EFFECT OF THE NORTH ATLANTIC OSCILLATION ON WATER LEVEL FLUCTUATIONS IN LAKES OF NORTHERN POLAND

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Abstract

The paper presents an analysis of correlations between water levels in Polish lakes and the rate of the North Atlantic Oscillation (NAO) in the years 1976-2010. The detailed analysis of the spatial variability of the effect of NAO on water levels in lakes concerned 19 lakes with statistically uniform hydrometric material. Two matrices were obtained for each of the lakes, composed of 156 coefficients of correlation calculated between monthly water stages and monthly and seasonal NAO indices. They provided the basis for performing two variants of classification of lakes by Ward's method. Four typological classes were distinguished for each variant. It was determined that stronger correlations occur in the case of water stages in lakes with seasonal than those with monthly NAO indices. The strongest effect of NAO on water stages is observed in the winter-spring period. Spatial variability of the effect has been recorded, resulting from the climatic conditions of a given region. Lakes located in the south-western part of the studied area constitute an evidently separate group. In the negative phase of NAO, they are distinguished by higher water stages in the winter-spring period. This may be associated with more frequent thaws during winters, and increased supply to lakes in the period.

Key words

teleconnections • water levels • lakes • NAO

Introduction

Water level fluctuations in lakes are a good indicator of changes in natural and anthropogenic factors determining the hydrological conditions in catchments. The former particularly include precipitation amount and air temperature, influencing evaporation volume. The latter involve all kinds of hydrotechnical activities aimed at the adaptation of lakes to human economic activity. Water stages can be affected by both kinds of the factors simultaneously. Due to this, the determination of the main cause of water level

fluctuations is often difficult or even impossible, as emphasised among others by Choiński and Jańczak (1988).

Water level fluctuations are among the basic limnological characteristics determining the course of a number of processes and phenomena affecting the functioning of a given lake. Molinos et al. (2015) emphasise that water level fluctuations may cause evident socio-economic as well as environmental effects. They include among others the variability of physico-chemical water parameters, biotic changes, etc. (Stefanidis & Papastergiadou 2013; Šikić et al. 2013; Cantonati et al. 2014; Dembkowski et al. 2014).

It is important to identify the tendencies concerning water stages, directly determining the volume of water stored in a lake. In the case of Poland, one of the countries with the lowest water resources in Europe (Kowalczak et al. 1997), information on water level fluctuations can prove particularly important in the context of implementation of tasks related to the improvement in water management and retention increase.

The issue of water level fluctuations in Polish lakes has been discussed in many publications (Skibniewski 1954; Pasławski 1972; Niewiarowski 1978; Konatowska & Rutkowski 2008; Wrzesiński & Ptak 2016; Ptak et al. 2017). They concern various aspects of the issue, and are based on varied groups of study objects, including from one to several tens of lakes.

The abundant literature shows an evident lack of a broader study referring to macroscale atmospheric circulation determining climatic conditions, and consequently water level fluctuations in Polish lakes. Research has shown an important climate-driving role of the North Atlantic Oscillation in Europe (George et al. 2004). This is confirmed by numerous studies in the area of climatology (Zveryaev et al. 2009; Twardosz et al. 2012; Bednorz 2013; Tomczyk 2015) and hydrology (Pociask-Karteczka 2006; Weyhenmeyer 2009; Wrzesiński et al. 2015a, b; Ptak et al. 2018). The effect of NAO on water level fluctuations in Polish lakes based on seven

objects from north-eastern Poland was analysed by Górniak and Piekarski (2002). The authors evidence the correlation of water stages with nival precipitation in the period from December to March. The current determinations encourage undertaking research on the effect of NAO on water stages in lakes based on more extensive hydrometric material concerning lakes from various regions of Poland. Wrzesiński and Ptak (2017) investigated the correlations of the winter NAO index with monthly, seasonal, maximum, and minimum water levels. Approximately 20% of the performed tests showed statistical significance. In the case of high mountain Lake Morskie Oko, the key role was played by local factors and not by macroscale atmospheric circulation (Wrzesiński et al. 2016).

The primary objective of the paper is to determine the effect of the rate of NAO on water level fluctuations in lakes in the years 1976-2010. The research covered 19 lakes located in north Poland. The regular distribution of lakes also permitted the determination of the regional variability of the effect of NAO on the water stages of the studied lakes.

Materials and Methods

The territory of Poland includes approximately 7000 lakes with an area equal to of higher than 1 ha. They are particularly located in the northern part of the country. This is related to the range of the last glaciation. According to Choiński (2006), only 4% of lakes occur south of the line. Therefore, it can be presumed that the analysis of lakes located in the northern part of the country (Fig.1) is representative of the entire Poland.

The paper applies monthly values of water levels in 19 lakes, and meteorological elements: air temperature and atmospheric precipitation from three meteorological stations – Fig. 1. The data were obtained from the collection of the Institute of Meteorology and Water Management (IMWM). Monthly and seasonal Hurrell NAO indices were also used (Hurrell & National Center for Atmospheric Research Staff 2017). The basic parameters
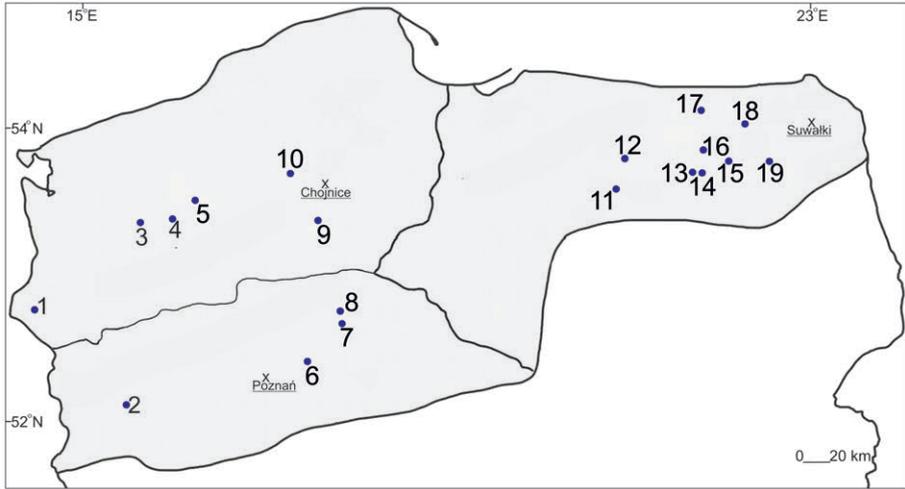
Figure 1. Location of lakes and meteorological stations

of the lakes analysed in the paper are presented in Table 1.

