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Seasonal structure of water stages on lakes in Northern Poland

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Abstract. The paper presents the characteristics of hydrological periods in an average annual cycle in Polish lakes. The types of period and their sequence determine the regime of water stages in lakes. The article applies the unsupervised approach to analysis of water level fluctuation patterns, where the regime is identified by grouping analytical parameters. Hydrological periods were designated by grouping elementary time units of the hydrological year (pentads) based on the similarity of their parameters, namely water level frequency distributions. The analysis covered daily water stages in 33 lakes in Poland from the period from 1984 to 2012. Five types of hydrological period were designated. The studied lakes differ in the number, type and sequence of hydrological periods in an average annual cycle. Most of the lakes (19 lakes) have a 4-period temporal structure of water stages with the course of water stages in a year characteristic of this geographical zone. No spatial patterns occurred in the location of lakes from particular groups. This suggests the dominant role of local factors in determining the seasonality of water stages.

Key words:
water level,
hydrological regime,
seasonal changes,
coefficient of water stages

Introduction

Water level fluctuations are a manifestation of the intensity of the water circulation cycle in a catchment. They are observed both on the seasonal scale – in the annual cycle – and the multiannual scale. Patterns of water level fluctuations in an average annual cycle result from the seasonal variability of climatic phenomena, lake morphometry, and the structure of the lake catchment. They can be modified as a result of human activity. Water level variability in a lake is one of the basic characteristics determining the functioning of the entire ecosystem. Water level fluctuations influence among others the physical-chemical properties of lake waters (Choiński et al. 2014; Christensen and Maki 2015; Liu et al. 2016) or biotic conditions (Crisman et al. 2014; Solis et al. 2016). The degree of filling of the lake basin with water, which is expressed in the water stage, is a result of co-occurring natural and anthropogenic processes. The natural processes are associated with the amount of precipitation and evaporation (Choiński et al. 2016), while the anthropogenic include various manifestations of human activity in the catchment (including land amelioration works, water transfers, etc.). In extreme cases, anthropogenic disturbance of the components of water balance in lakes can lead to a considerable decrease in lakes' water level and, consequently, to their disappearance (Oren et al. 2010; Ptak et al. 2013).

Patterns in the course of hydrological phenomena are defined as a regime. The issue of regime can be analysed in a comprehensive way by referring to, among others, water stages, lake water temperature or ice phenomena (Ptak et al. 2017). Hydrological regime in its broader sense is a popular issue that is discussed in many limnological studies (Gebre et al. 2014; Dabaeva et al. 2016; Kirillin et al. 2017). In the case of Polish lakes, the problem of regime in reference to water stages has already been addressed several times. Pasławski (1975) performed a hydrological classification of lakes based on the water exchange index and mean annual water level amplitude. Choiński (1985) designated the types of regimes of Polish lakes, taking water level variability (expressed in the multiannual mean value of annual water level amplitude) as the differentiating factor. Borowiak (2000) adopted the amplitude and temporal structure of water stages as the regime assessment criteria. The result of the paper is a typological diagram covering six groups of amplitudes, and four groups of seasonal structures of water stages. Twenty-four types of lake regimes were thus designated. Meanwhile, by analysing fluctuations in the water levels of Polish (16) and Belarusian (9) lakes, Volchak et al. (2016) determined 3 groups. Presumably, the increase in continentalism of climate in an eastwards direction is one of the key determinants of the detected regional diversity of lake water level fluctuations.

The paper presents a new approach to the analysis of water level regime in Polish lakes based on the characteristics of the seasonal structure of water stages in lakes. This structure is determined by the temporal differentiation of types and sequences of hydrological periods in an average annual cycle resulting from the lake's size and form of alimentation. The objective of the paper is to identify the annual temporal structure of water stages in Polish lakes by designating and parametrising hydrological periods, and determining their sequences.

Materials and methods

The article covers daily observations of water stages for 33 lakes in Poland from the years 1984–2012. They were obtained from the collection of the National Research Institute of Meteorology and Water Management. Information concerning the hydrotechnical infrastructure and flow-through character of the lakes was obtained from the geoportal of the National Water Management Authority (http://geoportal.kzgw.gov.pl/) and Raster Map of Hydrographic Division of Poland (http://mapa.kzgw.gov.pl). The basic morphometric data on the lakes are presented in Table 1.

