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STABILITY OF THE WATER LEVELS REGIME ON THE LAKES IN POLAND

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Abstract: The paper presents the results of a study into the stability of water-level regimes in Polish lakes. Stability is defined as a degree of regularity with which a certain phase of the hydrological regime occurs (high and low water levels). The hydrological regime is described with the use of the following 6 variables – first, second and third maximum; first, second and third minimum. Stability of the hydrological regime is determined by the stability coefficient (W_S). The analysis relies on data concerning average monthly values of water levels for 34 lakes located in Polish lake regions. There are characteristic spatial differences in the stability of maximum and minimum water levels which are usually caused by environmental factors and human activity. It was observed that the most stable dates were those of the 1st maximum and the 1st minimum. In the case of the lakes in the Pomeranian, Wielkopolsko-Kujawskie and Mazurian lake districts, the occurrence date of the 1st maximum is highly stable and stable, while the date of the 1st minimum is the most stable in the lakes of the Drawsko, Wielkopolsko-Kujawskie and Mazurian lake districts.

Keywords: water-level regime, stability coefficient, lakes

INTRODUCTION

The hydrological regime of lakes is determined by a lot of factors including water level fluctuations, flow regimes, type and structure of recharge, qualities of the drainage basin and terrain. Fluctuations in water levels are one of the key factors bearing upon the functioning of lakes. They influence many processes and phenomena of a hydrological, geomorphological and biological nature. They also have a significant impact on lake ecosystems. Water level fluctuations depend on a number of factors including mainly climate-related aspects (precipitation and evaporation), but also lake basin depth, relation with underground waters, surface and shape of the lake's drainage basin, degree and nature of water flows and human pressure (water uptake, land improvement works). From the theoretical and application perspectives, it is important to detect changes in water levels in annual and multi-annual cycles. It is therefore crucial to establish regularities in water level fluctuations (regime) in lakes, the duration of high and low water levels, the amount of water resources and the hydrological regime stability. The studies carried out so far have focused on the stability of hydrological regimes in rivers (Wrzesiński 2009, 2010, 2013, 2015) whereas the research methodology suggested here has been adapted to study the stability of water levels in lakes. The aim of the paper is to determine the stability of water levels in Poland through analysing the regularity of maximum and minimum water levels as well as its spatial differentiation.

RESEARCH AREA AND RESEARCH MATERIAL

The analysis relies on the data related to average monthly water-level values from the years 1976–2010 gathered for 34 lakes located in Polish lake regions (Fig. 1). The data was obtained from the Institute of Meteorology and Water Management of the National Research Institute. The group of lakes covered by the study includes quasi-natural lakes and those which have been strongly influenced by human economic activity. Most often, such activities consist in regulating water levels by constructing hydraulic structures, drainage ditches, polders and canals, regulating the flow of tributary rivers, using lake water to irrigate crops and taking water for industrial and municipal purposes.

RESEARCH METHODOLOGY

Stability of water-level regimes may be defined as a degree of regularity with which a certain phase of a water-level regime occurs in a year (high and

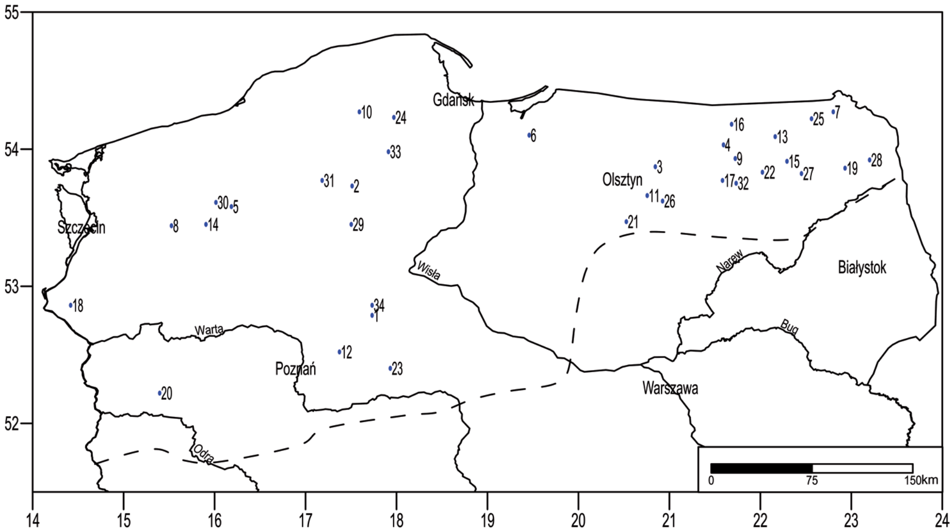

Fig. 1. Location of the lakes
(the numbering of lakes as in tab. 3, the dashed line indicated the maximum range of the last glaciation)