For the purpose of determination of the correlation between water stages in lakes, but also air temperature and precipitation and intensity of the North Atlantic Oscillation, Pearson linear correlation coefficients were calculated. The correlation coefficients were calculated between standardised monthly water stages in lakes, air temperature, and precipitation and monthly and seasonal (from three consecutive months) NAO indices.

The coefficients of correlation between the analysed variables were calculated for synchronic and asynchronic series, e.g. the NAO_N index (in the second variant NAO_{OND} index) was correlated with water stages recorded from November to October, NAO_D index (NAO_{NDJ}) with water stages recorded from December to October, and water stages from November were correlated with the NAO_D index (NAO_{NDJ}) from the preceding year, etc. Two matrices were obtained for each of the lakes, composed of 156 correlation coefficients. The first matrix includes correlation coefficients calculated between monthly water stages and monthly NAO indices, and the second with seasonal NAO indices. The statistical evaluation of significance of correlation coefficients employed the commonly applied *t* statistic (Norcliffe 1986). The determination of the significance of the correlation coefficient employed *t* statistic:

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

r – linear correlation coefficient
n – number of elements in a sequence

The calculated value *t* was then compared to the value read from the *t* Student chart at n-2 degrees of freedom.

The results of the correlation analysis are presented graphically in the form of matrices of correlation coefficients. The colour scale for the matrix of correlation coefficients is developed in such a way that values of ranges correspond with critical values of correlation coefficients.

At the next stage of the study, values of 156 correlation coefficients were treated as variables. They provided the basis for conducting two variants of classification of lakes by Ward's method (Ward 1963). The results of the classification are presented graphically in the form of a dendrogram reflecting the structure of similarity of the studied group of lakes. It provided the basis for the distinguishing of typological classes. The number

Table 1. Morphometric data of the studied lakes (numbering in accordance with Fig. 1)

No	Lake	Area [ha]	Volume [thous m^3]	Average depth [m]	Maximum depth [m]
1	Morzycko	317.5	49,826.9	14.5	60.7
2	Niesłysz	526.0	34,457.6	6.9	34.7
3	Ińsko	529.0	65,182.0	11.0	41.7
4	Lubie	1,487.5	169,880.5	11.6	46.2
5	Drawsko	1,797.5	331,443.4	17.7	82.2
6	Lednica	325.0	24,397.0	7.0	15.1
7	Biskupińskie	107.0	6,397.2	5.5	13.7
8	Żnińskie Duże	420.5	29,492.6	6.8	11.1
9	Sępoleńskie	157.5	7,501.6	4.8	10.9
10	Szczytno Wielkie	565.0	51,762.5	8.0	21.4
11	Kalwa	561.0	39,468.6	7.0	31.7
12	Dadaj	978.0	120,784.2	12.0	39.8
13	Mikołajskie	424.0	55,739.7	11.2	25.9
14	Śniardwy	11,487.5	660,211.8	5.8	23.4
15	Orzysz	1,012.5	75,326.2	6.6	36.0
16	Jagodne	872.5	82,705.2	8.7	37.4
17	Mamry	9,851.0	1,003,367.5	9.8	43.8
18	Litygajno	154.5	9,763.9	6.0	16.4
19	Selmęt Wielki	1,207.5	99,463.9	7.8	21.9

of classes was determined in the study based on the pattern, i.e. geometry of the dendrogram, and bond length curve.

The mathematical-statistical analysis of results used statistical procedures provided in *Excel* (Microsoft) and *Statistica* (StatSoft) software. The graphic design was prepared with the application of *Surfer 10* (Golden Software) and *CorelDraw 12* (Corel) software. In the development of the matrices of correlation coefficients, isocorrelates were developed by means of the kriging procedure.

Results

For the purpose of determination of the effect of changes in the North Atlantic Oscillation on water stages in Polish lakes, coefficients of correlation were calculated between monthly and seasonal (from three consecutive months) NAO indices and monthly water stages in lakes.

Based on values of 156 correlation coefficients, the performed classifications in both of the variants permitted distinguishing 5

(error sum of squares – ESS = 2.5) and 4 (ESS = 3.0) groups of lakes, respectively (Fig. 2). The spatial diversity of lakes in particular groups is almost identical. Because more statistically significant coefficients of correlation were obtained in the second variant (based on the correlation of seasonal NAO indices with monthly water stages (Fig. 3), the analysis of results only concerns this variant.

