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Spectral analysis of water level fluctuations in Belarusian and Polish lakes

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Abstract. Data regarding 25 lakes (9 Belarusian and 16 Polish) provided the basis for spectral analysis of water level fluctuations. The obtained output data concerned a 55-year observation sequence covering the years 1956–2010. The selection of lakes was determined by two factors, i.e. data continuity and inconsiderable anthropogenic impact. The lakes were divided into three groups depending on the course of the water level spectrum. The first group included the highest number of lakes (14) which were distinguished by smooth curves with no significant peaks (e.g. Lake Wygonoszczańskie). The second group shows a four-year variability (e.g. Lake Łukomskie). The third group is distinguished by an even peak of three-year water fluctuation (e.g. Lake Łebsko). The location of the lakes categorised into those three groups suggests a certain regionalisation. The first group is represented by lakes of central and northern Belarus, and eastern Poland. The second group includes lakes of eastern Belarus, and the third group – lakes of central and northern Poland. This suggests that alongside local factors, the location of the distinguished groups of lakes may also be determined by regional factors. Presumably, continentalism of climate increasing in an eastwards direction is one of the key factors responsible for the detected regional diversity of lake water level fluctuations.

Key words:
Belarusian and Polish lakes,
water level fluctuations,
spectral analysis

Introduction

While research on into water level fluctuations in lakes has relatively long-standing records, studies on the effect of local and regional conditions on water level fluctuations in lakes are not so less common. This paper presents the results of the spectral analysis of water level fluctuations carried out in 25 lakes located in two countries, namely Belarus and Poland. On that basis, a regionalisation of the investigated lakes was carried out. This is the first attempt atof a study of thisat kind and may constitute a basis for further research on into theat phenomenon.

Description of the studied lakes

The output data included water levels (mean annual values) for 25 lakes (9 Belarusian and 16 Polish) covering a 55-year observation sequence (1956–2010). The territory of Poland includes approximately 7,000 lakes with an area of more than 1 ha. They occupy a total area of approximately 2,800 km2. Their total water volume amounts to approximately 20 km3 (Choiński 2007). In Belarus, there are approximately 10,000 lakes, with a total area of approximately 2,000 km^2 and water resources of 7 km^3 (Jakuszko 1981). According to the above and related data (Table 1), the analysed lakes constitute a small share of their total number, surface area, and water resources. The research on water level fluctuations was based on data from the state hydrological services of Belarus and Poland. Out of the 25 studied lakes, 3 are located in the Wielkopolsko-Kujawskie Lakeland, 4 in the Pomeranian Lakeland, 9 in the Masurian Lakeland, 7 in the Belarusian Lakeland, and 2 in Belarusian Polesie. The selection of lakes was based on two criteria, namely data continuity and lack of significant anthropogenic impact. Nowadays, even if lakes with unaffected hydrological regime can be selected, practically all catchments are to a lower or higher degree subject to certain anthropogenic pressure. Therefore, the hydrological regime of the studied lakes is quasi-natural. In the future, a similar analysis can be conducted for mountain lakes, e.g. those located in the Carpathians. They have been subject to long observation series, and are under inconsiderable anthropogenic impact, as exemplified by Lake Morskie Oko (Wrzesiński et al. 2016).

The characteristics of lakes and the morphometric parameters of their basins and catchments determining water level fluctuations are presented in Tables 1 and 2.