One methods for analysing hydrological regime is the unsupervised approach (Krasovskaia et al. 1994; Wrzesiński 2005, 2008), which involves identifying the regime based on classification procedures, and particularly by grouping analytical properties. The water level regime of lakes was analysed and characterised based on hydrological periods. A hydrological period is a time period with a uniform correlation structure type between pentads (i.e. periods of five days) in terms of consistency of water stage occurrence distributions (Rotnicka 1988). Hydrological periods were designated by grouping elementary temporal units of the hydrological year based on the similarity of their properties. The pentad was recognised as the elementary time unit of the year. The water stage in the lake was recognised as the grouping property. The hydrological year is

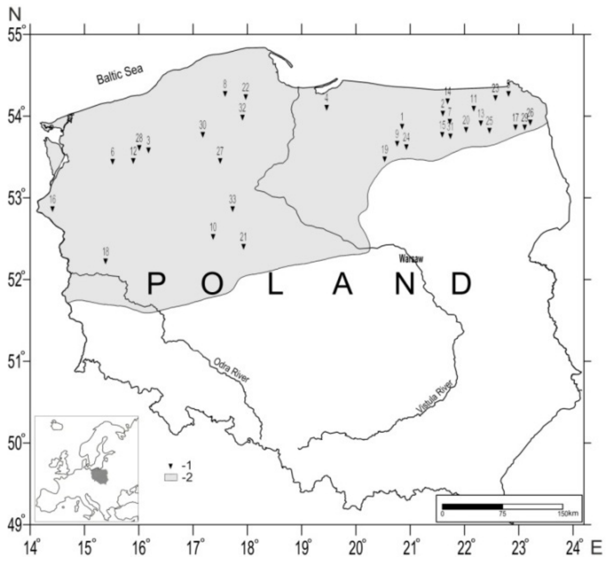

Fig. 1. Locations of the studied lakes

divided into 73 pentads. The first pentad is determined as 01.11–05.11, and the last as 27.10–31.10. The frequency of distribution of water stages was calculated for all pentads in the hydrological year based on accumulated water stage frequencies. Mutual similarity was determined for the entire collection of 73 water stage distributions by means of the Kolmogorov–Smirnov non-parametric conformity test. Absolute differences between empirical distribuends were calculated for the compared distributions (F_{n_k}, F_{n_p}), and characteristic D was determined, constituting the maximum difference:

$$D = \max |F_{n_k}(x) - F_{n_p}(x)| \quad (1)$$

The statistic λ takes the form of $\lambda = D\sqrt{n}$, where

$$n = \frac{n_k n_p}{n_k + n_p}, n_k, n_p$$

- number of samples based on which the empirical distribuends were determined. The statistic λ has a Kolmogorov distribution. Testing the hypothesis H_0 on the conformity of a pair of distributions, hypothesis H_0 was verified on levels of significance α=0.05 and α=0.01. For samples with abundance $n_1=n_2,\ldots=n_{73}=150$ and assumed level α, hypothesis H_0 was upheld when the maximum difference between the distributions was lower than:

$$D_{n_1 n_2} < \frac{\lambda\alpha=0.05}{\sqrt{n}} = \frac{1.36}{\sqrt{72.5}} = 0.1570 \quad (2)$$

$$D_{n_1 n_2} < \frac{\lambda\alpha=0.01}{\sqrt{n}} = \frac{1.63}{\sqrt{72.5}} = 0.1882 \quad (3)$$

When $D_{n_1 n_2}<0.1570$ the difference between distributions is insignificant, the distributions are similar. When $0.1570 \leq D_{n_1 n_2} < 0.1882$, the difference between the distributions is probably insignificant, and when $D_{n_1 n_2} \geq 0.1882$, the difference between the distributions is significant, and the distributions are not similar.

The test results were presented in the form of a similarity matrix for the annual collection of pentads. The similarity matrix diagram shows the structure of similarity of elementary time units of the hydrological year, and permits the identification of hydrological periods determining the characteristics of the lake regime and its typology (Figs 2 and 3).

