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Links between Teleconnection Patterns and Water Level Regime of Selected Polish Lakes

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Abstract: The paper identifies relationships between lake water levels and indices of macroscale atmospheric circulations: Arctic Oscillation (AO), North Atlantic Oscillation (NAO), East Atlantic (EA), and Scandinavian pattern (SCAND). Correlation coefficients between synchronous and asynchronous series of monthly water levels and 4 circulation indices were calculated. Based on Ward hierarchical grouping considering 156 correlation coefficients, the groups of lakes were designated due to the strength and term of relation of circulation indices with lake water levels. It was found that these links are not strong but noticeable. The strength of relationships varies in space and time, and the designated groups of lakes refer not only to the climatic diversity of the studied area, but also to some extent to the types of water levels regime. The observed relationships are the most important in the case of AO and NAO (particularly in winter period), and slightly weaker for EA and SCAND. The analysis used mean monthly water levels of 15 lakes in northern Poland from 1976–2015.

Keywords: lake water levels; teleconnections; indices of macroscale atmospheric circulations

1. Introduction

Water-level fluctuations are one of the basic characteristics of the hydrological regime of lakes determining the occurrence and course of many processes and phenomena affecting the functioning of a given water body [1]. Water level fluctuations are particularly determined by climatic factors and depth of the lake basin, connection with groundwaters, surface area and shape of the lake's catchment, surface area of the lake itself, degree and character of its flow-through character, and human pressure. Climatic factors determining the volume of river and lake alimentation include atmospheric precipitation and air temperature. They are in turn to various degrees determined by teleconnection patterns. Climatic conditions in Europe show the most thoroughly documented effect of the Arctic Oscillation (AO) (e.g., on terms of snowmelts [2], ice cover of the Baltic Sea [3], variability of air temperatures in winter [4]), and North Atlantic Oscillation (NAO) (e.g., on maximum and minimum air temperatures, cloudiness, and precipitation [5], humid and warm winters, as well as among others the period of plant flowering [6], atmospheric precipitation, flow rates in rivers, and water resources [7]). The importance of the East Atlantic (EA) and Scandinavian patterns (SCAND) is investigated more seldom. The effect of EA on e.g., exceptionally low temperatures in winter 2010 [8] and temperatures in Serbia [9], as well as effect of SCAND and other teleconnection patterns on extreme precipitation [10] and thickness of snow cover [11] has been confirmed. The combined effect of different teleconnection patterns and relationships between them have also been analyzed [12]. AO is related to the difference in pressures between the polar area and moderate latitudes [13]. NAO is strongly associated with it, with activity depending on the difference between the Iceland Low and Azores High [14]. Also, EA concerns baric differences in the Atlantic region, although in the latitudinal system. SCAND concerns circulation related to North Europe and the surrounding baric centers [15]. Their activity affects the properties of climate in Poland, particularly NAO, as confirmed by available studies, among others in the context of occurrence of frosty days [16], duration of the vegetation period [17], air and lake water temperature [18], and occurrence of snow cover [19,20]. Wibig [15] investigated the influence of circulation patterns on precipitation in Europe in winter months. According to Central and East Europe region, the greatest impacts have SCAND and CE (Central Europe) patterns—the positive phase of SCAND brings very dry weather in eastern Europe, and in negative phase it favors precipitation. The influence of circulation patterns on air and water of lakes temperature in northern Poland was described by [18]. The strongest positive impact of NAO was observed from December to March, especially high in the western part of the area. The impact of AO was quite similar in winter, but it has also positive correlation with temperatures in September and October. EA has the strongest positive impact on thermal conditions from September to November. From January to March there were negative correlations of SCAND indices and air and water temperatures, and positive ones in May (only with air temperatures).

The authors point to temporal and spatial variability of the impact of particular circulation types at the scale of Poland on the analyzed hydrometeorological elements. In limnological literature concerning the importance of teleconnection patterns among others on hydrological variables, relatively few papers refer to water level regime of Polish lakes. Many papers ascribe particular importance to NAO, the effect of which on the thermal and ice regime is thoroughly investigated [18,21–25]. The importance of changes in the intensity of NAO for the water levels, their fluctuations, stability, and change tendencies is shown in research by, e.g., [1,26–30]. The relations of NAO with water levels determined by the authors are not strong, but evident. In the context of lack of more extensive research, it is important to also determine the role of other teleconnection patterns in shaping features of the regime of lakes. Research on the thermal regime of lakes in Poland shows that among the analyzed teleconnection patterns (NAO, AO, EA, EAWR, and SCAND), the strongest correlations with water temperature concern NAO and AO in the winter period [18].

Research on lakes outside Europe covers the issue of the effect of among others AO, AMO (Atlantic Multidecadal Oscillation), NAO, PDO (Pacific Decadal Oscillation), and SOI (Southern Oscillation Index) on lakes in the Laurentian Great Lakes Region [31–37], SOI, PDO, and NAO on ice conditions in Lake Mendota in the State of Wisconsin [38], ENSO, AO, NAO, XZH (Tibetan High), WI (westerly index), and VPA (northern hemisphere polar vortex area index) on the catchment of Lake Bosten in China [39], and ENSO on the dynamics of water levels in Lake Hawassa [40].

The effect of teleconnection patterns on water level fluctuations in Polish lakes is weakly investigated, because the research has been usually limited to NAO, in the context of among others changes in the stability of the water level regime of Polish lakes [29], water level fluctuations in lakes in different phases of the winter NAO index [30], and water level fluctuations in lakes in North Poland [1]. Therefore, the objective of the paper was to determine temporal and spatial correlations of teleconnection patterns (AO, NAO, EA, SCAND) with water level fluctuations in the annual cycle of lakes in North Poland.

2. Materials and Methods

A total of 7081 Polish lakes have a surface area of more than 1 ha. The majority of the lakes (more than 90% [41]) is located north of the line designating the maximum range of the last glaciation.

In the research analyzed daily values of water levels in 75 lakes, and mean monthly air temperatures and atmospheric precipitation from meteorological stations of Poznań, Chojnice, Olsztyn, and Suwałki from the years 1976–2015 obtained from the Institute of Meteorology and Water Management—National Research Institute. They provided the basis for the calculation of mean monthly and annual water levels. The lakes were selected after the verification of the homogeneity of series of monthly and annual water levels by means of an Alexandersson test [42]. The critical values of the test, based on Monte Carlo simulations, were read from tables of critical values [43] at a level of $\alpha = 0.05$. Then, a non-parametric Mann-Kendall test was performed, detecting trends in temporal series [44]. The results of both tests provided the basis for selection of 15 lakes for further analysis (Figure 1) the monthly and annual water level series of which are homogenous, and show no statistically significant trend.

