Chapter 5
Water Resources of Stagnant Waters

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Abstract Total water resources of lakes in Poland for 7081 lakes (above 1 ha) equal 19.7349 km^3 (Masurian Lake District – 51.27%, Pomeranian Lake District – 36.12%), Wielkopolska-Kujawy Lake District – 11.93%, and area south of the delineated range of the last glaciation – 0.68%). Retention for the area north of the line delimiting the maximum range of the last glaciation is 162 mm. It constitutes only 10% of mean annual precipitation, and the value is approximately 3.5 times smaller than the amount of mean outflow from the territory of Poland.

Keywords Water resources of lakes and dam reservoirs · Changes in the surface area of lakes · Poland

5.1 Introduction

From the geological point of view, the age of lakes is exceptionally short. This particularly refers to postglacial lakes, predominating in Poland. Two usually co-occurring factors are considered to be responsible for the process of the decline of lakes, and therefore also their water resources. The first one is water level fluctuations, contributing to changes in the surface area. A decrease in the water level results in the intensification of the sedimentation process. Accumulation of sediments, i.e. sedimentation within the lake basin, determines the degree of shallowing, and therefore leads to a decrease in water resources.

Causes for water level fluctuations include: short- or long-term climate changes, determining changes in water supply to the lake from aquifers; deforestation of the lake's catchment, effect of local factors, for example determining changes in the

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erosion base, and variable time of the lake's incorporation into the hydrographic network; performance of different hydrotechnical works, both within the lake – outflow regulation, and within its catchment, e.g. meliorations, as well as natural factors that can contribute to water level increase, such as landslides or construction of beaver dams.

The second factor contributing to the decline of lakes, i.e. aggregation of sediments, can occur through: accumulation of biogenic mass, i.e. sedimentation; precipitation of chemical compounds; sedimentation of clastic sediments supplied by streams, colluvia and deluvia deposited in the lake; effect of aeolian processes.

The course of evolution of a given lake basin depends on many factors, among others: the genetic type of the basin; location in a given climate zone; individual features of the basin determining the morphometric parameters; size of the catchment and the ratio of its size to the surface area of the lake; stability of climate which determines water balance; effect of human pressure of water relations in the lake's catchment.

Three stages of development of lakes are usually designated. The first one is the youth stage, characterised by the basin's shape approximate to the original one, with no evident changes resulting from sedimentation processes. The second stage, i.e. maturity stage, is characterised by obscuring of depth contrasts as a consequence of deposition of a high amount of sediments. The final stage, i.e. the old age stage, is associated with complete disappearance and leads to filling the entire basin with sediments. The evolution of lake basins in some cases does not always follow the above pattern. Sometimes, with time, lakes not only fail to disappear, but even increase their surface area, and therefore their water volume. Moreover, in lakes with a very variable basin, their certain fragments can be in different stages of development due to their different depths.

In reference to stagnant waters, water resources and their variability can be considered in three aspects, i.e. in reference to lakes (natural water objects >1 ha), tarns (natural water objects <1 ha), and artificial reservoirs.

5.2 Water Resources of Lakes

Total water resources of lakes in Poland were estimated based on the Catalogue of Polish Lakes [1], including information concerning surface area for 7081 lakes (above 1 ha). The calculation procedure involved adding up known lake water volumes for more than 30% of lakes and adding the total water volume of unmeasured lakes. It was calculated as a product of their surface area and mean depth. Lake water resources calculated this way equal 19.7349 km^3. Water resources within particular lake districts are as follows: Masurian Lake District – 10.1183 km^3 (51.27%), Pomeranian Lake District – 7.1292 km^3 (36.12%), Wielkopolska-Kujawy Lake District – 2.3535 km^3 (11.93%), and area south of the delineated range of the last glaciation – 0.1339 km^3 (0.68%). Approximate values were also added in earlier Polish publications [2].

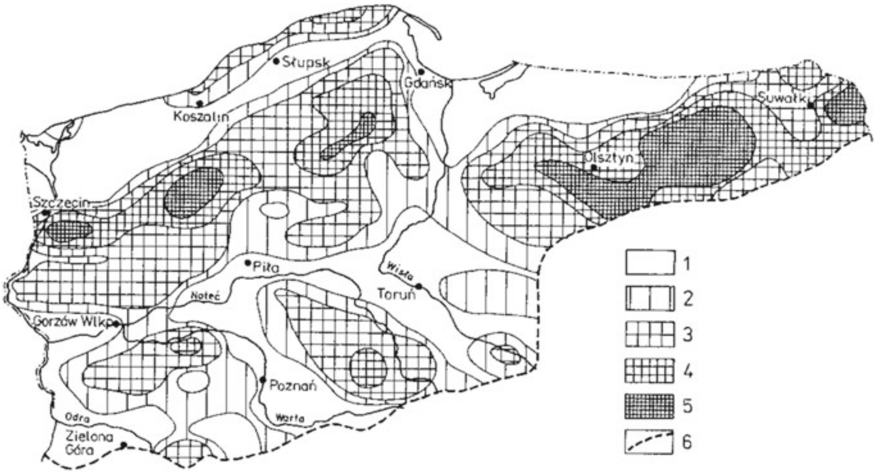

Fig. 5.1 Variability of the retention index of lake waters (mm): 1 – below 50, 2 – 50–100, 3 – 100–250, 4 – 250–500, 5 – above 500, 6 – delineated the range of the last glaciation

Figure 5.1 presents regional variability of water resources of lakes expressed as the retention index in mm. The map of retention capacities was prepared based on the outlines of maps at a scale of 1:50,000 for more than 200 sheets of topographic maps. The middle of each field was ascribed a retention value providing the basis for interpolation. Retention capacity was expressed in mm, permitting its comparison with other indices. The determined retention capacity for the area north of the line delimiting the maximum range of the last glaciation is 162 mm. An evident two-fold character of the analysed phenomenon is observed on the map, i.e. the Masurian and Pomeranian Lake District have considerably larger resources than the Wielkopolska-Kujawy Lake District. The zone of maximum resources has an evident latitudinal orientation and reaches the highest values, usually south of the I degree watershed, both in the case of the Pomeranian and Masurian Lakelands. Based on delineation of [3], the greatest resources within the Masurian Lake District occur in the following catchments: Węgorapa (404 A) – 1976 mm, Biała Hańcza (407) – 958 mm, and Pisa (227 A) – 893 mm, and in the Pomeranian Lake District in catchments of: Drawa (119 D) – 389 mm, Wda (237 B) – 196 mm, and in the Przymorze catchment from Wieprza to Słupia (310) – 184 mm. Within the Wielkopolska-Kujawy Lake District, lake catchments retain considerably less waters, and the most abundant ones include Vistula from Bzura to Skrwa (233 A) – 173 mm, Warta from Wełna to Obra (118 G) – 141 mm, and Noteć to Gwda (119 A) – 116 mm. Zones with the lowest retention capacity, i.e. up to 50 mm, are located in valleys of the largest rivers with the adjacent areas, and coasts: Gdańsk, East Baltic, Szczecin, and the southern part of the Koszalin Coast. Mean retention capacity determined within the three lake districts is exceptionally variable. In the case of the Masurian Lake District, it is 283 mm, for the Pomeranian Lake District the index equals 150 mm, and for the Wielkopolska-Kujawy Lake District only 58 mm. The division of the total volume of water resources of the lakes by the surface area of Poland provided a water layer of 63 mm. It constitutes only 10% of mean annual precipitation, and the value is approximately 3.5 times smaller than the amount of mean outflow from the territory of Poland.

