36	8.34	9.78	9.52	7.18	6.30	7.96	8.50	7.80
4	8.94	7.72	8.76	8.70	9.00	9.28	8.56	6.90	7.58	7.66	8.66	7.08
8	7.16	7.42	7.14	6.96	6.80	8.86	8.96	10.36	9.18	9.50	8.38	10.22
6	7.08	8.02	7.50	6.76	7.66	8.86	8.58	9.54	10.28	9.98	8.78	11.12
9	5.50	3.00	3.08	3.02	3.54	11.08	4.84	5.38	5.92	7.50	6.72	6.72
7	4.46	3.36	2.94	3.44	3.46	9.36	5.14	5.48	5.64	7.52	6.90	7.22
Syn.	58.54	62.70	62.26	62.76	61.20	42.78	54.40	55.16	55.10	49.88	52.06	49.84
Asyn.	41.46	37.30	37.74	37.24	38.80	57.22	45.60	44.84	44.90	50.12	47.94	50.16
						Gardno–Ustka						
1	32.66	31.64	31.42	32.82	31.38	25.8	30.42	28.64	29.46	30.26	28.72	32.94
5	17.28	10.74	15.48	16.22	13.04	9.62	11.20	11.06	12.54	9.16	9.30	14.34
9	33.92	27.52	32.90	32.74	30.82	26.58	26.06	30.68	30.42	26.30	25.74	28.90
2	3.82	5.36	5.36	4.68	6.32	8.78	5.12	6.92	6.74	6.10	6.14	4.32
4	4.26	4.92	5.62	4.64	6.06	8.66	5.36	7.42	6.20	5.76	6.54	4.46
8	4.02	8.08	3.94	4.60	5.14	6.90	9.18	5.86	6.34	8.96	8.78	7.38
6	3.82	9.00	4.60	4.12	5.76	7.30	8.72	6.12	6.44	8.98	9.70	6.90
9	0.10	1.22	0.36	0.04	0.88	3.04	2.12	1.54	0.96	2.26	2.38	0.46
7	0.12	1.52	0.32	0.14	0.60	3.32	1.82	1.76	0.90	2.22	2.70	0.30
Syn.	83.86	69.90	79.80	81.78	75.24	62.00	67.68	70.38	72.42	65.72	63.76	76.18
Asyn.	16.14	30.10	20.20	18.22	24.76	38.00	32.32	29.62	27.58	34.28	36.24	23.82

4. Discussion

According to earlier research concerning the correlations of water levels in Polish coastal lakes with sea water levels, the strongest correlations occur in the cool season of the year, from November to April (Lakes Gardno and Łebsko). Weaker correlations are observed in the warm season, from May to October, particularly in the case of Lakes Jamno and Bukowo [32].

The highest correlations of monthly water levels in the lakes and the sea were usually observed in autumn, winter, and spring (Figure 3). This is generally related to lake alimentation in the autumn–winter period, where marine waters enter lakes through canals as a result of storms [33,61]. Storms on the Baltic Sea are usually observed from October to March and last from four to seven days [62].

In spring, in the melt season, alimentation with river waters is dominant. Months in which strong correlations were observed also corresponded to the course of water levels in lakes in the annual cycle. This was exemplified by the presented graph on the course of maximum pentad water levels in Lake Jamno and the Baltic Sea at station Kołobrzeg in the analyzed multiannual period (Figure 6). The maximum pentad water level was calculated as the averaged value of maximum water levels in the lake for a consecutive five days. The highest maximum water levels in the average annual cycle in Lake Jamno and Kołobrzeg were observed from December to January and from September to October.