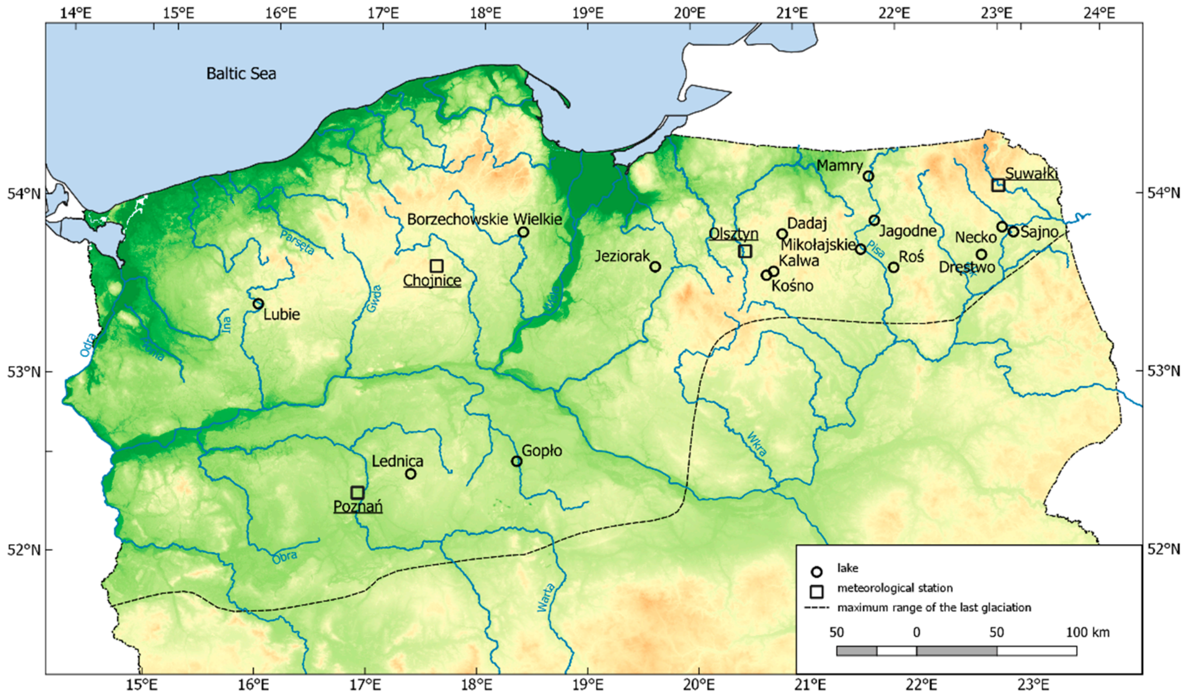

Figure 1. Location of the lakes.

It can be assumed that they are lakes in which water-level fluctuations are determined by physiography of the lake catchment and natural factors, including among others climatic factors such as precipitation and air temperature, shown to be affected by teleconnection patterns [45,46]. The analyzed lakes have a natural regime of water levels, as confirmed by papers [27,28,47,48]. Analyzed lakes are shallow, with average depth from 3.6 m (Gopło) to 13.7 (Kośno). Their annual mean water level amplitudes do not exceed 100 cm and range from 23 cm (Kośno) to 96 cm (Dręstwo). The highest extreme multi-year amplitudes are observed in Gopło Lake (273 cm), and the lowest ones in Kośno Lake (56 cm). These lakes are characterized by low coefficient of variation which varies from 0.02 (Jeziorak) to 0.38 (Roś) (Table 1).

The analyzed lakes represent 5 types of regimes of water levels based on the course of the water level coefficient (W), calculated as the product of mean water level in a pentad to mean water level from the multi-annual period (Table 1). Group 2b is characterized by the occurrence of high water levels (W > 1) at the turn of March and April, and low from December to March. This group included Lakes Necko and Sajno. In another type of regime (3a), Lakes Lubie, Roś, and Dręstwo were designated. High water levels are usually observed there from the second half of January to mid-May. Type 3b includes the Great Masurian Lakes. Here, high water levels in an average annual cycle occur in the period from the first half of February to mid-August, and low levels are observed in the autumn-winter period. Type 3c is represented by Lakes Kalwa, Jeziorak, Borzechowskie, and Lednica. High water levels usually occur from the second half of January to the first half of July, and low levels in the summer-autumn period. The last type of regime (4b) is represented by Lakes Kośno and Gopło. High water levels are observed from the second half of January to the turn of May and June, and low water levels begin in mid-June and persist until the first half of December [48].

Table 1. Morphometric data of the studied lakes, as well as their water level amplitudes and type of regime of water levels.

Lake	Area (ha) [1]	Volume (thousand m^3) [1]	Average Depth (m) [1]	Maximum Depth (m) [1]	Coefficient of Variation (Cv)	Amplitudes of Water Level (cm)			Type of Regime [2]	Area of Catchment (km^2) [3]	Schindler Index (m^{-1})	Ohle Index (-)	Elements of the Water Balance of Lake Catchment		Water Exchange Rate α
						Annual Max	Annual Mean	Extreme Multi-Year					Outflow (mm) [4]	Precipitation (mm) [5]	
Lubie	1487.5	169,880.5	11.6	46.2	0.061	65	71	84	3a	780.86	4.60	52.49	215	660	0.99
Lednica	325.0	24,397.0	7.0	15.1	0.173	118	58	186	3c	43.14	1.77	13.27	100	540	0.18
Gopło	2121.5	78,497.0	3.6	16.6	0.152	226	87	273	4b	1151.26	14.67	54.27	95	505	1.39
Borzechowskie	240.0	27,002.0	11.0	43.0	0.132	49	29	74	3c	17.25	0.64	7.19	210	630	0.13
Jeziorak	3152.5	141,594.2	4.1	12.9	0.017	76	44	90	3c	325.28	2.30	10.32	190	620	0.44
Kośno	562.5	75,767.3	13.7	44.6	0.063	56	23	56	4b	236.73	3.12	42.09	200	600	0.62
Kalwa	561.0	39,468.6	7.0	31.7	0.087	58	33	76	3b	75.70	1.92	13.49	195	600	0.37
Dadaj	975.0	120,784.2	12.0	39.8	0.189	141	71	154	4b	340.08	2.82	34.88	200	615	0.56
Mikołajskie	424.0	55,739.7	11.2	25.9	0.224	64	38	95	3b	1814.87	32.56	428.04	200	595	6.51
Mamry	9851.0	1,003,367.5	9.8	43.8	0.106	62	39	92	3b	618.52	0.62	6.28	180	600	0.11
Jagodne	872.5	82,705.2	8.7	37.4	0.111	62	39	95	3b	518.67	6.27	59.45	205	600	1.29
Roś	1808.5	152,924.9	8.1	31.8	0.378	140	88	177	3a	3033.07	19.83	167.71	215	600	4.26
Dręstwo	549.0	42,734.6	8.5	25.0	0.180	146	96	208	3a	827.87	19.37	150.80	160	590	3.10
Necko	400.0	40,561.4	10.1	25.0	0.028	106	46	132	2b	893.54	22.03	223.39	180	600	3.97
Sajno	494.0	52,446.8	10.0	27.0	0.116	161	90	183	2b	959.78	18.30	194.29	180	600	3.29

Elaboration based on: [1] [41], [2] [48], [3] [49], [4] based on the data from 235 precipitation gauges, [5] based on the data from 516 water gauges.

