

Article

The Influence of Hydrometeorological Conditions on Changes in Littoral and Riparian Vegetation of a Meromictic Lake in the Last Half-Century

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Abstract: Changes in water levels in lakes play an important role in the development of their coastal zones and water trophy. The aim of this study was to assess the role of changes in hydrometeorological conditions in the development of littoral and riparian vegetation of a meromictic lake during the last half-century. The study was carried out in Lake Powidzkie, one of the largest water reservoirs located in central Poland. Water level and meteorological conditions were analyzed in the period 1961–2015. Modifications in the range of plant communities were analyzed on the basis of cartographic materials and field studies. Meteorological conditions, especially precipitation and evaporation, were found to strongly affect the lake's water retention, whilst they had less of an effect on water levels. A significant effect of the lowering of the water level in Lake Powidzkie on the development of the littoral zone, whose area more than doubled over the last half-century, from 41.5 to 118.8 ha, was noted. The most dynamic development of the littoral was observed in the last quarter of the century, in which three of several years of low-flow were recorded. The occurrence of periods with an increased amount of precipitation, after dry periods, did not contribute to the reduction of the size of the rush zone and limitation of the development of woody vegetation.

Keywords: water level changes; climatic water balance; water retention; water quality; anthropogenic pressure

1. Introduction

In the last half-century, lakes have undergone many extreme phenomena, partly following natural causes, but above all, due to human activities [1–3]. Numerous droughts have alternated with extremely wet periods, which, in water bodies, are manifested by changes in water levels from extremely high to extremely low in a short period of time [4–6]. These changes have had a major impact on lake ecosystems, especially coastal and littoral vegetation [7–9].

The long-term occurrence of high water levels contributes to the transformation of zones towards the development of rush vegetation [10–13]. Then, the disappearance of vegetation characteristics of terrestrial and ecotone habitats can be observed. During dry periods, large areas previously covered with water are uncovered, which contributes to the rapid mineralization of accumulated organic matter that may cause rapid changes in lake functioning [14–16]. An increase in the contents of nutrients is most noticeable in lakes with low trophy levels [11]. Therefore, it is important to establish the extent of the area affected by changes in the water level of a given lake and predict long-term effects of these modifications. Moreover, due to the currently occurring significant changes in meteorological conditions caused by climate change, the dynamics of these processes can be significant [12].

Changes in the water level may cause important transformations in the composition of plant species, for instance, they may support the growth of fast-growing, highly plastic taxa. Recently, processes of lake overgrowth by reeds have been observed in many lakes [13,14], mostly due to lowering water levels. Additionally, the progressive succession of shrubs or trees may be observed with the depletion of water depth, mostly in the shallowest part of the water body. Taking into consideration the important roles of the littoral and riparian zone in lake functioning, recognition of the processes of plant succession and their direction is crucial.

Long-term studies of water levels in Polish lakes have been conducted for dozens of water bodies under the monitoring program carried out by The Institute of Meteorology and Water Management—National Research Institute (IMGW-PIB). One of them is Lake Powidzkie, located in Wielkopolska region, in the central-western part of the country. The studied lake is one of the most intensively used recreational areas in the region, among others, due to the varied coastline and good water quality.

The aims of the study were (i) to analyze the impact of selected hydrometeorological conditions on the development of vegetation in the riparian and littoral zones of a mesotrophic lake in the period from 1961 to 2015, and (ii) to assess the influence of meteorological conditions on water level changes, water retention, water quality, and morphometric parameters of the lake. Additionally, the factors influencing the changes in vegetation development in the riparian area were studied.

2. Study Area

Lake Powidzkie is located in Wielkopolska region, about 80 km east of Poznan, in central-western Poland (Figure 1). It is a gutter lake with an area of 1084 ha [15], with an elongated shape, varied shoreline, and diverse bottom morphology. The middle part of the lake is a wide main pool from which four branches extend, of which the southern one is the longest and deepest (max 47.0 m).

Hydrographically, the area covered by the study is a part of the drainage system of the Meszna River, having its origin at the southern part of Lake Powidzkie (Figure 1). Currently, it is a periodical watercourse whose flow rate during wet periods rarely reaches more than 100 L s^{-1} . The lake is fed by several small watercourses, characterized by small discharges on the level of a few to a dozen L s^{-1} , which mainly function during ice-free periods [16].

The catchment area is dominated by arable land, which occupies 68.9% of it. Dense forest complexes occur along the northern shores of the lake and in its south-western part, occupying about 15.7% of the catchment area. In the immediate proximity of the lake, there are several villages, the largest of which is Powidz. Lake Powidzkie, together with the other surrounding lakes, is protected as part of the Natura 2000 network, as the Special Habitat Protection Area PLH 300026—Gniezno Lakeland, due to the presence of several types of habitats, including *Chara* meadows.

3. Materials and Methods

The meteorological conditions and hydrological regime of the lake were characterized on the basis of the data from the Institute of Meteorology and Water Management—National Research Institute (IMGW-PIB). The hydrological data included daily measurements of the water level in the lake recorded by the water level gauge in Powidz, located in the western part of the basin, and in the Meszna River, which is the outlet of Lake Powidzkie (Kochowo cross-section). The precipitation data were obtained from the Powidz station. The distribution of precipitation within the lake was calculated for the plots of the size $100 \text{ m} \times 100 \text{ m}$, by interpolating the adjusted results from precipitation stations located nearest to the lake.