Table 5.1 presents lakes with the highest volumes, i.e. above 100 million m^3. This small group including only 26 lakes (0.4% of the total number of lakes) contains more than 6 km^3 of waters in their basins, which constitutes more than 30% of all lake water resources in Poland. A large majority of them, i.e. 16 lakes, is located in the Masurian Lake District.

Total lake water resources in Poland can be described as scarce in comparison to lake water resources of the globe. According to [5], they equal 176 400 km^3. Therefore, approximately 20 km^3 of waters accumulated in Polish lakes constitutes only 0.01% of global resources. The total water volume of all Polish lakes is also very low in comparison to the most abundant lakes in the world. For example, it is comparable to the water volume of Lake Como in Italy, occupying the 66th position in the ranking of the lakes the most abundant in water resources in the world [6].

5.3 Water Resources of Tarns

Postglacial tarns are defined as small, usually closed-drainage water bodies. They usually have a round shape, whereas their maximum depths exceptionally exceed 3 m. In the summer period in the case of natural decrease in groundwater level, they frequently remain without water. Therefore, depending on their location, they can be of permanent, periodic, or episodic character. Their permanent disappearance is usually associated with extensive melioration works. Tarns occur both north and south of the maximum range of the last glaciation. They are the most characteristic of zones of moraine plateaus and ground moraine areas. The spatial distribution of tarns was analysed by Choiński [7] within the area north of the maximum range of the Baltic glaciation. The number of tarns was determined based on the analysis of topographic maps at a scale of 1:50 000, edited in the mid-1970s. Tarns were classified as natural water bodies not exceeding 1 ha. The background of more than 200 maps at a scale of 1:50 000 was covered with a grid of primary fields with an area of 100 km^2. The determination of the number of tarns in primary fields permitted spatial presentation of the analysed phenomenon and interpolation (Fig. 5.2). The analysed area is characterised by a variable concentration of occurrence of tarns. In the Pomeranian Lake District, their largest clusters are located in the Kashubian and Drawa Lake Districts, in the eastern part of the Krajeńskie Lake District, and the western part of the Myśliborskie Lake District. A higher concentration of tarns also occurs over an extensive section of the watershed zone of coastal rivers and rivers flowing south of them. A small number of tarns occurs in the area of the West Pomeranian Coast, in zones directly adjacent to river valleys, and outwash plains.

In the Masurian Lake District, evident variability is observed between its northern and southern part, where the concentration of tarns is considerably lower. Their

Table 5.1 Lakes with the highest water volume (in million m^3) based on data of the Institute of Inland Fisheries in Olsztyn

No	Lake	Volume (million m^3)	Area (ha)	Location (according to [4])
1	Mamry	1 003.4	10 282.4	Poj. Mazurskie (Kraina Wielkich Jezior Mazurskich)
2	Miedwie	681.7	3 527.0	Poj. Pomorskie (Równina Pyrzycko-Starogardzka)
3	Śniardwy	660.2	11 340.4	Poj. Mazurskie (Kraina Wielkich Jezior Mazurskich)
4	Wigry	336.7	2 118.2	Poj. Mazurskie (Równina Augustowska)
5	Drawsko	333.4	1 871.5	Poj. Pomorskie (Poj. Drawskie)
6	Niegocin	258.5	2 600.0	Poj. Mazurskie (Kraina Wielkich Jezior Mazurskich)
7	Tałty-Ryńskie	248.4	1 831.2	Poj. Mazurskie (Kraina Wielkich Jezior Mazurskich)
8	Wdzydze	220.8	1 455.6	Poj. Pomorskie (Równina Charzykowska)
9	Lubie	169.9	1 439.0	Poj. Pomorskie (Poj. Drawskie)
10	Łańskie	168.0	1 042.0	Poj. Mazurskie (Poj. Olsztyńskie)
11	Roś	152.9	1 887.7	Poj. Mazurskie (Kraina Wielkich Jezior Mazurskich)
12	Rajgrodzkie	142.6	1 503.2	Poj. Mazurskie (Poj. Ełckie)
13	Jeziorak	141.6	3219.4	Poj. Mazurskie (Poj. Iławskie)
14	Pluszne	134.9	903.3	Poj. Mazurskie (Poj. Olsztyńskie)
15	Powidzkie	134.8	1 174.7	Poj. Wielkopolskie (Poj. Gnieźnieńskie)
16	Charzykowskie	134.5	1 363.8	Poj. Pomorskie (Poj. Charzykowskie)
17	Narie	124.6	1 240.1	Poj. Mazurskie (Poj. Ełckie)
18	Dadaj	120.8	976.8	Poj. Mazurskie (Poj. Olsztyńskie)
19	Żarnowieckie	120.8	1 431.6	Poj. Pomorskie (Wysoczyzna Żarnowiecka)
20	Hańcza	120.4	311.4	Poj. Mazurskie (Poj. Wschodniosuwalskie)
21	Łebsko	117.5	7 140.0	Poj. Pomorskie (Pobrzeże Słowińskie)

(continued)

Table 5.1 (continued)

No	Lake	Volume (million m^3)	Area (ha)	Location (according to [4])
22	Pile	115.2	980.1	Poj. Pomorskie (Poj. Szczecineckie)
23	Nidzkie	113.9	1 818.0	Poj. Mazurskie (Równina Mazurska)
24	Mokre	107.3	841.0	Poj. Mazurskie (Poj. Mrągowskie)
25	Siecino	104.4	729.7	Poj. Pomorskie (Poj. Drawskie)
26	Gołdapiwo	101.5	862.5	Poj. Mazurskie (Kraina Wielkich Jezior Mazurskich)

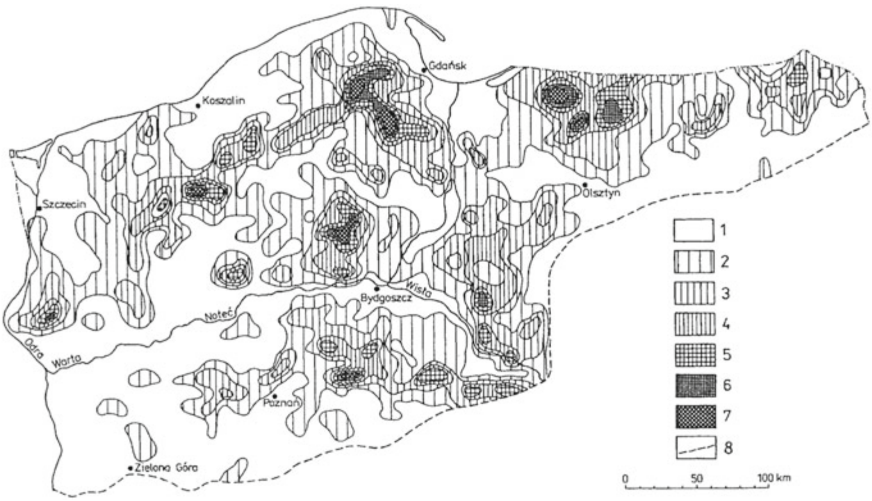

Fig. 5.2 Density of occurrence of tarns per 100 km^2: 1 – 0–50, 2 – 51–100, 3 – 101–150, 4 – 151–200, 5 – 201–250, 6 – 251–300, 7 – above 300, 8 – range of the last glaciation (according to [8])

largest clusters are located north of the Olsztyn Lake District, and on the Dobrzyń and Lithuanian Lake Districts.