The determination of dependencies of water levels in lakes on the intensity of particular teleconnection patterns involved the calculation of Pearson linear correlation coefficients. Correlation coefficients were calculated between monthly water levels in lakes and monthly NAO, AO, EA, and SCAND indices. Monthly values of teleconnection pattern indices for the years 1976–2015 were obtained from data bases of the Climate Prediction Centre (CPC), National Oceanic and Atmospheric Administration (NOAA). They were determined based on the principle component analysis of monthly anomalies of isobaric height of 500 hPa [14].

The correlation coefficients between the analyzed variables were calculated for synchronous as well as asynchronous series, e.g., the EA_{XI} index was correlated with water levels from November to October, EA_{XII} index with water levels from December to October, and water levels in November were correlated with the EA_{XII} index from the previous year, etc. For each lake, a matrix was obtained, composed of 156 correlation coefficients, including correlation coefficients calculated between monthly water levels and monthly indices of particular teleconnection patterns. The statistical assessment of significance of correlation coefficients (at significance levels of $p < 0.05$, $p < 0.1$, $p < 0.001$) was performed by means of statistic t:

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \tag{1}$$

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

At the next stage of work, values of 156 correlation coefficients for each lake were treated as variables that provided the basis for grouping of lakes by means of the Ward method. Ward [50] suggested that at each step of the analysis, the loss of information associated with merging objects was measured by the sum of squares of deviations of each object from the center of the cluster to which it belongs. At each step of grouping, the union of every possible cluster pair is considered and two clusters whose function results in the lowest increase in information loss are combined. The information loss in this method is referred to as the error sum of squares (E.S.S.), defined:

$$E.S.S. = \sum_{i-1}^{n} x_i^2 - \frac{1}{n}\left(\sum_{i-1}^{n} x_i\right) \tag{2}$$

where x_i is the score of the i-th object. The grouping results were presented in the form of a dendrogram reflecting the structure of similarity of the analyzed group of lakes, and served for the designation of typological classes. In the paper, the number of classes was determined based on the analysis of geometry of the dendrogram and the plot of the linkage distance curve. The presented methods are commonly used in hydrometeorological research [51–60].

The mathematical-statistical processing of the analysis results employed statistical procedures included in the *Excel* (Microsoft) and *Statistica 13* (TIBCO Software Inc.) software. The implementation of the graphic form employed the *Surfer 10* (Golden Software) and *Publisher* (Microsoft), *QGIS* software. The construction of the matrix of correlation coefficients of isocorrelate was performed with the application of the *kriging* procedure.

3. Results

3.1. Arctic Oscillation

The analysis of the matrix of coefficients of correlation of monthly water levels with AO indices shows that the strength of correlations between the variables is temporally and spatially variable. This is suggested by results of Ward hierarchical grouping of monthly correlation coefficients. The location of particular groups of lakes to a certain degree shows regional variability (Figure 2). The first group is represented by two lakes in the north-west of the study area—Sajno and Necko. Water levels in the lakes positively correlate with AO from November to March. Statistically significant positive and synchronous correlations of AO with water levels are observed in December at a level of $p < 0.05$, in January ($p < 0.01$), and in March, in Lake Sajno even at a level of $p < 0.001$, and in Lake Necko $p < 0.01$. From April to October in Lake Sajno, and until September on Lake Necko, synchronous, but negative correlations of monthly AO indices with water levels in the lakes are observed, whereas in Lake Sajno they are statistically significant in April ($p < 0.05$) and May ($p < 0.01$), and in Lake Necko in July ($p < 0.05$). Asynchronous correlations of AO indices in February with water levels in September ($p < 0.01$) and October ($p < 0.05$) in Lake Sajno, and in Lake Necko from May to October ($p < 0.05$) and in June ($p < 0.01$) draw attention. The second group includes 10 lakes, in great majority located in the Masurian Lakeland. Positive correlations of AO indices with water levels from December to March are observed here. In the case of the system of the Great Masurian Lakes (Mikołajskie, Mamry, Jagodne), they are observed until April, and in March they are significant at a level of $p < 0.1$. In the next months, the correlations are negative, and in the majority of cases statistically non-significant. Only in August AO indices show negative statistically significant correlations with water levels in Lakes: Kośno ($p < 0.01$), Jagodne, Jeziorak (Figure 3), and Kalwa ($p < 0.05$). The research also points to asynchronous correlations, statistically significant between AO indices from January to March with water levels from May to October. In the case of Lake Jeziorak (Figure 3), AO indices in January and February correlate at a level of $p < 0.01$ with water levels from May to September (without June). AO indices in January show correlations with water levels in February and March (Figure 3). The third group includes lakes located in the central part of the study area: Borzechowskie, Lednica, and Gopło. In a major part of the year, negative correlations of AO indices with water level in the lakes are observed in the group. Statistically significant correlations were determined in Lake: Gopło in December ($p < 0.01$) and January ($p < 0.05$), Lednica in December ($p < 0.01$), and Borzechowskie in November ($p < 0.05$). In the case of all lakes, positive, statistically non-significant correlations were determined between AO indices and water levels in June, and in Lake Gopło from February to April, and Lednica in March and April. In all the lakes, AO indices from January to February show synchronous correlations with water levels from December to January. As shown in Figure 3, the correlations are statistically significant at a level of $p < 0.001$ in May, June, and September.

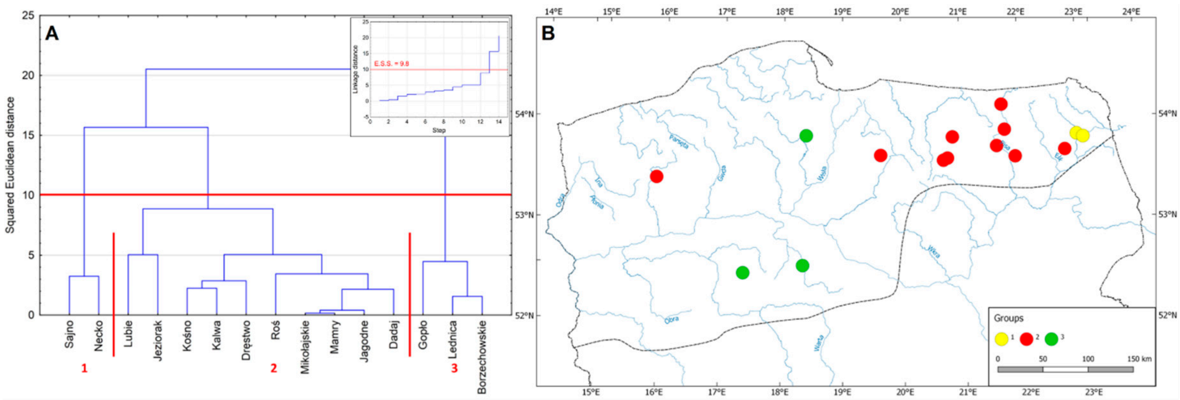

Figure 2. Dendrogram of grouping lakes by values of correlation coefficients of monthly AO indices with monthly water levels and the plot of the linkage distance (**A**); Spatial distribution of lakes in the performed grouping (**B**).