Another stage of the period designation procedure involved assessing the correctness of the performed classification. The basic condition that needs to be met for a correct division of the hydrological year is the non-similarity of consecutive periods. Periods adjacent on the time axis must differ significantly. Non-neighbouring periods can be similar (Rotnicka 1988). Determining differences between periods involved applying the Kolmogorov–Smirnov test. An empirical distribuend of occurrence of water stages was determined for each hydrological period, and the following hypothesis was tested:

$$H_0: F_{n_k}(x) = F_{n_p}(x) \;\; k,p = 1,2,\ldots,5 \;\; k \neq p \quad (4)$$

at level α=0.05 and α=0.01.

The test showed similarity for periods for six lakes (Drawsko, Druzno, Lubie, Niesłysz, Orzysz, Powidzkie). Periods mutually similar at a level of α=0.05 and α=0.01 were connected.

Each period was described by means of the following parameters: term of the beginning and end, duration, mean water stage (H), water stage coefficient (W), coefficient of variability (Cv), mean annual water level amplitude, and maximum amplitude from the multiannual period. The typology of hydrological periods was performed based on the water stage coefficient (W) and standard deviation. The water stage coefficient is the ratio of the mean water stage in a given hydrological period to the mean annual water level in the multiannual period.

The standard deviation of the water stage coefficient for the designated periods amounts to 0.058. Five types of periods were designated:

– period of very low water stages, when W<0.914;

– period of low water stages, when 0.914≤W<0.972;

– period of average water stages, when 0.972≤W<1.029;

– period of high water stages, when 1.029≤W<1.087;

– period of very high water stages, when W≥1.087.

Results and discussion

Based on the analysis of the regime of water stages in lakes, the number, type, and sequence of hydrological periods was determined by identifying the temporal structure of hydrological phenomena and their changes in an average annual cycle. From 1 to 6 periods were designated for the stud-

Table 1. Morphometric data of the studied lakes (after: Choiński 2006)

No	Lake	Area [ha]	Volume [thous. m^3]	Average depth [m]	Maximum depth [m]
1	Dadaj	975.0	120,784.2	12.0	39.8
2	Dejguny	762.5	92,617.4	12.0	45.0
3	Drawsko	1,797.5	331,443.4	17.7	82.2
4	Druzno	1,147.5	17,352.0	1.2	2.5
5	Hańcza	291.5	120,364.1	38.7	106.1
6	Ińsko	529.0	65,182.0	11.0	41.7
7	Jagodne	872.5	82,705.2	8.7	37.4
8	Jasień	575.0	48,048.0	8.3	32.2
9	Kalwa	561.0	39,468.6	7.0	31.7
10	Lednica	325.0	24,397.0	7.0	15.1
11	Litygajno	154.5	9,763.9	6.0	16.4
12	Lubie	1,487.5	169,880.5	11.6	46.2
13	Łaśmiady	940.0	84,607.8	9.6	43.7
14	Mamry	9,851.0	1,003,367.5	9.8	43.8
15	Mikołajskie	424.0	55,739.7	11.2	25.9
16	Morzycko	317.5	49,826.9	14.5	60.7
17	Necko	400.0	40,561.4	10.1	25.0
18	Niesłysz	526.0	34,457.6	6.9	34.7
19	Omulew	504.0	22,172.7	4.3	32.5
20	Orzysz	1,012.5	75,326.2	6.6	36.0
21	Powidzkie	1,097.5	134,776.2	11.5	46.0
22	Raduńskie Górne	362.5	60,158.7	15.5	43.0
23	Rospuda Filipowska	323.5	49,731.8	14.5	38.9
24	Sasek Wielki	866.0	71,194.8	8.2	38.0
25	Selmęt Wielki	1,207.5	99,463.9	7.8	21.9
26	Serwy	438.5	67,181.5	14.1	41.5
27	Sępoleńskie	157.5	7,501.6	4.8	10.9
28	Siecino	740.0	104,441.7	14.1	44.2
29	Studzieniczne	244.0	22,073.6	8.7	30.5
30	Szczytno Wielkie	565.0	51,762.5	8.0	21.4
31	Śniardwy	11,487.5	660,211.8	5.8	23.4
32	Wdzydze	1,417.0	220,800.0	1.2	69.5
33	Żnińskie Duże	420.5	29,492.6	6.8	11.1