low water levels) expressed by a selected descriptive variable. The water-level regime has been described with the use of 6 variables – the first, second and third maximum average monthly water level (high water-level phase) as well as the first, second and third minimum average monthly water level (low water-level phase). According to Corbus and Stanescu (2004), stability is determined by the frequency of a descriptive variable in the shortest possible period. Stability of the hydrological regime is determined by the stability coefficient expressed as:

$$W_S = F_A \cdot C_R,$$

where:
F_A – frequency of occurrence of a descriptive variable value (number or occurrences in m-consecutive months, m = 1, ...,12, in a multi-annual period),
C_R – distribution factor in the period expressed as:

$$C_R = \left[\frac{13 - m}{12}\right]^2$$

Regime is more stable when the frequency of a certain descriptive variable is higher and the period in which a given value occurred is shorter. Table 1 shows the degree of regime stability dependent on the range of the stability coefficient. As an increase in the number of months (longer study period) decreases the C_R distribution factor and raises the frequency of descriptive variable values, the W_S stability coefficient reaches its maximum value under specific, optimal circumstances. This is why the periods describing a given water-level regime phase (period with *I max*, *II max*, *III max*, *I min*, *II min*, *III min*) were selected through maximising the W_S coefficient values.

Table 1. Stability of water-level regimes depending on stability coefficient, after Corbus and Stanescu (2004).

F_A	C_R		W_S	Regime character
	m	$C_R = f(m)$		
0,9–1,0	1–2	0,69–1,00	0,62–1,00	Very stable
0,8–0,9	2–3	0,56–0,69	0,45–0,62	Stable
0,7–0,8	3–4	0,44–0,56	0,31–0,45	Relatively stable
0,6–0,7	4–5	0,34–0,44	0,20–0,31	Relatively unstable
0,0–0,6	6–12	0,00–0,34	0,00–0,20	Unstable

Stability coefficients for six descriptive variables were calculated for average conditions in the 1976–2010 multi-annual period. In order to maximise the stability coefficient for each descriptive variable, we analysed the period of their occurrence ranging from one (I, II, ..., XII) to six months (I–VI, II–VII, ..., XII–V). The analysis covered the total of 72 variants of period duration. Table 2 shows an example of calculating the stability coefficient for Lake Żnińskie Duże.

Table 2. Example of the calculation of the coefficient of I max stability over the years 1976–2010 for 6 periods selected from among the 72 analysed ones (Żnińskie Duże Lake)

Years	Months											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1976	x											
1977						x						
…	…	…	…	…	…	…	…	…	…	…	…	…
2009				x								
2010				x								
Total	4	5	8	12	1	1	1	1	0	0	1	1

Periods	F_A	C_R	W_S
IV	12/35 = 0,343	1,000	0,343
III–IV	20/35 = 0,571	0,840	0,480
II–IV	25/35 = 0,714	0,694	**0,496**
I–IV	29/35 = 0,829	0,563	0,466
XII–IV	30/35 = 0,857	0,444	0,381
XI–IV	31/35 = 0,886	0,340	0,301

The mathematical and statistical data was processes with the use of statistical procedures in the *Excel* programme [Microsoft]. Their graphical presentation was prepared in the *Surfer 10* programme [Golden Software].

