Chapter

Wigry Lake: The Cradle of Polish Hydrobiology - a Century of Limnological Exploration

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Abstract

Wigry Lake, located in North-Eastern (NE) Poland, has a century-old history of limnological exploration and is an excellent place to assess the impact of catchment changes caused by urbanization on the functioning of a large, polymictic, and flow-through lake. The history of prewar limnological research, the course of hydrochemical effects of urbanization in the river flowing into the lake since the 1970s, and long-term changes in the functioning of Wigry Lake are presented. The collected archival and current results indicate that the hydrochemical type of the lake's waters remained the same, and the inflow of river waters from the urban catchment strongly transformed the lake bay receiving the load. In the remaining part of the lake, the eutrophication load caused smaller changes because of a gradual reduction in the inflow of nutrients. Consequently, there was an increase in vertical differentiation of oxygen, algal biomass, and their structure. A significant share of supplying the lake with groundwater and the natural in-lake system of biotic and chemical regulations significantly reduced the effects of the eutrophication process. The existing lake biodiversity has been maintained, constituting a valuable element of the European NATURA 2000 system.

Keywords: Wigry Lake, long-term study, lake trophy, eutrophication, urbanization, history of limnology

1. Introduction

Wigry Lake in Poland is considered a historical place where an in-depth study of natural sciences was carried out, as it was here that a new, ecological approach was developed on the study of lake ecosystems. It was here that the theoretical and practical foundations of lake science were created. Intensive research of Wigry Lake, started in 1920 by Alfred Lityński, thanks to the establishment of the Hydrobiological Station on this lake, resulted in spread of the knowledge of the processes and phenomena occurring in the lake ecosystem, fundamental for limnology. They confirmed the high biodiversity and uniqueness of water ecosystems noted in earlier, random studies [1, 2]. A continuation of prewar research by teams of limnologists from several Polish academic centers since the 1970s made the collection of data and knowledge about the functioning of Wigry Lake exceptionally rich. In addition, state agency units dealing with the state of the atmosphere, water resources, and their quality systematically monitored the environment of this area. Since the 1990s of the twentieth century and the first monograph on the lakes of the Wigry National Park (WNP) [3], despite further monitoring of the water habitats of this region, no further general studies about the Wigry Lake have been made. Therefore, the aim of this study was to assess the state and functional changes of the Wigry Lake ecosystem for over 100 years from the first quantitative analyses. Particular attention was paid to extending the knowledge about the quantity and quality of lake's resources in the context of global climate change and the progressing urbanization of the catchment.

2. Wigry Lake environment

Wigry Lake, located in the north-eastern corner of Poland (54°01′09″N, 23°04′49″E), has an area of 21.7 km^2, a maximum depth of 74.2 m, water volume $352.1 \cdot 10^6 m^3$, and a catchment area of 466 km^2. It lies within the Lithuanian Lake District, which, belongs to Eastern Europe, on the course of the Czarna Hańcza River [4]. It has a characteristic location in two geographical subregions reflecting the geological sequence of the Pleistocene glaciation of Central Europe.

The northern part of the lake is located within the borders of the hilly and loamy Suwałki Lake District, while the southern part occupies a part of the outwash gravel and sandy Augustów Plain.

Intensive development of lake coastline with numerous bays indicates the polygenetic origin of this multichannel lake, with two directions of the N-S and E-W glacial channels. Detailed studies from the turn of the nineteenth and twentieth centuries indicate that the main assumptions of the lake's origin lie in the uniqueness in Poland, shallow, metamorphic Precambrian ground, and Pleistocene neotectonic activity causing cracks in the ice sheet, referring to the network of deep faults. These, in turn, shaped the main flow directions of in-glacial waters forming postglacial channels [5]. The second important moment in the genesis of the lake is the existence of two megafloods in the marginal and proximal part of the Scandinavian Ice Sheet (SIS), shortly after the ice sheet reaches its maximum extent. Two such megafloods occurring on the 19 and 16 ka (kiloannum, thousand years) ago were identified [6]. The first of them took place from the east (from the Nemunas River basin), and the second from the N-NE direction through the valley of the Czarna Hańcza River. Two prehistorical events with catastrophic loss of glacier mass had a water flow velocity of around 15–17 $m\ s^{-1}$. The large discharge of meltwater was estimated to be about $2 \times 10^6\ m^3\ s^{-1}$ and must have decisively affected the shaping of the river valley system in the European Lowland and possibly influenced global climate by flowing in significant volumes of freshwater into the North Atlantic Sea. The contemporary catchment of the Czarna Hańcza River belongs to the left-bank basin of the Niemen River, and thus to the catchment area of the Baltic Sea.

The economic history of the Polish-Lithuanian borderland, and the previous Yotvingian rule in this area, gradually changed the water ecosystems and their catchments. In particular, the activity of the Camaldolese Order from the sixteenth to nineteenth centuries led to gradual deforestation, utilization of bog ore in the surrounding peat bogs and changed the nature of the water circulation in the catchment area. Since the twentieth century, there has been a gradual increase in anthropogenic pressure on Wigry Lake as a result of urbanization in the city of Suwałki, located on the Czarna Hańcza River, the main lake tributary. The population of Suwałki in 1920

(17,000 inhabitants) slowly increased until 1939 (25,000 inhabitants). It was not until 1970 that the city's population reached its pre-World War II state. From 1974 to 1999, as the capital of the newly created voivodeship, intensive urbanization of the catchment took place. The changing economic situation and changes in the administrative structure stopped the population growth trend and since 2000, the number of inhabitants in Suwałki is approximately 70,000. It is recently estimated that in the entire catchment area of the Czarna Hańcza River, there are 90,000 people. It was not until 1986 that a new, biological wastewater treatment plant was built, and in 1994 the dephosphatation process of wastewater was started in this plant. An important action preventing the degradation of Wigry Lake was the creation of the Landscape Park in 1976, and the Wigry National Park in 1989, in accordance with the earlier proposals for its protection submitted in 1921–1924, among others by Dr. A. Lityński.