Due to high dispersion of tarns, the Wielkopolska-Kujawy Lake District differs from the lake districts mentioned earlier. Tarns occur much more seldom there, and their concentrations are considerably lower, whereas in the eastern part of the Lake District they are substantially more abundant than in the western part. In the case of the Wielkopolska-Kujawy Lake District, a considerably higher effect of human pressure is observed in comparison to the Pomeranian and Masurian Lake Districts. Table 5.2 presents the number of tarns within the designated lake districts [7].

Table 5.2 The occurrence of tarns within the designated lake districts (according to [7])

Lake district	Number of tarns	Share (%)	Surface area (km^2)	Mean density per 100 km^2
Pomorskie	36 657	44.6	48 330	75.8
Mazurskie	28 603	34.8	35 928	79.6
Wielkopolsko-Kujawskie	16 916	20.6	31 747	53.3
Summary	82 176	100.0	116 005	70.8

A total of 82 176 tarns were identified in the analysed area. Their highest number (as well as that of lakes with an area >1 ha) occurs in the Pomeranian Lake District, i.e. 36 657, constituting 44.6% of their total abundance. Their highest mean density, i.e. 79.6 tarns/100 km^2, occurs in the Masurian Lake District, although in terms of mean density of tarns, the Masurian and Pomeranian Lake Districts are similar. The Wielkopolska-Kujawy Lake District considerably differs from them in this aspect. The mean density of tarns in the Lake District is lower by approximately 30%. The mean density of tarns throughout the analysed area is 70.8 per 100 km^2. The highest density of tarns reached more than 300 per 100 km^2. Zones of the type occurring in the Kashubian, Drawa, Krajeńskie, Gniezno Lake Districts, and north of the Olsztyn Lake District. An evident tendency of dependency on the number of tarns on the type of substrate is observed. In zones covered by sands and gravels of fluvioglacial accumulation, the number of tarns is small and does not exceed 50 per 100 km^2. In zones of occurrence of glacial tills, it is several times higher.

The determination of the number of tarns permits the estimation of their total surface area. It is possible with the assumption of an average surface area of a tarn. In the case above, the adopted average surface area was 0.5 ha. Therefore, with such an assumption, the total surface area of tarns was estimated for 41 088 ha. The area is approximately 4 times larger than the largest Polish Lake Śniardwy.

A procedure analogical to the one described above can be applied in the estimation of total water resources of tarns. Assuming its previously determined total surface area of 41 088 ha and mean depth of 0.5 m, the total water volume in tarns can be estimated for 0.20544 km^3. The value constitutes 1.0% of water resources of lakes larger than 1 ha. For particular lake districts, the contribution is as follows: Pomeranian – 1.28%, Masurian – 0.71%, and Wielkopolska-Kujawy – 1.80%. Total resources accumulated in tarns determine the retention index within the analysed area equal to 1.8 mm.

Sebzda [9] analysing topographic maps at a scale of 1:50 000 from the 1970s determined the number of tarns in the area south of the range of the Baltic glaciation, i.e. over an area of 195 836 km^2. Only 10 676 tarns were identified there, corresponding to a mean density of only 5.5 per 100 km^2. With assumptions analogical to the previous ones, their total surface area can be estimated for 5 338 ha. It is therefore approximate to the surface area of Lakes Jeziorak and Jamno and constitutes 1.9% of Polish lakes larger than 1 ha. Their water resources can be estimated for 0.02669 km^3, which corresponds to only 0.13% of lake water resources in Poland. In the case of spatial distribution of tarns, their considerably lower densities of occurrence are observed south of the range of the last glaciation. This evidence suggests their high susceptibility to decline, depending on their age.

5.4 Water Resources of Dam Reservoirs

No favourable conditions for the construction of water reservoirs occur in Poland, particularly those with considerable surface areas. This results from small water resources in rivers, considerable variability of outflow, and unfavourable natural conditions for their construction. The largest reservoirs in terms of surface area as well as volume are approximate to natural lakes. The reservoir in Solina on the San River is the largest in terms of water resources. It accumulates 0.47 km^3 of waters, which constitutes approximately half of the water resources of Mamry, the lake with the richest water resources in Poland. In terms of surface area, the reservoir on the Vistula River above the barrage in Włocławek is the largest. Its surface area of 70.4 km^2 is comparable with that of Lake Łebsko, occupying the third position in this aspect in Poland.

Wiśniewski [10] listed dam reservoirs (more than 1 million m^3) and determined their number for 101 (Table 5.3). Only 11 among them have resources exceeding 100 million m^3. It is worth emphasising that 26 natural lakes are identified to have water resources exceeding 100 million m^3.

The location of dam reservoirs in Poland is presented in Fig. 5.3. Notice the very evident concentration of reservoirs in mountain and sub-mountain regions, in the Pomeranian Lake District, and on the Małopolska Upland. In the Masurian Lake District and the belt of lowlands, dam reservoirs occur sporadically. Rivers the best developed in terms of the number of reservoirs include Bóbr, Radunia, Nysa Łużycka, Nysa Kłodzka, Rega, Brda, and Soła.

It is worth emphasising that human activity in Poland in reference to the construction of large dam reservoirs dates back 170 years. The oldest reservoir with a volume of more than 1 million m^3 is Mylof on the Brda River, launched in 1848. Several reservoirs in the Sudetic region and the Pomerania come from the first quarter of the twentieth century. The construction of more than half of the reservoirs (with a volume of more than 1 million m^3) dates back to the period after World War 2.

The total volume of dam reservoirs (more than 1 million m^3) is approximately 3.5 km^3. This constitutes approximately 18% of water resources of Polish lakes and approximately 6% of the volume of waters outflowing annually from the territory of Poland. Their total surface area is approximately 500 km^2, i.e. around 18% of the area of lakes in Poland.