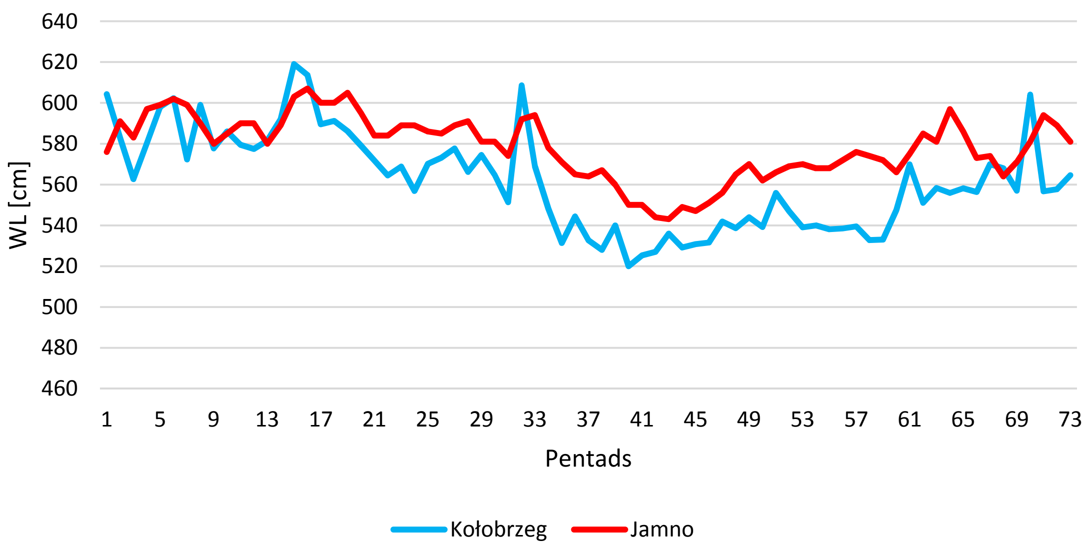

Figure 6. Course of maximum pentad water levels in Lake Jamno and the Baltic Sea at station Kołobrzeg.

The strongest correlation concerned water levels in Lakes Resko Przymorskie, Łebsko, and Gardno. In the case of the last two lakes, similar results were obtained by References [32,33] (the studies did not involve an analysis of the effect of the sea on water levels in Lake Resko Przymorskie). According to the author, strong correlations of water levels in the lakes and the sea can be justified by almost undisturbed water flow, which contributes to relatively fast evening of the water levels between the two water bodies. Fishing ports are located in the mouths of the Łupawa and Łeba canals (Rowy and Łeba), where dredging is performed on a current basis. The mouth of the Łupawa Canal is very rarely obstructed, and in the Łeba Canal, flow is practically undisturbed. In the mouth section of the Resko Canal (Błotnica), a marine port is also located in the municipality of Dźwirzyno. This may explain high correlations of water levels in Lake Resko Przymorskie with sea water levels. The weakest correlation with sea water levels concerned water levels in Lakes Jamno and Bukowo. According to Reference [32], this is related to inhibited water exchange with the sea, which is caused by the obstruction of the mouth sections of the canals to the sea by sand and frazil-ice banks. Blocking the outflow causes relatively high water levels in the lakes in comparison to the sea water level.

Moreover, as a result of climate change, positive trends of the maximum water levels in the Baltic Sea were detected. It was found that in the years 1889–2006, the maximum water levels increased on average from 0.39 cm/year in Świnoujście and Kołobrzeg to 0.54 cm/year in Gdańsk [6]. It is worth noting that correlations between the studied coastal lakes and the Baltic Sea refer not only to their water levels: the coast of the Baltic Sea is a place where high qualitative and quantitative variability of biotic [16–20] and abiotic elements [7–13,23] is observed, too.

Processes and phenomena occurring in coastal lakes are also characterized by enormous strength and dynamics. This was very evident, among other things, in the analysis of water level fluctuations in an average annual cycle. The highest mean monthly amplitudes in Polish lakes were recorded in coastal lakes [63]. The highest mean amplitude values were particularly observed in Lakes Druzno and Resko Przymorskie. In Lake Druzno, they were observed from October to April, varying from 45 cm in April to 53 cm in January. The highest mean amplitudes of water levels among the analyzed lakes were recorded in Lake Resko Przymorskie in the months from May to September. They reached values from 45 cm in May to 58 cm in August.

Another dynamically occurring process in the coastal zone of the South Baltic is the phenomenon of sea water intrusions [3,4]. The periodic inflow of marine waters into lakes results in changes in the water quality of the lake, particularly its salinity. A hydrodynamic comparative analysis of the waters of Lakes Jamno and Bukowo showed that they differ in terms of concentrations of indicators related to the inflow of sea waters. Considerably higher values were recorded in the case of Lake Bukowo. The waters of Lake Jamno were characterized by higher concentrations of indicators related to the inflow of waters from the catchment [64]. Similar patterns were observed in the analysis of the correlation of mean monthly water levels in the lakes with those in the Baltic Sea [33]. Stronger correlations of water level fluctuations were observed in the case of Lake Bukowo, and the weakest in Lake Jamno.