3. Limnological data collection and methods

The results presented in this paper are based on historical data, published limnological data, and own field research conducted in the years 1997–2022 by the Department of Hydrobiology of the University of Bialystok. Lake water level data and discharge in Sobolewo (1951–1992), Stary Bród (1992–2020), and Czerwony Folwark (1951–2020) stations of the Czarna Hańcza River come from the IMGW-PIB Warszawa database. Czarna Hańcza River discharge data for Sobolewo station (2000–2020) were collected from Wigry National Park database. In addition, the results of parallel, river flow measurements in 2011 and 2012 were used, the purpose of which was to determine the total amount of water flowing into Wigry Lake and the mutual relations under various hydrometeorological conditions. The missing data were supplemented by the authors using methods common in hydrology. Precipitation data for the Stary Folwark station from years 1928 to 2015 come from IMGW-PIB data, supplemented by earlier data from the Płociczno station (years 1922–1927) and data for years 2015–2021, converted from data from the Integrated Environmental Monitoring System (IEMS) in Sobolewo station. When preparing the annual lake water balances in the period 1951–2020 [7], the monthly evaporation rate was calculated using the Ivanov formula [see 8]. Results of the long-term National River Monitoring System (NRMS) provided on the Czarna Hańcza River in Sobolewo station and hydrochemical data collection from IEMS were used. Due to the state accreditation of laboratories, the collected hydrochemical data form a homogeneous set, and the methods of chemical analysis from the 1920s and 1930s are similar to those methods currently used. Own studies on Wigry Lake were carried out in the years 1997–2022 in seven companies at 6 to 13 stations (**Figure 1**), each time at the turn of July and August, when the thermocline is at its deepest [2]. Thermal and oxygen profiling were made at each station, as well as the Secchi Disk visibility noted. Water samples for a detailed chemical analysis were taken by Patalas sampler from epilimnion, metalimnion, and hypolimnion layers. Water analyses were provided in the Laboratory of the Department of Hydrobiology, University of Białystok. Standard analytical methods for water samples were used [8], but DIONEX ICS-1100 was applied for ion analysis from 2015 as well as the determinations of total chlorophyll concentrations from spectrophotometric change to fluorometric determinations. Applied FluoroProbe (bbe-Moldaenke, Kiel, Germany) identifies the four phytoplankton classes based on precalibrated excitation and emission spectra "fingerprints" programmed into the instrument, which include: (1) Green

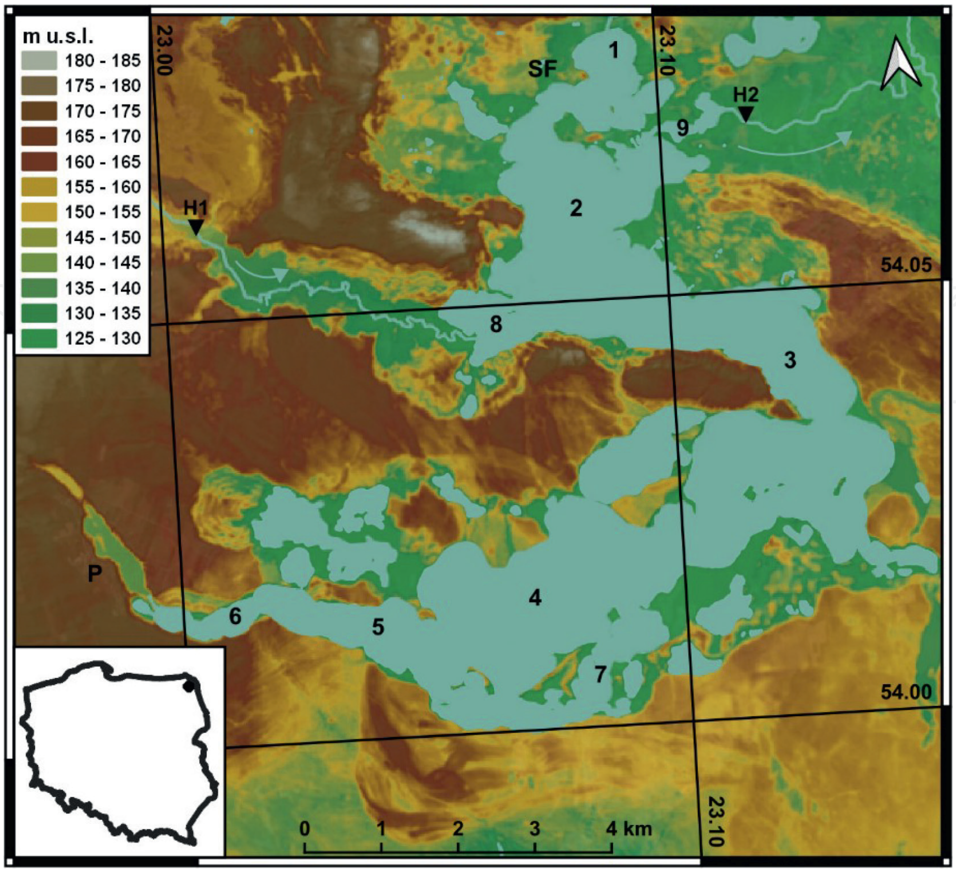

Figure 1.
Wigry Lake map with Hydrobiological Station locations (P- Płociczno, SF- Stary Folwark in 1928–1943), hydrological stations on the Czarna Hańcza River (H1- Sobolewo, H2- Czerwony Folwark), and sampling stations (1–8).

algae: Chlorophyta and Euglenophyta; (2) Cyanobacteria: phycocyanin (PC)-rich cyanobacteria; (3) Diatoms: Heterokontophyta, Haptophyta, and Dinophyta; and (4) Cryptophytes: Cryptophyta and the phycoerythrin (PE)-rich cyanobacteria. The lake's trophic state was evaluated using the Carlson formula [9]. The Mann-Kendall trend test was used to analyze the data, and the Kruskal-Wallis test for equal medians was used to demonstrate the statistical significance of differences between the study subperiods.

