Polish J. of Environ. Stud. Vol. 20, No. 4 (2011), 931-940

Original Research

Dynamics of Lake Morphometry and Bathymetry in Various Hydrological Conditions

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Received: 18 November 2010
Accepted: 24 February 2011

Abstract

During recent decades, human impact on lake ecosystems has increased due to intensification of agriculture, irrigation, water consumption, and electrical purposes. Particularly strong changes have been observed in shallow lakes, which are more sensitive to environmental changes and characterized by unfavourable morphometric parameters. The majority of transformations within a lake associated with changes in water level, progressing degradation, or plant succession leading to lake disappearance take place within the littoral zone. The aim of this study was to examine how human pressure, such as water level reduction, affect the surface and water volume of lakes, and estimate the rate and the extent of water loss from lakes during 1940-2008, and predict their potential changes over the next years. The importance of integrating vertical and horizontal considerations in the management of shallow lakes was illustrated. The study was carried out in the freshwater, postglacial lakes Niepruszewskie and Tomickie, located in the central-western agricultural region of Poland. The research comprised analyses of the lakes' morphometry base on topographic maps, aerial photos, GPS measurements, and data from bathymetric plans and morphometric cards. The study has shown that the observed transformations in the examined lakes are multidirectional and the entire process varies in changing trophic and hydrological conditions. The increase of water retention in the water body increased the lake area, but at the same time accelerated the sedimentation process of organic matter and gradual lake shallowing at the accompanying expansion of the littoral zone area. During almost 70 years, the area of Lake Niepruszewskie shrank by 9%. The shallowing rate, which is not directly visible, was about three times as fast as the contraction of the area itself. In the case of the second of the examined lakes, shallowing and overgrowing processes follow the same course, which will lead to the disappearance of the lake within less than 56 years. The area of Lake Tomickie decreased almost twofold during almost 70 years. Our study shows that analysis of the lake surface alone is insufficient to assess directions of lake development and shrinking.

Keywords: lake shrinking, lake morphometry and bathymetry, physical limnology

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Introduction

From different types of water bodies, lake ecosystems are among the most sensitive to environmental changes. Long water retention time, domination of sedimentation and accumulation processes over erosion, and the large contact area of the lake with the surrounding catchment all distinguish lakes from river ecosystems [1, 2]. These features have a significant impact on water quality and quantity in reservoirs and influence biological processes that occur in water bodies at different trophic levels [3, 4].

During recent decades, human impact on lake ecosystems has increased due to intensification of agriculture, irrigation, and electricity purposes, as well as a result of climate change [5] and landscape alteration [6]. These factors affect water quality and quantity in ecosystems and the functioning of water bodies around the world. Changes observed in lake ecosystems occur due to natural reasons and human pressure. During the past half century, water bodies have been strongly affected by human pressure caused by the acceleration of water eutrophication or acidification [7-10]. In Western and Central Europe, this problem was observed during the 1980s and appropriate action was been undertaken [11]. In Poland (Europe) from 1954 to 2006, a total of 2,215 lakes (i.e. 23.82% of all lakes), disappeared [16]. This process is especially pronounced in the agricultural Wielkopolska region (15.21% from 1920 to 1975), where the process of lake disappearance is much faster than in other regions of Poland where human pressure is much lower, such as the Pomeranian or Mazurian Lake Districts (9.69% and 9.98% for the same period, respectively).

Human impact on lake ecosystems, despite undertaking numerous activities, is still high [7, 12]. In Europe, the Water Framework Directive (WFD) places a strong emphasis on water quality improvement to achieve good ecological status of water [11]. Particularly, the biggest changes have been in agricultural areas where, due to non-point pollution sources, it is difficult to reduce nutrient input into water [2, 7, 12]. Moreover, the application of WFD and Nitrate Directive [13] has been realized during recent years, thus achieving the aim is difficult during a short time, compared to the long time of human pressure on the ecosystem. Many lakes have rich nutrient deposits found primarily in sediments or littoral vegetation.

Particularly strong changes are observed in shallow lakes, which are more sensitive to environmental changes and characterized by unfavourable morphometric parameters such as low depth, considerable shoreline length, competition for surface area, short retention time, and often big catchment areas compared to the lake surface [14, 15]. Often this situation creates good conditions for the lake turning into a sedimentation tank for migrating matter. The majority of transformations within a lake are associated with changes in water retention, progressing water degradation or plant succession leading to lake disappearance [4, 9].

Shrinkage of lakes is usually identified with the decline of their area [16-18]. However, this dimension is not the only one which indicates lake disappearance. A lake, as a three-dimensional object, is necessary to be analyzed in all directions, therefore it is also important to consider depth changes as components of this process [19]. In many studies, lake decline is analyzed in horizontal approaches on the basis of morphometric maps or aerial photos, orthophotomaps, remote senensing, or GIS methods [16, 20, 21]. These tools limit the possibility to analyze sufficiently the direction of lake changes and to estimate the prediction rate of disappearance of the lake. On the other hand, bathymetric plans for this kind of comparison are rare. Bathymetric maps have become available in recent decades, which means that due to the lack of such tools earlier made it difficult directly to perform this kind of comparison.

The aim of our study was:

1) to assess the effects of human pressure, such as water level reduction and increase of nutrient availability, on the surface and water volume of lakes
2) to illustrate the importance of integrating vertical and horizontal considerations in the management of shallow lakes
3) to estimate the rate and the extent of water loss from Niepruszewskie and Tomickie lakes during 1940-2008, and predict their approximate time of disappearance.