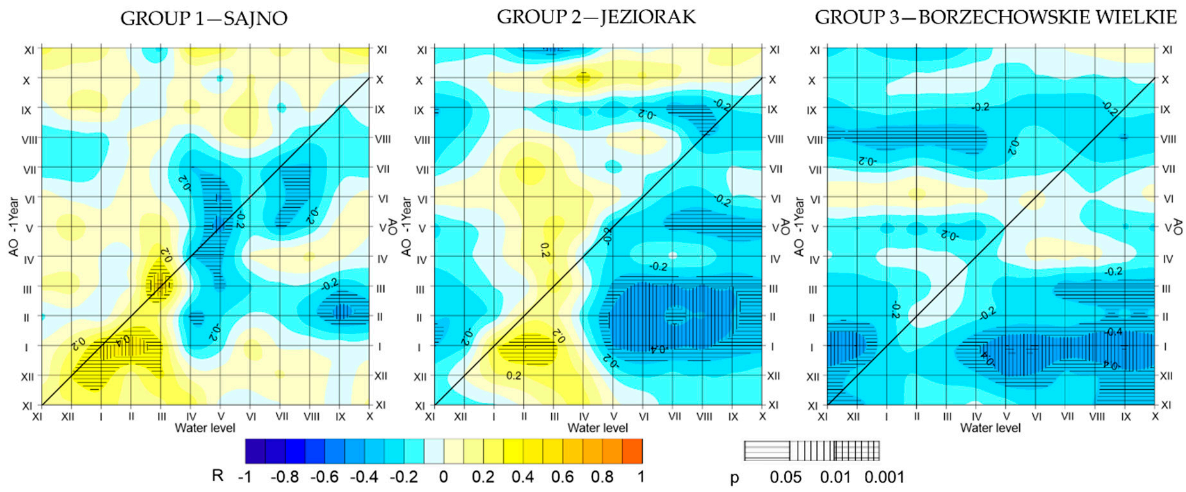

Figure 3. Matrices of coefficients of correlation for selected lakes in the designated groups (AO).

3.2. North Atlantic Oscillation

Based on grouping of coefficients of correlation between NAO and water levels in lakes, 4 groups of lakes were designated (Figure 4). Like in the case of AO, the first group included Lakes Sajno and Necko. Notice that NAO indices from November to March (Lake Necko) of April (Lake Sajno) positively correlate with water levels in those months. The group is characterized by statistically significant correlations in January. In Lake Necko they are statistically significant at a level of $p < 0.001$, in Lake Sajno $p < 0.01$, and in both lakes in March ($p < 0.05$). In spring and autumn, negative, statistically non-significant correlations are usually observed. An asynchronous correlation of NAO indices in February with water levels from May to October ($p < 0.05$) is also observed, and correlations of NAO in February are statistically significant with water levels in June at a level of $p < 0.01$. The second group included 5 lakes: Mikołajskie, Mamry, Jagodne, Roś, and Dręstwo (Figure 4). NAO indices usually show negative correlations with water levels in those lakes. In November and from February to April, positive statistically non-significant correlations are observed. Only in the case of Lake Jagodne, NAO indices in March correlate statistically significantly with water levels in March ($p < 0.05$). An asynchronous correlation is also observed between NAO indices from January to March and water levels from June to October (Figure 5). The third group also included five lakes, namely: Jeziorak, Lubie, Kośno, Kalwa, and Dadaj. They are in the western part of the Masurian Lakeland. Water levels in the lakes positively correlate with NAO from December to March, and in October. Statistically significant correlations ($p < 0.05$) are observed in the case of Lake Dadaj in February. From April to September, NAO indices negatively and statistically significantly correlate with water levels in August in Lakes Kośno ($p < 0.05$), Lubie, Dadaj, and Kalwa ($p < 0.01$). An asynchronous correlation of winter NAO indices with water levels in the summer-autumn period, and Nao indices in November with water levels in April and May ($p < 0.01$) of the following year is also observed. The fourth group included 3 lakes: Lednica, Gopło, and Borzechowskie. Throughout the year, NAO indices generally correlate negatively with water levels in lakes, statistically significantly in the case of Lakes Lednica and Gopło in August, respectively at a level of $p < 0.01$ and $p < 0.05$. Synchronous statistically significant correlations are also observed between NAO indices in January and water levels from April to October, and between NAO indices in August and water levels in lakes in September.

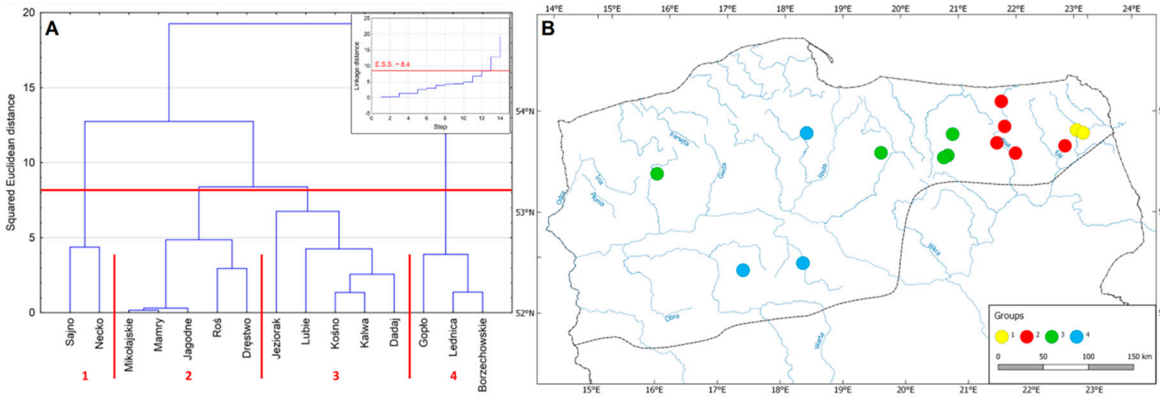

Figure 4. Dendrogram of grouping lakes by values of correlation coefficients of monthly NAO indices with monthly water levels and the plot of the linkage distance (**A**); Spatial distribution of lakes in the performed grouping (**B**).