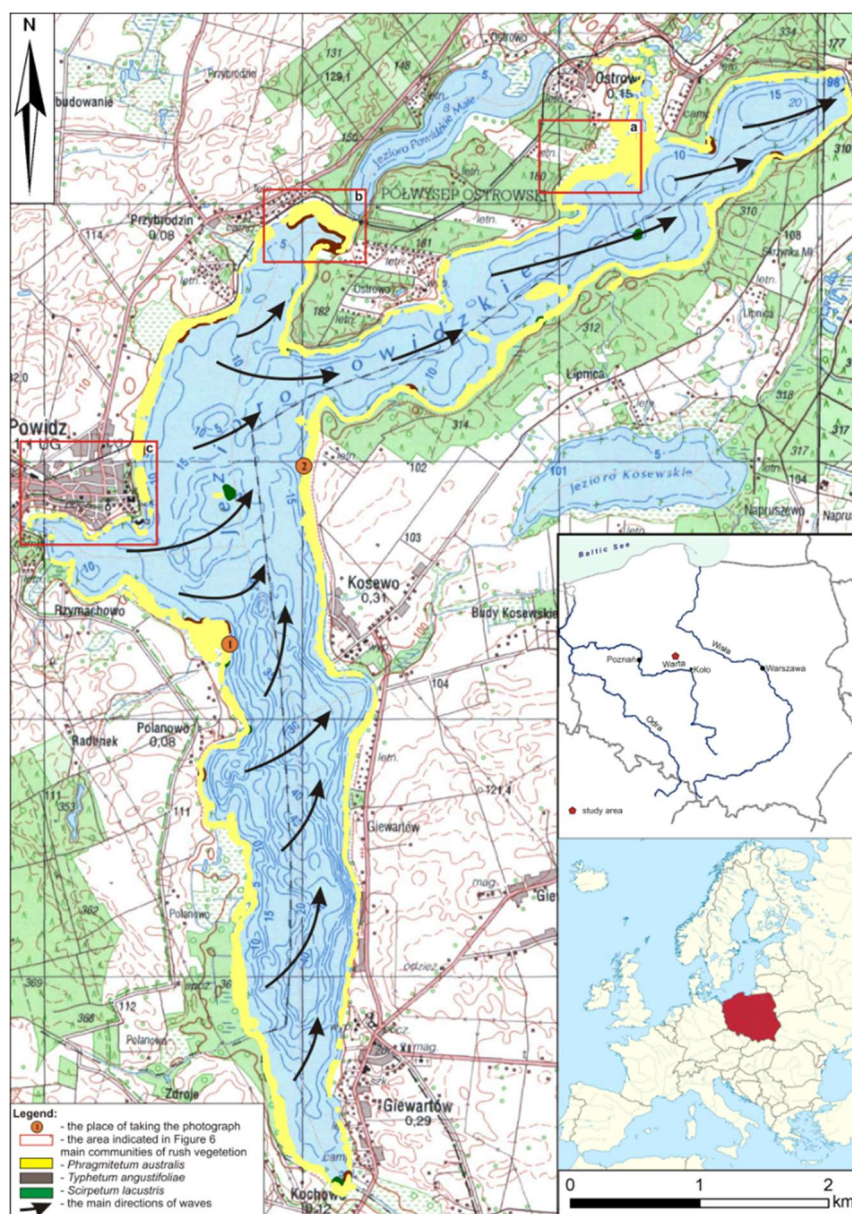


Figure 1. Location of Lake Powidzkie.

Rother meteorological conditions were obtained from the climatological station in Słupca (located 10 km to the south of the lake) and the synoptic station in Koło (located 40 km to the east of the lake). The division into dry, normal, and humid years was conducted according to the classification of Kaczorowska [17], assuming a normal year when annual precipitation falls in the range of 89–111% of the multi-annual mean (1961–2015), a dry year when annual precipitation does not exceed 89%, and a wet year when annual precipitation is higher than 111%. Climatic water balance was determined based on the differences between precipitation and evaporation [18].

Climatic water balance (CBW) was calculated as the difference between precipitation (P) and evaporation (E). For the years 1961–2015, the data were determined in monthly cycles, presented as the heights of water columns (mm) per mean surface area of the lake. The amount of precipitation was calculated on the basis of adjusted values evaluated by different formulas, in order to minimize measurement error caused by measurement instruments, wind effects, the splashing of raindrops, and other factors [19–22]. For Polish conditions, these values can vary from 8% to 22% for summer periods and from 18% to 55% for winter periods (e.g., [23–25]) evaluated for different regions and

years. For this study, we applied 20% correction for winter months (December–February), 15% for spring (March–May) and autumn months (September–November), and 10% for summer months (June–August), taking into account the investigations carried out by the Hydrological Station in Radzyń, located closest to the study area [24,25].

The evaporation from the water surface was calculated by the Jaworski formula and the data on real evaporation for summer periods, and by the Iwanow [20] and Jaworski formulas [26] for the winter periods.

Applied formulas:

- Iwanow's:

$$E = 0.0018 \times (t + 25)^2 \times (100 - h), \quad (1)$$

where,

E—monthly evaporation (mm),

t—mean monthly air temperature in a meteorological cage at a height of 2 m above ground surface (°C),

h—mean monthly relative air humidity (%).

- Jaworski:

$$E_0 = 0.225 \times (u_2 + 1)^{0.5} \times (e_{0j} - e), \quad (2)$$

where,

E_0 —daily evaporation (mm),

u_2 —mean daily wind speed at a height of 2 m above the ground surface (m s^{-1}),

e_{0j} —mean daily value of pressure of saturated water vapor at the lake water surface temperature (hPa),

e—mean daily value of water vapor pressure in air in a meteorological cage at a height of 2 m above ground surface (hPa).

For the ice cover periods, we applied the Iwanow formula based on the studies of Kędziora [20,21] and Rösler et al. [27], and the Jaworski formula for winter months with no ice on the lake.

The adopted rules required determination of the duration of ice cover for the studied lake. This was achieved on the basis of the daily log of water gauge observations run for Lake Powidzkie, and field surveys. The occurrence of ice cover in Lake Powidzkie was evaluated on the basis of field measurements and the daily log of water gauge observations run for Lake Powidzkie.

In the calculations of evaporation for the summer period, the real evaporation values were used, measured by evapometric rafts at two stations belonging to the IMGW-PIB network: Radzyń on Lake Sławskie and Buntowo on Lake Sławianowskie, since 1977. These results were interpolated for the area of Poland and transposed to Lake Powidzkie. This approach allows a reduction of evaporation error related to variations in atmospheric stability [28]. For the years in which measurements of evaporation were not performed, i.e., the period 1961–1976, the JAWORSKI formula was used [26]. The results obtained in accordance with the IMGW-PIB standards show the lowest error in comparison to the actual measurements [27].

Hydromorphological and meteorological trends were determined by linear regression. All statistical analyses were performed using Statistica version 13.0 (license of the Poznan University of Life Sciences).

Water quality was determined from the monitoring carried out by the Voivodship Inspectorate for Environmental Protection in Poznań [29] and the measurements carried out by IMGW-PIB. The lake's water quality was assessed on the basis of Carlson's [30] criteria, taking into account the concentration of total phosphorus, chlorophyll a, Secchi disk depth, and nitrogen [31] measured in summer (June–August) in the period from 1985 to 2015. Values of each indicator were calculated according to the following formulas:

$$\text{TSI(Chl)} = 9.81 \ln(\text{Chl}) + 30.6 \quad (3)$$

$$\text{TSI}(\text{SD}) = 60 - 14.43 \ln(\text{SD}) \quad (4)$$

$$\text{TSI}(\text{TP}) = 14.43 \ln(\text{TP}) + 4.15 \quad (5)$$

$$\text{TSI}(\text{TN}) = 54.45 + 14.43 \ln(\text{TN}). \quad (6)$$

Carlson's trophic state index was calculated as a mean value of the tested parameters:

$$\text{TSI} = [\text{TSI}(\text{Chl}) + \text{TSI}(\text{SD}) + \text{TSI}(\text{TP}) + \text{TSI}(\text{TN})]/n, \quad (7)$$

where, TSI—Carlson's trophic state index, TP—total phosphorus ($\mu\text{g/L}$), Chl—chlorophyll a ($\mu\text{g/L}$), SD—Secchi disk depth (m), TN—total nitrogen (mg/L), and n—number of analysed parameters.

Based on the TSI values, the lakes were classified as oligotrophic (low productivity; $\text{TSI} < 40$), mesotrophic (moderate productivity; $\text{TSI} = 40\text{--}50$), eutrophic (high productivity; $\text{TSI} = 50\text{--}70$), and hypereutrophic (very high productivity; $\text{TSI} > 70$).