Over the last 20 years, copula functions have been found to have broad applications in hydrological, meteorological, and climatological data analyses. One of the methods of their application is the analysis of synchronicity and asynchronicity of occurrences of phenomena. According to other authors, copula functions have proven efficient in comprehensive analyses of, e.g., dependencies between the discharge volume and volume of supplied debris [44,45]. They also permit the quantitative determination of the frequency of occurrence of phenomena or disasters and can be used to prevent undesirable events (i.e., drought and floods) and limit the risk of their occurrence, i.e., their use in shaping the rational management of water resources in a given area [43,45–47]. This paper presents the possibility of applications of synchronicity analyses in the analysis of the dependency of maximum water levels in coastal lakes on sea water levels, which can also contribute to an increase in the level of water management in coastal areas.

In a broader approach, copula functions have also been used in limnological analyses, as shown in the introduction. The research was primarily conducted in the context of the possibility of the occurrence of forecasting drought. As in this paper, other publications [40,41] have presented analyses of maximum water levels in lakes. The analyses, however, were performed particularly for the purpose of determining changes in the value of average water levels and their variability in a given multiannual period. The authors did not focus on the direct analysis of correlations of water levels between water bodies. Coastal lakes are an exceptional group of lakes. Their analysis permits a determination of the strength of impact of the sea on the water conditions of the coast: Similar research has not been sufficiently presented in global literature.

5. Conclusions

This paper confirmed the effect of water level fluctuations in the Baltic Sea on water levels in coastal lakes. The analysis of maximum correlations of maximum annual water levels in the lakes confirmed strong correlations with sea water levels. The highest correlation coefficients for maximum annual water levels were recorded on Lakes Resko Przymorskie, Gardno, and Łebsko. In the case of maximum monthly water levels, the highest correlations were observed for Lakes Łebsko, Gardno, and Resko Przymorskie in autumn–winter months, and the lowest for Lakes Jamno and Bukowo in spring and summer. The application of a copula function permitted the calculation of probable maximum water levels in the lakes and the sea and a determination of the degree of synchronicity of occurrence of maximum water levels in the lakes and the sea.

The research showed the usefulness of advanced statistical tools in the analysis of correlations between water levels in coastal lakes and the sea. Considering the fact that correlation coefficients (also rank correlation coefficients) provide incomplete information on correlation, copulas were applied as a tool for modelling the correlation structure. The application of copulas proved to be a flexible tool for modeling the correlation structure in both distribution tails. Dependencies in the tails determine higher or lower degrees of synchronicity for differently correlated variables.

The analysis of correlations of maximum annual water levels in the lakes and the sea revealed that the highest water levels in all of the analyzed cases showed higher synchronicity than the lowest water levels. In the annual cycle, maximum monthly water levels in the lakes and the sea showed that in the cool half-year from November to April, the correlation between the highest water levels, particularly in the case of Lake Jamno, was stronger than between the lowest water levels, as evidenced by higher synchronicity values (Table 7). In the summer half-year (May–October), the situation was the opposite. A stronger correlation and higher synchronicity occurred in the lowest water levels in lakes and the sea than in the highest water levels. Despite doubts and limitations [65,66], copulas and related measures of correlation strength are an exceptionally useful approach in the issue of the analysis of correlations between hydrological and hydroclimatic variables.

Given the relatively small number of studies of that kind in the world scientific literature, this research is of great importance both on a regional and global scale. Due to climate warming, the sea level has been increasing, which may have a significant impact on the functioning of coastal lakes, including fluctuations of their water levels, chemistry, and ecological status. Thus, more detailed studies on these issues are necessary, and this research can be the starting point for such studies in the future.

Author Contributions: Conceptualization, D.W.; methodology, A.P. and L.S.; software, K.P., A.P., L.S.; validation, K.P., A.P.; formal analysis, K.P., A.P.; investigation, K.P., A.P.; resources, K.P.; writing—original draft preparation, K.P., A.P.; writing—review and editing, K.P., A.P., D.W., L.S.; visualization, K.P., A.P.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

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