4. Hydrobiological Station's activity and the first period of lake exploration

In 1920, Dr. Alfred Lityński, as a young researcher of the lakes of the Tatra Mountains (Carpathians) and the lakes of Polesie Lubelskie, began limnological research at the Hydrobiological Station on the Wigry Lake (**Figure 2**).

It was initially located in the village Płociczno on the south-western shore of the lake. The Nencki Institute in Warsaw was the founder institution of the station, which was constantly supported by government subsidies and funds, obtained thanks to the activity of its founder [10]. Initially, under "spartan" conditions (**Figure 3**) and with the increasing staff of the station, the bathymetry of the lake, the structures of phytoplankton, zooplankton, and ichthyofauna were analyzed in detail. In 1921, a meteorological station began its work, which in the following year became part

Figure 2.
Alfred Lityński (1880–1945)—Source: Wigry Lake Museum archive (WNP permission).

Figure 3.
Hydrobiological Station in the first location in Płociczno (1920–1927); source: Wigry Lake Museum archive (WNP permission).

of the national network of meteorological stations in Poland. From 1922, constant measurements of the lake water level began, and from 1926, the temperature of the lake water was measured daily at 7 am. In 1928, the station and the staff of the station were moved to a newly built facility in Stary Folwark, in the north-western part of the lake (**Figure 4**). The new building, specially designed for the needs of the station, was furnished with an electrical network and direct supply of the station with lake

Figure 4.
Hydrobiological Station on Wigry Lake building in Stary Folwark. Source: National Archive of photography.

water for biological experiments. The station housed numerous laboratories, vivaria, offices, and apartments for the staff. Diverse and modern equipment of the station with the most modern limnological equipment, microscopes, measuring devices, and a motorboat were great assets of the Station. The high level of research conducted at the station, the great enthusiasm and commitment of Dr. A. Lityński were confirmed by Prof. Naumann and scientists from Lund (Sweden) during their visits to the Wigry Lake station. In the interwar period, it was one of the first four hydrobiological stations in Europe.

The first limnological studies on Wigry Lake appeared as early as 1922. Thanks to the efforts of Dr. A. Lityński, the Hydrobiological Station on Wigry River in 1926 started publishing the first Polish limnological journal—Archives d'hydrobiologie et Ichthyologie (Archives of Hydrobiology and Fisheries). The results of subsequent floristic and zoological research on Wigry Lake were noticed among limnologists around the world, and Dr. A. Lityński, as a representative of Poland, directly participated in the founding meeting of the SIL Society of Limnology and in its subsequent Congresses in Innsbruck and Kiel. The ability to cooperate, the good working atmosphere created by the founder of the station, resulted in a large group of limnologists working at the station and who became well known among water ecologists. These include Dr. J. Wiszniewski—the discoverer of the psammolitoral, Dr. Z. Koźmiński—as the first scientists who had measured chlorophyll concentrations in North American lakes, Prof. M. Stangenberg—who had documented the hydrochemical state of waters in the 1930s, and Prof. J. Wołoszyńska—phycologist— who had first described Wigry Lake phytoplankton community.

The station on Wigry lake organized summer hydrobiological schools for students and young adepts at limnology. Two doctoral dissertations on zooplankton and bacterioplankton of Wigry Lake were written by young hydrobiologists from the University of Warsaw under the supervision of A. Lityński. The Jagiellonian University in

Krakow, on the other hand, awarded him the degree of Habilitated Doctor, as the first in Poland in this field. Thanks to the Scientific Station on the Wigry Lake, a modern fish hatchery was created, supporting the fishing economy of the lakes in the entire region. Field experience, numerous scientific trips, and a rich limnological library gathered at the station enabled Dr. Lityński to create the first Polish textbook on "General Hydrobiology," published a few years after the end of World War II, thanks to the involvement of Prof. L. K. Pawłowski [11].

Unfortunately, World War II and the events related to it contributed to the end of the Station's activity, the death of Dr. A. Lityński in 1945 (near Smoleńsk, Russia) and many of his associates. Station equipment was plundered and part of it was taken away by the German occupiers to their fishing stations. The war activities of Prof. A. Neuman, a "friend" of Dr. Lityński from the prewar period, as a Nazi functionary, and his personal visits to Wigry Lake did not save the Station from its complete devastation and liquidation.

Because of its natural values, the Wigry Lake was "adopted" in 1998 by the International Association of Theoretical and Applied Limnology (SIL "Lake Adoption" Project) [12]. In 2009, thanks to the initiative of the Wigry National Park, the Museum of Wigry Lake was established in the restored building of the former Hydrobiological Station, and a monument to Dr. Alfred Lityński stands in front of its building.

5. Results and discussion

5.1 Hydrological history of the Wigry Lake in the last 100 years

Significant long-term and seasonal atmospheric dynamics is characteristic of the temperate climate zone and translates into the dynamics of the land water cycle [13]. The natural and man-induced hydroclimatic cycle of Central Europe caused changes in water resources in lake basins, observed especially in the dynamics of the water level [14, 15]. The analyzed lake is characterized by a moderate long-term fluctuation in the average annual water level of the order of 50 cm (**Figure 5**), with seasonal increase of water level during April–May and minimum in July. It is the effect of high lake capacity, moderately long (2.96 years) average time of lake water exchange. Most of the flow-through lake types have the same annual amplitude, as that observed in