The tables present the location of the studied lakes according to geographical coordinates (longitude, latitude, altitude a.s.l.). The maximum distance between the lakes from west to east amounts tois 710 km – Lake Sławskie 16°01'E and Lake Siemno

Table 1. Location and morphometric parameters of lakes

No.*	Lake	Altitude a.s.l.	Coordinates		Area km^2	Volume million m^3	Maximum depth m	Mean depth m	Exposure index	Depth index	Ohle coefficient
			Latitude	Longitude							
1	Sławskie	56.9	51º54'	16º01'	8.23	42.66	12.3	5.2	1.59	0.42	24.4
2	Jamno	0.1	54º17'	16º08'	22.32	31.53	3.9	1.4	15.80	0.36	22.5
3	Łebsko	0.2	54º43'	17º25'	70.20	117.50	6.3	1.6	41.94	0.25	25.7
4	Charzykowskie	120.0	53º47'	17º30'	13.36	134.50	30.5	9.8	1.33	0.32	68.4
5	Biskupińskie	78.6	52º48'	17º45'	1.07	6.38	13.7	5.5	0.18	0.40	73.7
6	Ostrzyckie	160.1	54º15'	18º06'	2.96	20.79	21.0	6.7	0.42	0.32	67.9
7	Gopło	76.8–77.2	52º36'	18º22'	21.22	78.50	16.6	3.6	5.74	0.22	66.4
8	Jeziorak	99.2	53º42'	19º37'	31.53	141.59	12.9	4.1	7.02	0.32	9.99
9	Drwęckie	94.8	53º43'	19º53'	7.80	50.14	22.0	5.7	1.21	0.26	130.1
10	Nidzkie	117.9	53º36'	21º36'	17.50	113.87	23.7	6.2	2.69	0.26	9.83
11	Roś	114.4	53º40'	21º54'	18.09	152.92	31.8	8.1	2.14	0.25	167.1
12	Ełckie	119.9	53º49'	22º21'	3.85	57.42	55.8	15.0	0.26	0.27	254.6
13	Rajgrodzkie	118.4–118.6	53º46'	22º38'	14.99	142.62	52.0	9.4	1.58	0.18	49.4
14	Białe	122.2	53º52'	23º03'	4.53	41.72	30.0	9.2	0.49	0.29	8.1
15	Wigry	131.9	54º03'	23º04'	21.15	336.73	74.2	15.4	1.33	0.21	23.0
16	Studzieniczne	123.4	53o52'	23º07'	2.44	22.07	30.5	8.7	0.27	0.28	10.0
17	Wygonoszczańskie	151.0	52º39'	25º56'	26.00	32.10	2.3	1.2	21.06	0.52	2.4
18	Narocz	163.7	54º53'	26º41'	79.62	710.00	24.8	8.9	8.93	0.36	2.5
19	Miastro	163.7	54º52'	26º51'	13.10	70.10	11.3	5.4	2.45	0.48	9.2
20	Drywiety	129.5	55º38'	27º01'	36.14	223.50	12.0	6.2	5.84	0.51	11.7
21	Czerwone	134.5	52º23'	27º56'	40.82	27.35	2.9	0.7	60.92	0.24	4.6
22	Oświejskie	128.4	56º01'	28º07'	52.80	104.00	7.5	2.0	26.81	0.27	3.9
23	Nieszczerdo	147.0	55º57'	29º03'	24.62	84.72	8.1	3.4	7.15	0.42	5.8
24	Łukomskie	163.5	54º39'	29º06'	37.71	249.00	11.5	6.6	5.71	0.57	4.8
25	Sienno	142.1	54º49'	29º42'	3.13	26.83	31.5	8.6	0.37	0.27	21.7

* numeration in accordance with that in Fig. 7; Source: after: Choiński (2006), Bathymetric maps (1958–1968), Vlasov B.P. et al. (2004)