Due to the inconsiderable economic importance of artificial reservoirs with small surface areas, they are not included in any comparisons. Obtaining an answer to the question, however, is equivalent to the determination to what degree man managed to increase the system of stagnant surface waters in comparison with what nature created. The analysis of the above issue was performed for the zone south of the

Table 5.3 Artificial water reservoirs in Poland with water volume exceeding 1 million m^3 (elaboration based on [10] and Yearbooks of the Central Statistical Office)

No	Reservoir	River	Year of launching	Total volume (million m^3)	Surface area (km^2)
1	Solina	San	1968	472.0	21.1
2	Włocławek	Wisła	1970	408.0	70.4
3	Czorsztyn-Niedzica	Dunajec	1997	231.9	12.3
4	Jeziorsko	Warta	1986	202.8	42.3
5	Goczałkowice	Mała Wisła	1956	166.8	32.0
6	Rożnów	Dunajec	1941	166.6	16.0
7	Dobczyce	Raba	1986	125.0	10.7
8	Otmuchów	Nysa Kłodzka	1933	124.5	19.8
9	Nysa	Nysa Kłodzka	1972	113.6	20.4
10	Turawa	Mała Panew	1948	106.2	20.8
11	Tresna	Soła	1967	100.0	10.0
12	Dębe	Narew	1963	94.3	30.3
13	Dzierżono Duże	Kłodnica	1964	94.0	6.2
14	Sulejów	Pilica	1973	88.1	19.8
15	Koronowo	Brda	1960	80.6	15.6
16	Siemianówka	Narew	1995	79.5	32.5
17	Mietków	Bystrzyca	1986	70.5	9.2
18	Pilchowice	Bóbr	1912	54.0	2.4
19	Dziećkowice	Przemsza	1976	52.5	7.1
20	Klimkówka	Ropa	1994	43.5	3.1
21	Słup	Nysa Szalona	1978	38.6	4.9
22	Pławniowce	Potok Toszewski	1976	29.1	2.4
23	Porąbka	Soła	1936	28.4	3.7
24	Poraj	Warta	1978	25.1	5.5
25	Chańcza	Czarna Staszowska	1984	24.5	4.7
26	Rybnik	Ruda	1972	22.0	4.7
27	Przeczyce	Czarna Przemsza	1963	20.7	5.1
28	Leśna	Kwisa	1906	18.0	1.4
29	Bukówka	Bóbr	1987	16.8	2.0
30	Żur	Wda	1929	16.0	3.0
31	Besko	Wisłok	1978	16.0	1.3
32	Kozłowa Góra	Krynica	1937	15.8	5.8

(continued)

Table 5.3 (continued)

No	Reservoir	River	Year of launching	Total volume (million m^3)	Surface area (km^2)
33	Dzierżono Małe	Drama	1938	14.1	1.3
34	Złotniki	Kwisa	1934	12.4	1.2
35	Czchów	Dunajec	1949	12.0	2.5
36	Pogoria III	Pogoria	1974	12.0	2.0
37	Łąka	Pszczynka	1986	12.0	4.2
38	Pierzchały	Pasłęka	1916	11.5	2.4
39	Dobromierz	Strzegomka	1986	11.3	1.0
40	Myczkowce	San	1961	10.9	2.0
41	Rosnowo	Radew	1922	8.8	1.9
42	Brzeg Dolny	Odra	1958	8.0	2.1
43	Lubachów	Bystrzyca	1917	8.0	0.5
44	Sromowce Wyżne	Dunajec	1994	7.4	0.9
45	Brody Iłżeckie	Kamienna	1964	7.3	2.6
46	Mosty	Kanał Wieprz-Krzna	1969	6.9	3.9
47	Żelizna	Kanał Wieprz-Krzna	1971	6.9	3.5
48	Słupca	Meszna	1965	6.4	2.6
49	Zemborzyce	Bystrzyca	1974	6.3	2.8
50	Jastrowie	Gwda	1931	6.2	1.5
51	Gródek	Wda	1923	5.5	1.0
52	Niedalino	Radew	1913	5.5	0.9
53	Strzegomino-Konradów	Słupia	1924	5.0	1.0
54	Mylof	Brda	1848	5.0	1.2
55	Borowo	Drawa	b.d	1.9	b.d
56	Wisła-Czarne	Mała Wisła	1973	4.9	0.4
57	Niedów	Witka	1962	4.9	1.9
58	Raduszew Stary	Bóbr	1935	4.7	1.9
59	Rejowice	Rega	1924	4.6	2.2
60	Łączany	Wisła	1958	4.5	b.d
61	Opole-Podedworze	Kanał Wieprz-Krzna	1970	4.5	2.8
62	Zahajki	Kanał Wieprz-Krzna	1968	4.4	2.4

(continued)

Table 5.3 (continued)

No	Reservoir	River	Year of launching	Total volume (million m^3)	Surface area (km^2)
63	Wąglanka-Miedzna	Wąglanka	1979	4.2	1.8
64	Dychów	Bóbr	1936	4.1	1.0
65	Ptusza	Gwda	1933	4.0	2.0
66	Podgaje	Gwda	1930	3.9	1.2
67	Nielisz	Wieprz	1976	3.8	3.8
68	Kamienna	Drawa	1939	3.5	b.d
69	Pogoria I	Pogoria	1943	3.4	0.7
70	Straszyn	Radunia	1910	3.4	0.7
71	Bledzew	Obra	1909	3.0	3.2
72	Przewóz	Wisła	1955	2.5	b.d
73	Dąbie	Wisła	1961	2.5	b.d
74	Paprocany	Gostynia	b.d	2.5	b.d
75	Bielkowo	Radunia	1924	2.4	0.6
76	Krzywaniec	Bóbr	b.d	2.4	b.d
77	Smukała	Brda	1951	2.2	b.d
78	Tryszczyn	Brda	1960	2.2	b.d
79	Dobrzyca	Gwda	1912	2.2	0.9
80	Zesławice	Dłubnia	b.d	2.2	b.d
81	Zatonie	Plebanka	b.d	2.0	b.d
82	Krzynia	Słupia	b.d	2.0	b.d
83	Brąsław	Łyna	1936	1.9	0.6
84	Rzeszów	Wisłok	1974	1.8	b.d
85	Husynne	Udal	b.d	1.8	b.d
86	Wrzeszczyn	Bóbr	b.d	1.7	b.d
87	Likowo	Rega	1926	1.6	1.5
88	Łapino	Radunia	1927	1.6	0.4
89	Cedzyna	Lubrzanka	b.d	1.6	b.d
90	Bielawa	Brzęczek	b.d	1.5	b.d
91	Gołuchów	Ciemna	b.d	1.4	b.d
92	Stronie Śląskie	Morawka	b.d	1.4	b.d
93	Czaniec	Soła	b.d	1.3	b.d
94	Wrzosy	Juszka	b.d	1.3	b.d
95	Bytów	Bytowa	b.d	1.2	b.d

(continued)

Table 5.3 (continued)

No	Reservoir	River	Year of launching	Total volume (million m^3)	Surface area (km^2)
96	Chechło	Chechło	b.d	1.2	b.d
97	Wapienica	Wapienia	b.d	1.1	b.d
98	Środa	Moskawa	b.d	1.1	b.d
99	Kaczorów	Kaczawa	b.d	1.0	b.d
100	Drzewica	Drzewiczka	b.d	1.0	b.d
101	Zielona	Mała Panew	1925	1.0	b.d