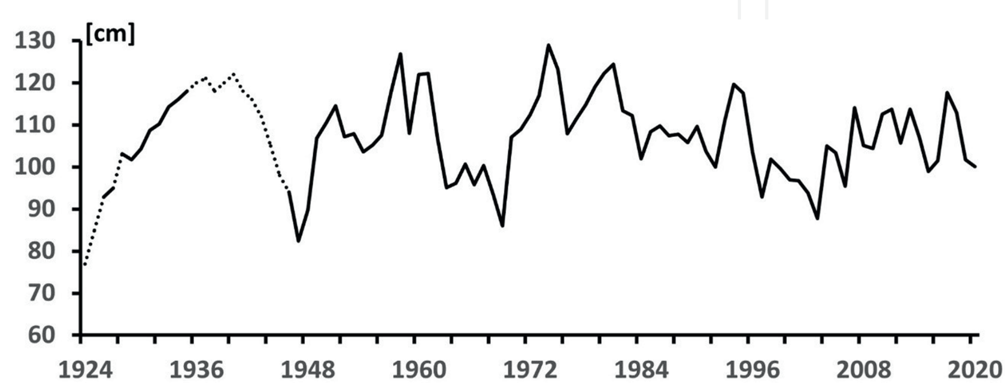

Figure 5.
Wigry Lake water level changes in years 1924–2021, gathered on the base of Hydrobiological Station observations and published IMGW-PIB data; the dotted line shows approximate data.

Wigry Lake [16]. In more than 100 years of observations, there is no significant trend of lowering or increasing the water level of the lake (Mann-Kendall test confirmed a lack of its trend), but only its periodic fluctuations. As in many other lakes in Poland, hydrological and climatic factors have a smaller impact on the long-term dynamics of lake water levels than anthropogenic changes in water circulation in the catchment area [15]. The polygenetic nature of the lake, the hydrographic network and the morphology of the lake basin cause the dominant inflow and outflow of river waters to reach the northern lake part.

The main part of surface water reaches the lake along with the Czarna Hańcza River. According to own hydrological measurements in 2011 and 2016, it currently accounts for 60% of the entire river inflow to the lake. This value is lower than the previously estimated value [7].

Riverine waters constitute 59% of the annual volume of water circulated in the lake, the underground supply vector has a share of 38%, and only 3% is the result of the vertical exchange of the lake with atmosphere (P-E). More than fourfold differences in the volume of groundwaters involved in the lake's annual water circulation volume (from $53.5{\cdot}10^6{\cdot}10^6$ m^3 to $204.6{\cdot}10^6$ m^3) were observed (**Figure 6**). The volume of water from tributaries flowing into the lake per year had a twofold smaller variability than that noted for groundwater inflows (variation coefficient, respectively, 43.8% and 21.8%). Similar estimates, but for a shorter period of analysis, were presented earlier [7].

There is a statistically significant long-term trend (confirmed by the Mann-Kendall trend test with $p < 0{,}001$) of decreasing the share of underground supply (**Figure 6**), which in recent years has been disturbed by a significant increase in the intensity of vertical lake water exchange due to progressing global warming. During the 70-year period of measuring the flow of the Czarna Hańcza River below the lake, no statistically significant trends were noted, similarly to the inflow to the lake (**Figure 7**). Mann-Kendall trend test confirmed its absence in both cases. Despite changes in the hydroclimatic balance of the catchment, gradually urbanized catchment supplies the lake with treated sewage, partly produced from groundwater.

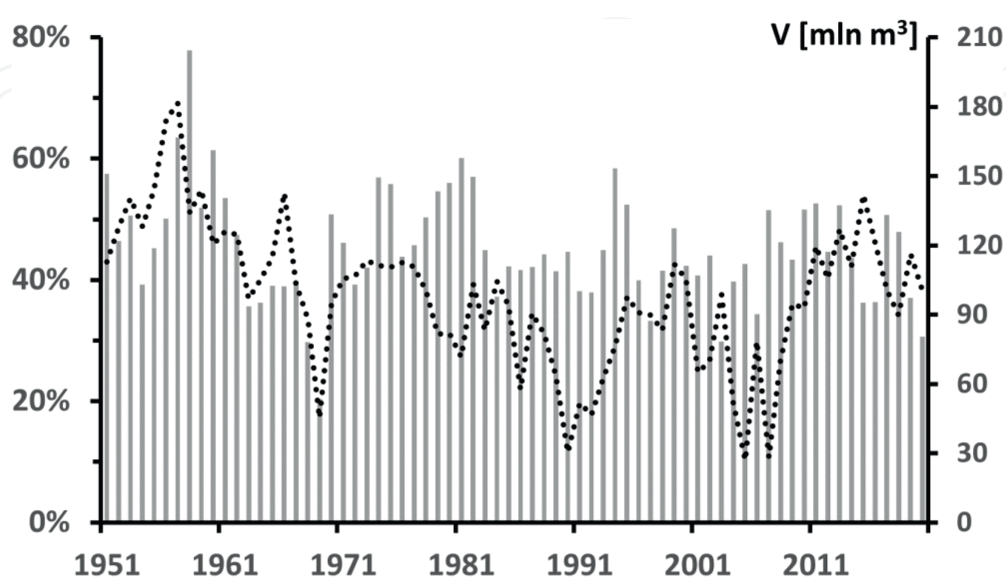

Figure 6.
Wigry Lake water volume under annual cycle in years 1951–2020 (right axis and bars) and groundwater share (in % dots, left axis) in yearly water cycle.