Detailed studies of the vegetation covering the coastal and littoral zone were performed, taking into account changes in the lake water level in the analyzed period. The study was carried out on the basis of field measurements, and an analysis of cartographic and archival materials. The shoreline range and the corresponding surface of the lake at a given elevation of the water table were determined using the ArcGIS 10.0 software. The bathymetry plan of Lake Powidzkie made by the Institute of Inland Fisheries in 1960 [31], topographical maps at the scale 1:10,000 from 1980, and binary files containing a point cloud from aerial laser scanning (LIDAR) covering the studied area were used. After recording all the map sheets and giving them appropriate georeferences, the shoreline of the lake was digitized and its shape was incorporated into the previously vectorized bathymetric plan of the lake using the function of flexible matching (Rubbersheet tool). The vectorized isobatas were given appropriate depth values, and were assigned absolute values of altitudes according to the Kronsztadt '86 reference system. Then, vectorization screen contour lines were located in the immediate vicinity of the water body. Next, interpolation was carried out using a Raster Topo vector, by which elevation data from the area of the lake and its immediate surroundings were transformed into the raster model. Using the Mosaic tool, a numerical model of the lake basin was integrated with the numerical terrain model, obtained from LIDAR data. Then, the contour lines were generated with the Contour cutting tool. In this step, the range of changes in the shoreline of the lake studied was determined and the morphometric indices of the examined water reservoir (lake surface and shoreline range) at various levels of the water table were calculated.

Detailed field studies, including an inventory of coastal vegetation, were made in 2009. The studies were repeated in 2014 and 2015. They included determination of the area covered by emerged vegetation, with particular emphasis on the type of dominant plant communities and range of communities developing in recent years. Measurements of coastal vegetation ranges were carried out from the boat and land using a measuring tape and a handheld GPS of the Garmin GPSmap 60Cx type. In randomly selected locations, an additional measurement was made using a measuring tape in transects located perpendicular to the shoreline, from the first compact occurrence of rush vegetation to its maximum extent in water. The obtained field data were applied to orthophotomaps at the scale of 1:5000 using the ArcGIS 10.0 program. At the same time, photographic documentation of the described zones was made. In the littoral and coastal zones, the areas of the dominant communities were calculated, taking into account the presence of trees within the areas covered with rushes.

The range of vegetation from the 1960s was established on the basis of the data contained in the bathymetric cart [32] and archival topographic maps at a scale of 1:10,000 in projection GUGiK 1965 (sheets: 424.114—Powidz, 424.132—Giewartów, and 424.123—Budziśław Kościelny).

4. Results

4.1. Hydrometeorological Conditions

The catchment area of Lake Powidzkie is characterized by low annual precipitation, which, on average, does not exceed 510 ± 113 mm/year (Figure 2). The average annual air temperature is around 8.5 ± 0.9 °C. During the analyzed 55 years (1961–2015), an increase in the average annual temperature of 0.32 °C dec^{-1} was observed, accompanied by slight changes in precipitation (Figure 2). The occurrence of several alternating very dry years (i.e., 1982, 1989, 1992, 2003, and 2015) and wet years (i.e., 1967, 1970, 1980, and 2010) was detected (Figure 2). As a result of the increase in the annual temperature and decrease in the relative air humidity, the potential evaporation rate is systematically increasing and currently reaches values exceeding 637 ± 90 mm/year. Winds dominate from the western sector (Figure 3).

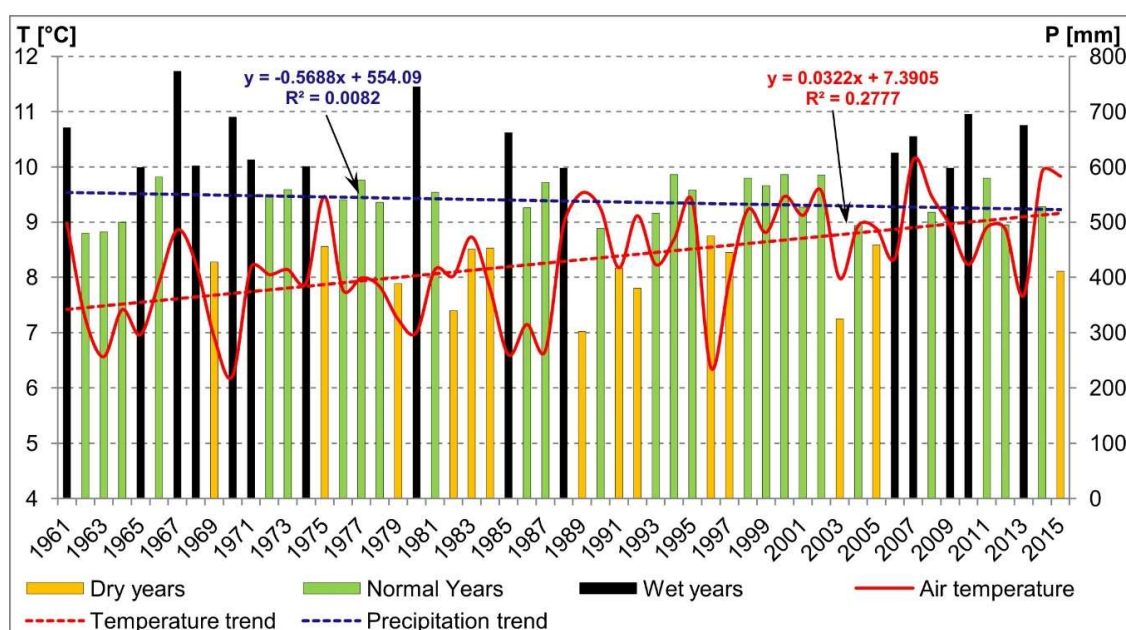


Figure 2. Annual average temperatures and annual precipitation divided into dry, normal, and wet years in the region of Lake Powidzkie (based on The Institute of Meteorology and Water Management—National Research Institute (IMGW-PIB) data).

Meteorological conditions had a significant impact on the hydrology of the studied reservoir. The maximum amplitude of lake level fluctuations in the analyzed half-century was 1.3 m. In the 1990s, the water level decreased by 0.6 m compared to that in the 1960s. Figure 4 presents the fluctuations of mean monthly water levels in Lake Powidzkie in the years 1961–2015, with subsequent periods of occurrence of high and low water levels, overlapping with seasonal fluctuations. In the analysed multiannual period, the highest water levels were recorded in April/May 1968 and July/August 1980 (about 98.85 m a.s.l.), and the lowest were recorded in October/November 1992 and October/November 2006 (about 97.70 m a.s.l.). The multiannual amplitude of water level fluctuations in the lake amounted to 1.2 m. The average water level of the lake in the period 1961–2015 was 98.34 m a.s.l. Considering the obvious response of the discussed lake to natural climatic fluctuations, the water level fluctuations are unfavourable. The trend of a decreasing water level in the lake is evident, amounting to 9 cm/decade. The highest annual average water level was recorded in the 1960s, and decreased with every decade until the first decade of the 21st century (Figure 4). Only after 2010 was the process temporarily inhibited as a result of both natural factors (high precipitation) and human activity (hydropower infrastructure on the outflow from the lake) [16]. Since 2011, the lake's water has been re-dammed, which has caused an increase in the water level of 0.5 m.