Material and Methods

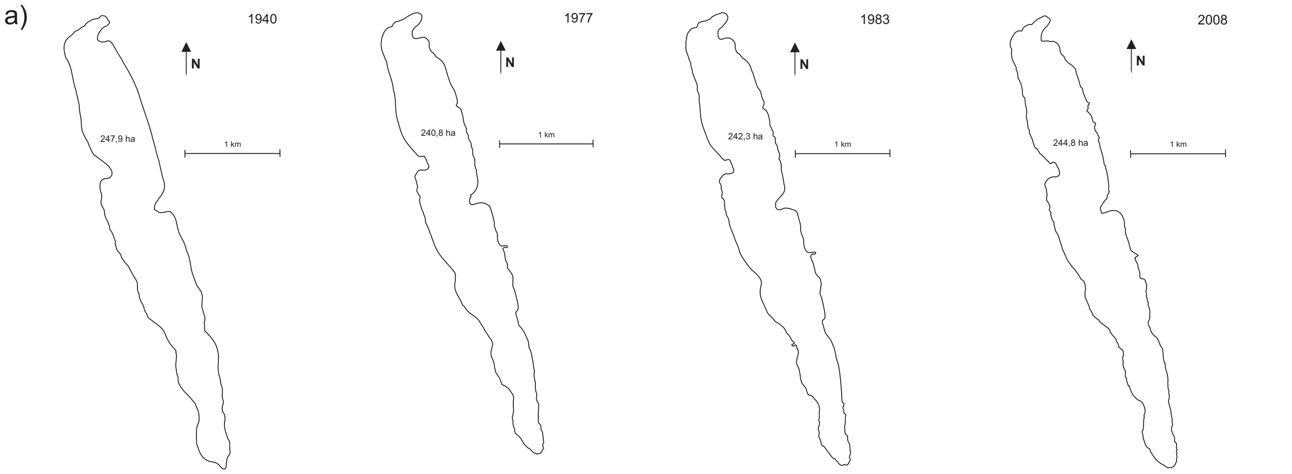
Study Site

The studied lakes, Niepruszewskie (52º22.700' N, 16º37.200' E) and Tomickie (52º19.200' N, 16º38.400' E), are located in the central-western agricultural region of Poland (Wielkopolska Region). Both studied lakes are situated in the Samica Steszewska River Basin and function as major subbasins of the river basin area. The lakes are interconnected via the Samica Stęszewska River with other 5 lakes.

These lakes belongs to the central part of the Poznań Lake District [22], filling the northern part of Niepruszewo-Strykowo tunnel valley that was formed as a result of subglacial erosion during the Early Leszno Phase [23]. According to Gogołek [23], until the beginning of the Holocene, the tunnel valley of lakes Niepruszewskie and Tomickie were filled with dead ice.

Lake Niepruszewskie is the first in a system of lakes interconnected by the Samica Steszewska River. This is a freshwater, postglacial lake, highly elongated in N-S direction. The water level was regulated at its outlet by a weir for irrigation purposes, from 1974 to 2002 with average amplitude of 0.8 m. During this period, the lake surface area varied between 260 ha, with a minimum water level of 76.50 m a.s.l., to 281 ha, with a maximum water level of 77.25 m a.s.l. Since 2003, water level has been reduced by 0.60 m during winter and by 0.40 m in summer. At the present time, the highest water levels still occur during early spring, mostly due to management of fisheries and after winter snow melt.

Lake Tomickie is the second in the line of lakes connected by the Samica Steszewska River and is located 4 km to the south of Lake Niepruszewskie. This is also a freshwater postglacial lake, elongated in N-SE directions. Water level in this lake had never been regulated, although the



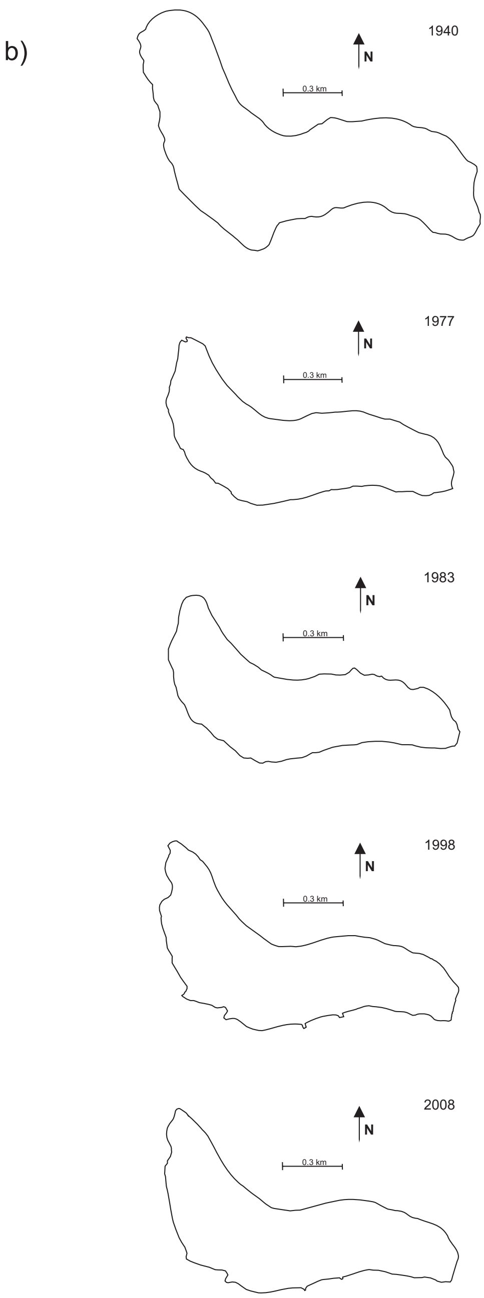


Fig. 1. Changes of the surface area of a) Lake Niepruszewskie and b) Lake Tomickie during 1940-2008.

regulation of water retention in Lake Niepruszewskie influenced water discharge of the Samica Steszewska River [25] and, automatically, affected the amount of water supplied to Lake Tomickie.

The lake, situated in the buffer zone of Wielkopolski National Park and Trzcielinskie Bagno reserve, is in the lake direct catchment area. This natural reserve was established to protect wetland, particularly nesting site wetlands and water birds and covers 38.14 ha of the buffer zone of the lake.