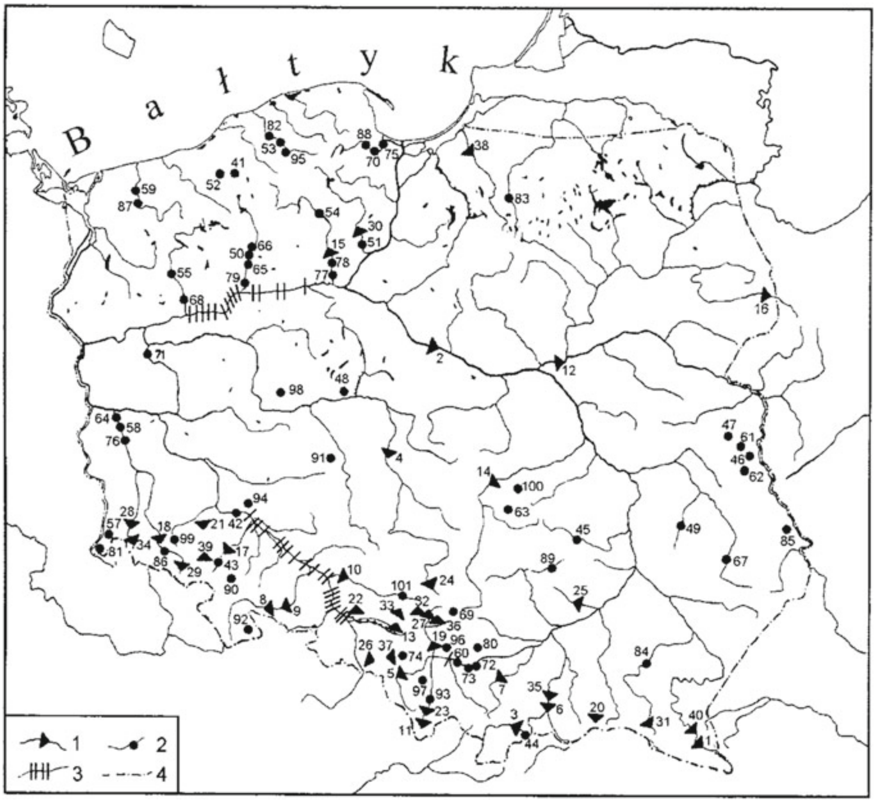

Fig. 5.3 Distribution of dam reservoirs in Poland according to [10] – numbering of reservoirs as in Table 5.3

range of the last glaciation, approximately overlapping with the Oder and Vistula River catchments. Materials used for calculations were hydrographic maps of Poland at a scale of 1:50 000 and topographic maps at the same scale (both cartographic documents were largely edited after 2000). A total of 712 maps were used for the analysis. Within the Oder River catchment, measurements were performed by Choiński [11], and the surface area of the Vistula River catchment was determined based on calculations of Lipiecka [12].

The result of the above analysis is the map of the percent share of dam reservoirs (Fig. 5.4). The applied ranges of the percent share correspond with those presented by Majdanowski [13] on the map of lake density of Poland. The procedure permitted direct comparison of the north and south Poland. The surface area of the Oder River catchment south of the range of the last glaciation is 58 618.6 km^2. Within the catchment area, the total surface area of artificial water reservoirs was estimated for 402.06 km^2. The value is equivalent to 0.69% of the cover of the area with dam reservoirs. The analogical range of the Vistula River has a surface area of 139 012.8 km^2. The total surface area of dam reservoirs within its boundaries was determined for 524.85 km^2, equivalent to 0.38% of share in the total area. The surface area of the western part of the country is therefore considerably more abundant in

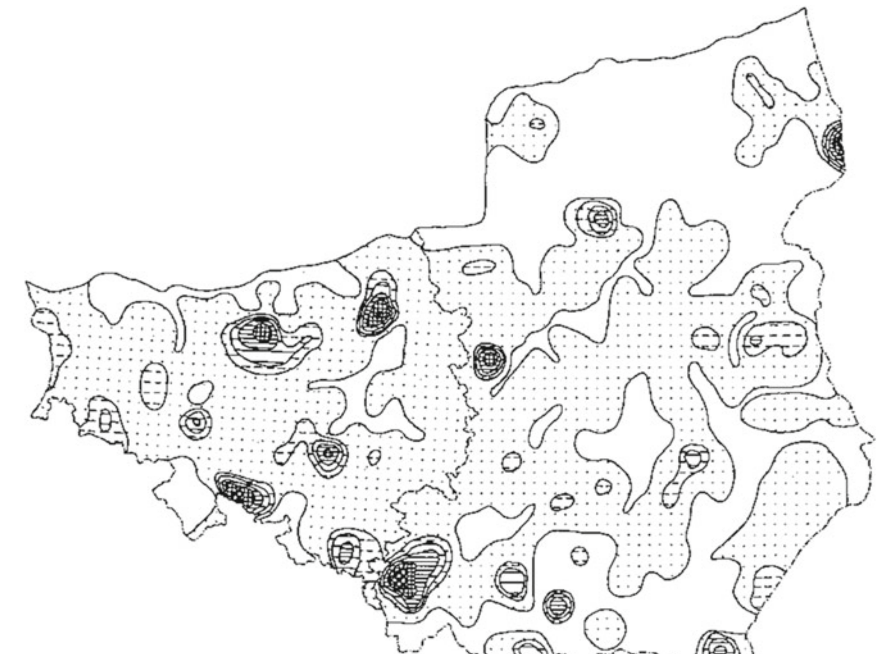

Fig. 5.4 Percent share of dam reservoirs south of the range of the last glaciation ranges in accordance with those adopted by Majdanowski [13]

dam reservoirs in comparison to the eastern part. The area south of the range of the last glaciation occupies 197 631.4 km^2, and the occurring dam reservoirs have a surface area of 926.91 km^2. The value constitutes 33% of the surface area of Polish lakes and is equivalent to the index of cover with dam reservoirs of 0.47%. It is, therefore, a very substantial value in comparison to the mean lake density of Poland equal to 0.9%. The number of dam reservoirs in the analysed area can be estimated for a dozen thousand. It should be mentioned that in the lake district zone, covered by the range of the last glaciation, many dam reservoirs are also located. The areas should be therefore considered in the total balance for the country.

Despite the known total surface area of dam reservoirs (approximately 1000 km^2), it is difficult to adopt their mean depth due to high depth variability. Their total water resources, however, are at a level of several km^3 and can constitute approximately ¼ of surface waters.

5.5 Changes in the Surface Area of Lakes and Their Water Resources

Lake Districts in north Poland cover an area of approximately 110 thousand km^2, which constitutes approximately 35% of the area of the country. They include 6 793 lakes (with an area of more than 1 ha), occupying approximately 2.77 thousand km^2 [1].