RESULTS AND DISCUSSION

Stability of maximum water levels

High and low water levels in the lakes covered by the study occurs with a stability which is characteristically variable in both time and space. The first maximum water level (*I max*) in the lakes covered by the study appears with a rather high regularity as is evident from the values of stability coefficients ranging from 0.34 (Druzno) to 0.66 (Szczytno Wielkie) – Tab. 3. The most stable date of the first water level maximum (W_S >0.65) in the average annual cycle can be observed in the case of lakes Hańcza (III–IV) and Szczytno Wielkie (VII–IX). Most lakes have stable *I max* dates ($0.46<W_S<0.61$) falling practically in all seasons from the winter-summer (Niesłysz, Sępoleńskie, Żnińskie Duże) to summer-autumn (Charzykowskie) periods. However, the spring *I max* dates are dominant. This applies mainly to the lakes from the Wielkopolsko-Kujawskie Lake District and most lakes in the Mazurian Lake District. In the case of other lakes, *I max* dates are relatively stable. The differences between them are rather characteristic. They fall in the winter or winter-spring period (Siecino) in the Pomeranian Lake District (Raduńskie Górne, Jasień) and Lake Druzno, or else in spring (III–IV or IV–V) in the case the Mazurian Lake District – Table 3.

The date of the 2nd maximum is stable, relatively stable, and, in the case of lakes Omulew and Litygajno, relatively unstable. Coefficient value is distributed meridionally - Fig. 2. 14 lakes have stable *II max* dates. The stability coefficient ranges from 0.46 in Lake Orzysz to 0.62 in Lake Szczytno Wielkie. The date of the *II max* is varied and usually falls in spring (III–V) on lakes Dadaj, Drawsko, Hańcza, Orzysz, Rospuda Filipowska, Serwy (III–V), Morzycko and Powidzkie (IV–V); spring-summer on lakes Jagodne, Mamry, Mikołajskie and Śniardwy (IV–VI); summer-autumn on Lake Szczytno Wielkie (VII–IX); and autumn on Lake Charzykowskie (IX–X).

A relatively stable date of the *II max* usually falls at the turn of spring for lakes Druzno, Raduńskie Górne (XII–III), Łaśmiady (I–IV), Biskupińskie, Jasień, Lednicy, Niesłysz, Sępoleńskie and Siecino (II–IV), Wdzydze (II–V); in spring for lakes: Lubie, Sasek Wielki (III–IV), Dejguny, Kalwa, Selmęt Wielki, Żnińskie Duże (III–V); and in the spring-summer period for lakes Necko (III–VI) and Ińsko (IV–VI). In the case of two lakes, the date of the *II max* water level is relatively unstable (W_S 0.30–0.31) falling in the winter-spring period (II–V) for Lake Omulew and in the spring period (III–V) for Lake Litygajno.

Stability of *III max* occurrence is much lower. The date of the 3rd water level maximum in a year is stable only for 3 lakes: Niesłysz – II–IV, Lednica – II–V, Szczytno Wielkie – VII–X – Rig. 2. Most of the studied lakes have relatively stable *III max* dates ($0.32< W_S <0.43$). The dates fall in different seasons. Most often, they occur in the winter-spring period, but also in the winter, spring-summer, summer-autumn and winter-summer periods. The *III max* date is the least stable (relatively unstable regime) in the case of two lakes – Druzno and Necko – where it falls in the winter (I–II) and spring-summer (IV–VI) periods respectively.

Stability of low water levels

The stability of the first average low water level of the lakes covered by the study is very varied. The highest values of the water-level stability coefficient (very stable regime) – W_S>0.62 – can be observed for lakes in the Wielkopolsko-Kujawskie Lake District (Lednica, Powidzkie), the Drawskie Lake District (Lubie, Siecino) and the Mazurian Lake District (Mamry, Dejguny, Jagodne, Mikołajskie, Śniardwy and Orzysz). In the case of all the lakes listed above, the

Table 3. Stability coefficients of maximum water levels and the dates of their occurrence.