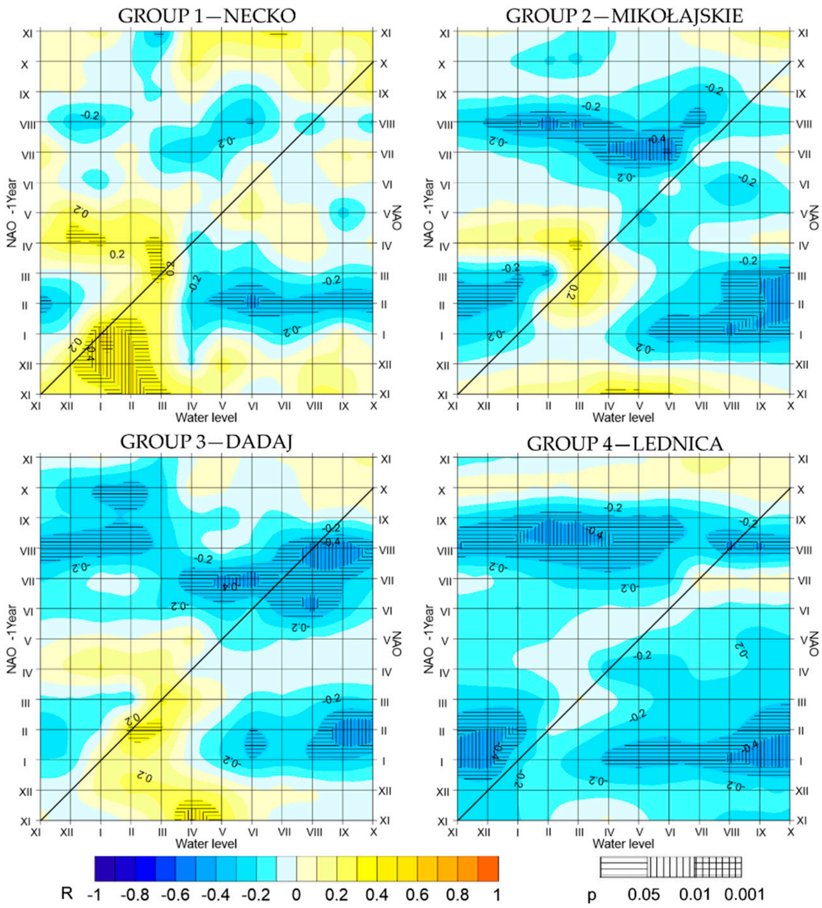

Figure 5. Matrices of coefficients of correlation for selected lakes in the designated groups (NAO).

3.3. East Atlantic Pattern

In the case of grouping correlation coefficients of EA indices with water levels in lakes, 3 groups of lakes were designated (Figure 6). Lakes included in the groups also show quite a characteristic spatial distribution, although it is not as unambiguous as in the case of groups for AO and NAO. The first group included Lakes Sajno, Necko, and Dręstwo located in the eastern part of the study area, and lakes located in its central part: Jeziorak and Gopło. For a major part of the year, positive statistically non-significant correlations of EA indices with water levels are observed. In the spring-summer period, in some lakes (Sajno, Necko, Jeziorak, Kalwa, Dręstwo), negative correlations are recorded, but they are statistically significant only in Lake Sajno in May ($p < 0.05$). An asynchronous correlation of EA indices in May with water levels in summer is also observed. Statistically significant correlations were recorded in Lake Sajno in June and August ($p < 0.01$) as well as July ($p < 0.001$), in Lake Gopło in August and September ($p < 0.05$), and in Lake Dręstwo (Figure 7) from July to October ($p < 0.05$) and in August ($p < 0.01$). An asynchronous correlation of EA indices from December was also identified with water levels in the summer-autumn period. In Lake Dręstwo, the correlation is positive and statistically significant at a level of $p < 0.05$. The second group included lakes mainly located in the Masurian Lakeland, with the exception of Lake Lubie located in the western part of the study area. Like in the first group, positive, but statistically non-significant correlations are prevalent here. In the case of Lake Roś (Figure 7), EA indices in September statistically significantly correlate with water levels ($p < 0.05$). An asynchronous correlation is also observed between the indices in November and December and water levels from July to October ($p < 0.05$). The last group included 2 lakes: Borzechowskie and Lednica. Mainly positive correlations between synchronous variables are observed in this group. The correlations are statistically significant in February, July, and October ($p < 0.05$) in Lake Lednica (Figure 7), and in July in Lake Borzechowskie ($p < 0.05$). In the case of Lake Borzechowskie, also EA indices in January and March show negative, but statistically non-significant correlations with water levels in those months. In the case of both lakes, a correlation between teleconnection indices in July and water levels in lakes from August to October was also observed. In the case of Lake Lednica, the correlation was negative and statistically significant ($p < 0.01$).

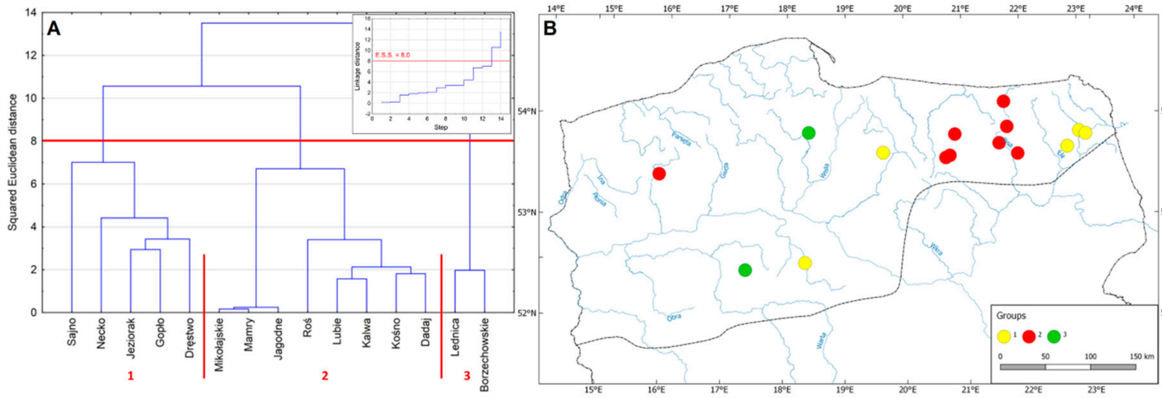

Figure 6. Dendrogram of grouping lakes by values of correlation coefficients of monthly EA indices with monthly water levels and the plot of the linkage distance (**A**); Spatial distribution of lakes in the performed grouping (**B**).

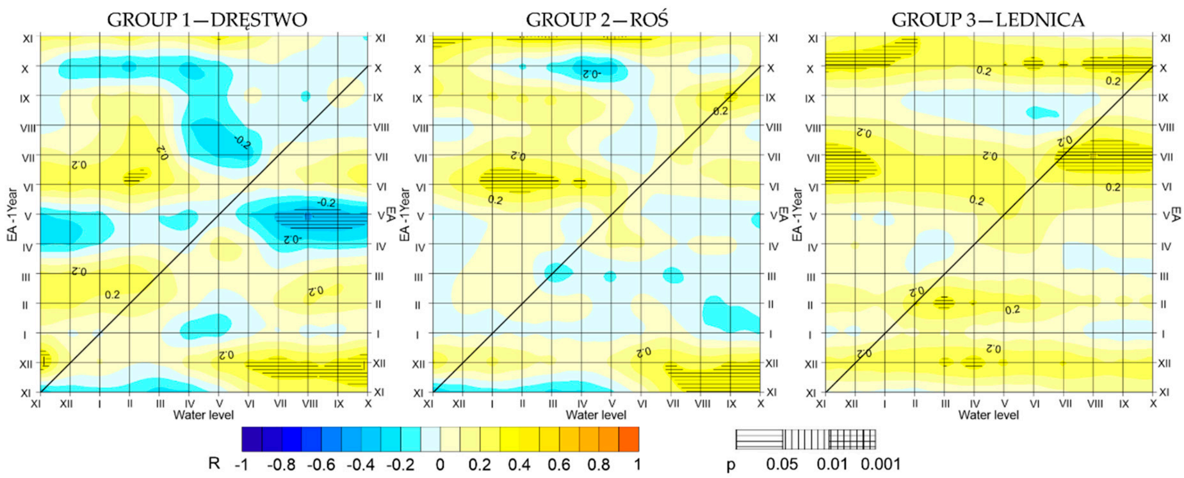

Figure 7. Matrices of coefficients of correlation for selected lakes in the designated groups (EA).