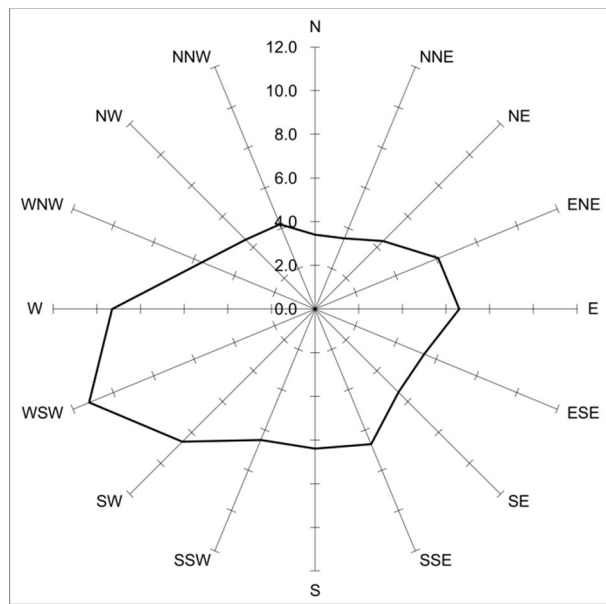


Figure 3. Wind directions in the area of Lake Powidzkie based on the average values from 1966 to 2015.

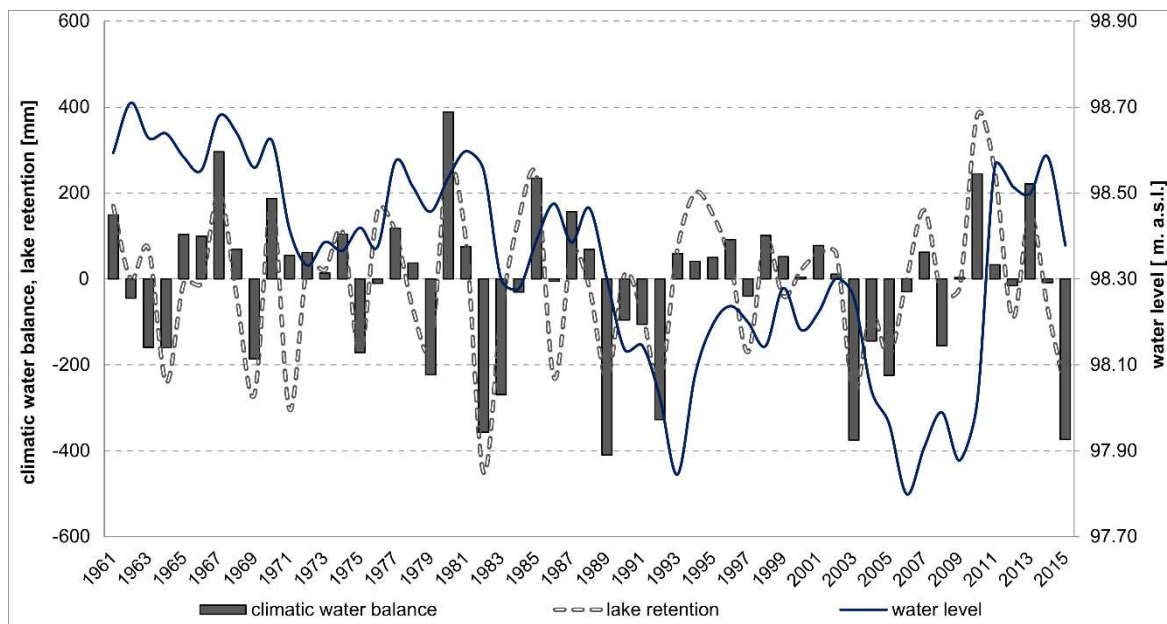


Figure 4. Changes in the average annual water levels, climatic water balance (differences between precipitation and evaporation), and water retention in Lake Powidzkie during 1961–2015.

Differences between evaporation and precipitation (climatic water balance) and water level fluctuations did not show significant correlations (Figure 5), in opposition to the water retention. Pearson correlation between water retention and the climatic water balance was strong and highly significant ($p < 0.0001$).

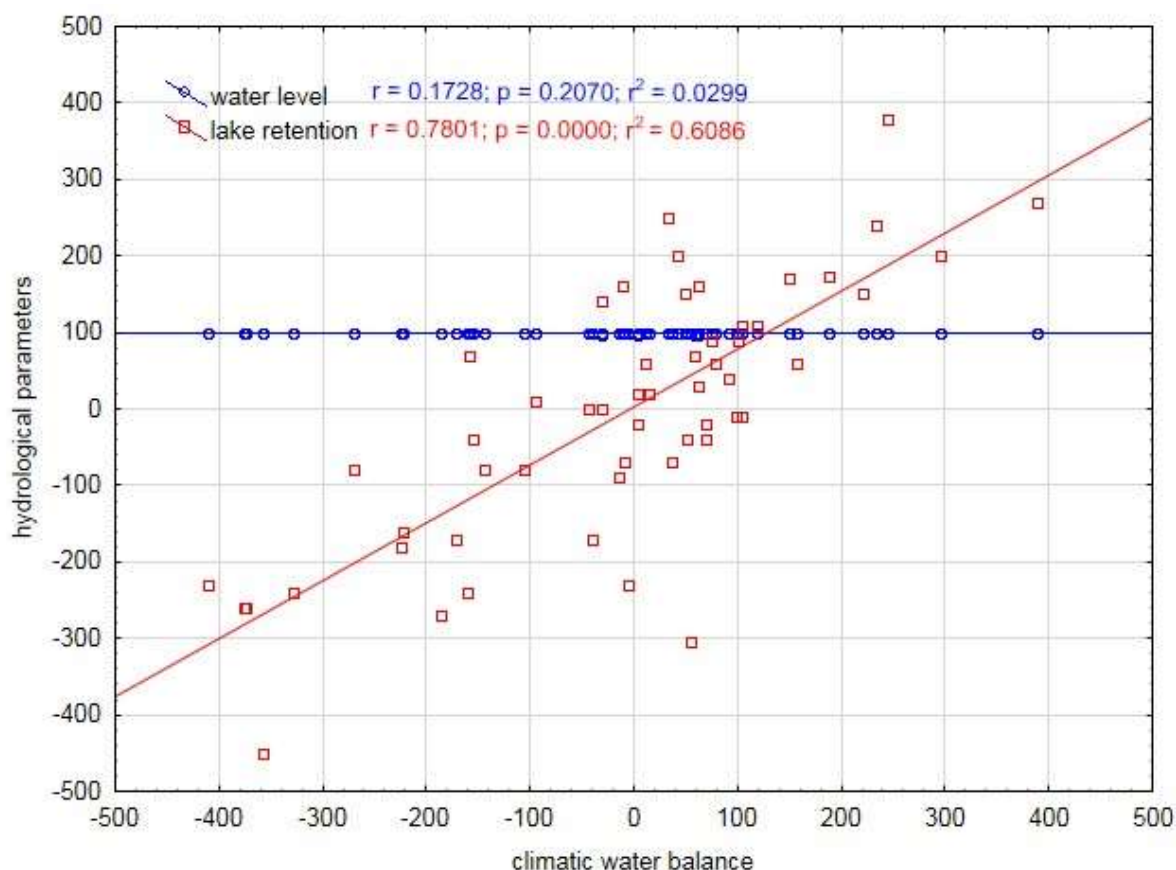


Figure 5. Changes in the average annual water levels, climatic water balance (differences between precipitation and potential evaporation), and water retention in Lake Powidzkie during 1961–2015.

4.2. Lake's Area Changes

Fluctuations of the water table in Lake Powidzkie were accompanied by significant changes in the shoreline, which, in the shallow zones, even moved 100 m into the basin. In the 1960s, the area of the lake was 1134.5 ha and decreased to 1007.3 ha in the first decade of the 21st century (Table 1). The most significant loss in the lake area was recorded in the 1980s—during the smallest of the analyzed periods of water table level decline in the lake—which was associated with the shape of the lake basin and the tilting of the bottom of the reservoir. As a result of lowering the average water level by 0.6 m, the lake area decreased by 127.2 ha and water resources by 6.4 million m³.