The decline of lakes is usually associated with a decrease in their surface area and water volume. This results from the fact that lakes in Poland are usually small and in the majority of cases shallow. The process of decline of lakes is determined by two primary factors: lake water level fluctuations and aggradation of sediments in the lake basin. Water level fluctuations in lakes are caused by climate changes, deforestation of the direct catchment, incorporation of lakes to the system of surface runoff, and various hydrotechnical works [14]. An increase in bottom sediments can be a result of deposition of mineral sediments supplied by rivers, aeolian processes, or those related to overland flow (deluvia) or mass movements, aggradation of the mass of biogenic sediments, and precipitation of chemical compounds. Sedimentation and sedimentation processes in lakes occur very rapidly, especially that over the last centuries in northern Poland strong deforestation took place. A decrease in the surface area of lakes has been very evident even over several decades. The process is considerably affected particularly by the location of a given lake in the hydrographic system, size of the (direct) catchment feeding the lake, surface formations (e.g. permeability), land use in the catchment, and human activity.

Several factors have been responsible for transformations of lakes. The following ones played the most substantial role: variable rate of melting of lumps of dead ice, short- and long-term climate changes, variable time of incorporation of lakes into the surface outflow system, catchment deforestation (concerning both the entire and direct catchment), hydrotechnical measures (from the mid-eighteenth century) and extensive melioration works. The rate of transformations of the lake basin from the moment of its origin to modern times, as a consequence leading to a decrease in their surface area, was characterised by high fluctuations. It was determined by two primary factors, namely: lake water level fluctuations (decrease), and filling the basin with accumulated biogenic and terrestrial sediments. Although in the process of evolution lakes underwent several stages of similar transformations, they are in different stages of development of their basins.

An attempt of determination of changes occurring in lake basins in the twentieth century was presented based on the example of selected lakes in Poland described in the relatively rich literature.

According to research conducted by various authors, a decrease in the water level in many lakes by 05–0.7 m caused an evident decrease in their surface area, sometimes even by 25–30% [15]. In some lakes, the water level decreased by even 2.5 m (Lake Miedwie) and more (Lake Gopło), causing a decrease in their surface area by more than 50% [16–18]). Choiński and Madalińska [19], analysing bathymetric plans of lakes in the Masurian and Pomeranian Lake District, concluded that over 60–70 years in the twentieth century, the surface area decreased by several percent, and the volume by several tens percent.

In a group of 18 lakes located in the Wielkopolskie Lake District throughout approximately 50 years, their considerable transformation was observed. Research evidenced a considerable decrease in the surface area by 14.8% (i.e. 172.6 ha). As a result of changes in the surface area and shallowing of lakes, water resources accumulated in the lakes decreased by a total of 7.7%, which constitutes 3.6 million m^3 [20]. It should be remembered, however, that the transformations are a natural element of their evolution. In the case of the analysed lakes, evolution is accelerated by human activity and climate changes.

Mięsiak-Wójcik et al. [21] presented changes in the surface area of stagnant waters in the western part of West Polesie (East Poland). The research was based on the analysis of the content of archival topographic maps of Poland at a scale of 1:10 000, presenting the situation from the early 1980s, and orthophoto maps and satellite images from the years 2010–2014. The objective of the analysis was the determination of the direction of transformations, as well as the presentation of results at variance with the opinion commonly adopted in Europe on a progressing decrease in the surface area of water bodies. The number of objects and their surface area increased over the last three decades. This resulted from the co-occurrence of natural factors and human activity, both destructive and aimed at the restoration of postglacial areas unique at the European scale.

Based on analyses of bathymetric plans of Lake Jamno from 1889 and 1960, [15] obtained an image of transformations of not only the surface area but also water resources. Throughout 71 years, the surface area of the lake decreased by approximately 150 ha, and the volume of the lake decreased by 9.247 thousand m^3, i.e. by 22.7%.

Water level fluctuations in 24 lakes of the Pomeranian Lake District were presented by Dąbrowski [22]. The author concluded that in addition to the primary elements of the climate, they are also largely determined by a group of individual features of lake catchments.

Very considerable changes occurred within the range of Lake Gopło as a result of regulatory measures and melioration works performed in the Noteć River valley in the years 1775–1878. The measures caused a decrease in the water level in the lake by 3.2–3.3 m, from 80.20 m amsl to below 77.00 m amsl [17]. A consequence of the changes is the division of former Lake Gopło into the modern lake and several smaller ones (Szarlej, Tryszczyn, Łunin, Gocanowskie, and Mielno) (Fig. 5.5). For Lake Gopło, changes in the volume of the lake in the analysed period of 246 years decreased from 235.8 to 76.7 million m^3. Therefore, the present lake only fills the deepest parts of the former Lake Gopło, constituting only 23.4% of its original surface area, and only 32.5% of its volume.

In the Pomeranian Lake District, the effect of all processes occurring in lakes is an evident succession of vegetation in lakes [23]. A good indicator showing an increase in vegetation succession is the index of overgrowing of the shoreline ($ha \cdot km^{-1}$). The value of the index from the turn of the 1950s and 1960s (preparation of bathymetric plans) is 0.98 $ha \cdot km^{-1}$, and that from the turn of the first and second decade of the twenty-first century (60 years of difference) already reaches 1.14 $ha \cdot km^{-1}$. This is strong evidence of an increase in overgrowing of lakes and vegetation succession irrespective of the type of vegetation [24].

The performed calculations with the application of a digital terrain model showed that the surface area of Lake Gopło in the period from the second half of the eighteenth century to the end of the first decade of the nineteenth century (1772–2010) decreased from 9 245.2 to 2 163.9 ha, i.e. by 76.6%.

Lake Ostrowskie (Gnieźnieńskie Lake District) also decreased its surface area but to a considerably lower degree. In the years 1887–2010, the total decrease in the surface area was 74.9 ha, i.e. 23.5%. Simultaneously with a decrease in the surface area of the analysed lakes, their water resources were also reduced. Lake Gopło decreased its volume by more than 67%, and Lake Ostrowskie by 21% [18].

Based on cartographic and teledetection materials, and geodesic measurements, changes in the morphometry of Lake Ostrowskie were traced throughout the last 123 years. As a result of a decrease in the water level, caused by various factors, the modern lake was divided into two separate basins (eastern and western). It caused a decrease in its surface area by 242.0 ha, and volume by 28.9%, whereas over the last 28 years by as much as 18.3% [25].

The effect of extensive regulation works conducted in the area of Wielkopolska and Kujawy generally involving drying of wetlands, straightening of river channels, channelling many sections of rivers, and incorporation of closed-drainage lakes to the outflow system was a decrease in the water level on many lakes by an average of 0.6–0.8 m, and in extreme cases even by 1.1–1.4 m. Such a considerable interference caused a decrease in their surface area by a dozen, and in extreme cases even by 80% [16].