Item	Lake	Water-level maxima					
		I max		*II max*		*III max*	
		W_S	Date	W_S	Date	W_S	Date
1.	Biskupińskie	0.55	III-IV	0.44	II-IV	0.38	II-IV
2.	Charzykowskie	0.50	VIII-IX	0.48	IX-X	0.36	VIII-IX
3.	Dadaj	0.54	IV	0.58	III-V	0.39	II-V
4.	Dejguny	0.44	III-V	0.44	III-V	0.38	II-IV
5.	Drawsko	0.58	III-IV	0.56	III-V	0.43	II-III
6.	Druzno	0.34	XII-III	0.32	XII-III	0.26	I-II
7.	Hańcza	0.65	III-IV	0.54	III-V	0.37	III-VI
8.	Ińsko	0.54	III-V	0.42	III-VI	0.43	V-VI
9.	Jagodne	0.55	IV-V	0.46	IV-VI	0.35	III-VI
10.	Jasień	0.35	XII-III	0.34	II-IV	0.38	XII-II
11.	Kalwa	0.54	III-V	0.40	III-V	0.39	III-VI
12.	Lednica	0.54	III-V	0.44	II-IV	0.47	II-V
13.	Litygajno	0.41	III-IV	0.30	III-V	0.32	II-IV
14.	Lubie	0.46	II-IV	0.43	III-IV	0.35	II-V
15.	Łaśmiady	0.58	III-IV	0.37	I-IV	0.37	XII-III
16.	Mamry	0.55	IV-V	0.48	IV-VI	0.37	II-VI
17.	Mikołajskie	0.55	IV-V	0.48	IV-VI	0.38	IV-VI
18.	Morzycko	0.54	III-V	0.50	IV-V	0.40	III-VI
19.	Necko	0.41	IV-V	0.32	IV-VI	0.30	IV-VI
20.	Niesłysz	0.46	I-III	0.42	II-IV	0.48	II-IV
21.	Omulew	0.38	III-IV	0.31	II-V	0.34	I-IV
22.	Orzysz	0.57	IV	0.46	III-V	0.40	II-V
23.	Powidzkie	0.58	IV-V	0.53	IV-V	0.40	III-VI
24.	Raduńskie Górne	0.44	XII-II	0.32	XII-III	0.34	XII-I
25.	Rospuda Filipowska	0.62	III-V	0.48	III-V	0.35	II-V
26.	Sasek Wielki	0.43	IV-V	0.38	III-IV	0.32	III-V
27.	Selmęt Wielki	0.49	IV	0.42	III-V	0.32	III-V
28.	Serwy	0.60	IV-V	0.54	III-V	0.39	III-VI
29.	Sępoleńskie	0.46	II-IV	0.36	II-IV	0.32	III-V
30.	Siecino	0.34	I-IV	0.38	II-IV	0.40	II-IV
31.	Szczytno Wielkie	0.65	VII-IX	0.62	VII-IX	0.50	VII-X
32.	Śniardwy	0.58	IV-VI	0.52	IV-VI	0.42	III-VI
33.	Wdzydze	0.40	II-V	0.35	II-V	0.34	II-V
34.	Żnińskie Duże	0.50	II-IV	0.40	III-V	0.42	I-IV