Water quality is characterized by high concentrations of phosphate and intensive algae bloom in both lakes [26]. Between the 1960s and 1990s, the catchment of the Samica Stęszewska River was heavily polluted and the water quality of the studied lakes was strongly affected by this period. Since the end of the 1990s, the point wastewater sources were eliminated in the catchments and measurements were taken to reduce nitrate water pollution from agricultural sources [12]. A slight improvement of water quality was observed, but water quality is still classified as very eutrophic [12, 26]. In 2005, chlorophyll a concentrations measured in Lake Niepruszewskie was 90 $\mu g \cdot dm^{-3}$. In 2008, a significant decrease of algae bloom was observed and chlorophyll a concentrations accounted for 28.35 $\mu g \cdot dm^{-3}$. In Lake Tomickie, high chlorophyll a concentrations were still measured during recent years (from 33.5 to 67.01$\mu g \cdot dm^{-3}$) [26].

Material and Methods

Surface shoreline area length of both lakes were determined by interpretation of aerial photos, ortho- and topographic maps, and on the basis of the materials presented in Table 1.

In 2008, surface and shoreline length of the studied lakes were measured in the field using GPS 12 Garmin Magellan. The measurements were made at the beginning of June at the average annual water level. All data were transformed to MapInfo Professional Program version 9.0 (license Poznań University of Life Sciences), and then lake surfaces were calculated.

All cartographic materials (orthophotomaps, aerial photography) were purchased in the Main Geodetic and Cartographic Documentation Centre in Warsaw, topograph-

Table 1. Sources used for surface and shoreline length calculations of the both lakes.

Type of maps	Scale	Year
Lake Niepruszewskie		
Topographic map of Buk commune	1:25,000	1940
Black-white aerial photography	1:13,000	1976
Topographic map of Dopiewo commune	1:25,000	1977
Topographic map of Dopiewo commune	1:25,000	1983
Topographic map of Dopiewo commune	1:25,000	1998
Ortophotomaps (pixel 0.5 m)	1:26,000	2007
Lake Tomickie		
Topographic map of Stęszew commune	1:25,000	1940
Topographic map of Stęszew commune	1:25,000	1977
Topographic map of Stęszew commune	1:10,000	1983
Black-white aerial photography	1:25,000	1986
Color aerial photography	1:26,000	1996
Topographic map of Stęszew commune	1:10,000	1998
Ortophotomaps (pixel 0.5 m)	1:26,000	2007

ic maps in the Voivodeship Geodetic and Cartographic Documentation Centre in Poznań, the topographic maps from 1940 were obtained from the Cartographic Archives of Adam Mickiewicz University.

Bathymetric maps of both lakes were carried out in June 2008 using an echo sounder Garmin Fishfinder 100. The measurements were performed from a pontoon using a GPS-coupled echo sounder (and a lead line to corroborate its readings). The depths of about 340 positions in Lake Niepruszewskie and 272 in Lake Tomickie were determined.

Based on the performed measurements, the following parameters describing lakes were analyzed: lake area (km^2), shoreline length (L_s), maximum lake length (L_{max}), volume (V), maximum and mean width (B_{max}, B_{mv}, respectively), maximum and mean depth (D_{max}, D_{mv}, respectively), relative depth (D_{rel}), elongation index (λ), shore development (L_{d1}, L_{d2}), index of lake exposure (Wo), and compactness index (Wz) [15, 17, 27].

The maximum length of Lake Niepruszewskie was determined as the maximum distance on the lake surface between two points on the shoreline, measured along the longest axis. To estimate the maximum length of Lake Tomickie, the shortest polygonal line connecting the two most distant points was designated [17]. The capacity of the lake volume was calculated as a sum of partial volumes corresponding to the area between the subsequent isobaths. Each volume was determined as truncated pyramids with bases delineated by two adjacent isobaths [15, 17, 27].

For comparive purposes, bathymetric maps and morphometric cards of Niepruszewskie and Tomickie Lakes from 1961 [28, 29] and 2008 were used. The first set of data came from the Institute of Inland Fisheries in Olsztyn and was collected in 1961 (Figs. 2, 3). For reference purposes, the volume and area of the lakes from IIF were assumed as 100%. It was assumed that, in both cases, the mapping was carried out at roughly mean water level.

To created a spatial image of shallowing, from each bathymetric plan around 20 latitudinal cross-sections of the bottom were made, starting from the western shore, and overlaid upon one another. This allowed the determination of the degree of shallowing, both in terms of the thickness of accumulated sediments and their spatial extent. Thus values were put inside the shoreline contour, which provided a basis for plotting isolines (isopachyte) showing changes in the bottom morphology. This method allowed us to bypass a small number of isobaths and determine depth changes of lakes more precisely. To calculate the changes of water volume and shallowing rate, planimetric measurements of the areas between determined isopachytes were taken.

The average increase of sediments also was calculated as a ratio between relative depth from 1961 and 2008. Next, shallowing rate was obtained by dividing the relative depth ratio by the number of analyzed years.

Results

Morphometry

Examination of the morphometric cards, topographic maps, and field measurements showed that surface area of Lake Niepruszewskie during almost 70 years decreased by 25.7 ha (Table 2, Fig. 1a). In the period from 1940-77, the lake shrank by 9% (5.3 ha). The biggest changes were noted

Table 2. Changes of the surface area and shoreline of lakes Niepruszewskie and Tomickie during 1940-2008.

Year	1940	1961	1977	1983	1998	2008
Source	Topographic map	Morhometric cart (IIF 1961a, b)	Topographic map	Topographic map	Topographic map	GPS measurements
Lake Niepruszewskie						
Altitude (m a.s.l)	77.8	75.8	76.3	75.8	76.0	76.34
Surface area (ha)	247.9	242.3	227.5	242.3	243.5	253.2
Shoreline (km)	11.1	11.1	11.0	11.3	11.3	11.4
Lake Tomickie						
Altitude (m a.s.l)	69.0	69.0	69.9	66.9	67.4	67.42
Surface area (ha)	62.0	47.2	39.2	36.0	40.7	38.7
Shore line (km)	4.22	3.55	3.19	3.1	3.52	3.340

Table 3. Changes of the morphometric parameters of the studied lakes in 1961 and 2008.