Four lakes from group 1 are located in the Pomeranian Lakeland. The strongest effect of the North Atlantic Oscillation on water stages in the lakes is observed in the winter-spring period, and coefficients of correlation with water stages in lakes in February and March are statistically significant at the level of $p < 0.05$ – Fig. 4. In the case of these lakes, the correlation of NAO_{JFM} and NAO_{FMA} with water stages in Lakes Lubie and Drawsko in the summer-autumn period (from August to October) is also evident. The calculated coefficients of correlation, however, are negative ($p < 0.01$). Similar correlations were observed in the case of Lakes Ińsko and Szczytno Wielkie between NAO_{MAM} and NAO_{AMJ}
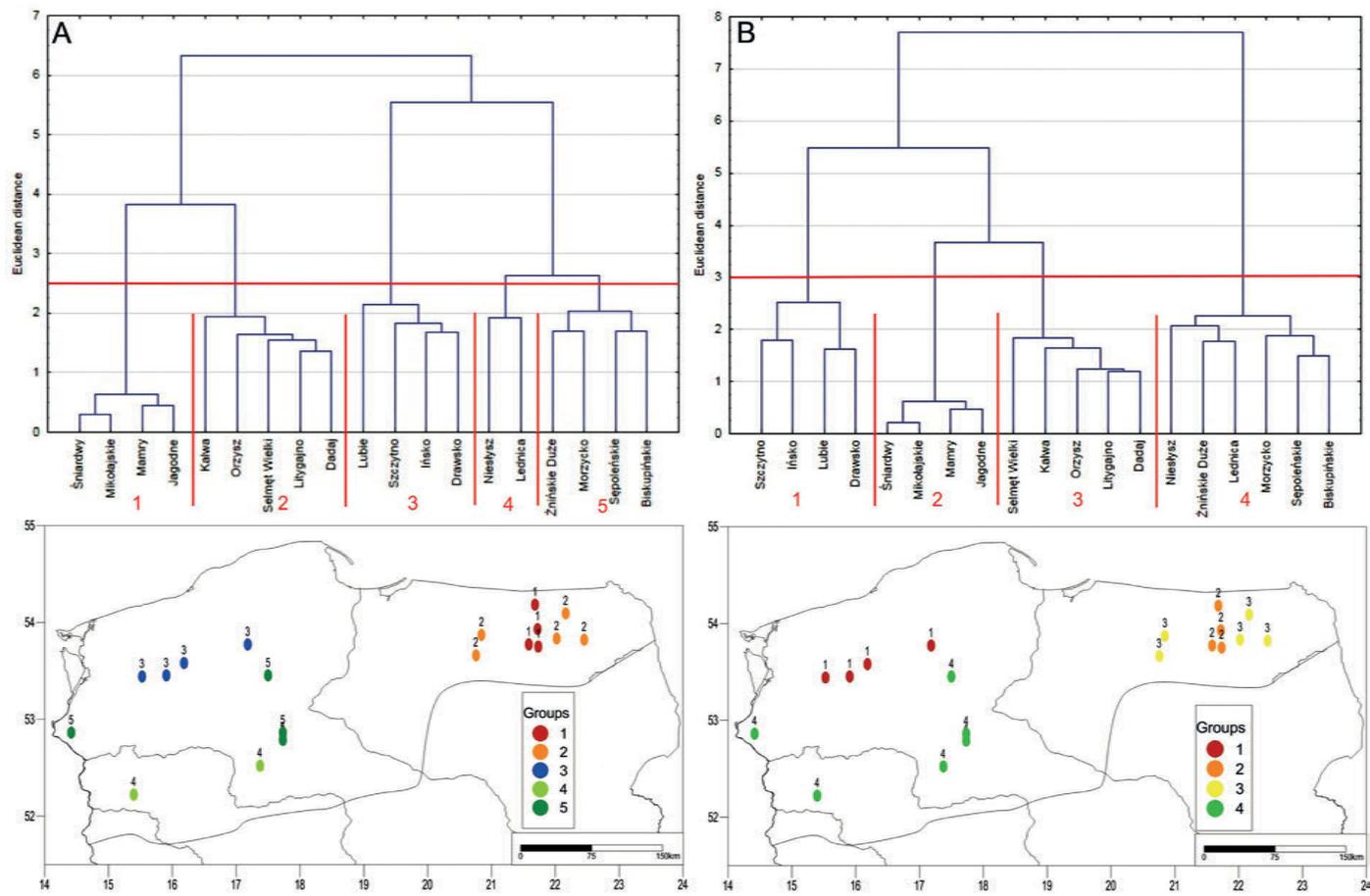
Figure 2. Dendrogram of the classification of lakes – Ward's method. Classification of 19 lakes by correlations of monthly (A) and seasonal (B) NAO indices with monthly water stages
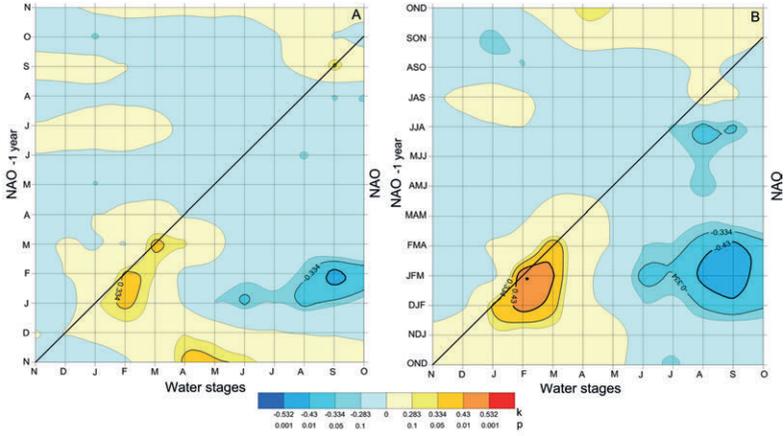
Figure 3. Example matrices of coefficients of correlation of monthly water stages in Lake Dadaj with monthly (A) and seasonal (B) NAO indices
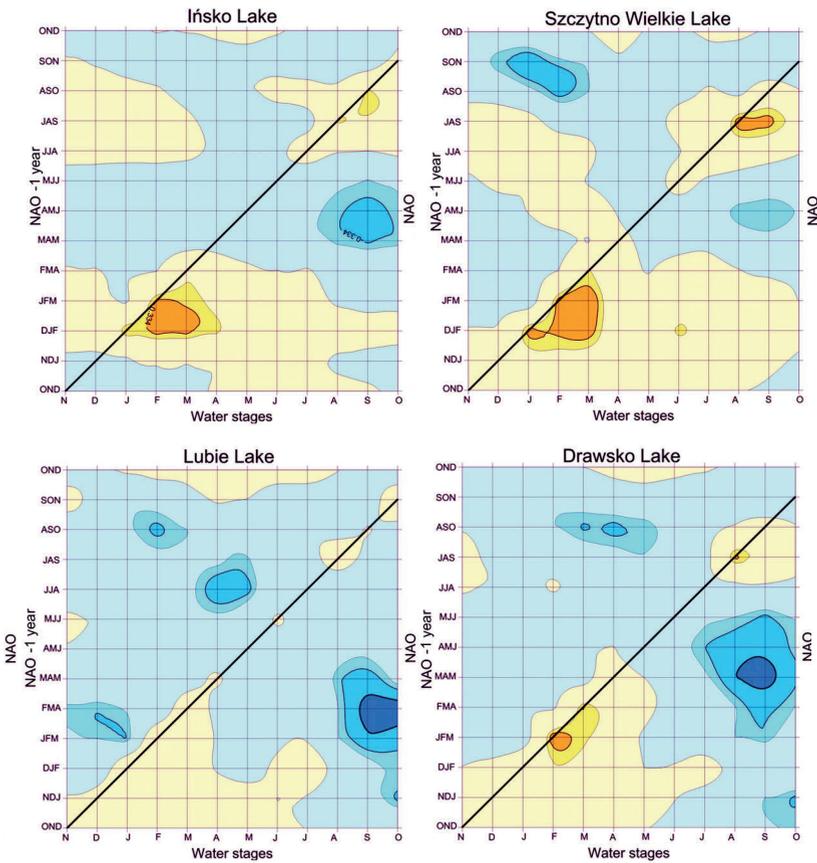