ied lakes. Eight of the lakes in the studied group have a 1-period temporal structure of water stages in the annual cycle. Low seasonal water level fluctuations (suggested by a small range of variability of water stage coefficients in consecutive pentads of the year) determine the occurrence of only one period of average water stages on lakes throughout the year (Fig. 4). A characteristic feature of such lakes is very low variability of daily water stages (from Cv=0.015 for Raduńskie Lake to 0.049 for Powidzkie Lake), and very variable amplitudes of both annual means (from 17 cm for Jasień Lake to 94 cm for Druzno Lake), and maximum water levels (from 36 cm for Jasień Lake to 162 cm for Druzno Lake).

Lake Hańcza in the north-east of the country is the only lake with a 2-period structure of water stages. The majority of the year (more than 300 days) is a period of average water stages, and the range of daily variability of water stage coefficients in successive pentads of the year is small. The period of higher water stages is only observed for 40 days, from April to the first decade of May (Fig. 3).

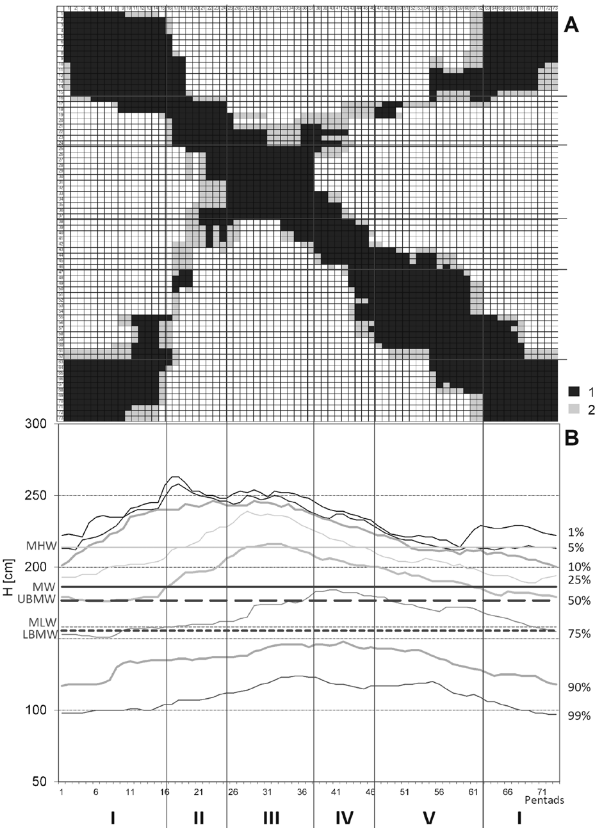

Fig. 2. Determining hydrological periods on Lake Lednica: A – similarity matrix diagram: 1 – similar distributions, 2 – probably similar distributions; B – hydrogram of water levels with specified probability of occurrence, with characteristic levels and boundaries of range of medium water levels: MHW – medium high water level, MW – medium water level, MLW – medium low water level, UBMW – upper boundary of range of medium water levels, LBMW – lower boundary of range of medium water levels; I – V – hydrological periods

The range of daily variability of water stage coefficients also increases only slightly. The lake has one of the lowest coefficients of daily water level fluctuations (Cv=0.027) and an average mean annual (49 cm) and maximum amplitude (96 cm) in comparison to other lakes.