	Lake Niepruszewskie		Lake Tomickie	
Year	1961	2008	1961	2008
Source	Morhometric cart (IIF 1961a)	GPS measurements	Morhometric cart (IIF 1961b)	GPS measurements
Length (m)	4,900	4,920	1,450	1,340
Maximum width (B_{max}) (m)	700	700	450	380
Mean width (B_{mv}) (m)	495	500	326	289
Elongation index (λ) (-)	7.0	9.55	3.2	3.5
Shore Development Index L_{d1} (-)	2.01	2.07	1.46	1.5
Shore Development Index L_{d2} (-)	46	43.8	75	86
Volume (thousands m^3)	7578.3	7301.6	786.7	429.5
Maximum depth (Z_{max}) (m)	5.2	4.8	2.7	1.7
Mean depth (Z_{min}) (m)	3.13	2.93	1.7	1.1
Relative depth (Z_r) (m)	0.0033	0.0030	0.0039	0.0027
Depth Index (-)	0.60	0.64	0.62	0.65
Lake Exposure Index (Wo) (-)	78.16	80.26	27.77	34.87
Compactness Index (Wz) (-)	0.0313	0.0304	0.017	0.011

during 1940-77, when surface area decreases were observed. Since 1977, an opposite trend occurred. The surface area increased by 10% to 253.2 ha. The biggest changes occurred in the northern part of the lake (Fig. 2b, 3b). The length of the lake increased by 20 m (Table 3), although maximum width and development of the shoreline L_{d1} did not change significantly. Mean width of the lake increased by 5 m in comparison with the data from 1961, and the development of shoreline L_{d2} was enhanced by 4.8% (Table 3).

Significant changes were observed in Lake Tomickie, whose area decreased almost twofold during the studied period (Table 3, Fig. 1b). The smallest area was observed in 1983 – 36.0 ha, which was 41.9% smaller as compared to 1940. With the reduction of the surface area, water level decreased by 1.58 m from 1940 to 2008. During the late 1970s, the increase of water level was 0.9 m higher then was observed 9 years earlier (69.0 m a.s.l., and 69.9 m a.s.l., in 1940 and 1977, respectively) and then, during the following years, it sharply decreased by 3 m (67.42 m a.s.l. in 2008). Actual surface area of Lake Tomickie is 38.7 ha at average annual water level of 67.42 m a.s.l. (Table 2). The most significant changes were determined in the northern and southern parts of the lake (Figs. 2b, 3b), i.e. at the inflow and outflow of the river, and in the western part, near villages.

Changes of Lake Tomickie surface reflect changes of morphometric parameters, i.e. width and length. Maximum length decreased by 110 m and width by 70 m, which gives a higher shore development index (Table 3). The shoreline of the lake declined by 900 m during the analyzed period (Table 3). The shortest line was recorded in 1983, and it was nearly 26% longer than the length of the lake 43 years earlier. The actual length of shoreline has moved into the lake in comparison with 1961. The maximal and relative length of the lake reduced by 110 m and 37 m, respectively, and maximal width by 70 m. Other parameters such as elongation index λ, and shoreline development L_{d1} and L_{d2} also decreased significantly (Table 3). Between 1961 to 2008, a matter of 47 years, Lake Tomickie dwindled by about 23.3 ha, which gives a rate of 0.3 ha per year, which will lead to the disappearance of the lake within less than 113 years if current conditions persist.

Bathymetry

Analyses of bathymetric plans from 1961 and 2008 showed reduction of the capacity of both studied lakes (Table 4, 5, Figs. 2, 3). Maximum and relative depths of Lake Niepruszewskie were reduced by 0.4 m and 0.1 m, respectively. During a period of 47 years, the capacity of the lake decreased by 4% (276.7 thous. m^3). The reduction of the water capacity was strongest in the upper part of the lake, between isobaths 0-2.5 m. This layer decreased by 4,542.900 m^3 (60%). Nevertheless, increased water capacity was determined between isobaths below 2.5 m. Enhanced water capacity was around 64%, i.e. 4,815.400 m^3. During 47 years, the volume of Lake Niepruszewskie decreased by 4%, which gives a rate of 0.08% per year, which will lead to the disappearance of the lake within 1,230 years.

However, these differences were estimated on the basis of the bathymetric plans determined on annual water level. In fact, this level was reduced by 0.9 m. The capacity of Lake Tomickie shrank almost by 357,200 m^3. Maximum and relative depth of Lake Niepruszewskie were reduced by 1.0 m and 0.6 m, respectively. The biggest changes in water volume were noted below isobaths 1.0 m, which decreased by 30% (232,400 m^3) (Table 5). During 47 years, the volume of Lake Tomickie decreased by 83.17%, which gives a rate of 7.8% per year, which will lead to the disappearance of the lake within less than 56 years.

Shallowing Rate

The fastest process of lake shallowing were observed along the longitudinal axis in both lakes. This process was very significant in both cases because shallowing achieved more than 0.8 m (Figs. 2c, 3c). Maximum sediment increases were observed in the zone where, in the beginning of the 1960s, isobaths of the greatest depths were situated.