Figure 4. Matrices of coefficients of correlation of monthly water stages with seasonal NAO for lakes from group 1

and water stages in the lakes in September, and the calculated coefficients of correlation are significant at a level of $p < 0.05$.

Group 2 includes four lakes of the Masurian Lakeland belonging to one drainage system. Therefore, the regime of their water stages as well as correlations with NAO indices are almost identical. Water stages in the lakes show negative correlations with NAO_{JFM} and NAO_{FMA}, the most statistically significant ($p < 0.01$) from August to October – Fig. 5. Less significant, but positive coefficients of correlation (only in the case of lake Jagodne at a level of $p < 0.05$) are recorded between these seasonal NAO indices and water stages in lakes in February and March.

Water stages in lakes in this group from July to October also show negative, but less statistically significant ($p < 0.05$) correlations with NAO_{AMJ} and NAO_{MJJ}.

Group 3 includes the remaining analysed lakes of the Masurian Lakeland, and matrices of coefficients of correlation of their water stages with seasonal NAO indices are similar to those observed in the case of lakes from group 2. Water stages in the lakes in March and April show considerably stronger correlations with NAO_{DJF} and NAO_{JFM}, expressed in higher positive coefficients of correlation at a level of $p < 0.01$ – Fig. 6. The majority of lakes in the group also show negative correlations of NAO_{JJA} with water stages from
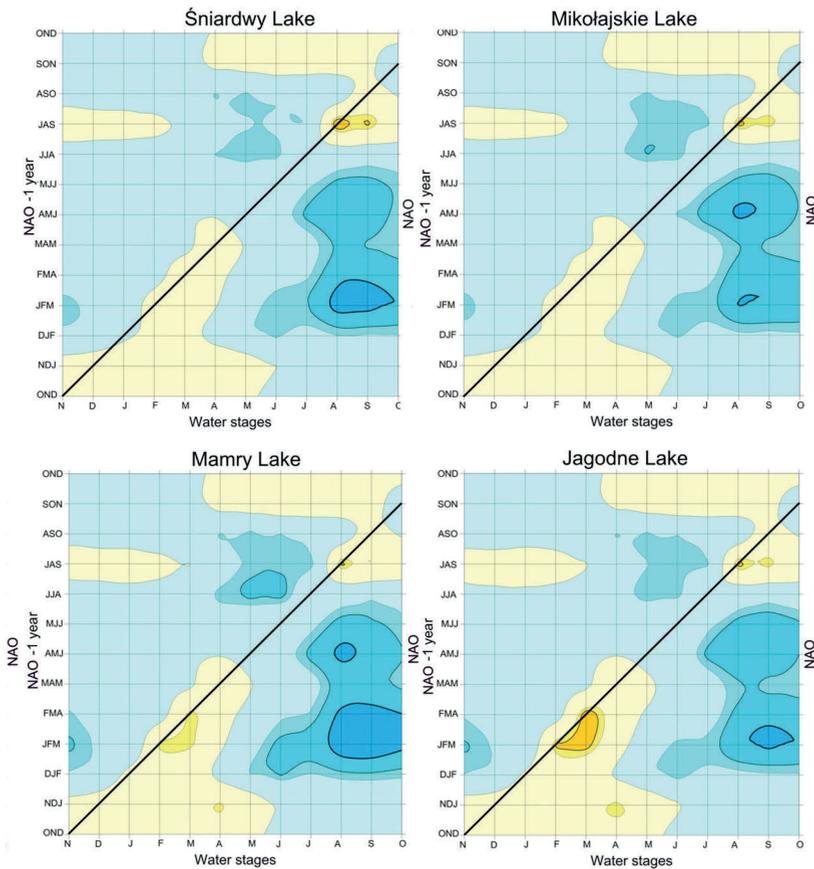

Figure 5. Matrices of coefficients of correlation of monthly water stages with seasonal NAO indices for lakes from group 2