Table 2. Primary characteristics of the studied lakes

No.*	Lake	Types of basins	Catchment area km²	Character of water exchange	Trophic status
1	Sławskie	channel	201.0	weakly flow-through	eutrophic
2	Jamno	coastal	503.0	weakly flow-through	eutrophic
3	Łebsko	coastal	1801.0	weakly flow-through	eutrophic
4	Charzykowskie	channel	914.0	weakly flow-through	eutrophic
5	Biskupińskie	channel	78.9	outflow	eutrophic
6	Ostrzyckie	channel complex	201.0	outflow	eutrophic
7	Gopło	channel complex	1408.0	outflow	eutrophic
8	Jeziorak	channel complex	315.0	weakly flow-through	eutrophic
9	Drwęckie	channel complex	1015.0	weakly flow-through	eutrophic
10	Nidzkie	channel complex	172.0	weakly flow-through	eutrophic
11	Roś	channel complex	3022.0	weakly flow-through	eutrophic
12	Ełckie	channel complex	980.0	outflow	eutrophic
13	Rajgrodzkie	channel complex	740.0	weakly flow-through	mesotrophic
14	Białe	channel	36.7	weakly flow-through	mesotrophic
15	Wigry	channel complex	487.0	weakly flow-through	mesotrophic
16	Studzieniczne	channel	24.4	weakly flow-through	mesotrophic
17	Wygonoszczańskie	marshy	61.1	outflow	eutrophic
18	Narocz	moraine	199.0	outflow	mesotrophic
19	Miastro	moraine	120.0	outflow	eutrophic
20	Drywiety	moraine	423.0	outflow	eutrophic
21	Czerwone	marshy	187.0	weakly flow-through	dystrophic
22	Oświejskie	moraine	206.0	outflow	eutrophic
23	Nieszczerdo	channel complex	143.0	outflow	eutrophic
24	Łukomskie	channel	179.0	outflow	eutrophic
25	Sienno	channel	67.9	outflow	mesotrophic

* numeration in accordance with that in Fig. 7; Source: after: Loginov (2005), Vlasov B.P. et al. (2004)

29°42'E, and from south to north to 360 km – Lake Sławskie 51°o54'N and Lake Oświejskie 56°01'N. The maximum altitude of the water surface amounts isto 163.7 m a.s.l. in the case of Lakes Narocz and Miastro, and the minimum to is 0.1 m a.s.l. – Lake Jamno.

The water volume of the studied lakes varies from 6.4 million m³ (Lake Biskupińskie) to 710.0 million m³ (Lake Narocz), whereas the mean volume of the studied lakes isamounts to 121.0 million m³. The maximum water depth in the lakes ranges from 2.3 m (Lake Wygonoszczańskie) to 74.2 m (Lake Wigry). The mean maximum water depth for the lakes is amounts to 21.9 m. The mean depth varies from 0.7 m forin the case of Lake Czerwone to 15.4 m for Lake Wigry, withat a mean depth for the lakes of 6.5 m.

The exposure (openness) index was calculated as the ratio of a lake's surface area to its mean depth. It varied from 0.18 (lake Biskupińskie) to 60.92 (Lake Czerwone). The mean value amounts tois 8.93.

The depth index was calculated as the ratio of a lake's mean depth to its maximum depth. It varied from 0.18 (Lake Rajgrodzkie) to 0.57 (lake Łukomskie). The mean value amounts to is 0.34.

The Ohle index for the lakes was calculated as the ratio of a lake's catchment area to the lake's surface area. It varied from 2.35 (Lake Wygonoszczańskie) to 254.55 (Lake Ełckie), averaging 63.19.

The surface areas of the lake catchments are largely varied. The smallest one is that of Lake Studzieniczne – 24.4 km², and the largest is that of Lake Roś – 3,022 km². The mean value amounts to is 539 km².

The types of the lake basins are particularly post-glacial, but also coastal and marshy basins also occur. In terms of character of water exchange, the lakes are weakly flow-through or outflow lakes, and in terms of trophic status – mesotrophic, eutrophic, and dystrophic.

Due to the existence of small breaks in the observations, they data series were supplemented by means of the application of the multiple regression analysis. This concerned, among others, Lakes Łukomskie, Wygonoszczańskie, Miastro, Czerwone, and Drywiaty.