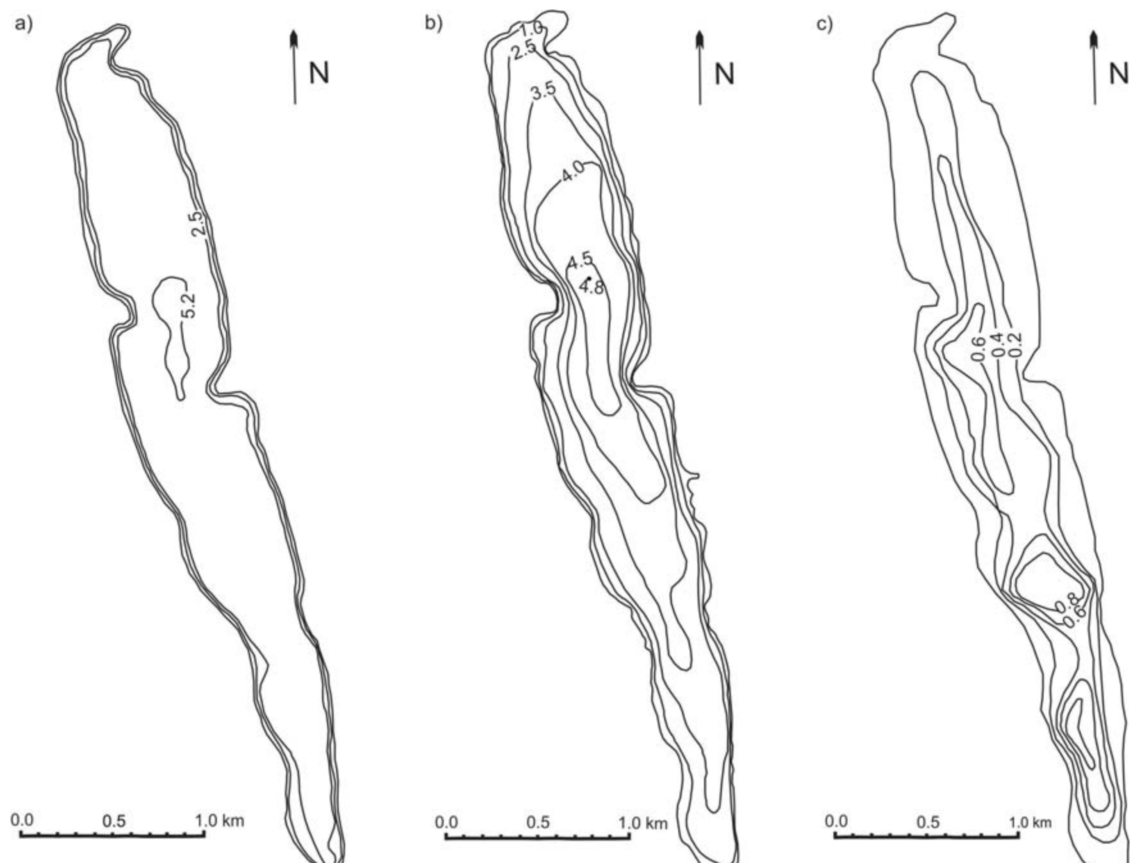


Fig. 2. Bathymetric plan of Lake Niepruszewskie from a) 1961 [15], b) 2008 and shallowing of Lake Niepruszewskie c) between 1961 and 2008.

Table 4. Bathymetric card of Lake Niepruszewskie from 1961 and 2008.

Izobaths (m)		Isobath surface	Surface area between isobaths		Volume between isobaths	
		(ha)	(ha)	(%)	(thous. m³)	(%)
Niepruszewskie Lake			Year 1961		[28]	
0.0	0-1	242.3	15.4	6.4	2,345.6	30.9
1.0	1-2.5	226.9	27.4	11.3	3,193.0	42.1
2.5	2.5-5.0	199.5	192.4	79.4	2,035.0	26.9
5.0	>5.0	7.1	7.1	2.9	4.7	0.1
Niepruszewskie Lake			Year 2008		(GPS measurements)	
0.0	0.0-1.0	253.2	31.5	12.4	157.5	2.2
1.0	1.0-2.5	221.7	47.9	19.0	838.2	11.5
2.5	2.5-3.5	173.8	71.2	28.1	2,136.0	29.3
3.5	3.5-4.0	102.6	47.24	18.7	1,771.5	24.3
4	4.0-4.5	55.36	43.51	17.2	1,849.2	25.3
4.5	>4.5	11.85	11.85	4.7	549.2	7.5

Table 5. Bathymetric card of Lake Tomickie from 1961 and 2008.

Izobaths (m)		Isobath surface	Surface area between isobaths		Volume between isobaths	
		(ha)	(ha)	(%)	(thous. m³)	(%)
Tomickie Lake			Year 1961		[29]	
0.0	0.0-1.0	47.2	7	14.8	436.6	55.5
1.0	1.0-2.5	40.2	30.9	65.5	343.9	43.7
2.5	>2.5	9.3	9.3	19.7	6.2	0.8
Tomickie Lake			Year 2008		(GPS measurements)	
0.0	0.0-1.0	75.8	8.8	22.7	311.8	72.6
1.0	1.0-1.5	29.9	27.2	70.3	99.7	23.2
1.5	>1.5	2.7	2.7	7.0	18.0	4.2

The average increase of sediments, calculated as the ratio between relative depth from 1961 and 2008, was for Lake Niepruszewskie at 2.3 cm per year, and for Lake Tomickie at 3.07 cm per year. Shallowing rate, obtained by comparison of the bathymetric maps, for first lake in the series was 30 cm and for the second one 39 cm during 1961-2008, which gives 0.6 cm per year and 0.8 cm per year for each lake, respectively. This process in Lake Tomickie was 1.3 times faster than in Lake Niepruszewskie.

Discussion

The performed investigations revealed that lake shallowing may be faster than the reduction of water areas. In addition, observation of the lake surface alone may be misleading and result in misinterpretation of the lake disappearance or enlargement. The performed investigations indicated that the area of Lake Niepruszewskie increased in comparison with earlier years, albeit at a simultaneous decrease of lake volume. In the case of Lake Tomickie, these processes are quite complex and accompanied by intensive processes of lake shallowing. Therefore, analyses of aerial and satellite pictures fail to reflect the true rate of shrinkage of water areas, particularly in view of the fact that these processes can take place with varying intensity and in different directions. According to Munyaneza et al. [21], the combination of a technique of estimating water levels by combining information from satellite images may provide accurate analyses of lake development.