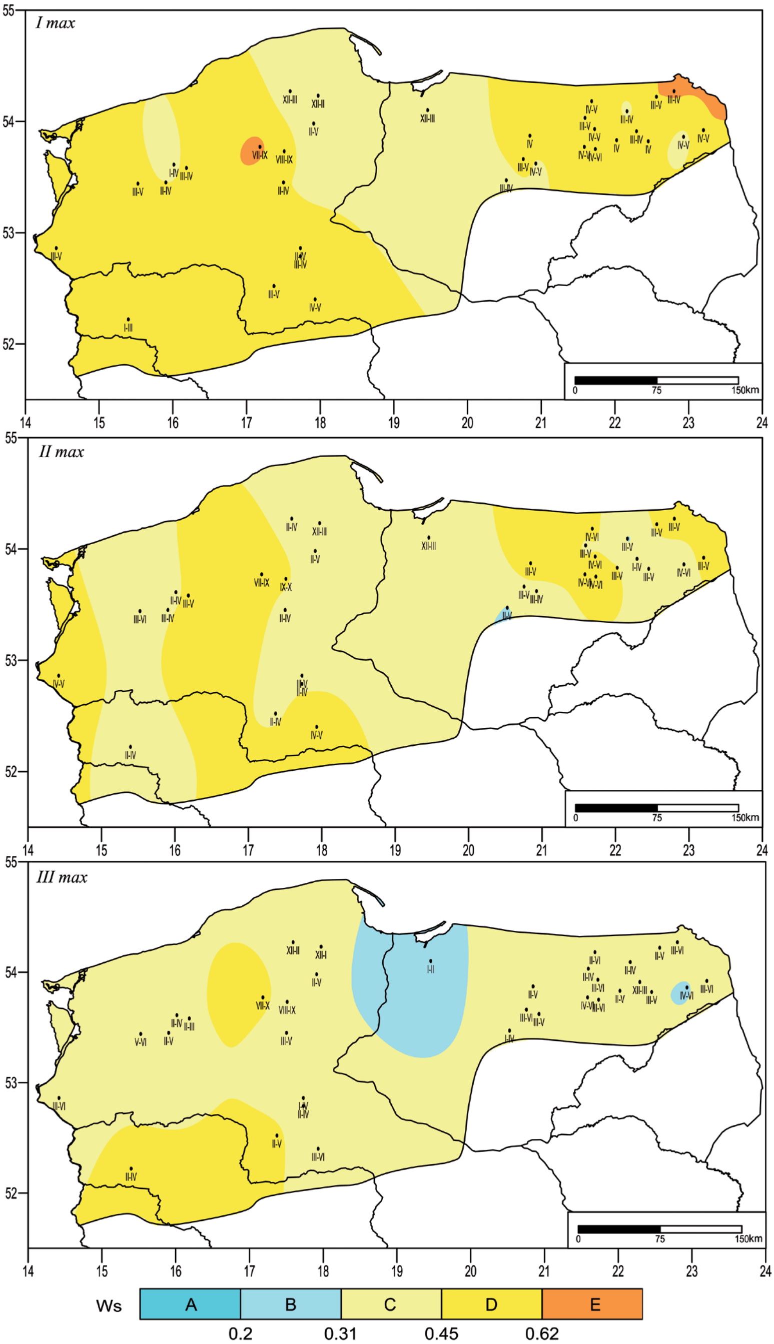

Fig. 2. Stability of the 1st, 2nd and 3rd maxima of monthly water stages

W_S – coefficient of stability; type of regime: A – unstable, B – relatively unstable, C – relatively stable, D – stable, E – very stable

I min date falls in the autumn period (X–XI) – Fig. 3, Table 4. Most of the analysed lakes have stable water-level regimes, the *I min* date falling in the autumn period (IX–XI). Three lakes located in the eastern part of the Pomeranian Lake District (Jasień, Raduńskie Górne and Wdzydze) and single lakes in the Mazuriuan Lake District (Sasek Wielki, Łaśmiady and Selmęt Wielki) have relatively stable *I min* dates usually falling in the summer-autumn period (VIII–XI). Only Lake Druzno has a stability coefficient of W_S <0.30. A relatively unstable date of the *I min* for that lake falls in the autumn-winter period (X–I).

In the case of the *II min*, occurrence dates are stable and relatively stable. 15 lakes covered by the study have stable water-level regimes. Stability coefficient ranges between 0.46 (Siecino) and 0.55 (Powidzkie). The date of the *II min* usually falls in the autumn-winter (IX–XII) autumn (Drawsko IX–X) or summer-autumn (VII–X) periods. Most of the studied lakes have relatively stable water-level regimes. In such cases, dates of the II water-level minimum are very varied and appear in all the seasons.

The *III min* date is the least stable. It is relatively stable and falls in all the seasons for most of the studied lakes. Stable dates of the *III min* can be observed in three lakes: Mikołajskie (XI–I), Powidzkie (XII–I) and Serwy (VIII–X). Conversely, in the case of Dejguny and Necko lakes III minimum dates are relatively unstable (W_S =0.30), falling in the autumn-winter (XI–I) and winter-spring (I–III) periods.