Methodology

The methodology of grouping lakes is based on analyses of the similarity of spectral images of water surface tightness (Drużynin, Sikan 1999). The spectral tightness of the studied lakes was analysed

$$S(w) = \frac{1}{\pi}\int_0^m \lambda(\tau) r(\tau)\cos(w\tau)d\tau$$

where: $w = 2\pi T$ – frequency; T – time interval; m – maximum change at the assessment of the autocorrelation function; $\lambda(\tau)$ – smooth function; $r(\tau)$ – autocorrelation function

in time intervals according to the following formula (Marpł 1990):

$$\lambda(\tau) = \sum_{k=0}^{3} a_k \cos\left[(\pi\kappa\tau)/m\right]$$

where a_k – weight indices (a_0 = 0.364; a_1 = 0.489; a_2 = 1.137; a_3 = 0.011)

In the case of the smooth function, the Nattoł's correlation window was adopted (Marpł 1990):

Nattoł's window was used for the simplification of the division of typical spectra, i.e. its changes, and allowed the value of noise components to be decreased and equal spectra to be obtained.

The maximum duration of the interval designated from the spectrum should not exceed 1/3 of the row length. The analysis of the significance of the peak is preceded by testing of the hypothesis on a potential deviation from the above norm. The level of significance of the peak starts from the zero hypothesis, assuming that it represents "white noise".

$$\frac{\chi^2_{1-a}}{\nu 2\pi} < S^* < \frac{\chi^2_a}{\nu 2\pi}$$

where: χ^2_{1-a} and χ^2_a represent the value of the right-side distribution function of Pearson's distribution χ^2; ν is the number of degrees of freedom; then the degree of significance amounts to 2α (α is adopted as 0.05)

The confidence interval for empirical values S* is expressed with the following formula:

$$\nu = \frac{5,5n}{m}$$

The number of degrees of freedom for Nattoł's window at longitude of n and maximum change m is calculated by means of the following formula:

Results

Depending on the course of the spectrum of the water level of the analysed lakes, they were divided into three groups. The first group shows a smooth curve with no significant peaks in an image of exceptional frequency. This case was determined for the majority of the studied lakes. A typical representative of the group is the spectrum of Lake Wygonoszczańskie (Fig. 1). This is confirmed by spectra of water levels of other lakes, both Belarusian and Polish (Fig. 2).

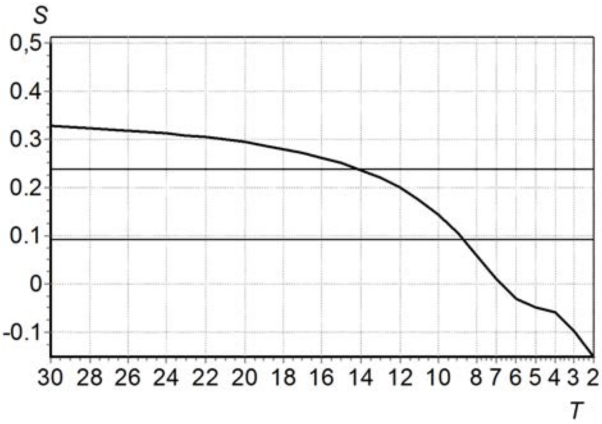

Fig. 1. Water surface spectrum of Lake Wygonoszczańskie typical of the first group