There is no doubt that both the intensity and direction of occurring transformations are affected by the type of the analyzed water area [18, 30]. On the one hand, shallow lakes are believed to be more susceptible to continentalization processes due to increased availability of the surface to rush vegetation and reduced ability for nutrient compound reduction, as well as to accelerated eutrophication processes in which succession of the emergent vegetation occurs rapidly [31, 32]. However, as indicated by the performed investigations, in increased organic matter sedimentation the shallowing of the body may occur intensively [33]. The process was found to occur in polimictic Lake Tomickie, in which both processes are intense. In the case of glacial lakes, in particular those situated in mountain areas, analysis of the lake surface is insufficient [34]. This is caused by considerable quantities of drifted material, especially during intensive rainfall, snow thaws, or falling avalanches. Usually, isolation of these water bodies favours the oligotrophic character of such waters and indicates that these reservoirs are not subjected to shallowing processes and, additionally, they are

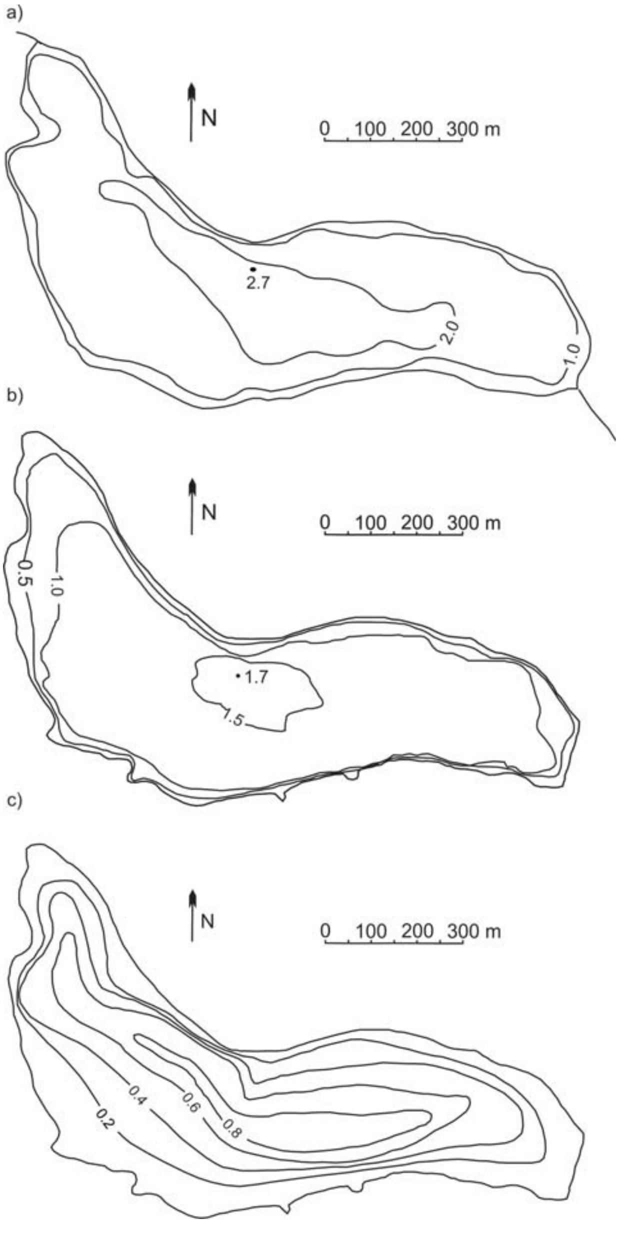


Fig. 3. Bathymetric plan of Lake Tomickie from a) 1961 [16], b) 2008 and shallowing of Lake Tomickie, c) between 1961 and 2008.

not observed to be taken over by plants. Therefore, surface analysis of such water bodies not only fails to reflect the process of lake reduction but also makes impossible the assessment of its retention capabilities. The assessment of the lifespan of lakes and the direction of processes taking place in them can only be reliably estimated by analyzing changes in lake capacity.

A ratio between surface area and volume retention of the studied lakes increased, during almost 70 years, from 0.03 (for both lakes) to 0.08 and 0.09, respectively. Calculated ratios indicate direction of lake changes and can be a useful tool for lake disappearance.

Changes taking place in the lakes can occur with different intensity, which is the result of natural and anthropogenic factors. The performed investigations revealed that the area increase of Lake Niepruszewskie was caused by damming of the lake. Increased water levels, on average, by 0.5 m resulted in the increase of the area of the reservoir by 10%. However, the analysis of the volume of Lake Niepruszewskie showed its decline by 4% and reduction of average annual level by 0.9 m. Taking into consideration changes in the water level, the degree of shallowing amounted to 0.8 m. As confirmed by numerous studies [35, 36], water level regulation exerts a significant impact on changes in lake area and capacity. In addition, it also affects river flows down the water body and, consequently, influences the supply of the remaining water areas situated along the river flow. In the majority of the analyzed cases, damming is associated with increased retention of a given water body. However, as indicated by many investigations, retention of a water body, in the result of silting and sedimentation, can decrease significantly and lose its function. Such a mechanism is observed in the case of artificial dam reservoirs [35, 36], whereas in the case of natural lakes in which the water table is regulated, there is still insufficient evidence.