The majority of the analysed lakes (19) have a 4-period structure of water stages. The lakes are located in all lakeland areas of Poland. The most frequently observed sequence of types of hydrological periods is as follows: period of low water stages – period of average water stages – period of high water stages – period of average water stages. The timings of the onset of these stages, and their durations, vary. The duration of particular types of periods is highly variable. Periods of high water stages last from 55 days (Litygajno Lake) to 160 days (Mamry Lake, Żnińskie Duże Lake), and periods of low water stages from 60 days (Lubie Lake) to 205 days (Żnińskie Duże Lake). Periods of average water stages on such lakes last the longest, from 100 (Ińsko Lake, Siecino Lake) to 245 days (Omulew Lake). Lakes with a 4-period structure of types of hydrological periods also have highly variable maximum amplitudes, ranging from 35 cm (Omulew Lake) to 166 cm (Lednica Lake), and high variability of daily water stages, ranging from Cv=0.051 (Omulew Lake) to Cv=0.241 in the case of Lake Żnińskie Duże. Lakes Żnińskie Duże and Mikołajskie have the most variable structure of hydrological period types. The sequence of periods on such lakes includes extreme periods – periods of both very low and very high water stages. Their term of occurrence and duration are variable (Fig. 3). Of the 4-period lakes, three have a different sequence of periods, namely Lakes Omulew, Sasek Wielki, and Selmęt Wielki. On those lakes, the hydrological periods occur in the following order: period of average water stages – period of high water stages – period of average water stages – period of low water stages. The lakes have a short period of high water level (30–45 days), a period of low water stages (90–110 days), and a very long duration of periods of average water stages (210–245 days). Daily water level fluctuations, mean annual (16–54 cm), and maximum amplitudes (35–132 cm) are also varied.

Three of the investigated lakes have a 5-period structure of water stages (Łaśmiady Lake, Orzysz Lake and Szczytno Wielkie Lake). The lakes' sequences of hydrological periods are very variable (Fig. 3). The term of occurrence of high water stages on Lake Szczytno Wielkie is particularly noteworthy. It is completely different than that for all the other lakes. On average, it lasts from mid-June to the end of October. The durations of particular periods are similar within the group of lakes, however. The period of high water stages lasts from 120 to 145 days, the period of low water stages from 145 to 190 days, and the period of average water stages from 40 to 75 days. The lakes also have similar maximum amplitudes, ranging from 74 cm (Orzysz Lake) to 98 cm (Łaśmiady Lake), but varied amplitudes of daily stages, ranging from Cv=0.079 (Szczytno Wielkie Lake) to Cv=0.1118 (Orzysz Lake).

A 6-period structure of hydrological periods was observed for two lakes (Dadaj Lake and Drawsko Lake). The structure includes periods not only of very low water stages (usually from August to December) lasting approximately 100 days, but also periods of very high water stages. The term of their occurrence differs, however. On Lake Dadaj, term of high water stages occurs at the end of January and lasts until mid-May (110 days), and on Lake Drawsko it occurs later (at the beginning of March) and lasts for 70 days until the middle of May. In total, periods of high water stages last for 110–175 days, and periods of low water stages 185–190 days. Periods of average water stages are very short on these lakes (70 days on Lake Dadaj) or do not occur at all (Drawsko Lake). The 6-period lakes have a very high variability of daily water stages (Cv>0.180), as well as having the greatest range of daily variability of water stage coefficients of all the analysed lakes. At similar values of the coefficient of daily water level variability (Cv=0.183–0.192), the lakes differ in the value of maximum amplitudes – 95 cm (Drawsko Lake), 149 cm (Dadaj Lake) and annual means – 47 cm (Drawsko Lake) and 70 cm (Dadaj Lake).

The issue of water level fluctuations is addressed in many limnological studies. The issue is analysed among others in the long-term (Van Der Kamp et al. 2008; Propastin 2012; Kaiser et al. 2015; Wrzesiński and Ptak 2016) as well as in reference to seasonal fluctuations in the annual cycle (Quinn 2002; Gronewold and Stow 2014; Assani 2016). The present results refer to those of this last set of works, which analysed seasonal water level fluctuations based on hydrological periods designated in the case of lakes in the new methodological approach. Depending on regional or local conditions, water level fluctuations can show a different character. The complexity of the issue is determined by the co-occurrence of natural and anthropogenic factors. It is difficult to determine the hierarchy of dominance of such factors, as suggested by among others Bonacci et al. (2015) in describing the case of Lake Dojran in Southern Europe. In the case of lakes in Poland, earlier studies on long-term water level fluctuations in lakes showed the variability of the course of their tendencies (Wrzesiński and Ptak 2016). As determined based on data concerning mean annual water stages in 32 lakes in the years 1976–2010, 18 lakes had an increasing tendency, and the remainder had a decreasing tendency. It is also worth