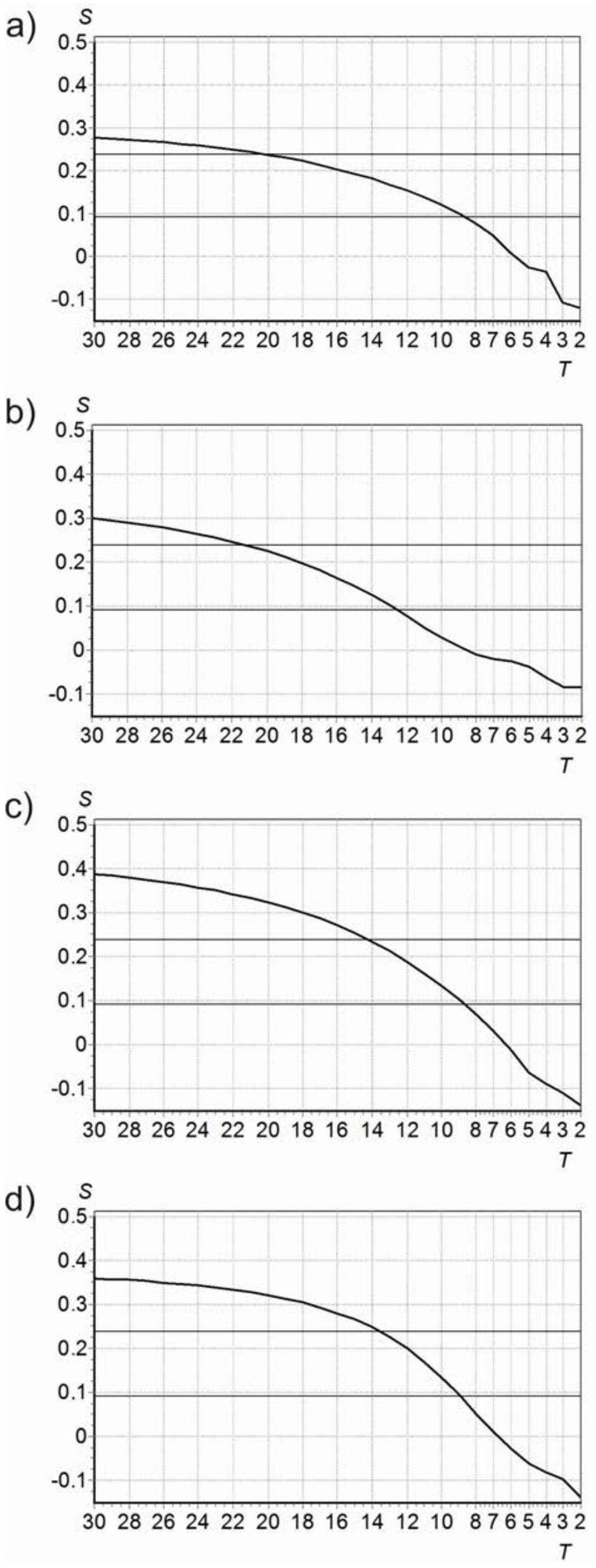

Fig. 2. – The most characteristic water level spectra of lakes from the first group: a – Narocz, b – Drwęckie, c – Ełckie, d – Wigry

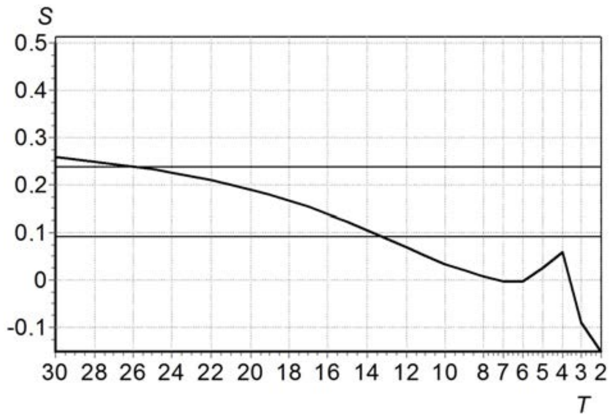

Fig. 3. Water level spectrum of Lake Łukomskie, typical of the second group

Four-year variability is characteristic of the water level spectrum of lakes of the eastern part of Belarus and Lake Studzieniczne. A typical representative of the group is the water level spectrum for Lake Łukomskie (Fig. 3). Other lakes in the group are presented in Fig. 4.

The third group includes the lakes of NW Poland. This group of spectra presents a curve with an even peak of a three-year water level fluctuation. A spectrum typical of this group is presented in Fig. 5. It is of the water level of Lake Łebsko. Figure 6 presents spectra of the remaining lakes included in the group.