The greatest area changes were observed in the case of Lake Tomickie, where the gradual process of its overgrowth is observed. In the period from 1940 to 2008, the area of the lake decreased by 37.6% in comparison with 1940. This shows that the lake shrinking process is more intense than indicated by the average level of the total area decrease for the Wielkopolska-Kujawy Lake District, which amounted to 15.21% over a period of more than a half century [16]. A rapid current rate of lake area decrease in the above-mentioned region is also confirmed by investigations conducted by Nowacka and Ptak [37]. Another factor indicating unfavourable changes taking place in Lake Tomickie is its shallowing, which amounts to, on average, 0.8 cm a year. This is more than three times faster than the rate recorded for polimictic Lake Jamno [17], exposed to strong anthropopressure. The principal cause of the shallowing of Lake Tomickie was the increase of the organic matter volume that had accumulated in bottom sediments resulting in intensive water blooming as well as high productivity of this water body. This resulted from, among other factors, considerable supplies of biogenic compounds to this water body as well as high degradation sensitivity caused, primarily, by such parameters as: Schindler coefficient and the utilization of the catchment characterized by high proportions of arable land

(60.8% in the lake direct catchment basin). Despite high levels of water contamination with nitrates, the lake is not included on the list of areas vulnerable to agricultural contamination, especially in view of the fact that it receives significant quantities of contaminants brought in with the waters of the Samica Steszewska River from Lake Niepruszewskie and the agricultural area of the catchment. This is confirmed by numerous publications concerning the area of the Samica Steszewska River catchment [25, 26, 38]. Moreover, elevated nitrate concentrations were recorded during the spring period, evidently confirming the agricultural origin of water contamination. On the other hand, Lake Niepruszewskie and its catchment were included in the nitrate vulnerable zones (NVZ) due to high levels of water eutrophication [12]. This poses a considerable hazard to the water quality of Lake Tomickie, which is situated below and to the protected area of "Trzcielińskie Bagno," which lies within the range of influence of the lake waters.

The process of succession of Lake Tomickie could have been accelerated by land improvement work as evidenced by numerous melioration ditches found around this water body. It is clear from literature [16, 17] that changes in lake areas due to intensive land improvement works were observed, particularly in the 19th century. The smallest area of Lake Tomickie so far was recorded during damming of waters in Lake Niepruszewskie, when the outflow of waters from that lake was considerably reduced. Despite the current reduction of water lifting, the water area in Lake Tomickie continues to decline. It can be presumed that the current state of this lake may be attributed to the complexity of overlapping events, including low precipitation in the entire catchment basin situated in the centre of Wielkopolska region characterized by the lowest mean-annual precipitation of 550 mm [39]. This leads to periodical drying of the Samica Stęszewska River, as well as other sources of water supply. Moreover, household sewage discharges also contributed to the acceleration of the eutrophication rate of this water body [25], leading to its disappearance. Regulation of the Samica Stęszewska River further below the lake, which took place in the 1970s, increased the water outflow from this body and dramatically lowered the water level. Our results revealed that if no actions are undertaken to stop degradation of Lake Tomickie, it will disappear within the period of about 56 years. The obtained results also indicate that it is necessary to undertake immediate and radical actions aimed at improving water quality and limiting the impact of further water eutrophication.

Conclusions

The study has shown that the observed transformations in the examined polimictic lakes are multidirectional and the entire process varies in changing trophic and hydrological conditions. The increase of water retention in the water body increased the lake area, but at the same time accelerated the sedimentation process of organic matter and gradual lake shallowing. In the case of the second of the examined lakes, shallowing and overgrowing processes follow the same course, which will lead to the disappearance of the lake within less than 56 years.

The performed investigations also showed that the analysis of the lake surface alone is insufficient to assess directions of development or overgrowing (changes) of these lakes. The combination of evaluation methods, for example remote sensing and GIS technologies with lake bathymetric measurements, make it possible to determine exactly the direction of changes occurring in water bodies. This knowledge will allow managers to elaborate the most effective methods of improvement of water ecological condition thanks to the application of appropriate restoration methods of water bodies or other actions in the area of the catchment basin.

Acknowledgements

This research was supported by grants contract No. N N305 055234 from the Ministry of Science and Higher Education. The authors are also grateful for technical assistance provided by Henryk Szwedt.

References

1. KLING G.W., KIPPHUT G.W., MILLER M.M., O'BRIEN W.J. Integration of lakes and streams in a landscape perspective: the importance of material processing on spatial patterns and temporal coherence. Fresh. Biol. **43**, 477, **2000**.
2. NEAL C., JARVIE H.P., LOVE A., NEAL M., WICKHAM H., HARMAN S. Water quality along a river continuum subject to point and diffuse sources and canal water interchange. J Hydrol. **350**, (3-4), 154, **2008**.
3. NAIMAN R.J. Characteristics of sediment and organic carbon export from pristine boreal forest watersheds. J. Fish. Aquat. Sci. **39**, 1699, **1982**.
4. PARTANEN S., LUOTO M., HELLSTEN S. Habitat level determinants of emergent macrophyte occurrence, extension and change in two large boreal lakes in Finland Aquatic Botany, **90**, 261, **2009**.
5. HOLLIS G.E., STEVENSON A.C. The physical basis of the Lake Mikri Prespa systems: geology, climate and water quality. Hydrobiologia **351**, 1, **1997**.
6. CHAPMAN C.A., CHAPMAN L.J. Deforestation in tropical Africa: impacts on aquatic ecosystems. In: Crisman T.L., Chapman L.J., Chapman C.A., Kaufman L.S. (Eds.), Conservation, Ecology, and Management of African Freshwaters. University Press of Florida, Gainesville, FL, pp. 229-246, **2003**.
7. DEFRA The protection of waters against pollution from agriculture. Consultation on implementation of the Nitrates Directive. ADAS Report, England, 56, **2007**.
8. NIEDZIELSKI P., SIEPAK J., SIEPAK M., KRASKA M. Occurrence of arsenic, antimony and selenium in surface waters of Drawienski National Park. Polish Journal of Environmental Studies **11**, (1), 41, **2002**.
9. MITRAKI C., CRISMAN T.L., ZALIDIS G. Lake Koronia: shift from autotrophy to heterotrophy with cultural eutrophication and progressive water-level reduction. Limnologica **34**, 110, **2004**.
10. PUACZ W., SZAHUN W., SIEPAK J., SOBCZYNSKI T.