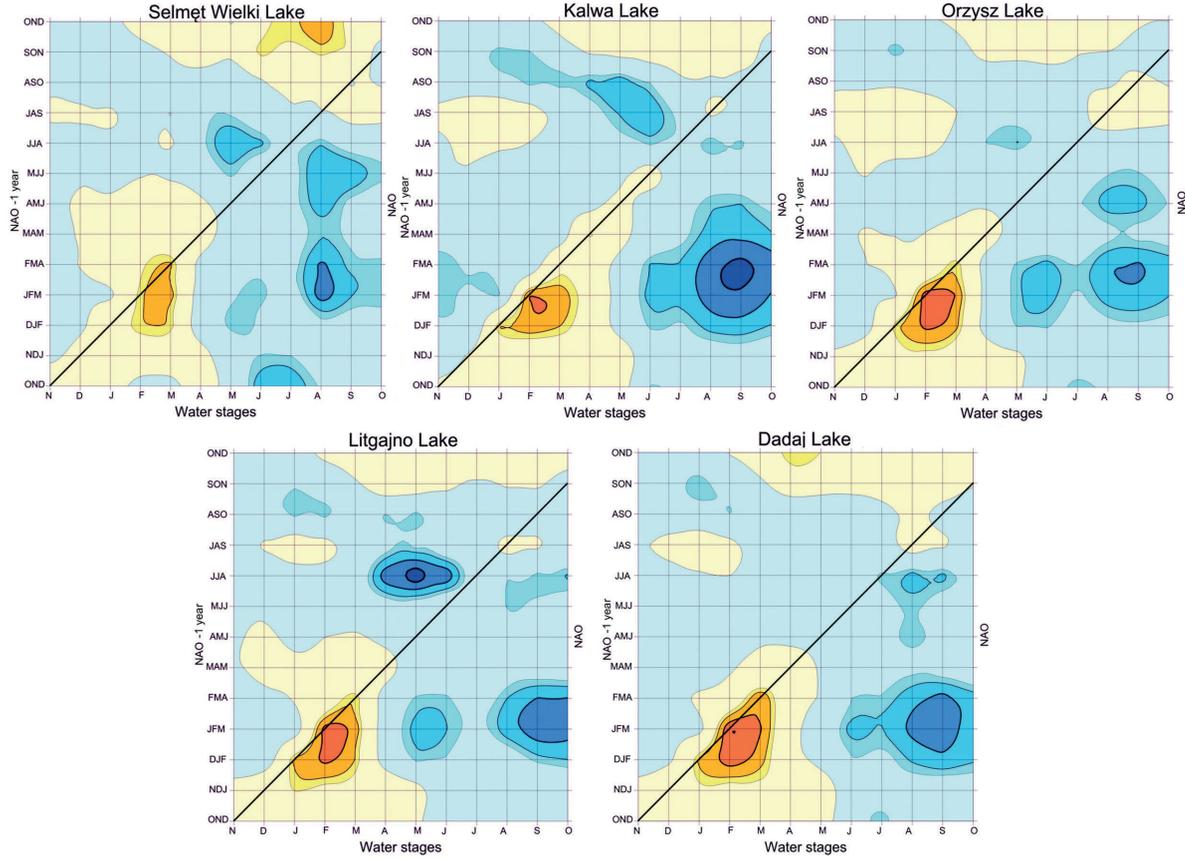Dariusz Wrzesiński • Mariusz Ptak • Katarzyna Plewa

Figure 6. Matrices of coefficients of correlation of monthly water stages with seasonal NAO indices for lakes from group 3

April to June of the following year, however they are strongly statistically significant only in the case of Lake Litygajno ($p < 0.001$).

Group 4 includes 5 lakes located in the southern part of the lakeland belt, particularly in the Wielkopolsko-Kujawskie Lakeland, but also on the Szczecin Lowland (Morzycko) – Fig.7. Water stages of only these lakes show negative correlations with winter-spring indices in all months in a year. Stronger negative correlations occur between NAO_{DJP}, NAO_{JFM}, and NAO_{FMA} and water stages in the lakes from April to October. The strongest correlations ($p < 0.001$) are observed in May and June (Lake Żnińskie), or only in May (Lake Sępoleńskie). The effect of the North Atlantic Oscillation in the winter-spring period on water stages in the lakes in November, December, and in the case of Lakes Lednica, Sępoleńskie, and Niesłysz even January of the following year draws attention due to the calculated coefficients of correlation statistically significant at a level of $p < 0.05$. In the case of three Lakes: Żnińskie, Lednica, and Sępoleńskie, statistically significant ($p < 0.01$) negative correlations also exist between NAO_{JJA} and NAO_{JAS} and water stages in the lakes from February to June of the following year.

Because the natural regime of water stages is considerably affected by climatic factors, the next stage of work involved the analysis of the effect of the rate of the North Atlantic Oscillation on air temperature and atmospheric precipitation. Matrices of coefficients of correlation of seasonal NAO indices with monthly temperatures at sites located in various physico-geographical regions are almost identical (Fig. 8). Research confirmed that the North Atlantic Oscillation has the strongest effect on air temperature in the cold part of the year. The strongest coefficients of correlation were obtained for each site between NAO_{DJF} and air temperature from January to March (Poznań) or April (Chojnice, Suwałki), and NAO_{JFM} and air temperature from February to March. Notice that the significance of the coefficients of correlation increases from station Poznań located in the belt

of lowlands in the northern and eastern direction. Stations Chojnice and Suwałki are located in cooler regions, and are distinguished by lower temperatures. This is determined by higher location in the belt of moraine hills (Chojnice), and an increase in continentalism and severe character of the climate (Suwałki). At those stations, the level of significance of the calculated coefficients of correlation is even lower than $p = 0.001$.

The analysis of matrices of coefficients of correlation of seasonal NAO indices with monthly precipitation also shows low variability of the effect of changes in NAO on precipitation amounts in various parts of the country – Fig. 9. Similarly as in the case of air temperature, also precipitation shows stronger correlations with seasonal NAO indices in the winter-spring period. Indices NAO_{DJP}, NAO_{JFM}, and NAO_{FMA} correlate positively, although statistically insignificantly, with precipitation amount from January to April. Significant ($p < 0.05$) negative coefficients of correlation were obtained between winter-spring NAO indices and precipitation amount in August and September, in the case of Chojnice even at a level of $p < 0.001$.