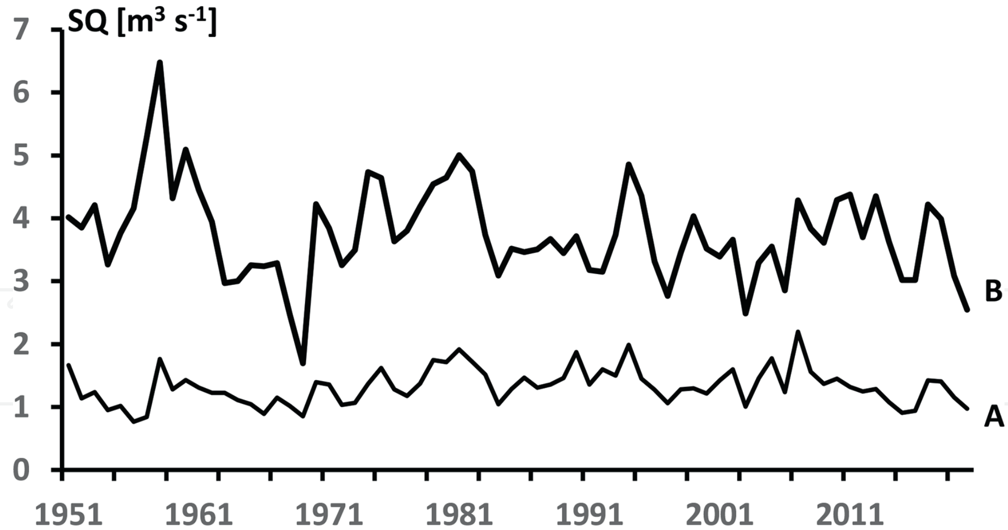

Figure 7.
Yearly (calendar) discharge of Czarna Hańcza River upstream (a) and downstream of Wigry Lake (B) in years 1951–2020; source data are IMGW-PIB and integrated environmental monitoring system (IEMS) archive with own calculations.

Before the intensive process of urbanization of the catchment, the share of inflowing sewage was small, now especially in years with low flow, e.g., in 2019, it reached 14%.

5.2 Water quality of Wigry Lake tributaries

The use structure of the Czarna Hańcza River basin upstream of the lake, its urbanization, and also tourism on the lake itself, have been changing for over 100 years, gradually affecting the quality of the hydrosphere. In addition, the effects of global warming progress, which appeared as lake epilimnion water temperature increase not only in summer period, but for mean annual values also [14]. For the first time during limnological monitoring, the ice phenomena were not observed in winter 2019/2020 at all.

The main source of long-term changes in the water quality of the analyzed lake should be seen as significant changes in the chemical composition of the Czarna Hańcza River during urbanization of the city of Suwałki and the surrounding area. The hydrochemical condition of the Czarna Hańcza River at the end of the 1980s indicated strong water pollution and the need to take protective actions for the Wigry Lake ecosystem. Collected hydrochemical data for the Czarna Hańcza River from the last 40 years document effects of wastewater treatment plant's work, including phosphorus removal technology from 1996. This led to a decrease in the average annual concentrations of total phosphorus in the river waters from 0.8–1 g $P{\cdot}m^{-3}$ to 0.05–0.1 $gP{\cdot}m^{-3}$, and total nitrogen concentrations from about 4–5 $gN{\cdot}m^{-3}$ to about 2 $gN{\cdot}m^{-3}$ (**Figure 8**).

Therefore, the total load of eutrophication (including atmospheric load) on a unit of lake surface has radically decreased. The catchment load reduction below the limit of hazardous unit values for nitrogen and phosphorus occurred at the same time, but for nitrogen periodical fluctuations were noted (**Figure 9**). At the same time, it was accompanied by a constant increase in mineral substances' concentrations that were present in river waters, which confirm the increase in water conductivity (**Table 1**). In the quality of river water, there were changes in the ionic structure, the share of

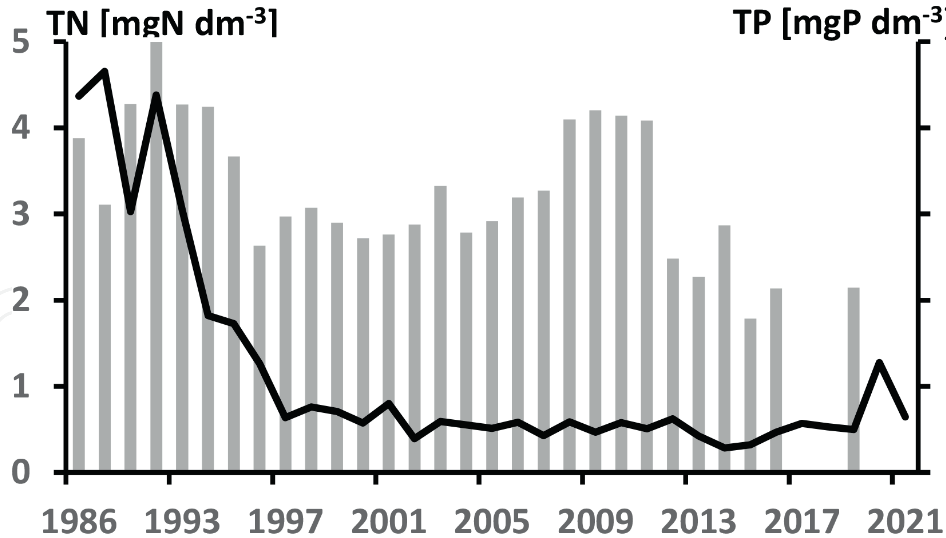

Figure 8.
Average of yearly total phosphorus (TP) and total nitrogen (TN) concentrations in the Czarna Hańcza River, upstream of Wigry Lake in years 1986– 2020; data from archives of the National River Monitoring System (NRMS) and integrated environmental monitoring system (IEMS).