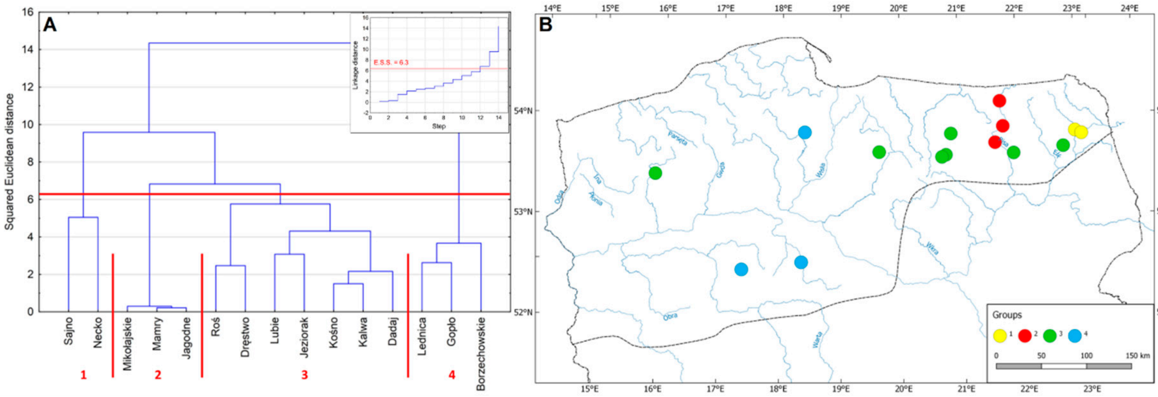

Figure 8. Dendrogram of grouping lakes by values of correlation coefficients of monthly SCAND indices with monthly water levels and the plot of the linkage distance (**A**); Spatial distribution of lakes in the performed grouping (**B**).

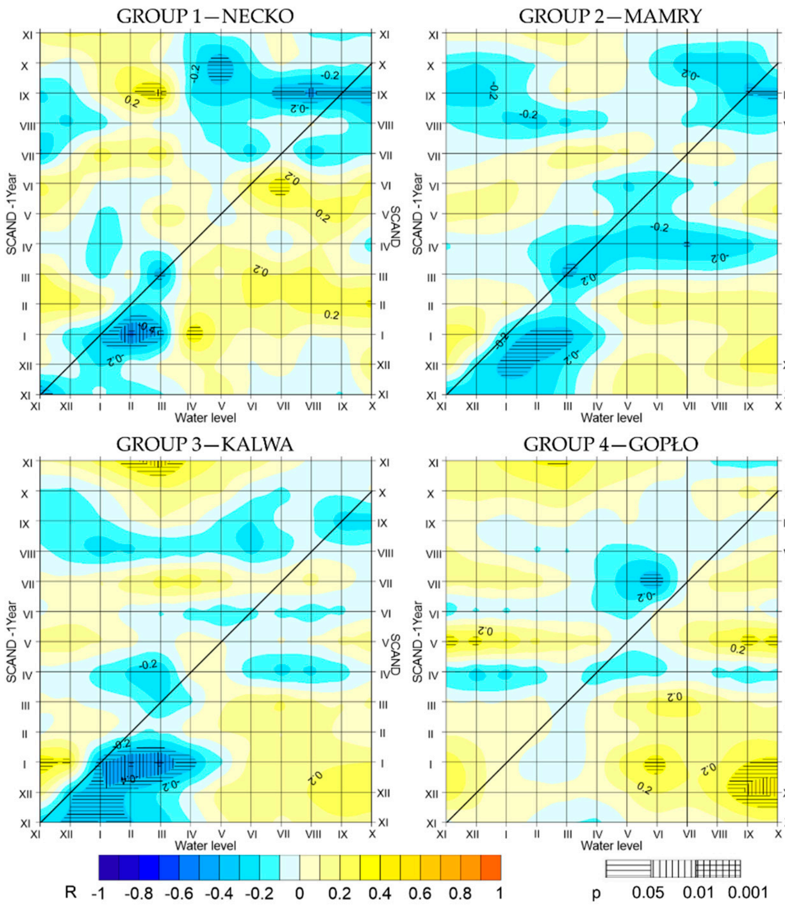

Figure 9. Matrices of coefficients of correlation for selected lakes in the designated groups (SCAND).

3.4. Scandinavian Pattern

In grouping of lakes by correlation and term of occurrence of correlations of SCAND indices with water levels in the analyzed lakes, 4 groups were designated (Figure 8). One of the groups again includes Lakes Sajno and Necko (group 1). Almost throughout the year, SCAND indices negatively, but statistically non-significantly correlate with water levels in lakes. This is exemplified by the matrix of correlation coefficients for Lake Necko. SCAND indices in October correlate statistically significantly at a level of $p < 0.05$ with water levels in that month (Figure 9). Positive, statistically non-significant correlations are observed between SCAND indices and water levels in April and June, and in the case of Lake Sajno only in April. In both lakes, asynchronous correlations of the teleconnection indices in January with water levels in February and March were observed. Water levels in the lakes show negative, statistically significant correlations (Sajno, $p < 0.05$ and Necko, $p < 0.001$). Water levels in Lake Necko in April was positively, statistically significantly ($p < 0.05$) correlated with SCAND index in January. The second group includes lakes belonging to the system of the Great Masurian Lakes, interconnected with canals (Mikołajskie, Mamry, and Śniardwy). Negative correlations of SCAND indices with water levels are observed here over a major part of the year. The indices correlate statistically significantly at a level of $p < 0.05$ with water levels in lakes in March. Positive, but statistically non-significant correlations occur in February, and in Lakes Mikołajskie and Mamry also in July. In the case of Lakes Mamry and Jagodne, asynchronous correlations of SCAND indices in December with water levels in January, and indices in January with water levels in the lakes in February and March are also observed ($p < 0.05$). Group 3 includes 7 lakes (Figure 8). The matrix for Lake Kalwa is presented as an example (Figure 9). Negative, statistically non-significant correlations are generally observed between monthly SCAND indices and water levels in the lakes. Only water levels in Lake Roś in November and Lakes Kośno and Kalwa in January correlate with SCAND statistically significantly ($p < 0.01$). Positive correlations usually occur in the period from April to June, and in Lake Kalwa also in July. Asynchronous correlations of SCAND indices in January with water levels from February to March ae also observed, and in Lake Kalwa even until April. Negative correlations are statistically significant in all the lakes, and in the case of Lake Kalwa even at a level of $p < 0.001$. In group 4, water levels show positive or negative, statistically significant correlations with synchronous SCAND indices. Significant correlations are observed in the case of asynchronous series—SCAND indices in December and January with water levels in August ($p < 0.05$) in Lake Lednica, and in September and October ($p < 0.01$) in Lakes Lednica and Gopło.