The problem of the decline of lakes is exceptionally complex, particularly in the Wielkopolska-Kujawy Lake District, located in an area exceptional at the scale of the country due to low supply of atmospheric precipitation and therefore small water

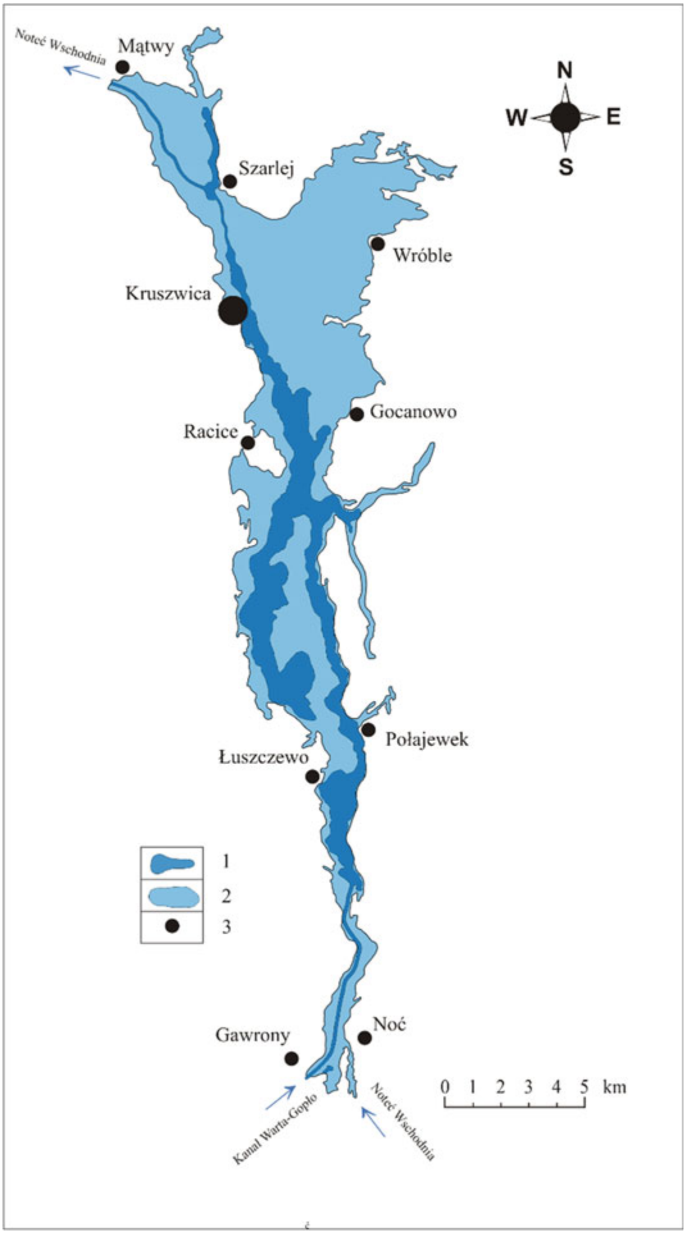

Fig. 5.5 Situational draft and changes in the range of Lake Gopło: 1 – today (77.00 m above sea level, 2 – rage of the lake at datum 80.00 above sea level (1772), 3 – localities

resources. Due to the combined effect of many natural and anthropogenic factors, it is difficult to perform hierarchization of their effects on a given lake. Due to this, attempts to solving the problem of the decline of lakes in the Wielkopolska-Kujawy Lake District require the collaboration of specialists from different disciplines of Earth sciences [26].

Changes in the surface area of lakes are undoubtedly largely determined by local factors. An example of this type of determination are results of research by [27]. Changes in the surface area of three lakes located near each other (in the Oder River catchment) were completely different. Over approximately 170 years, the surface area of one lake was absolutely stable, that of the other drastically decreased, and the third one was divided into three smaller basins – Fig. 5.6.

In order to determine how the course of time affects the longevity of lakes [28] performed the following analysis. In zones located between the ranges of subsequent phases of the last glaciation, i.e. the Leszno and Poznań, Poznań and Pomneranian, and north of the Pomeranian phase, the number of lakes was determined along with their total water resources, and total surface area. Knowing the surface area of the designated areas, three indices were determined for each of them, i.e. lake density, mean depth of lakes, and water resources in mm. The values were referred to the surface area, obtaining the layer of lake waters. The analysis shows that the lakes are increasingly "older" towards the south. Lake density consequently decreases southwards, and mean depth of lakes and the layer of water resources decreases [28].

Apart from many described cases of a decrease in the surface area of lakes, also cases of complete disappearance occur. The disappearance of Lake Jelenino near Szczecinek can be described as spectacular [29]. At the end of the eighteenth century, the lake had a surface area of 495.2 ha. As a result of intensive melioration, its basin lost water entirely. If the lake existed nowadays, it would be one of the largest lakes in Poland in terms of surface area.

A decrease in the total area of lakes in the Pomeranian Lake District throughout 40–50 years in the twentieth century by 9.69% suggests the process of their decline. This also concerns the remaining regions (Lake Districts) where the decline is even greater [1]. The decline of lakes is justly particularly associated with a decrease in the water level, accumulation of sediment in the lake basin, and progressing eutrophication.

Based on cartographic materials for 256 lakes in the Wielkopolska Lake District, [30] analysed changes in the degree of overgrowing of lakes throughout the last 60 years. As a result, a decrease in the surface area of lakes by 0.6% was determined (from 28 152.6 to 27 983.7 ha). Simultaneously, the surface area occupied by emergent vegetation increased by 1.7%. The tendency is confirmed by overgrowing presented for two selected lakes in the region with polymictic character [31].

Based on cartographic materials and aerial photographs, [14] analysed changes in the degree of overgrowing of lakes for 893 lakes located in lake districts in Poland (Pomeranian, Masurian, and Wielkopolska Lake District). The lakes were selected based on the existing bathymetric plans and information on their overgrowing and depth relations. Over the last 60 years, a decrease in the surface area of lakes by 1.9% was observed (from 140 975.0 to 138 273.7 ha). The surface area of lakes occupied