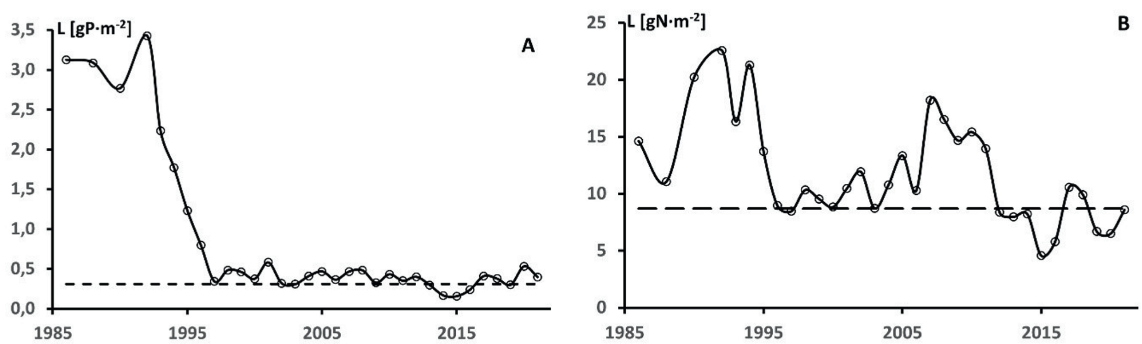

Figure 9.
Average of yearly total phosphorus (TP) and total nitrogen (TN) unit loads to Wigry Lake in years 1986–2020; the broken line indicates the level hazard unit load calculated using Vollenweider criteria [see 7].

chlorides among anions and the share of sodium and potassium ions among cations increased. These changes are statistically significant, as confirmed by the Kruskal-Wallis test for equal medians ($P < 0.0001$). Changes in the sewage management of urbanized areas and the improvement in the quality of river waters in Poland at the end of the 1990s took place a decade later than in Western Europe or the USA [3, 7].

An increase in the concentrations of basic cations and anions as well as biogenic elements in the river-lake system quickly activates eutrophication process in the receiver of river waters, which is Wigry Lake [3, 7].

5.3 Long-term hydrochemical changes of Wigry Lake

Already during the first stage of the study of Wigry Lake, it was indicated that the northern part of the lake, the shallower one with the highest flow rate, had transitional features between the state typical of oligotrophic and eutrophic waters [2]. Most of the lake's (1920s and 1930s) water mass was characterized by good oxygenation of the waters to the bottom. Qualitatively and spatially diversified bottom sediments, ranging from gravel, sandy to carbonate gytties and lacustrine chalk [17, 18], provided

EC and ions	1994–1997			2018–2021			Test for equal medians
	Average	SD	% of anions or cations	Average	SD	% of anions or cations	
Conductivity	462.6	53.8		575.7	75.2		*
HCO_3^-	305.6	81.3	82.9%	344.6	27.9	80.3%	
SO_4^{-2}	26.9	6.0	9.3%	27.8	4.2	8.2%	
Cl^-	16.8	6.7	7.8%	28.4	9.5	11.4%	*
Ca^{+2}	79.3	8.1	69.5%	77.7	5.7	63.3%	
Mg^{+2}	14.3	1.7	20.6%	14.4	1.3	19.3%	
Na^+	11.8	3.9	9.0%	23.9	8.5	16.9%	*
K^+	4.2	1.7	0.3%	7.1	2.5	0.5%	*

Data from the National River Monitoring System (NRMS) and Integrated Environmental Monitoring System (IEMS) archives for Sobolewo station (station 8—see **Figure 1***). Statistically significant differences ($p < 0.001$) are indicated in the last column.*

Table 1.
Change in water conductivity [$\mu S\ cm^{-1}$] and ions' composition in Czarna Hańcza River upstream of Wigry Lake in the last 30 years.

effective, intralake protection against periodic eutrophic inflows from the catchment. The late summer Secchi's disk visibility was over 6 m in the first half of the twentieth century [3, 19].

The increasing pressure on the lake, mainly from the central-western direction (station 8 see **Figure 1**), since the mid-1970s has triggered the process of eutrophication of waters, resulting in a dramatic decrease in the photic zone thickness, especially in the eutrophication front zone of the lake (**Figure 10**). In parallel, oxygen orthograde, dominating in the lake, turned into a negative heterograde in the central and southern parts of Wigry Lake. Clinograde type has developed in the north lake part and Wigierki Bay (station 6 in **Figure 1**), when hypolimnion becomes anaerobic during the summer thermic stratification (**Figure 11**).

For the last 100 years, the waters of Wigry Lake have constantly maintained their bicarbonate-calcium hydrochemical type, just like most of the harmonious lakes of northern Poland [20]. Due to its extent, complex bottom shape, and water supply structure changing over time, it is characterized by periodic fluctuations of chemical composition in time and space, especially during the summer thermal stratification of waters (**Table 2**). Generally, the amount of minerals dissolved in lake water increases from the south lake part to the north of lake in the summer epilimnion; therefore, the average electric conductivity (EC) difference between them is over 20 $\mu S\ cm^{-1}$.

Along with thermal stratification, there is a chemical diversification of the chemical composition of the surface water layer (**Table 2**), as a result of biogenic utilization and geochemical processes, such as sedimentation of carbonates and tryptone to the bottom of the lake [21].

Therefore, the water is decalcified, which has been going on in this lake for several thousand years with varying intensity. This is evidenced by several-meter thick carbonate gyttja deposits with numerous underwater landslides and tectonic disturbances [18]. Significant plankton activity in the trophogenic layer is evidenced by a clear difference in the concentrations of easily utilized nutrients between the epi- and