3.5. Effect of Teleconnection Patterns on Air Temperature and Precipitation

Because the regime and fluctuations of water levels in lakes are largely determined by meteorological factors affecting the volume of alimentation, the analysis also covered correlations of the analyzed teleconnection patterns (AO, NAO, EA, SCAND) with air temperature and atmospheric precipitation in 4 meteorological stations: Poznań, Chojnice, Olsztyn, and Suwałki. Because the correlation analysis provided similar results for all the stations, both for air temperature and atmospheric precipitation, the results of the correlation analysis were presented only for station Olsztyn (Figure 10). The research showed that correlations of teleconnection indices with air temperature are considerably stronger than in the case of atmospheric precipitation. Changes in the intensity of monthly AO and NAO indices show high similarity in terms of both the strength and terms of the observed most significant correlations with air temperature and precipitation amount. Monthly AO and NAO indices show positive correlations with air temperature throughout the year, although the strongest, statistically significant synchronous correlations are observed from December to March ($p < 0.001$). Correlations with atmospheric precipitation are weaker. Positive and statistically significant synchronic correlations of AO and NAO with air temperature are observed in January ($p < 0.05$), and negative, statistically significant correlations from July to August. Asynchronous correlations of AO and NAO indices in January and February are determined for precipitation in August ($p < 0.01$).

Monthly EA indices have the strongest effect on air temperature in September and October ($p < 0.001$), and precipitation shows a negative, statistically significant correlation only in September ($p < 0.05$).

The SCAND pattern in January and February statistically significantly correlates with air temperature in those months. Positive, statistically significant correlations occur in May ($p < 0.01$). SCAND indices in May show asynchronous correlations with air temperature in September ($p < 0.05$). Statistically significant correlations of SCAND with atmospheric precipitation were also determined in the cool half-year from January to March ($p < 0.01$), and in October ($p < 0.001$).

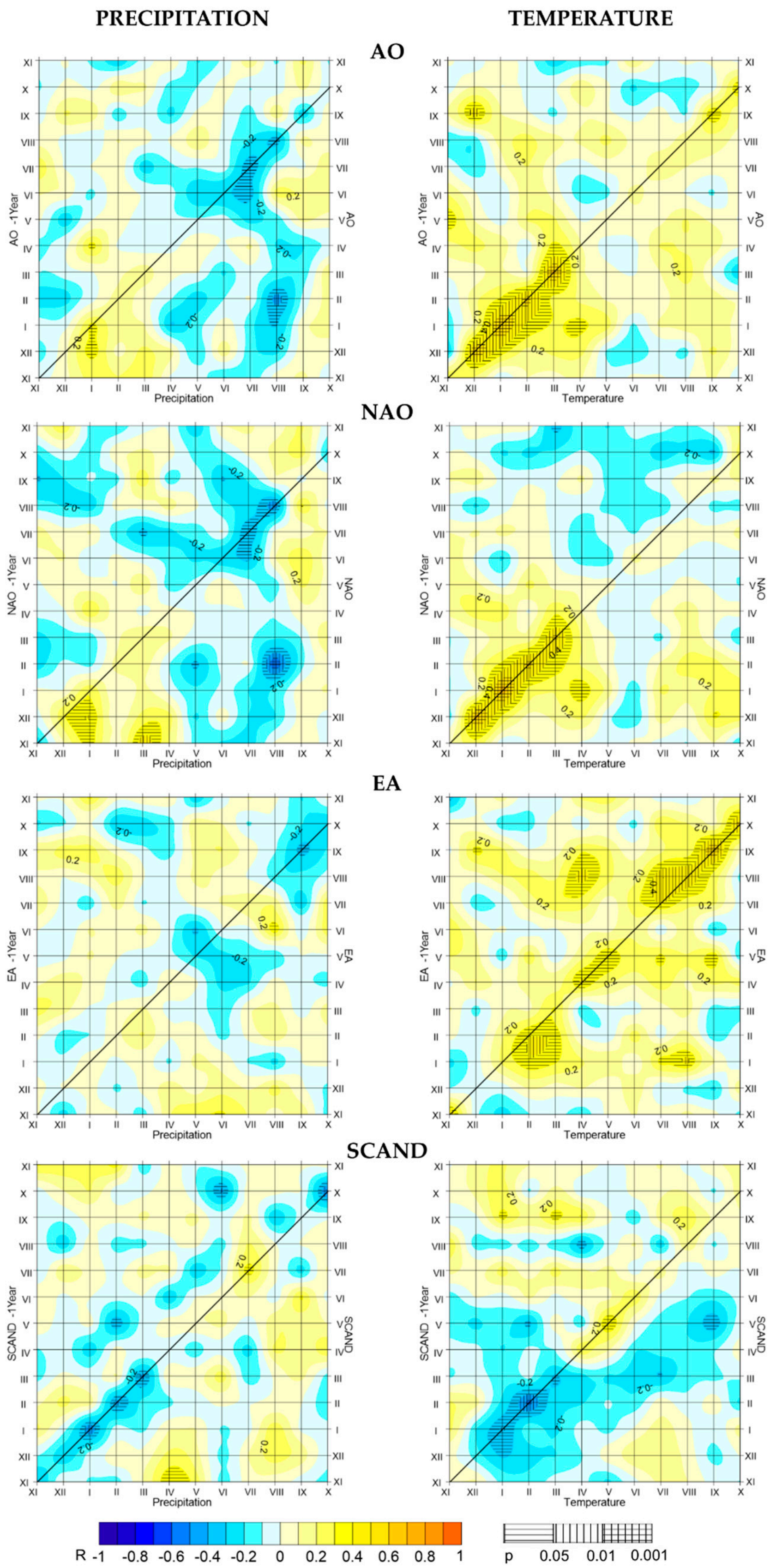

Figure 10. Matrices of coefficients of correlation for temperature and precipitation in Olsztyn station in considered circulation types.

The results of the analyses show that during warm winters in the positive phase of NAO/AO and in the negative phase of SCAND there are observed not only higher air temperatures, what cause mid-winter snowmelts and increased water supply, but also higher precipitation, what can even intensify this process. Weak correlations of EA with precipitation do not cause significant changes of lake water levels.

4. Discussion

The obtained results show that the observed correlations of teleconnection patterns with water levels in lakes are not strong, but evident. They also show temporal and spatial variability. The strongest and most significant correlations were observed in the case of AO and NAO in the winter period. This is also confirmed by findings of other authors, particularly in reference to the effect of the North Atlantic Oscillation. Nõges et al. [61] showed a strong effect of NAO on water levels in Lake Võrtsjärv in Estonia. Soja et al. [62] showed a statistically significant effect of winter NAO_{DJFM} index on water levels in Lake Neusiedl in Austria in the years 1976–2010. Sheida et al. [63] pointed to the effect of NAO on the cyclical variability of water levels in Lake Urmia in Iran, and [64] to the statistically significant negative correlation of water level in Lake Balkhash with NAO indices (winter and annual). Numerous studies evidence the effect of different teleconnection patterns on water levels and thickness of ice cover in the Great American Lakes [31–37]. The aforementioned papers, however, focus on a detailed analysis of single or several lakes, and do not present the regional variability of the degree and direction of correlations of water levels in different lakes, as is attempted to evidence by the authors of this paper.