SUMMARY

The paper identifies the stability of water-level regimes in lakes over an average annual cycle with the use of 6 variables describing water levels in high and low phases. The most stable dates were those of the 1st maximum and the 1st minimum. Usually, maximum water levels occur in the spring after the winter thaw, representing stable and very stable regime types. This does not apply to lakes Raduńskie Górne, Druzno and Jasień where *I max* appears already in the winter-spring period as well as Szczytno Wielkie and Charzykowskie achieving *I max* in summer-autumn. Minimum water levels are typically registered in the summer-autumn period as in the case of the Mazurian Lake District and lakes located in the Drawsko and Wielkopolsko-Kujawskie lake regions. They represent very stable and stable water-level regimes. The least stable dates of minimum and maximum water levels are observed in the case of lakes exposed to strong human pressure. Such is the case of Lake Druzno where the situation may be influenced by fluctuations in water levels depending primarily on water level changes in the Vistula Lagoon in addition to the amount of river water flowing into the lake determined by human land improvement activity (Fac-Beneda 2013).

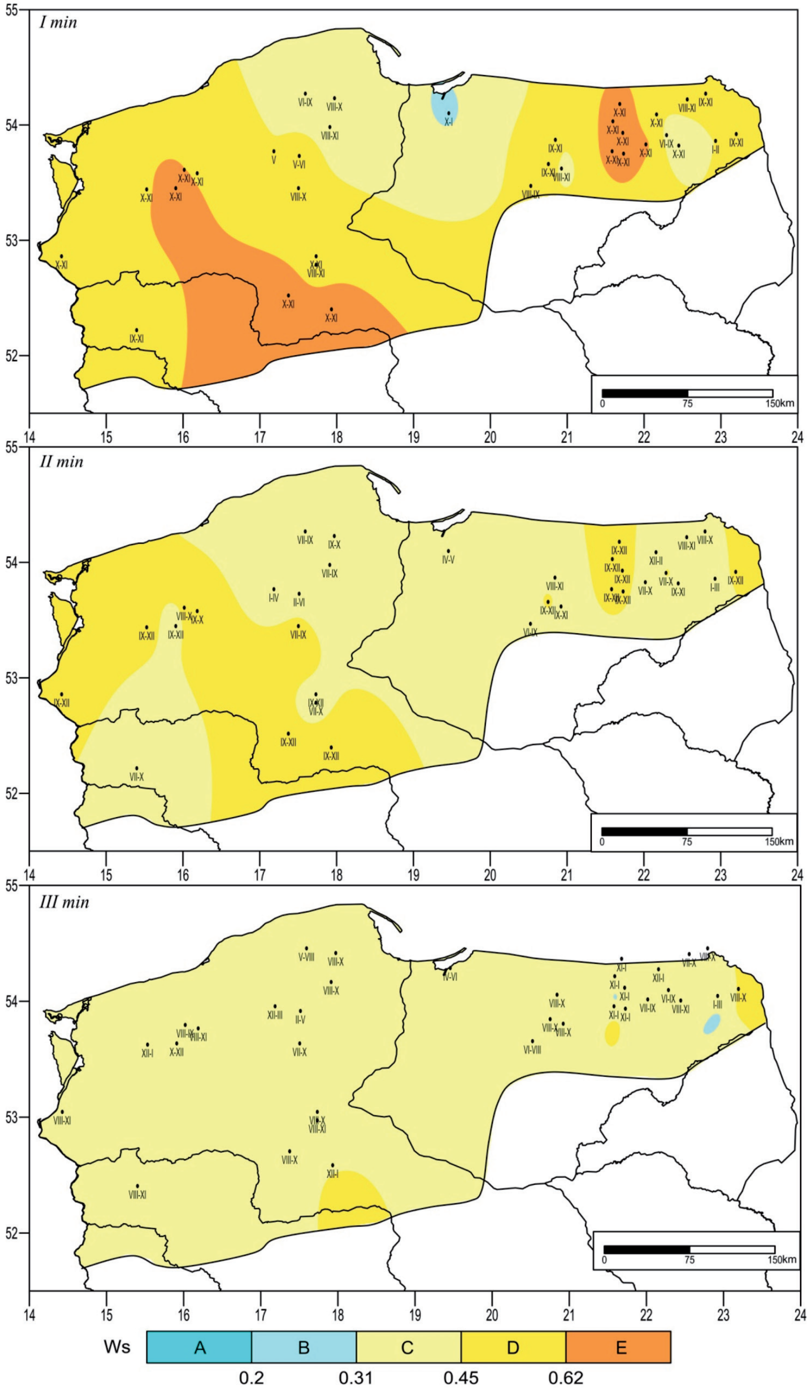

Fig. 3. Stability of the 1st, 2nd and 3rd minima of monthly water stages
Legend as in Fig. 2

Table 4. Stability coefficients of minimum water levels and the dates of their occurrence.