Table 1. Changes in the area of Lake Powidzkie over the last 50 years.

Period	Water Level/m a.s.l.*	Lake Surface/ha	Loss of Area Compared to 1960/%
1960s	98.60 ± 0.10	1134.5	-
1970s and 1980s	98.44 ± 0.16	1051.2	7.3
1990s	98.20 ± 0.17	1025.3	9.6
2010s	98.00 ± 0.14	1007.3	11.2

* in *Kronstadt-86* Ordnance Datum.

4.3. Water Quality

The water quality of Lake Powidzkie evaluated in terms of the Carlson index [30], based on transparency, chlorophyll a, total phosphorus, and nitrogen concentrations, was characteristic of a mesotrophic stage (Table 2). There has been a clear trend of improving water quality in the last decade

(Table 2), despite a slight deterioration in 2015. In the 1960s, the transparency was well above 6–7 meters (based on personal communication with the inhabitants and lake users).

Table 2. Changes in water quality in Lake Powidzkie in 1985–2015 based on summer measurements of Carlson’s Trophic Index [30].

Year.	TSI (Chl)	TSI (SD)	TSI (TP)	TSI (TN)	TSI	Classification
1985	51.6	39.0	82.6	61.2	58.6	eutrophy
1991	52.5	46.8	66.5	53.2	54.8	eutrophy
1996	44.4	45.1	52.7	59.6	50.5	eutrophy
2000	41.4	44.1	70.7	56.6	53.2	eutrophy
2004	46.8	35.9	40.0	52.6	43.8	mesotrophy
2009	41.7	35.7	29.5	46.1	38.8	oligotrophy
2012	36.4	37.4	27.4	53.9	38.3	oligotrophy
2015	45.4	40.4	47.4	57.2	47.6	mesotrophy

TSI—Carlson's trophic state index (TSI) and its components, based on chlorophyll-a concentrations—TSI (Chl), phosphorus concentrations—TSI (TP), Secchi disk visibility—TSI (SD), and nitrogen concentrations—TSI (TN).

The worst water quality was recorded at the turn of the 1990s, when, in the summer months, due to intense phytoplankton blooms, the transparency of water did not exceed 3 m (based on personal communication). From 2000 to 2004, the Secchi disk transparency showed a tendency to increase (Figure 6). Since 2008, a decline in the Secchi disk transparency has been observed, which, in 2015, was at a level of 4 m (Figure 6). Correlation between the water level and Secchi disk visibility, determined during the summer time, was low, but statistically significant ($r = -0.29$, $p < 0.05$).

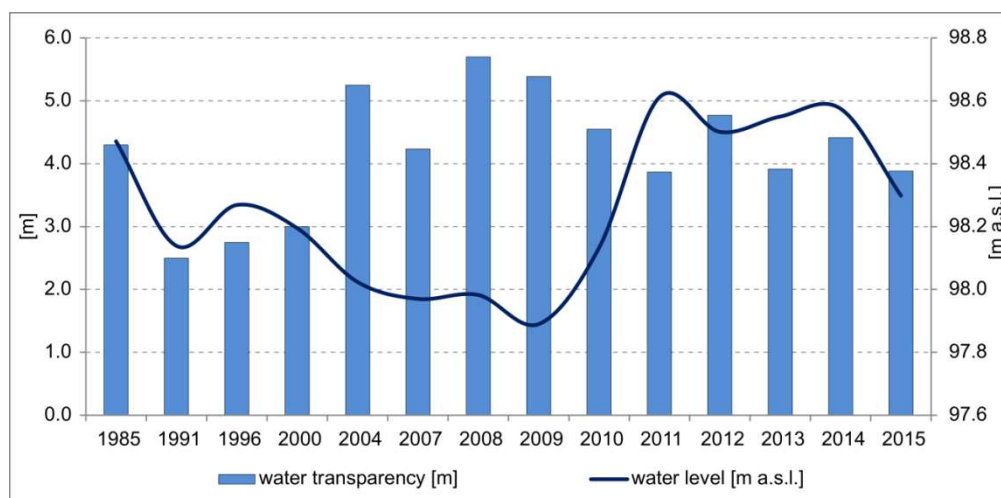


Figure 6. Changes in the water transparency and water level of Lake Powidzkie in the years 1985–2015.

The condition of the lake, assessed according to the Water Framework Directive based on macrophytes and phytoplankton, as well as the physicochemical parameters of waters and hydromorphological elements, indicated a good status [28]. Earlier studies based on physicochemical parameters indicated that the lake had maintained the second class of cleanliness, equivalent to a good ecological status [29], for over 20 years.

4.4. Vegetation Dynamics of the Littoral and Coastal Zone of the Lake

According to the bathymetric map of Lake Powidzkie from the 1960s [32], the vegetation in the littoral zone covered an area of 41.5 ha, which accounted for 3.5% of the lake’s surface. The vegetation covered 24.8% of the coastline’s length. The highest abundances had reed beds (*Phragmites australis*)

(Figures 7 and 8), covering over 95% of the zone. The share of narrow-leaf stick (*Typha angustifolia*) was much smaller. A few sites were covered by aggregations of Common Club-rush (*Scirpus lacustris*).

The coastal zone, dominated by coltsfoot beetles grasslands (*Senecioni-Tussilagonetum*), was used for domestic and wild animal grazing. Only some parts of the shoreline of the lake were covered with forests. Coastal zones in the area neighboring the towns were devoid of emergent vegetation. This situation has been relatively stable over the last 25 years.

In the mid-1980s, the structure of the banks that were not subjected to intensive regulatory measures began to change, and they started to be overgrown by trees, especially willows and poplars. The former meadows slowly began to give way to willow orchard and riparian tall herb fringe communities [33]. Furthermore, the open areas became systematically overgrown by vegetation. At the end of the 1980s, the area of rushes within the water table increased to 66.5 ha.

At the beginning of the 1990s, when the water level in the lake significantly decreased and water quality deteriorated (Table 2), the process of the succession of rushes into the reservoir began to take place. Species such as common reed (*Phragmites australis*), narrowleaf cattail (*Typha angustifolia*), and broadleaf cattail (*Typha latifolia*), as well as therophytes and common rush (*Juncus effusus*), massively began to colonize water-free shallow areas [33]. However, the dominant role was played by the common reed, whose extensive system of rhizomes facilitated the colonization of the reservoir's bottom sites exposed during dry periods (Figure 7). As a result of long periods of a low water level, the most shallow parts of the littoral, previously occupied by reeds, were colonized by hygrophilous trees and shrubs, mainly willow species (*Salix alba*, *Salix pentandra*, and *Salix aurita*) and black alder (*Alnus glutinosa*) (Table 3, Figures 7 and 9).

Table 3. Dynamics of the area covered by dominant plant communities in the littoral and riparian zones of Lake Powidzkie.