For the purpose of determination of patterns of water level fluctuations in an average annual cycle, monthly coefficients of water stages were calculated for each of the lakes. The value of the monthly water stage coefficient was calculated as the quotient of the average water level in a given month to the value of the average annual water level, and expressed as a per cent value. Regimes of water stages of the studied lakes from the point of view of the term of occurrence of periods of high and low water stages are similar, although they differ considerably in terms of the amplitude values – Fig. 10. Water stages in the majority of lakes from the beginning of the hydrological year (November) increase to the maximum reached in March or April in group 4, in April in group 1 and 3, and in April and May in group 2. The exception is Lake Szczytno with a maximum in August. From June or July, the lakes enter the period of low water stages with the minimum
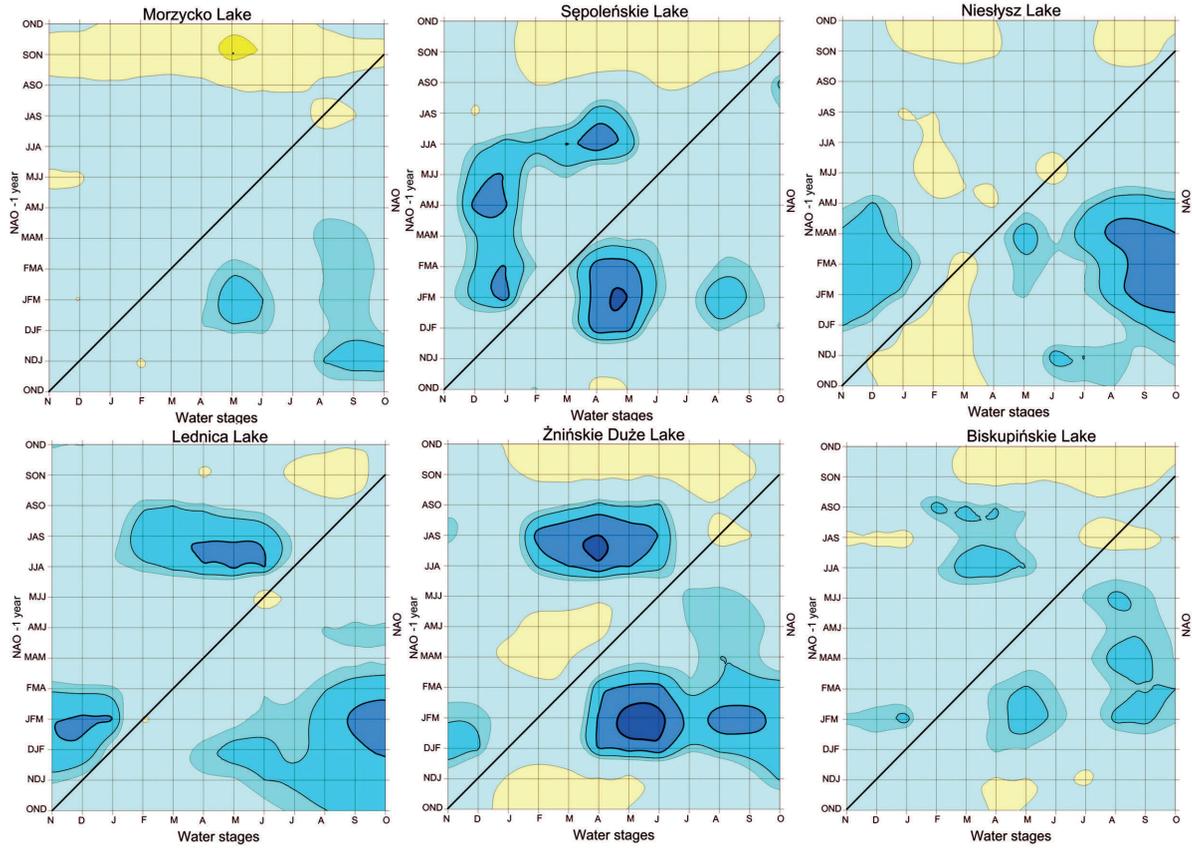
Figure 7. Matrices of coefficients of correlation of monthly water stages with seasonal NAO indices for lakes from group 4
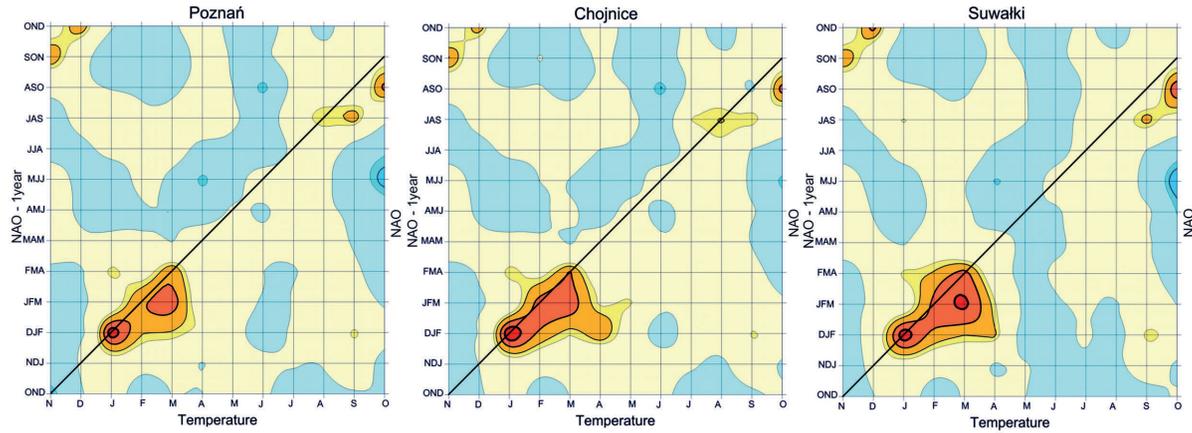
Figure 8. Matrices of coefficients of correlation of monthly air temperatures with seasonal NAO indices
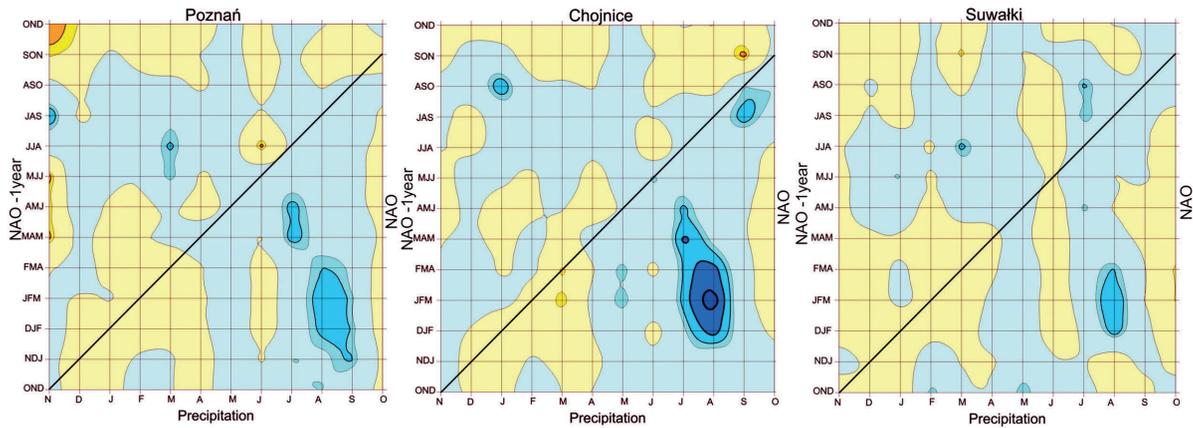