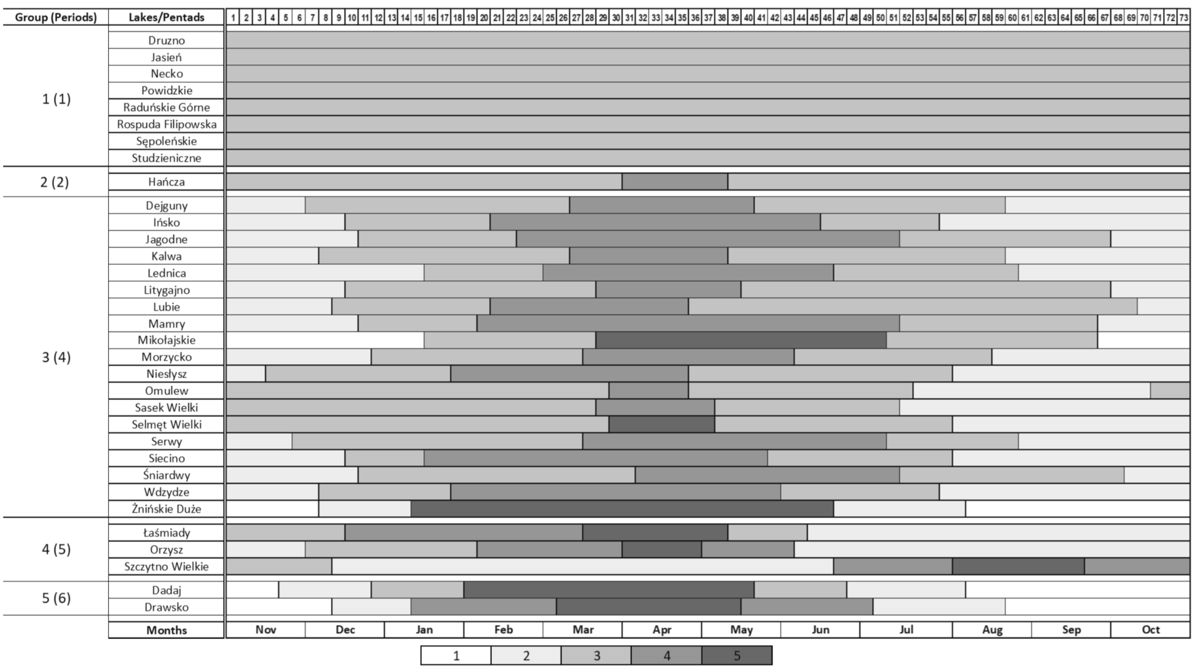

Fig. 3. Sequences of hydrological periods in the average annual cycle.
Type of period: 1 – very low water stages, 2 – low water stages, 3 – average water stages, 4 – high water stages, 5 – very high water stages