Plant Communities	Area of Emerged Littoral Zone in 1960	Area of Emerged Littoral Zone in the First Decade of the 21st Century	Areas of Littoral and Riparian Zones (ha) in the First Decade of the 21st Century
Reeds—dense <i>Phragmitetum australis</i> (Gams 1927) Schmale 1939	nd *	86.72	91.58
Reeds—thin <i>Phragmitetum australis</i> (Gams 1927) Schmale 1939	nd	28.14	28.21
Narrow-Leaved Cattail community—dense <i>Typhetum angustifoliae</i> (Allorge 1922)	nd	1.55	1.55
Narrow-Leaved Cattail community—rare <i>Typhetum angustifoliae</i> (Allorge 1922)	nd	0.25	0.25
Common club-rush—dense <i>Scirpetum lacustris</i> (Allorge 1922) Chouard 1924	nd	0.33	0.33
Common club-rush—rare <i>Scirpetum lacustris</i> (Allorge 1922) Chouard 1924	nd	0.1	0.1
Reeds, narrow-stem and eyeball reed, unsealed	nd	1.65	1.65
Total	41.5	118.75	123.67
Trees and shrubs for several years (<i>Alnus glutinosa</i> , <i>Salix cinerea</i> , etc.), include trees and shrubs within the rushes	nd	45.81	56.79
Trees and shrubs of several decades (<i>Alnus glutinosa</i> , <i>Salix cinerea</i> , etc.)	nd	24.09	26.35
Total	9.7	38.9	164.36
Rushes, bushes and trees—total	51.2	84.71	221.15
		203.46	344.82

* nd—no data.



Figure 7. Dense rush reed (*Phragmitetum australis*) limited from the open water side by an underwater slope, near Polanowo (No. 1 in Figure 1; photo: B. Nowak, 2009).



Figure 8. Colonization of the exposed shallow part of Lake Powidzkie by reeds (No. 2 in Figure 1; photo B. Nowak, 2005).

At the beginning of the 21st century, water conditions improved and the level of the water table in the lake increased (Table 2, Figure 6). The process of vegetation succession in the reservoir and colonization of the rushes in the sublittoral by sedges and other wetland species was inhibited. In the years 2003–2005, another dry season occurred (Figure 2), which caused an even greater retreat of the lake shoreline. It resulted in the appearance of trees, among others, silver birch (*Betula pendula*) and, to a lesser extent, rushes, which widened their reach to the open water (Table 3). Changes in the structure of dominant communities were noted.

Young reeds were smaller, with a lower vitality, and did not form dense clusters (Figure 8), as a result of their rapid entry into the poor organic substratum, hitherto subjected to processes of the waving and leaching of organic parts. The expansion of reeds into the water body was interrupted by the rapid rise of the lake level in 2011. The high water level resulted in the death of trees and withdrawal of plants that do not tolerate flooding the whole year round from the littoral zone. At present, rushes are beginning to regain their previous dominant role in the littoral zone of Lake Powidzkie. In relation to the situation 50 years ago, they occupy a much (three times) larger area along almost the entire shoreline, from 40 to 165 ha (Table 3).

The most dynamic changes were observed in the shallowest areas, which were dried yearly, where the succession of trees and shrubs (mainly willows—*Salix* sp., alder—*Alnus glutinosa*, and aspen—*Populus tremula*) was observed, and zones of a 50–100 cm water depth (estimated at an average water level in 1961–2015), temporarily deprived of water in periods of low water levels and colonized to a significant extent by rushes (Figures 9–11). Within the coastal shallows, both the shifts in lines marking the occurrence of individual plant communities and significant species transformations were detected (Figures 9–11). The shallowest zone, which was a rush habitat, was colonized by trees and hygrophilous shrubs. Rushes, however, moved towards the depth of the lake, often exceeding the minimum range of the water table (Figure 9).

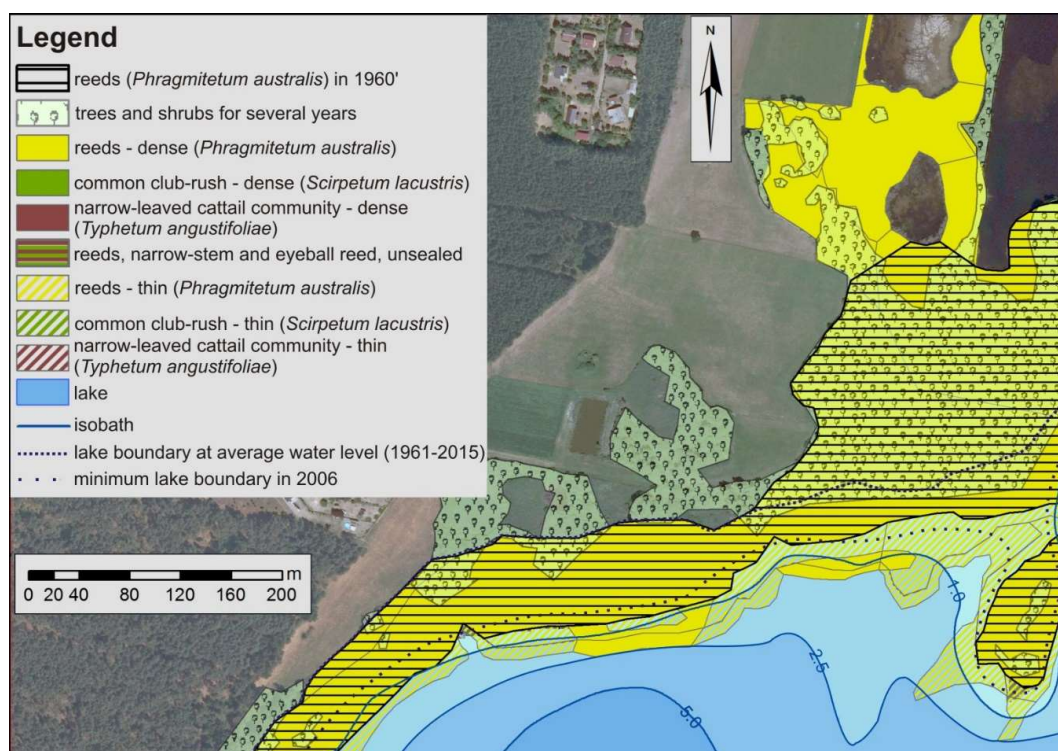


Figure 9. Range of the littoral and riparian zones of Lake Powidzkie in the Rusin cross-section in 2009.