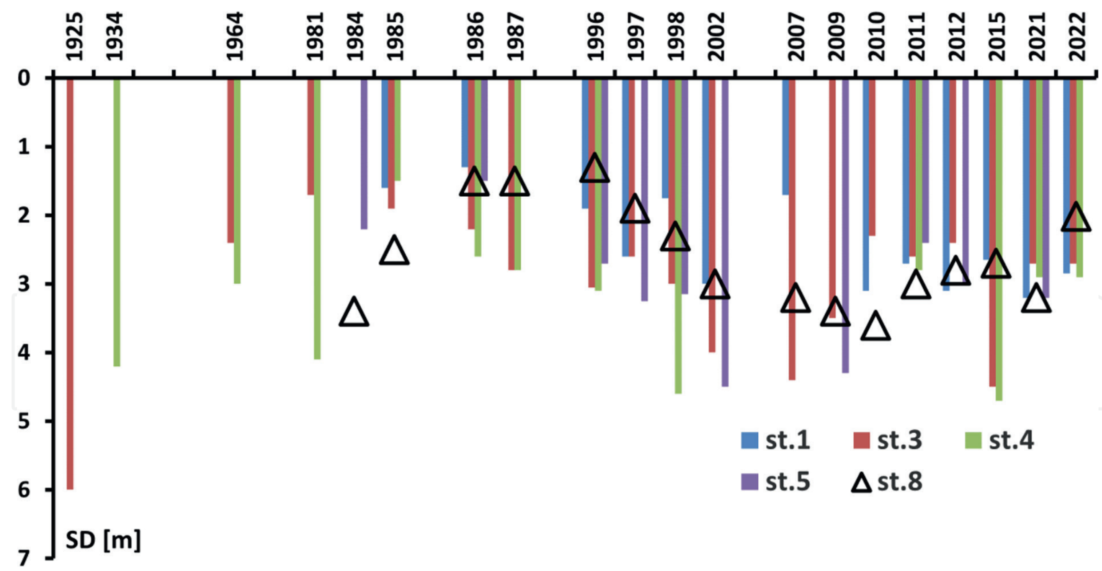

Figure 10.
Secchi disk visibility changes in Wigry Lake in years 1925–2022; data from [3] and own measurements.

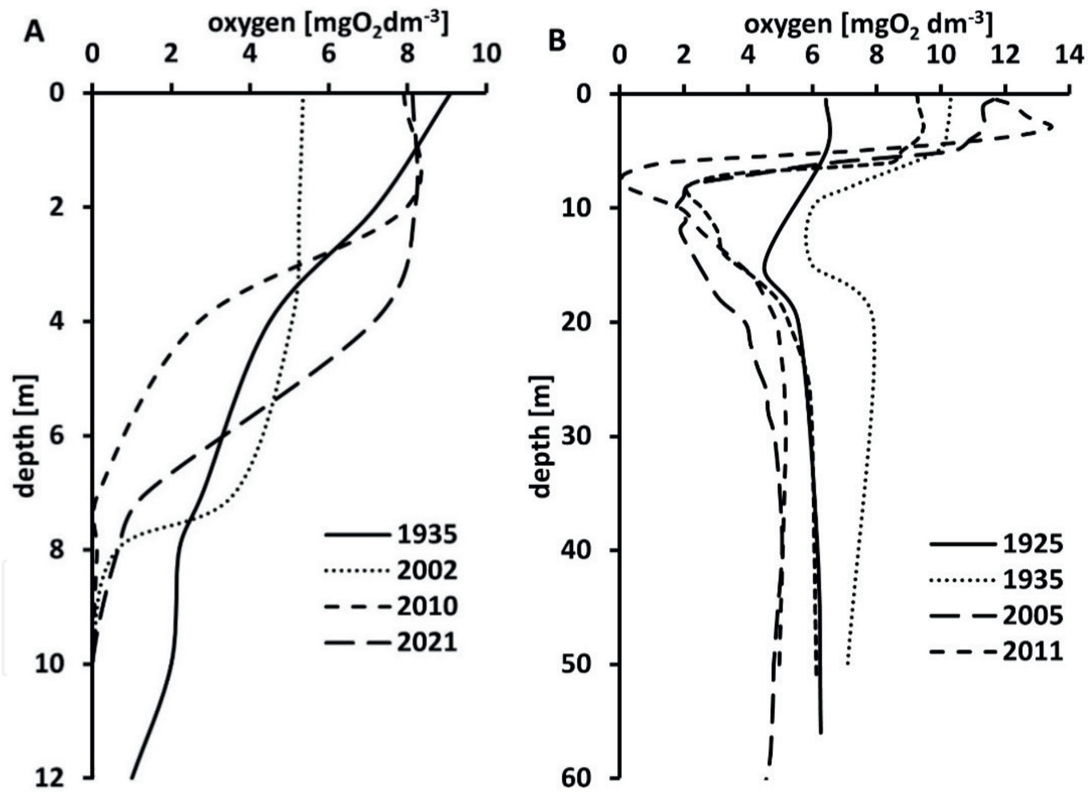

Figure 11.
Summer oxygen profiles in the shallow station 1 and deep station 3 (see **Figure 1***) at Wigry Lake in years 1925–2021; data for 1925 from [2] and data for 1935 from [19].*

hypolimnion, as well as the effects of increased accumulation of organic matter in the epilimnion than in the hypolimnion.

With the seasonal phytoplankton development in dimictic lakes, the resources of biogenic elements in some hydrological situations may become scarce. In the analyzed lake, a gradual decrease in silicon concentrations was noted (**Table 2**), which is an impulse for spontaneous changes in the structure of algae.

Parameters	Layers	2002	2009	2012	2021	2022
Sampling stations		15	6	13	9	8
EC [μS cm^{-1}]	Epil	309.1	349.8	373.9	383.6	404.9
	Met	342.4	373.6	420.2	405.5	423.0
	Hypo	353.2	372.6	414.1	421.5	431.5
Ca [mg dm^{-3}]	Epil	51.5	59.7	61.7	42.9	50.7
	Met	60.1	64.3	60.8	49.3	54.6
	Hypo	72.9	60.1	62.8	48.1	61.7
$N\text{-}NO_3$ [μgN dm^{-3}]	Epil	24.0	75.5	149.5	62.4	<10.0
	Met	27.0	369.6	158.6	79.6	
	Hypo	296.9	484.7	506.3	74.3	55.6
DOC [mgC dm^{-3}]	Epil	7.32	n.d.	6.70	5.59	6.03
	Met	7.23		6.56	5.18	6.02
	Hypo	7.73		5.23	4.95	5.23
SRP [μgP dm^{-3}]	Epil	18.3	7.6	20.5	8.6	<5.0
	Met	15.2	7.2	18.7	<5.0	
	Hypo	75.0	8.5	19.2	5.5	
TP [μgP dm^{-3}]	Epil	49.1	119.4	48.6	102.1	37.1
	Met	53.8	74.5	47.3	66.4	42.7
	Hypo	117.1	164.9	47.0	92.0	42.9
SiO_2 [mgSi dm^{-3}]	Epil	1.54	0.49	1.48	0.10	0.44
	Met	1.87	1.14	1.88	0.07	0.36
	Hypo	2.54	1.39	3.38	0.09	0.24

Table 2.
Water conductivity and concentration of selected water parameters in three thermic layers of Wigry Lake in years 2002–2022.