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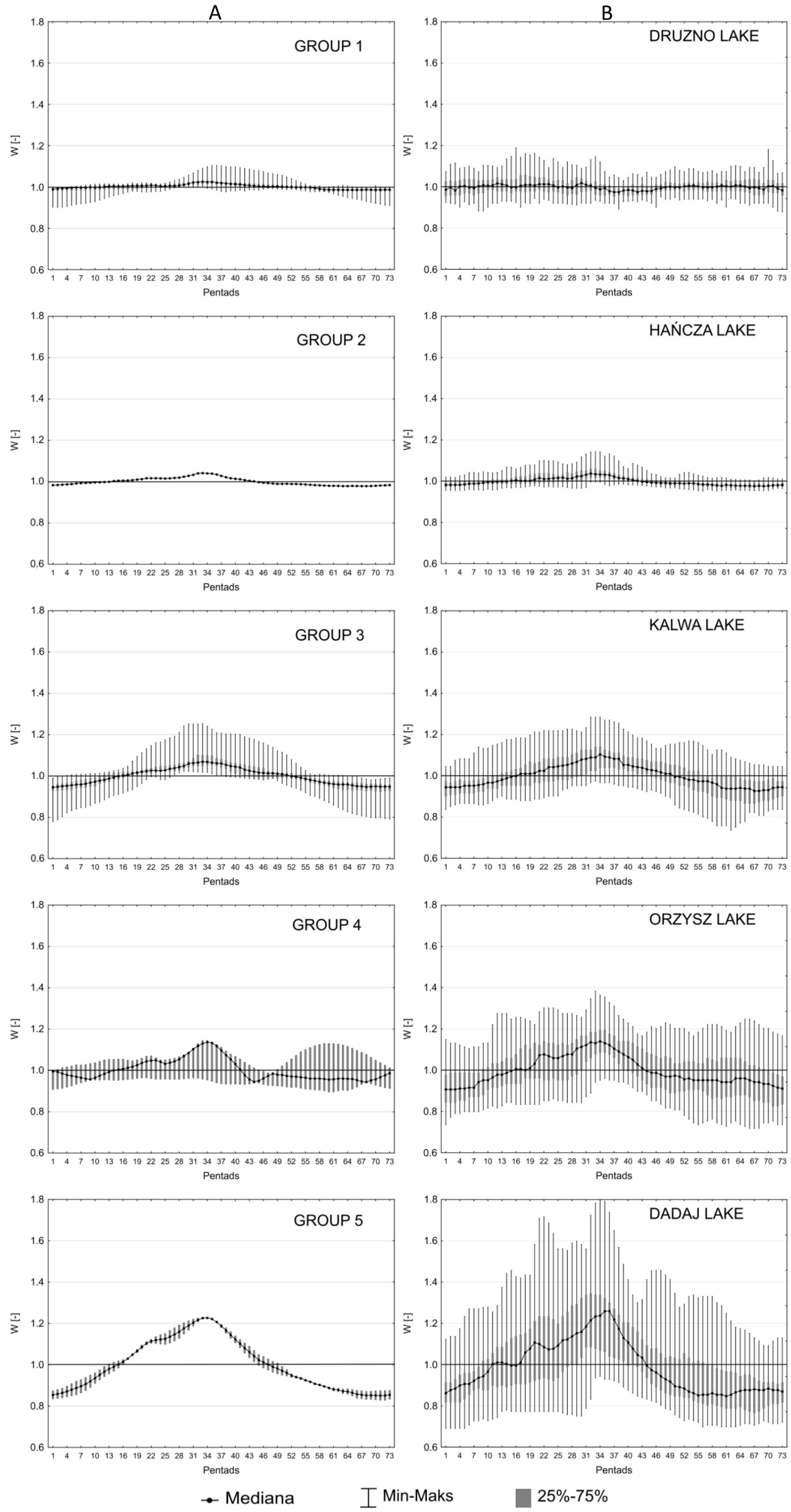

Fig. 4. Range of variability of water level coefficients in pentads of the hydrological year in particular groups of lakes (A) and for their selected examples (B). Group 1: 1-period lakes, Group 2: 2-period lakes, Group 3: 4-period lakes, Group 4: 5-period lakes, Group 5: 6-period lakes

noting that no spatial patterns were determined in their distribution, i.e. different tendencies occurred even in lakes located very close to each other. Such a situation suggests the dominant role of local factors in determining water level fluctuations. Their primary role is also reflected in the number of hydrological periods in the annual distribution, where no significant patterns in their location is also observed in such terms.