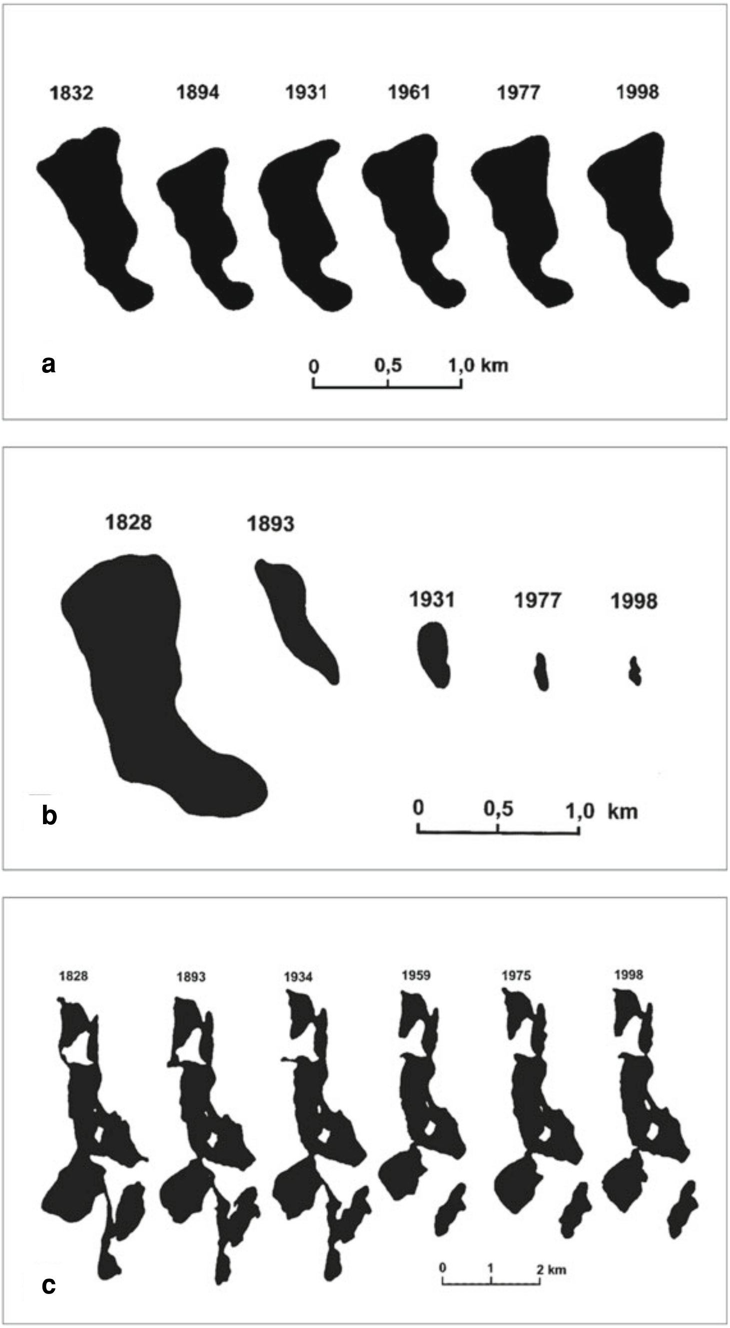

Fig. 5.6 Variability of the surface area of lakes located near each other; A – Lake Cisie – example of stability of surface area; B – Lake Grążyk – an example of drastic disappearance; C – a system of Lakes Chobienicko-Wielkowiejskie-Kopanickie – development of new lakes as a result of a decrease in the surface area of larger lakes

by emergent vegetation also decreased by 0.27% (from 11 219.0 to 10 637.2 ha). The surface area of lakes occupied by emergent vegetation averages 7.69%. In the case of lakes with small (below 80 ha) and medium surface areas (80 ÷ 200 ha), the degree of overgrowing was the highest, and equalled, respectively: 14.3 and 9.6%. Fast rate of overgrowing of the lakes is related to the amount and quality of biogenic substances migrating to lakes from the catchment area, the resistance of lakes to degradation, the contribution of the littoral zone in the surface area of lakes, and age of the lake.

A tangible effect of the changes in the lake basin was usually a shift of isobaths from the shores to the middle of the lake, and development of new peninsulas, islands, and in some cases the division of the original lake into several smaller ones [32]. An example is Lake Jamno where in the period 1889–1960 a decrease in the surface area by 6.5% and volume by 22.7% was determined [15]. Similar situations of changes were observed in other regions of the Polish Lowland ([25, 33–36]).

Similar changes also occur in lakes in Lithuania, Latvia, Estonia, and Finland. In Lake Luupuvesi (central Finland), the range of macrophytes increased from 96 ha in 1953 to 355 ha in 1996 [37]. Research conducted in shallow lakes: Engure (Latvia) and Võrtsjärv (South Estonia) confirm an increase in the range of macrophytes in the second half of the twentieth century [38].

The range of changes in water resources accumulated in lake basins, tarns, and artificial reservoirs can be insubstantial, which is undoubtedly particularly related to the process of decline of lakes. The parameter largely reflecting the predisposition of particular lakes to decline is mean depth. The value of the parameter for lakes in Poland is very variable, and in the Pomeranian Lake Districts it equals 6.84 m, in the Masurian Lake District – 7.45 m, in the Wielkopolska-Kujawy Lake District – 5.70 m, and in lakes south of the range of the last glaciation – 4.34 m [8]. Assuming that the mean depth of Polish lakes is 7.02 m, and mean annual accumulation of sediments is approximately 1 mm, the range of loss of water resources can be concluded. Considering only the sedimentation process in lake basins, the loss of resources is 0.014% annually, which permits the estimation of the prospective age of lakes for approximately 7 thousand years [8].

5.6 Conclusions

The total water resources comprised of lakes in Poland were estimated based on the Catalogue of Polish Lakes (Choiński 2006a) including information concerning surface area for 7081 lakes (above 1 ha). The calculation procedure involved summating known lake water volumes for more than 30% of lakes, and adding the total water volume of unmeasured lakes. This was calculated as a product of their surface area and mean depth equalling to 19.7349 km^3. Water resources within particular lake districts are as follows: Masurian Lake District – 10.1183 km^3 (51.27%), Pomeranian Lake District – 7.1292 km^3 (36.12%), Greater Poland-Kujavian Lake

District – 2.3535 km^3 (11.93%), and area south of the delineated range of the last glaciation – 0.1339 km^3 (0.68%).

Retention capacities were prepared based on the outlines of maps at a scale of 1:50,000 for more than 200 sheets of topographic maps. The determined retention capacity for the area north of the line delimiting the maximum range of the last glaciation is 162 mm. The greatest resources within the Masurian Lake District occur in the following catchments: Węgorapa (404 A) – 1976 mm, Biała Hańcza (407) – 958 mm, and Pisa (227 A) – 893 mm; and in the Pomeranian Lake District in catchments of: Drawa (119 D) – 389 mm, Wda (237 B) – 196 mm, and in the Przymorze catchment from Wieprza to Słupia (310) – 184 mm. Within the Greater Poland-Kujavian Lake District, lake catchments retain considerably less waters, and the most abundant ones include: Vistula from Bzura to Skrwa (233 A) – 173 mm, Warta from Wełna to Obra (118 G) – 141 mm, and Noteć to Gwda (119 A) – 116 mm. Zones with the lowest retention capacity, i.e. up to 50 mm, are located in valleys of the largest rivers with the adjacent areas, and coasts: Gdańsk, East Baltic, Szczecin, and the southern part of the Koszalin Coast. Mean retention capacity determined within the three lake districts is exceptionally variable. In the case of the Masurian Lake District, it is 283 mm, for the Pomeranian Lake District the index equals 150 mm, and for the Greater Poland-Kujavian Lake District only 58 mm. The division of the total volume of water resources of the lakes by the surface area of Poland provided a water layer of 63 mm. It constitutes only 10% of mean annual precipitation, and the value is approximately 3.5 times smaller than the amount of mean outflow from the territory of Poland.

5.7 Recommendations

Determining the volume of available water resources is of key importance in water resources management and also in defining the thermal budget of water, flood protection capabilities, fish farming and agriculture. The issues discussed should be of interest to a wide spectrum of researchers, decision makers and policy planners.

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