Figure 9. Matrices of coefficients of correlation of monthly precipitation amounts with seasonal NAO indices
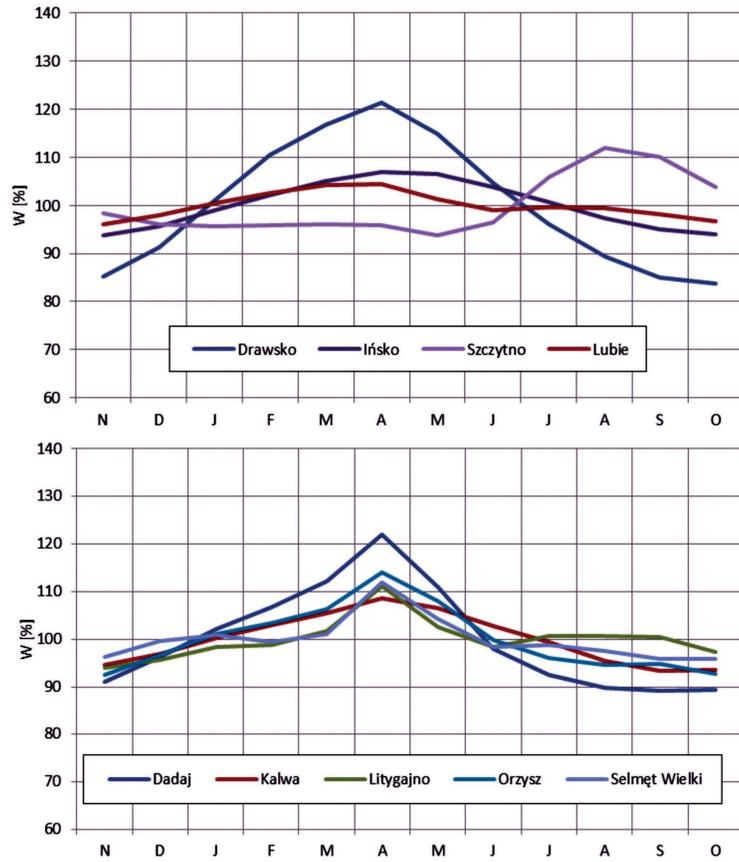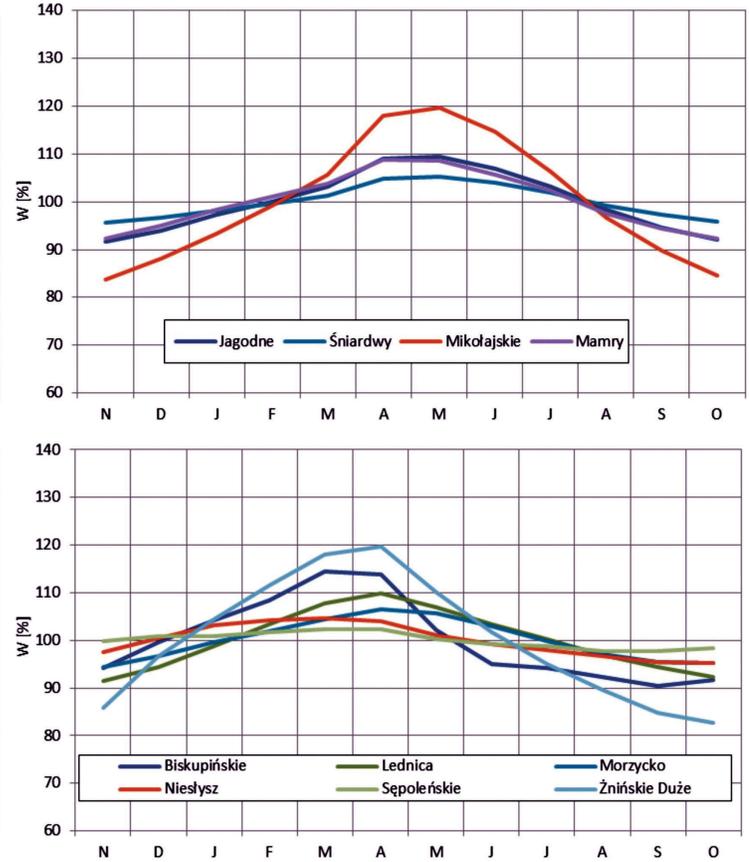
Figure 10. Monthly water stage coefficients for lakes in the distinguished groups

in September or October. All of the afore-mentioned groups include lakes with high amplitude of monthly water level fluctuations, as well as lakes showing very uniform water levels in the annual cycle. In the case of four lakes, the highest monthly water stages are approximately 20 percent higher than the mean annual values. They represent each of the groups. In the first group, it is Lake Drawsko, second – Lake Mikołajskie, third – Dadaj, and in the fourth group – Lake Żnińskie. The lakes are also distinguished by the lowest monthly stages in comparison to the mean annual value. Values of water stage coefficients in months with the lowest water stages for the lakes vary from 80 to 90% of the mean annual water stage value.