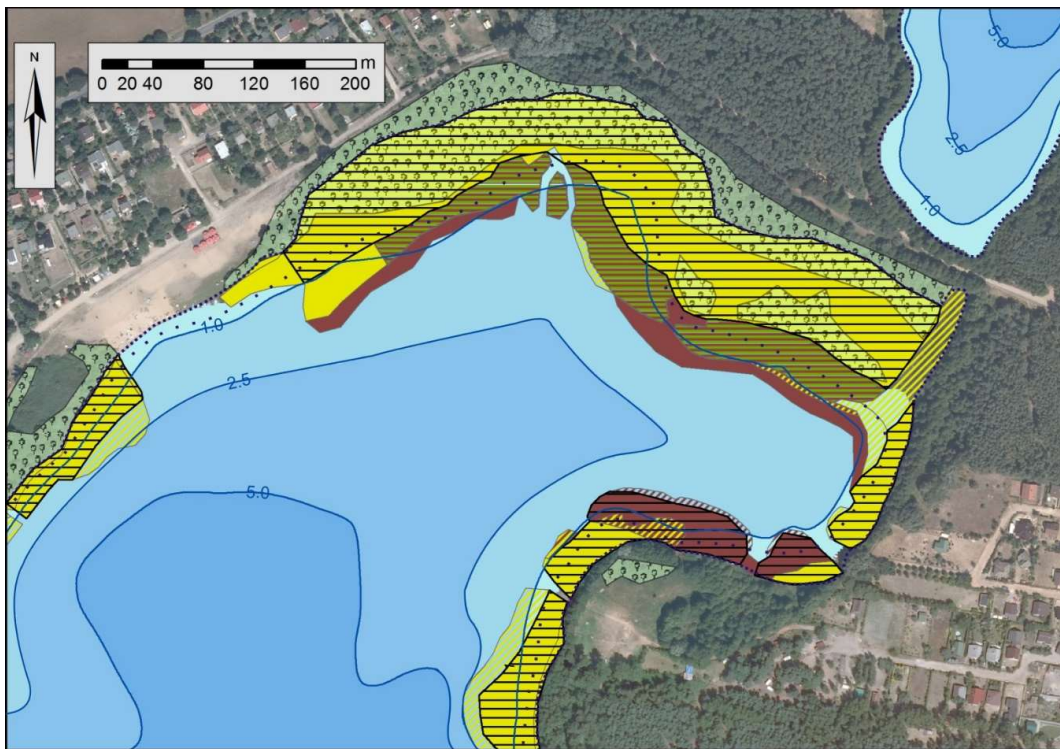


Figure 10. Range of the littoral and riparian zones of Lake Powidzkie in the Przybrodzin cross-section in 2009 (legend is shown in Figure 9).

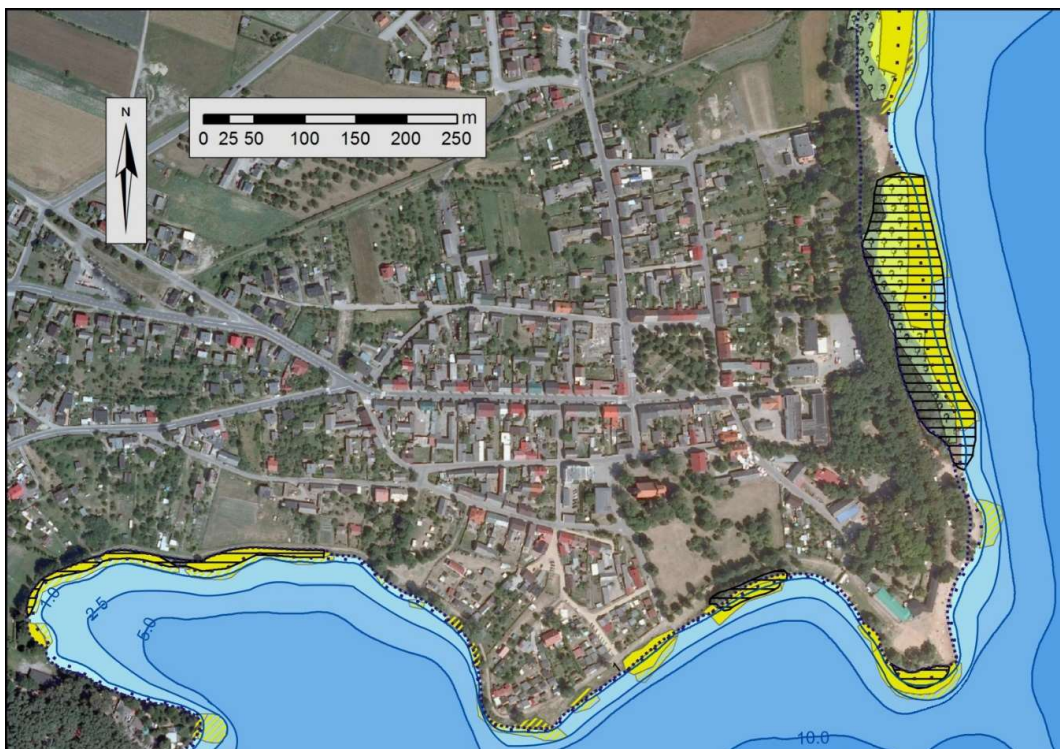


Figure 11. Range of the littoral and riparian zones of Lake Powidzkie in the Powidz cross-section in 2009 (legend is shown in Figure 9).

Analysis of the dominant communities showed that they are more diverse on the west side of the lake and in the area of wind-protected bays (Figure 1). Only these sites were occupied by narrowleaf cattail (*Typha angustifolia*), broadleaf cattail (*Typha latifolia*), and sedges (Table 3, Figure 10).

This vegetation was more susceptible to waves than the common reed. Open areas subjected to waving were primarily occupied by common reeds (*P. australis*), or lake bulrush (*S. lacustris*) (Figure 1). In turn, sheltered bays and branches of the lake were characterized by greater species variability within the rushes and the faster expansion of vegetation deep into the reservoir. Then, bulrush (*T. angustifolia* and *T. latifolia*) was often the dominant species (Figures 1 and 11). The greatest impact of waves, due to the prevailing winds, was found at the eastern shores of the lake (Figure 1).

The comparison of the vegetation range from the 1960s and the beginning of the 21st century indicates that it was developing more dynamically in the area of inlets to the lake and in the area of shallow, sheltered bays. In these places, the greatest accumulation of silts and gyttja was found, which was conditioned by the point influx of pollution from the catchment and difficult contact of these parts of the lake with open water.

Bathymetry and plant coverage analysis showed that the shallower parts of the lake with a gently falling bottom were more quickly overgrown (Figures 9–11). In these places, the width of the strip of rushes reached several dozen meters. However, more than half of the area was covered by species which have entered the depths of the lake over the past few decades (Figures 9–11). In turn, parts of the lake with a steeply sloping shores and bottom configuration, as analyzed above (gently falling bottom), inhibited the entry of vegetation deep into the lake. In these zones, the width of the strip of reeds ranged from a few to several meters, because the entry of vegetation deep into the basin is limited by the occurrence of a steep underwater slope.

Nearby resorts and yachting marinas located on the banks of the lake, the littoral zone was devoid of macrophytes. A similar situation, although on a much smaller scale, was found at all major platforms used permanently. Near the beaches, the factor preventing plant rooting was trampling of the bottom and banks by bathers. Near marinas, yachts and other vessels that were moored to jetties were responsible for a similar effect. In the area of private property, with had direct descent to the lake, several treatments were used, like the mowing or systematic uprooting of existing vegetation, and filling or covering by foils and tarpaulins, in order to ensure easy access to the water deprived of rushes.

5. Discussion

The aim of the study was to analyze hydrometeorological conditions (water level changes, precipitation, evaporation, and strength and direction of the wind) for the development of vegetation in the littoral and riparian zones of Lake Powidzkie in the period from 1961 to 2015. The influence of the water level changes on the lake area and the water quality was assessed. Analysis of the meteorological conditions in the period 1961–2015 showed a significant impact of precipitation and evaporation changes on water retention and morphology of the lake and on the dynamics of the riparian zone development of Lake Powidzkie. Low annual amounts of atmospheric precipitation and increasing annual values of potential evaporation were the major reasons for the largest water deficits in Poland [22,26]. This was reflected in changes in the water table level, which were especially problematic in dry years (i.e., 1992–1994, 2006, and 2009). A drop in the amount of rainfall of 30–40%, with a simultaneous increase in potential evaporation of 10–20%, resulted in a reduction of the lake area by several dozen hectares and a shifting of the shoreline by 50–60 meters. As a consequence, changes in the vegetation structure in the littoral and riparian zones in the lake were observed. We also have to take into account that precipitation provides around 71% of the input, and evaporation 80% of the output, in the total water budget in Lake Powidzkie [33]. Moreover, a deficit of precipitation and elevated evaporation may have a negative impact on the water velocity in the lake's inflows. Then, changes in the riparian and littoral zones could be even more significant during long periods of drought.