Determination of selected sulphur speciation forms in fresh water lakes and bottom sediments. Polish Journal of Environmental Studies, **10**, (5), 365, **2001**.
11. EUROPEAN COMMISSION Directive 2000/60/EC of the European Parliament and of the Council – Establishing a framework for Community action in the field of water policy. Brussels, Belgium, 23 October **2000**.
12. LAWNICZAK A.E., ZBIERSKA J., KUPIEC J. Changes of nutrient concentrations in water sensitive to nitrate pollution from agricultural sources in the Samica Stęszewska River catchment. An. of War. Univ. of L. Sci., Land Recl. **40**, 15, **2008**.
13. EUROPEAN COMMISION Council Directive concerning the protection of waters against pollution caused by nitrates from agricultural sources 91/676/EEC, Off. J. Eur. Commun. L375 31/12/1991: 1-8, **1991**.
14. SCHEFFER M. Ecology of Shallow Lakes. Chapman and Hall, London, pp. 357, **1998**.
15. WETZEL R.G. Limnology: Lake and River Ecosystems. Academic Press, San Diego, pp. 1006, **2001**.
16. CHOINSKI A. Polish Lake Catologue. Adam Mickiewicz University Publishing, Poznan, pp. 599, **2006** [In Polish].
17. CHOINSKI A. Physical limnology of Poland. Adam Mickiewicz University Publishing, Poznan, pp. 547, **2007** [In Polish].
18. REBELO L.-M., FINLAYSON C.M., NAGABHATLA N. Remote sensing and GIS for wetland inventory, mapping and change analysis. J.of Env. Manag. **90**, 2144, **2009**.
19. CRISMAN T.L., MITRAKI CH., ZALIDIS G. Integrating vertical and horizontal approaches for management of shallow lakes and wetlands. Ecol. Eng. **24**, 379, **2005**.
20. CHOINSKI A., PTAK M. Lake infill as the main factor leading to lake's disappearance. Polish J. of Environ. Stud. **18**, (3), 347, **2009**.
21. MUNYANEZA O., WALI U.G., UHLENBROOK S., MASKEY S., MLOTHA M.J. Water level monitoring using radar remote sensing data: Application to Lake Kivu, central Africa. Phys. Chem. Earth. **34**, 722, **2009**.
22. KONDRACKI J. Polish Regional Geography, Wydawnictwo Naukowe PWN, Warszawa, pp. 440, **2000** [In Polish].
23. GOGOŁEK W. Explanation of the detailed geological map of Poland 1: 50 000. Arkusz Buk. Wydawnictwa Geologiczne, Warszawa. **1993** [In Polish].
24. LAWNICZAK A.E., CHOINSKI A., ZBIERSKA J., SZCZEPANIAK W. Response of emergent macrophytes to hydrological changes in a shallow lake, with special reference to nutrient cycling. Hydrobiologia, **656**, 243, **2010**.
25. ZBIERSKA J., MURAT-BŁAŻEJEWSKA S., SZOSZKIEWICZ K., LAWNICZAK A.E. The nutrients balance in Wielkopolska agro-ecosystems with respect to water quality protection using the Samica Stęszewska river watershed as example. Wyd. AR, Poznan, pp. 133, **2002** [In Polish].
26. LAWNICZAK A.E., ZBIERSKA J., CHOINSKI A. Ecological status assessment of lakes from the point of view of Water Framework Directive. Zesz. Post. Nauk Rol. **540**, 55, **2009** [In Polish].
27. WETZEL R.G., LIKENS G.E. Limnological Analyses. 3rd Ed. Springer, New York, pp. 429, **2000**.
28. IIF. Bathymetric map of Lake Niepruszewskie. Institute of Inland Fisheries, Olsztyn, **1961**.
29. IIF. Bathymetric map of Lake Tomickie. Institute of Inland Fisheries, Olsztyn, **1961**.
30. ROSENQVIST A., FINLAYSON C.M., LOWRY J., TAYLOR D. The potential of long wavelength satellite borne radar to support implementation of the Ramsar Wetlands Convention. Aqu.Cons.: Marine and Fresh.Ecos. **17**, 229, **2007**.
31. HELLSTEN S., KETO A., SUORANIEMI M., PARTANEN S. Long term changes in the aquatic vegetation of Lake Päijänne, Southern Finland. Verh. Int. Ver. Limnol. **29**, 1167, **2006**.
32. MÄEMETS H., FREIBERG L. Characteristics of reeds on Lake Peipsi and the floristic consequences of their expansion. Limnologica **34**, 83, **2004**.
33. BRENNER M., KEENAN L.W., MILLER S.J., SCHELSKE C.L. Spatial and temporal patterns of sediment and nutrient accumulation in shallow lakes of the Upper St. Johns River Basin, Florida. Wetlands Ecol. Manag. **6**, 221, **1999**.
34. CHOINSKI A. Changes in bathymetry of Maly Staw and Wielki Staw in the Karkonosze (Giant) Mountains. Limnological Review **3**, 37, **2003**.
35. HAIRSINE P. Controlling sediment and nutrient movement within catchments. Industry report, Cooperative Research Centre for Hydrology, Melbourne, **1997**.
36. SYARIMAN S., SYARIMAN P. Sedimentation control: part II. Intensive measures the inside of the Mrica reservoir, Central Java. J. of App. Sc. Env. San. **3**, (1), 17, **2008**.
37. NOWACKA A., PTAK M. The change of the surface lakes on lake district wielkopolsko-kujawskie in XX age. Bad. Fizj. nad Pol Zach. Seria A – Geog. Fiz. **58**, 149, **2007** [In Polish].
38. ZBIERSKA J., LAWNICZAK A.E. Impact of through-flow lakes on the quality of water in the Samica Stęszewska River. Zesz. Nauk. A.R. Kraków, Inż. Środ. **433**, 7, **2006** [In Polish].
39. WOS A. Climate of Poland. PWN, Warszawa, pp. 303, **1999** [In Polish].