Discussion

In the majority of cases, the obtained results concerning the effect of NAO on water level fluctuations in Polish lakes show a significant correlation between the two variables. It was important from the methodological point of view to analyse only 19 lakes with quasi-natural water level regime and statistically uniform hydrometric material in the paper. The effect of NAO on water stages is not strong, but evident, particularly in winter-spring months. During that period, statistically significant coefficients of correlation with seasonal NAO $_{DJF, JFM, FMA}$ indices are observed on the majority of lakes. Changes in values of NAO indices, however, explain only 25-50% of water level fluctuations in lakes.

Multiple correlations of water levels in lakes with NAO are suggested by numerous papers analysing lakes in Europe (Nõges et al. 2003; Soja et al. 2013; Sheida et al. 2015), North America (Biron et al. 2014), and Asia (Krupa et al. 2014). The complexity of the correlation of water stages with the NAO index is demonstrated in the paper by Küçük et al. (2009).

The performed analysis referring to Polish lakes also suggests regional variability

of the effect of changes in the rate of the North Atlantic Oscillation on their water stages in spite of lack of such variability in the case of air temperatures and precipitation amounts. In the case of the first three groups of lakes, obtained in the conducted typological classification, correlations between NAO indices and water stages are similar. The division is particularly determined by correlation coefficient values. In years with high values of NAO indices from the winter-spring period, at considerably higher air temperatures observed from January to April, inconsiderably higher precipitation in the conditions of warm winter with numerous thaws, conditions favourable for increased supply to lakes develop. As a consequence, in the majority of the lakes, higher water stages are then observed from January to March. The strongest effect of NAO concerns Masurian lakes located in the coldest region, and somewhat weaker – lakes of the Pomeranian Lakeland. Due to the high retention capacity of the catchment of the lakes of the Pomeranian Lakeland (Wrzesiński 2013), in certain cases, water stages higher than average are also maintained during the remaining months. In the warm part of the year, however, water stages in the majority of lakes, and particularly Masurian lakes, are usually considerably lower than average. This may result from lower precipitation observed in August in the positive phase of NAO $_{DJF}$ and NAO $_{JFM}$.

The effect of NAO $_{DJF}$ and NAO $_{JFM}$ on water stages in the southern part of the study area (particularly Wielkopolskie Lakeland) is different. Here, the majority of lakes show higher water stages in winter and spring months in years with low seasonal values of NAO $_{DJF}$ and NAO $_{JFM}$ indices. This is determined by the climatic conditions of the region, considered the driest in the country (Ilnicki et al. 2014). Air temperature also plays an important role. In this region, the mean annual value is higher by $2°C$, and in winter by more than $3°C$ than in the north of the country (Woś 2010). Therefore, even in the period of the negative phase of NAO, winter thaws are possible, causing increased supply and

therefore an increase in water levels in lakes. Czarnecka and Nidzgorska (2013), analysing the occurrence of thaws in Poland in the years 1960-2010, recorded their highest frequency in the western and north-western part of Poland. This corresponds with the location of lakes with recorded higher water stages in winter and spring in the negative phase of NAO. The correlation of an increase in water flow with rapid warming is described by among others Stasik et al. (2007) based on the example of two streams in south Wielkopolska. In 2002, as a result of a rapid increase in temperature, in the middle of winter (end of January) the authors recorded the highest discharge values in the entire year. An increase in surface runoff in the period of rapid winter warmings magnifies the lack of infiltration capacity of the frozen ground. The correlation of this phenomenon with the volume of thaw-related water level increases is suggested by among others Krasowska and Banaszuk (2011), and Jania and Zwoliński (2011). The different character of the region is also suggested by research concerning the effect of the rate of the North Atlantic Oscillation on river runoff (Wrzesiński 2011). In years with negative values of index NAO_{DJFM}, higher runoffs are observed in Wielkopolska for certain rivers in February, and the majority in March, whereas the rivers of the Pomeranian and Masurian Lakelands show higher runoffs in these months in the positive phase of NAO_{DJFM}.

Conclusions

NAO is the primary type of macroscale atmospheric circulation determining climatic conditions in Europe, including precipitation and air temperature. According to the study, changes in the rate of the North Atlantic Oscillation affect meteorological elements and therefore also determine the supply of lakes and their water stages. The applied research procedure and assessment of the effect of NAO on water stages based on correlation analysis suggests that more important coefficients of correlation were obtained

in the case of correlation of seasonal NAO indices with monthly water stages in lakes.

The strongest effect of changes in the rate of the North Atlantic Oscillation on water stages in Polish lakes is observed in the winter-spring period, and it shows spatial variability. The determined regional variability of the effect of changes in the rate of the North Atlantic Oscillation on their water stages is observed in spite of lack of such variability in the case of air temperatures and precipitation amounts. The strength and direction of the North Atlantic Oscillation is largely determined by the natural conditions of the region. As a consequence, the lakes of the lakelands in the northern part of the study area with more severe climate are distinguished by a decrease in water stages in the winter-spring season in the period of cold winters in the negative phase of NAO_{DJF}. The lakes of the Wielkopolsko-Kujawskie Lakeland with a milder climate, higher temperatures, but also lower precipitation, show an increase in water stages in the cold phase of NAO_{DJF} due to an increased supply during winter thaws.

The study showed that a change in the rate of the North Atlantic Oscillation in the winter-spring season affect water stages in lakes also in the summer-autumn period. In the majority of the lakes, irrespective of their location in the negative phase of NAO, lower water stages are observed. This is associated with lower precipitation. The strength of the effect of NAO on water stages in the period, however, shows regional variability, and is most significant in the case of lakes of the Wielkopolsko-Kujawskie and Masurian Lakelands.

Because the distinguished groups include lakes with varied water stages, it can be assumed that this element does not considerably affect the direction of effect of the rate of the North Atlantic Oscillation on water stages, but can probably modify its strength. The North Atlantic Oscillation is of high importance for the prediction of changes of water stages in lakes in later periods. In the case of several lakes, however, the study showed

the existence of statistically significant coefficients of correlation between seasonal NAO indices, e.g. NAO_{JJA} and water stages in lakes in March and April of the following year. Such correlations may be incidental, and would require further detailed analyses.

Editors' note:
Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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