Complete results of the spectrum analysis of water level fluctuations in lakes are presented in Table 3 and Fig. 7.

The group with the highest number of lakes (14) is the first group, while the lowest number (5) is for the second, with 6 in the third group. The classification of the lakes into the designated groups can be considered in geographic terms. The first and most abundant group is represented by lakes from central and northern Belarus, and from central and eastern Poland. The second group includes lakes of eastern Belarus (and Lake Studzieniczne – at the border with Belarus), and the third group – lakes from central and northern Poland. Therefore, the location of the designated groups of lakes based on the spectral analysis of their water level fluctuations can be determined not only by local, but also by regional factors.

The classification of lakes according to the analysis of similarity of images of water level spectrum density facilitates the assessment of the prima-

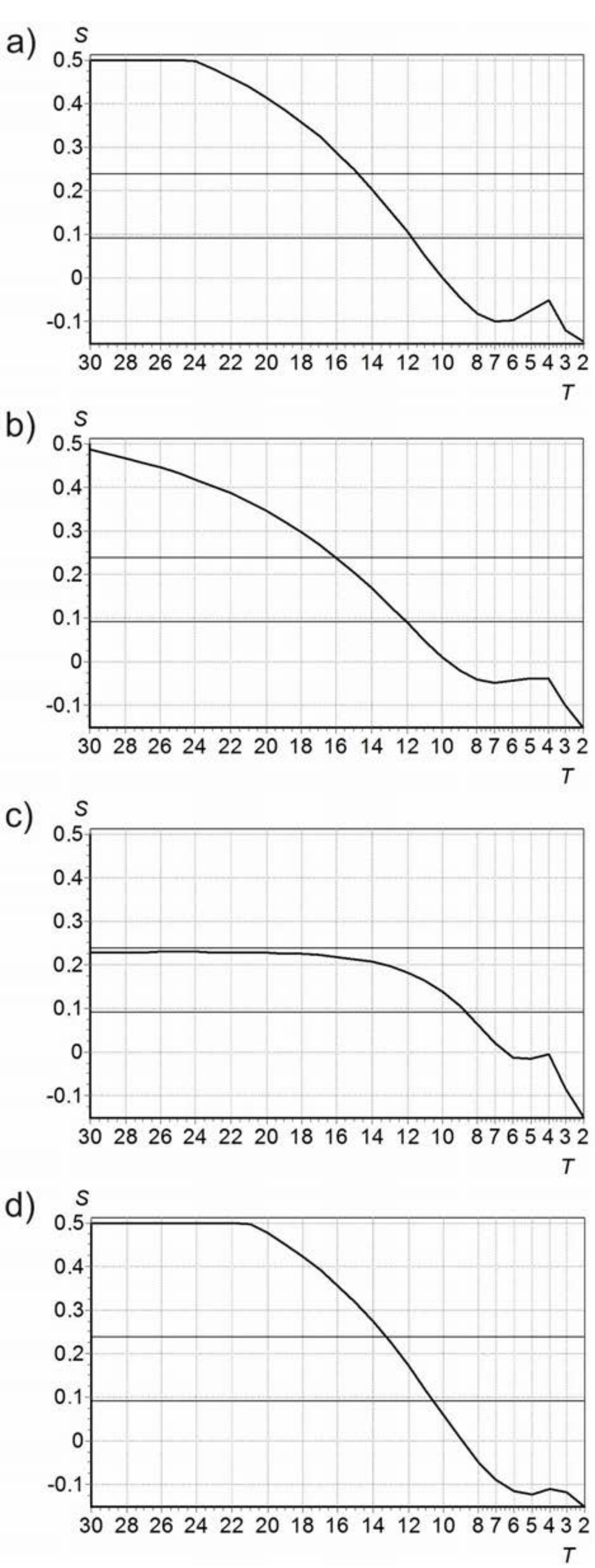

Fig. 4. Water level spectra most characteristic of lakes from the second group: a – Sienno, b – Nieszczerdo, c – Czerwone, d – Studzieniczne