Item	Lake	Minimum					
		I min		*II min*		*III min*	
		W_S	Date	W_S	Date	W_S	Date
1.	Biskupińskie	0.48	VIII-XI	0.39	VII-X	0.34	VIII-XI
2.	Charzykowskie	0.50	V-VI	0.32	II-VI	0.35	II-V
3.	Dadaj	0.46	IX-XI	0.39	VIII-XI	0.38	VIII-X
4.	Dejguny	0.67	X-XI	0.48	IX-XII	0.30	XI-I
5.	Drawsko	0.60	X-XI	0.50	IX-X	0.40	VIII-XI
6.	Druzno	0.29	X-I	0.36	IV-V	0.34	IV-VI
7.	Hańcza	0.52	IX-XI	0.42	VIII-X	0.42	VIII-X
8.	Ińsko	0.60	X-XI	0.47	IX-XII	0.36	XII-I
9.	Jagodne	0.67	X-XI	0.53	IX-XII	0.40	XI-I
10.	Jasień	0.37	VI-IX	0.34	VII-IX	0.32	V-VIII
11.	Kalwa	0.63	IX-XI	0.48	IX-XII	0.44	VIII-X
12.	Lednica	0.74	X-XI	0.48	IX-XII	0.38	VIII-X
13.	Litygajno	0.48	X-XI	0.34	XII-II	0.36	XII-I
14.	Lubie	0.70	X-XI	0.43	IX-XII	0.38	X-XII
15.	Łaśmiady	0.42	VI-IX	0.47	VII-X	0.43	VI-IX
16.	Mamry	0.67	X-XI	0.51	IX-XII	0.38	XI-I
17.	Mikołajskie	0.70	X-XI	0.50	IX-XII	0.50	XI-I
18.	Morzycko	0.58	X-XI	0.50	IX-XII	0.35	VIII-XI
19.	Necko	0.46	I-II	0.32	I-III	0.30	I-III
20.	Niesłysz	0.52	IX-XI	0.39	VII-X	0.34	VIII-XI
21.	Omulew	0.48	VIII-IX	0.34	VI-IX	0.36	VI-VIII
22.	Orzysz	0.65	X-XI	0.35	VII-X	0.34	VII-IX
23.	Powidzkie	0.74	X-XI	0.55	IX-XII	0.48	XII-I
24.	Raduńskie Górne	0.42	VIII-X	0.38	IX-X	0.34	VIII-X
25.	Rospuda Filipowska	0.51	VIII-XI	0.45	VIII-XI	0.42	VII-X
26.	Sasek Wielki	0.39	VIII-XI	0.38	IX-XI	0.36	VIII-X
27.	Selmęt Wielki	0.36	X-XI	0.38	IX-XI	0.32	VIII-XI
28.	Serwy	0.60	IX-XI	0.51	IX-XII	0.48	VIII-X
29.	Sępoleńskie	0.46	VIII-X	0.50	VII-IX	0.32	VII-X
30.	Siecino	0.62	X-XI	0.46	VIII-X	0.38	VIII-IX
31.	Szczytno Wielkie	0.46	V	0.39	I-IV	0.32	XII-III
32.	Śniardwy	0.67	X-XI	0.48	IX-XII	0.40	XI-I
33.	Wdzydze	0.42	VIII-XI	0.38	VII-IX	0.38	VIII-X
34.	Żnińskie Duże	0.53	X-XI	0.43	IX-XII	0.40	VIII-X

Studies have confirmed changes in the natural water-level regimes identified in previous publications (Górniak, Piekarski 2002). As the changes in seasonal and multi-annual water levels are influenced by a wide range of concurrent factors, lake processes cannot be analysed on the regional level (Wrzesiński, Ptak 2016). Establishing clear determinants of hydrological regimes in lakes and their transformations is a complex task requiring individual studies based on multi-annual observation series as well as studies into the surface and underground drainage basins of individual water bodies (Plewa et al. 2015).

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