Lake Powidzkie is one of the deepest meromictic lakes [34]. A large volume of accumulated water and a small catchment area make the lake one with reservoirs that exhibit a high resistance to degradation [35]. There was no direct impact of water level changes on water quality. The low

water quality in the period 1985–2008 was associated with a high inflow of nutrients from agricultural areas into the lake and the uncontrolled discharge of untreated wastewater from villages located in the catchment area. However, positive trends of nutrient concentration decrease were observed from 1985 to 2012, which occurred due to legislative restrictions concerning sewage management. However, we did not observe a strong relationship between changes in the water level and the Secchi disk transparency. Usually, climate changes manifested as changed rainfall, temperature, and wind conditions have an impact on the physical conditions in lakes [36–38]. Most often, these changes implicate a decrease in the water level and increase in water temperature, which results in top-down and bottom-up effects on the structure and functions of biological communities [1,38]. An increased water temperature stimulates the growth of phytoplankton, in particular, the toxic bloom-forming cyanobacteria [39,40], which reduces the water transparency. In Lake Powidzkie, these changes of water level did not cause a deterioration of water quality, which can be explained (at least partly) by intensive macrophyte development and competition between submerged macrophytes and phytoplankton for nutrients [41,42]. However, changes in water level fluctuations caused shifting of the lake shoreline and transformation of the vegetation structure. The greatest transformations were recorded in the last quarter of the century, during which several very dry periods of several years occurred. In the shallowest parts of the water basin, the succession of bushes and shrubs was observed (mainly willows—*Salix* sp. and alder—*Alnus glutinosa*) into the riparian zone, leading to the appearance of *Salicetum pentandro-cinereae* willow thicket. The major contribution to forest succession was brought about by willows (*Salix* sp.) and black alder (*Alnus glutinosa*) and aspen (*Populus tremula*) in littoral, replaced reeds, and small rushes. However, in many lakes [12,43], only the succession of *Phragmites australis* is indicated as a result of the reduction in the water level.

The age of tree stands is associated with the occurrence of dry years. The formation of two populations of different ages related to the drought in the early 1990s and low-water rates in 2003–2005, was distinguished (Figures 7 and 8). Since 2011, due to the rising of the lake level and the persistence of a higher water level, a regression of trees whose root system has been completely flooded was observed. Therefore, fast-growing rushes greatly differed from those growing in previous decades. The difference was the most pronounced for reeds which were less compact than those of the former range and comprised individuals with a smaller biomass. At that time, rapid silting and the deposition of large amounts of organic matter in the littoral zone was noted with the lowering of the water level, which contributed to the growth of herbs, grasses, and sedges in this zone.

Factors Shaping the Development of Vegetation in the Littoral and Coastal Zones

Analysis of the dynamics of changes in the riparian and littoral zones of Lake Powidzkie showed that plant succession was very variable in various parts of the water body. Map analysis of the range of rushes showed that the width of the zone depended on the water level, and the vegetation growth was determined by the water depth. The rush vegetation occurred at depths between 1.5 and 2.0 m [13,44], with the dominant species of reeds (*Phragmites australis*), narrowleaf cattail (*Typha angustifolia*), and spotted lakes (*Scirpus lacustris*). In areas with a rapidly falling slope, the occurrence of reeds was recorded even in zones with depths exceeding 2.5 m. Reed can grow in a relatively large amplitude of lake depth, but its optimal growth is observed in the range of 0 to 1.6 m [39,41], with roots reaching a maximum depth of 1.7 m [44]. The shift of vegetation zones and expansion of plants into open water would not have been possible if not for the large fluctuations in the water level in the lake and the continuing trend of a lowering water level observed since the beginning of the 1990s (Figure 4). In addition to the hydrology of the reservoir itself and the morphology of the lake basin, the wind exposure and hence the height of the waving were very important factors affecting the development of vegetation [45,46].

At sites where the eulittoral is very long, especially on the eastern side of the central basin, the reeds reached a depth of 1.0 m. Their succession was probably limited by the strong influence of wind and waves [37,38]. Morillo et al. [36] have demonstrated a limit of vegetation succession to open

waters due to the strong influence of wind, which was particularly observed in large lakes. In Lake Powidzkie, the parts exposed to waves were more slowly colonized by rush vegetation. The waves worked in two ways: firstly, they uprooted young plants with a weak root system and, on the other hand, they washed out finer material, leaving a stony-gravel bottom, hindering the rooting of plants. Stronger waving is often an obstacle for the development of communities of *Typha angustifolia* and *Acorus calamus*, and completely eliminates the possibility of the occurrence of tall sedge rush and hydrophyte with floating leaves [36,37].

The species composition of the developing riparian vegetation had an impact on the plant species composition in the littoral zone. Another scheme was observed in the areas that bordered on the forest, parks, or belt of coastal trees, and those adjacent to fields or meadows. The proximity of dense shelterbelt trees facilitated the rapid colonization of trees in the shallowest parts of coastal zones. However, in the littoral zone, species uncharacteristic of reed zones were noted, i.e., pine (*Pinus sylvestris*), silver birch (*Betula pendula*), or aspen (*Populus tremula*). Coastal polygons were then mainly occupied by various willow species (*Salix* sp.) and black alder (*Alnus glutinosa*). Near arable fields and meadows, a natural sequence of entering tree vegetation into the rushes was observed. An important role in shaping the range of rushes was also played by anthropogenic pressure, particularly mechanical activities that would hinder or even prevent the development of coastal vegetation [47,48].

6. Conclusions

This study has shown a significant effect of the water level in Lake Powidzkie on the development of the rush zone, whose area has more than doubled over the last half-century—from 41.5 to 118.8 ha. The most dynamic development of the littoral zone was observed in the last quarter of the century, in which three periods of low-water level were recorded. During the periods of a low water level in the lake, the expansion of rushes, mainly reeds (*Phragmites australis*), took place at the expense of uninhabited shallow parts of the lake, as well as in open water. Lowering the water level in the lake has also increased the share of woody vegetation, including willow (*Salix* sp.), black alder (*Alnus glutinosa*), and aspen (*Populus tremula*), in the littoral zone. Among them, two populations of different ages associated with the occurrence of periods of a low water level were distinguished. Therefore, the lowering of the water level, despite the fact that it caused a decrease in the lake's area, contributed to the restoration of natural coastal habitats, which were removed by man in the 19th century.

Moreover, the occurrence of periods of increased rainfall after dry periods did not contribute to a reduction in the fringe zone and did not limit the development of woody vegetation. These results indicate the intensification of vegetation development, which could have contributed to the increased nutrient uptake by macrophytes and limitations of phytoplankton growth, which, as a consequence, increased the transparency of water. Moreover, the reduction in the water level in Lake Powidzkie in periods of low rainfall did not result in a deterioration of the water quality in the basin. However, this aspect requires further research, taking into account, among other factors, the activities within the catchment area and lake.

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