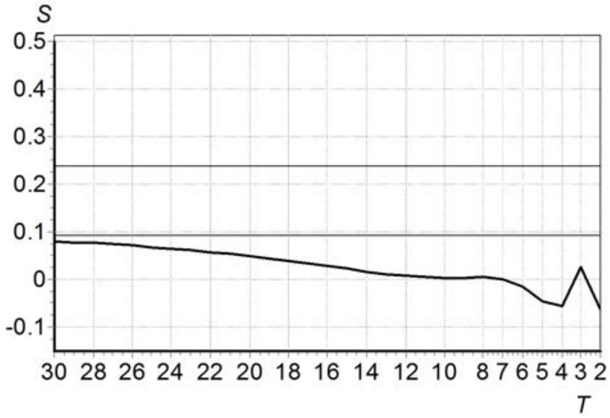

Fig. 5. Water level spectrum of Lake Łebsko, typical of the third group

ry statistical parameters. The mean significance of the variability coefficient *(C_v)*, and asymmetry and variability coefficients *(C_s/C_v)*, as well as the autocorrelation coefficients *(r(1))* for the analysed lakes classified in separate groups are presented in Table 4.

Coefficients of variability and autocorrelation have the highest values for lakes from the second group. The ratio of the coefficients of asymmetry and variability has a very evident tendency to increase from the first to the third group.

Water levels in lakes of the designated groups differ in the strength of long-term components in the spectrum. The maximum "degree of redness" of the lakes' water level spectrum is observed for the second group. In the first group, the strength of long-term components of the spectrum is lower than that in the second group. In the third group of lakes, the "red noise" is less evident.

Summary and conclusions

Data for 25 lakes allowed for spectral analysis of water level fluctuations in the lakes. The analysis was based on data of a 55-year observation sequence covering the years 1956–2010. Based on the course of the spectrum, the lakes were divided into three groups. The first, most abundant group, distinguished by smooth curves with no evident peaks, includes 14 lakes. The second, least abundant group, including five lakes, is distinguished by four-year variability. The third group, represented by six lakes,