Considering the latitudes of the discussed lakes and their lowland character, the distribution of water stages in the annual cycle should generally exhibit maximum values in spring resulting from the melting of snow cover, and minimum values in summer as a consequence of a decrease in resources due to temperature rises and evaporation-related losses. Assuming the above, the present results, which designate five types of water stage periods in lakes suggest the occurrence of conditions for magnifying the initial state. The occurrence of a 1-period temporal structure of water stages in the annual cycle suggests the influence of factors stabilising the water level. One example is the precise, planned regulation of water level for commercial purposes. This happens on, among others, Lake Studzieniczne, which is part of the Augustów Channel waterway that was constructed in the first half of the 19th century. In this case, depending on navigation needs, the water level is regulated by means of locks and weirs on both sides of the lake. The same group also includes Lake Druzno, where Fac-Beneda (2013) associates the main causes of water level fluctuations with water discharges from adjacent polders and water level fluctuations in the Vistula Lagoon, with which the lake has a direct hydraulic connection. Lake Hańcza is the only lake with a 2-period structure. Its specificity in contrast to the remaining lakes should be associated with its morphometric parameters. The lake's waters fill a deeply incised post-glacial channel (max depth: 106.5 m) making the lake the deepest on the Middle European Lowland. In such a context, the water level stabilisation observed for a major part of the year should be associated with the possibility of supply by groundwaters uniformly alimenting the lake throughout the year, thus decreasing its susceptibility to the direct effect of climatic factors and the related higher variability of water stages. Lakes in the designated groups are characterised by a different course and value of pentad coefficients of water level in the average annual cycle (Fig. 4A). The scope of changes in such coefficients is small, suggesting that the water level regime in lakes within individual groups are highly similar. Groups 3, 4, and 5 include lakes with a high range of changes of water level coefficients in pentads of the hydrological year (Fig. 4B). The higher the range of changes, the higher the fluctuations and water level amplitudes on such lakes. Due to this, the lakes have a multi-period structure of water levels in the average annual cycle. Lakes in such groups show a distribution of hydrological periods typical of lakes of average latitudes. The most abundant group of lakes has a 4-period structure of water levels in the annual cycle.

As was mentioned before, the group shows variability in the term of occurrence and duration of particular periods. This includes lakes with water relations strongly transformed by human activity, as well as quasi-natural lakes. The former includes, among others, the lakes of the Land of Great Masurian Lakes (Śniardwy, Mamry, Jagodne, Mikołajskie), which are connected by a system of man-made canals. The latter situation is exemplified by, among others, Lake Lubie, which is not subject to direct hydrotechnical construction.

The detailed identification of the occurrence of characteristic periods of water stages in lakes provides the basis for the management of water resources. This is particularly important in the context of increasingly frequent extreme meteorological-hydrological situations. These can result in, among other things, water deficits in areas affected by long-term droughts, etc. According to Kowalczak et al. (1997), Poland has some of the smallest water resources in Europe – comparable to those of Egypt. The situation can be improved by, for example, increasing retention in catchments. Activities undertaken for the purpose by governmental agencies (including the Small Retention Programme) aim to retain water at the moment of its excess, and then use the surplus in deficit situations. Hydrotechnical works on lakes are an important link of such activities. Damming is a relatively easy measure providing measurable increases in water resources (Nowak and Grześkowiak 2010). This method is being applied on as many as 385 lakes in Poland (Ochrona... 2015). The present results constitute a theoretical basis for the implementation of such undertakings in the future, where the observed climatic changes may force more extensive human interference in water relations for the purpose of their rational use.

Conclusions

The paper presents an analysis of hydrological periods in Poland based on their typology and sequence in the average annual cycle. A new method of determining periods was applied that is based on grouping elementary time units of the hydrological year (pentads) by similarity of properties, namely distributions of water stage frequencies. In the case of lakes, this is a new approach to water level fluctuations at the annual scale. The studied lakes represent a temporal structure of hydrological periods that is typical of this climatic zone, with the highest water stages in spring months, and low water stages in summer–autumn months. The results suggest both temporal and typological differentiation of the designated hydrological periods. Due to the broad spectrum of human uses of the lakes, lakes subject to water management measures and quasi-natural lakes can co-occur within individual groups. The analysed lakes also include those distinguished by a different sequence of hydrological periods and their typology. Such a situation occurs in the case of 1-period lakes and the 5-period Lake Szczytno Wielkie. This fact suggests local factors, both natural (morphometric parameters of the lake and physiographic parameters of its catchment) and anthropogenic dominate over climatic factors in determining the regime of water stages.

The results have not only scientific, but also applicative importance. Identification of the seasonal structure of water stages is necessary in research on water balance and resources. It will enable the proper design of further hydrotechnical measures aimed at the increasing and rational management of lake water resources.

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