Several publications can be found in the literature on the impact of the teleconnection patterns on a river flow. For instance, connections between the river flows of the Iberian peninsula and NAO indices were found [65]. The results of research indicate that NAO has a significant impact on surface water resources throughout the Iberian Peninsula during winter, and autumn, particularly in the Atlantic watershed. The authors also found the positive streamflow anomalies during extreme negative NAO phases, and vice versa. The relation between river flows of northern hemisphere and ENSO and AO was confirmed, and linear negative teleconnection of river flows in Europe to AO was identified [66].

What is more, also the correlations between flows of Mississippi River and ENSO and NAO indices [67], winter Mississippi Valley stream flow and AMO, ENSO and PNA indices [68] and winter streamflow over Romania and AO/NAO, EA, EAWR and SCAND [69] were found.

In Polish scientific literature the impact of NAO was widely described, on both meteorological and hydrological variables. The strong influence of NAO was confirmed on air temperature in cold season [70–73], precipitation [74,75], radiation and humidity conditions [76] and on the thickness of the snow cover [77,78]. In the consequence the impact of NAO on the size and dynamics of river outflow is observed. Kaczmarek [79,80] found the influence of NAO on the height of snowmelt floods of the rivers in Central Europe. In the positive phase of NAO the spring floods are usually lower than in the negative phase. It was also confirmed that NAO has impact on Warta river flows [81,82] and that there are asynchronous connections between winter NAO indices and flows of the Vistula and several Carpathian rivers [83,84]. It was also found that NAO has strong impact on the height and seasonality of the Polish rivers outflow [85,86].

Limnological research confirmed the significant correlations between NAO and water temperature [24], ice cover [25,87], and water level fluctuations [1,30]. The strongest impact of NAO on mean annual water temperature of lakes in Poland was observed in winter-spring period. Depending on the NAO phase, temperatures differ from mean values. In the positive phase they significantly exceed mean temperature, and in the negative one they are lower than mean values [24]. In case of ice phenomena, it was observed that in the negative phase they occurred later, the ice cover was thicker, and it lasted longer than average. The opposite dependence was observed in the positive phase of NAO—the duration of the ice cover phenomena was shorter than average, and the ice cover was thinner [25]. Also, the impact of NAO on lakes water level was confirmed. Stronger correlations between water levels and seasonal NAO indices were recorded in winter-spring period [1,30].

The influence of macroscale circulation types (NAO, AO, EA, EAWR, SCAND) was also analyzed in accordance to air and lakes water temperature in Poland. The strongest impact on water temperature was observed in winter for NAO and AO indices [18]. The carried-out analysis referring to Polish lakes points to regional variability of the effect of changes in the intensity of the analyzed teleconnection patterns on water levels in lakes despite a lack of such variability in reference to air temperatures and amount of atmospheric precipitation.

The lakes are located in the zone of moderate latitudes, where high water levels occur in spring due to intensified meltwater alimentation, and low levels in summer as a result of reduction of the resources due to an increase in temperature and losses related to evaporation. Despite their location practically in a single zone, the terms of occurrence of minimum and maximum values, as well as the range of their fluctuations [48], and water level amplitudes [88] are somewhat different. Therefore, the paper verifies to what degree changes in the intensity of the most important teleconnection patterns can contribute to changes in water levels in lakes. Results of the correlation analysis and Ward hierarchical grouping point to a certain correlation of changes in water levels in lakes with the intensity of particular teleconnection patterns. Results of grouping to a certain degree relate to type of lake regime designated by [48] due to the value and course of the water level coefficient representing water level fluctuations in an average annual cycle. It is the most noticeable in case of two lakes—Necko and Sajno. In each grouping they were in the same group. They are the only lakes (type 2b) which in the sequence of hydrological periods are characterized by the occurrence of very low water levels period in winter and high water levels during the period of intensified water supply caused by spring thaws with the maximum at the turn of March and April.

5. Conclusions

The applied research procedure and assessment of the importance of changes in teleconnection patterns (AO, NAO, EA and SCAND) for water level fluctuations in lakes based on the correlation analysis shows statistically significant correlations of water levels in lakes with monthly indices of the analyzed teleconnection patterns. The observed correlations are the most significant in the case of AO and NAO, and somewhat weaker for EA and SCAND. These teleconnection patterns particularly affect air temperature, and to a lower degree precipitation. Therefore, they may indirectly affect the conditions of alimentation of lakes. In positive phases of AO and NAO during warmer winters, the type of alimentation changes from nival to rain. Due to winter snowmelts, also more frequent in the period, the alimentation increases, and water levels in lakes are higher. The existence of very significant negative asynchronous correlations of AO and NAO indices in February with the amount of precipitation in August is interesting. Lower precipitation in the summer period may be reflected in lower summer-autumn water levels in lakes, which would confirm similar correlations of AO and NAO indices in February with water levels in lakes in the period. The weakest correlations with water levels in lakes were determined in the case of EA. Although in the positive phase, particularly in the summer-autumn period, the teleconnection pattern contributes to an increase in air temperature and a decrease in atmospheric precipitation, it is reflected in changes in water levels in lakes to a low degree. The effect of changes in the intensity of SCAND on water levels is observed, however, particularly in lakes located in the eastern, cooler part of the study area. In the positive phase of SCAND, in the winter-spring period, from January to March, atmospheric precipitation and air temperature (particularly in February) are considerably lower. As a consequence, alimentation of lakes decreases, and water levels in the lakes also decrease in the period.

In the case of such research, aimed at the determination of correlations between variables, it is very important to previously verify the hydrometric material for the purpose of avoidance of incidental dependencies. For this purpose, all lakes showing anthropogenic disturbances in the water level regime, lack of homogeneity of observation series, or statistically significant tendencies in the analyzed variables were eliminated from the analysis. It should be remembered, however, that linear correlation is not a resistant measure [89]. This means that untypical observations (so-called outliers) may considerably affect the value of the correlation coefficient. Moreover, the analysis of the obtained coefficients does not permit simultaneous determination of the strength of correlation between hydrological variables and indices of particular teleconnection patterns. Statistically significant correlation coefficients only point to the same (positive correlations) or opposite (negative correlations) direction of correlation. In the scope of continuation of research on the effect of different teleconnection patterns, it seems necessary to introduce more advanced statistical analyses. An attempt of such research was conducted by among others [90]—the authors analyzed the effect of variability of climate features (expressed in among others NAO and ENSO indices) on values of the SPEI index (Standard Precipitation Evapotranspiration Index) in the Yangtze River Basin, with the application of combined distribution calculated on the basis of Copula functions. Even more advanced computational methods (like machine learning and artificial neural networks) can be used to predict future values of given hydro- and meteorological variables. These methods were used for instance to forecast runoff values for the effective reservoir management [91], to predict evaporation [92,93] or to establish a rainfall-runoff models for forecasting the river flow [94–97].

To sum up, climate conditions variability has an impact on lakes water level fluctuations. In the time of progressing climate change, particular attention should be paid to the fact that Poland is one of the countries with the smallest water resources in Europe [98]. Therefore, in the light of the declining lakes water resources observed [99], it is really important to monitor the fluctuations in lakes water levels and to determine their causes for the purposes of rational and effective water management.

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