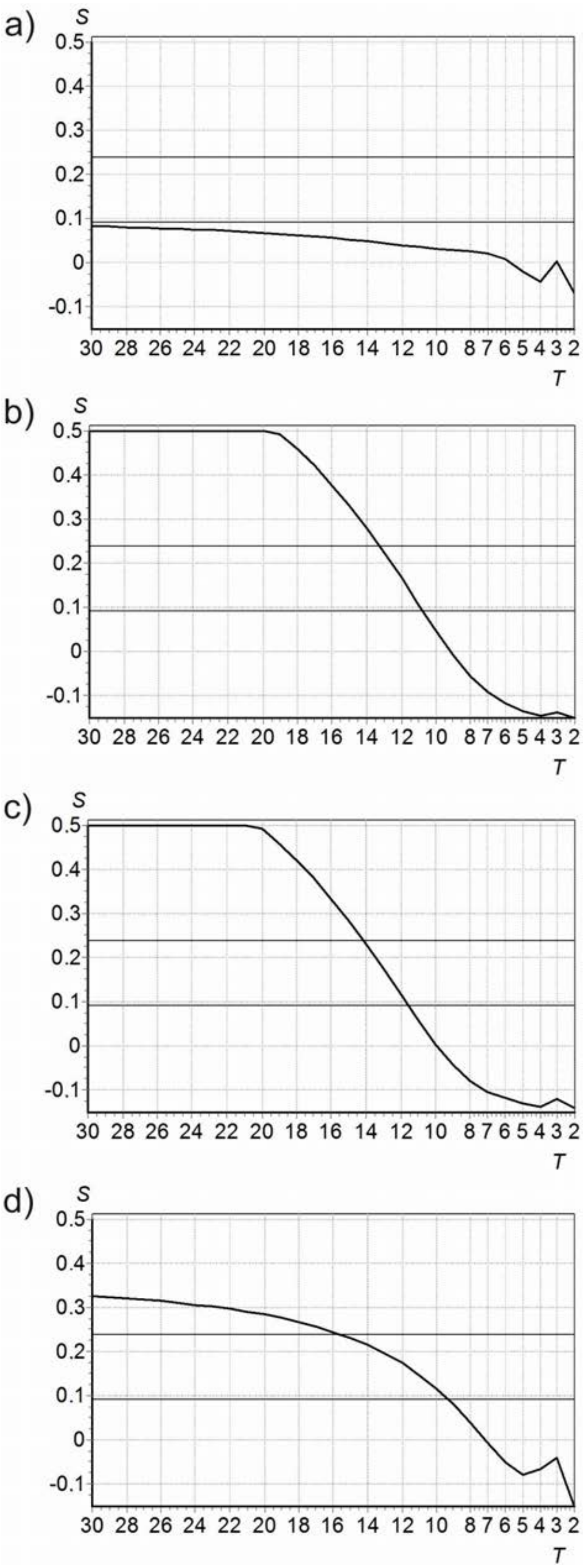

Fig. 6. The most characteristic water level spectra of lakes from the third group: a – Gopło, b – Ostrzyckie, c – Jamno, d – Sławskie

Table 3. Categorisation of lakes by character of water level spectrum

No.*	Lake	Group
1	Sławskie	3
2	Jamno	3
3	Łebsko	3
4	Charzykowskie	1
5	Biskupińskie	3
6	Ostrzyckie	3
7	Gopło	3
8	Jeziorak	1
9	Drwęckie	1
10	Nidzkie	1
11	Roś	1
12	Ełckie	1
13	Rajgrodzkie	1
14	Białe	1
15	Wigry	1
16	Studzieniczne	2
17	Wygonoszczańskie	1
18	Narocz	1
19	Miastro	1
20	Drywiety	1
21	Czerwone	2
22	Oświejskie	1
23	Nieszczerdo	2
24	Łukomskie	2
25	Sienno	2

* numeration in accordance with that in Fig. 7

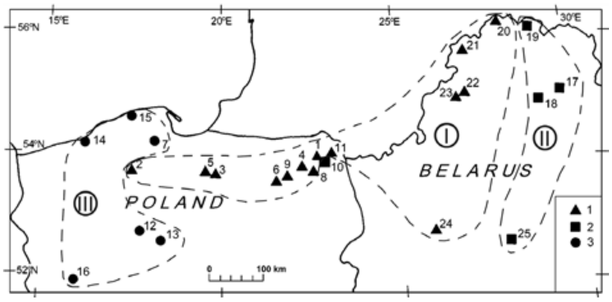

Fig. 7. Classification of the analysed lakes into the designated groups by water level spectrum: 1 – group I; 2 – group II; 3 – group III; numeration in accordance with that in Tables 1, 2 and 3

Table 4. Primary statistical parameters of the analysed lakes divided into groups

Group number	Cv	Cs/Cv	r(1)
I	0.06	-2.1	0.57
II	0.18	-0.4	0.64
III	0.07	0.2	0.49

shows an even peak of a three-year water level fluctuation. The three designated groups of lakes show a certain geographic regionalisation. Lakes in the first group are located in central and northern Belarus, and central and eastern Poland. Lakes from the second group are located in eastern Belarus, and those from the third group – in central and northern Poland. The location of lakes from a given group seems to be determined (apart from local factors) by regional-scale factors. The continentalism of climate increasing in an eastwards direction may be one of the key factors responsible for the detected regional diversity of lake water level fluctuations. The obtained analysis results encourage future expansion of the study area, e.g. to German, Lithuanian, and Russian lakelands. This will permit the narrowing or expansion of the obtained regional ranges of the designated groups, designation of others, or identification of regional factors determining the designated types of water level fluctuations.

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