In the analyzed lake, after a strong eutrophication impulse in the 1980s and 1990s, reduced concentrations of phosphorus and nitrogen were noted especially in the bay of the lake receiving the waters of the Czarna Hańcza River (**Table 3**).

Although the reduction in the phosphorus load on the lake was many times greater than in the case of nitrogen, the average concentrations of total phosphorus (TP) in the analyzed bay of the lake, and at the same time, the main receiver of fertilizing load, remain within the limits accepted for eutrophic waters. Results from Wigry Lake confirm observations from other European lakes that their regeneration (re-oligotrophication) is much slower in deep lakes than in shallow ones [23].

Mainly phosphorus and also nitrogen are factors that increase trophy, and thus the phytoplankton production [21, 24]. As can be seen in the example of Wigry Lake, along with the increase in catchment load, since the 1990s, the range of concentrations of chlorophyll has been increasing in the entire lake, especially in station 8 (**Figure 12**), characteristic of strongly eutrophic waters. The long-term fluctuation in algae biomass was dependent on the amount of river inflow, and the periodic decrease in the amount of algae should be partly associated with an increase in groundwater

Years	SRP	TP	TN
	[μgP dm^{-3}]		[mgN dm^{-3}]
1991–1994*	296.0 ± 87.0	424.0 ± 88.0	2.66 ± 1.27
1997	91.1 ± 11.9	124.3 ± 2.0	n.d.
2002	55.5 ± 39.4	120.3 ± 37.3	n.d.
2012	26.5 ± 6.5	56.3 ± 9.8	n.d.
2021	1.1 ± 0.7	66.8 ± 6.4	1.08 ± 0.04
2022	0.3 ± 0.1	52.1 ± 10.4	0.81 ± 0.09

*n.d. – not determined. *data for years 1991–1994 after [22].*

Table 3.
Annual concentrations of phosphorus and total nitrogen in water of the Hańczańska Bay (station 8 in **Figure 1***) of Wigry Lake in years 1991–2022.*

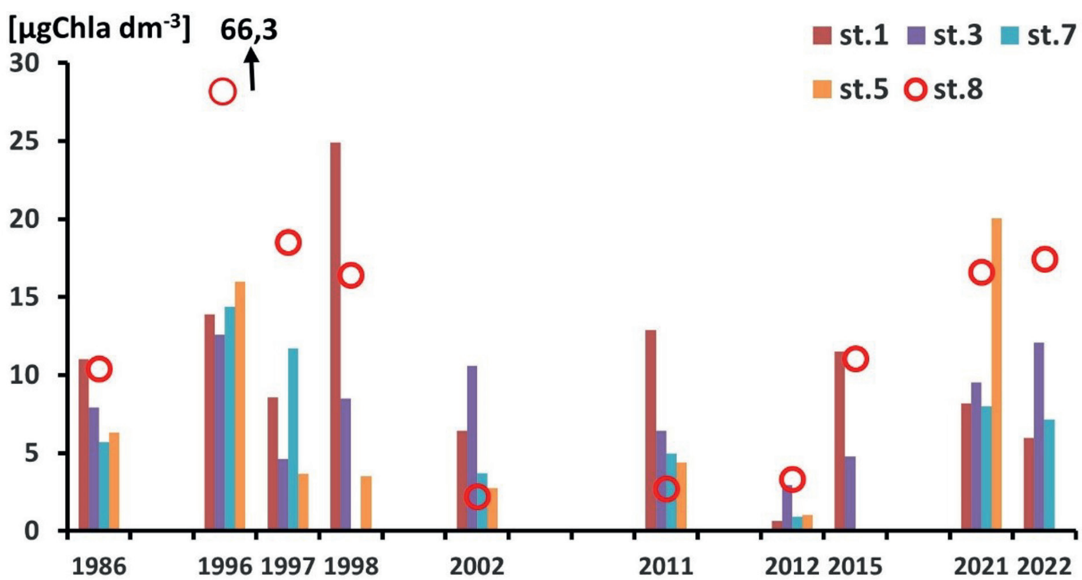

Figure 12.
Multiannual changes of summer epilimnion chloropyll "a" concentration in Wigry Lake; data for 1986 from [25].

supply. In the years 1980–2022, the previously observed [2, 3] dichotomy of the lake's pelagial in terms of phytoplankton biomass persisted, with the northern part of the lake being richer than the southern.

The increase in the lake's trophy was also accompanied by a change in the vertical distribution of algae, consisting in a stronger development of the lower epilimnion maximum of chlorophyll (**Figure 13**). More accurate *in situ* fluorometric measurements also reveal the changing taxonomic structure of phytoplankton. It turns out that in the summer epilimnion, the algal community is green-diatom-cryptophyte. In the metalimnion, the share of diatoms and green algae decreases in favor of cyanobacteria, which become absolute dominants in the hypolimnion (**Figure 13**). A characteristic feature of Wigry Lake are periodic, summer mass blooms of the genus *Ceratium* found in the lake as early as 1916 [26], with high morphological diversity, and their density is inversely proportional to TP concentrations [27].

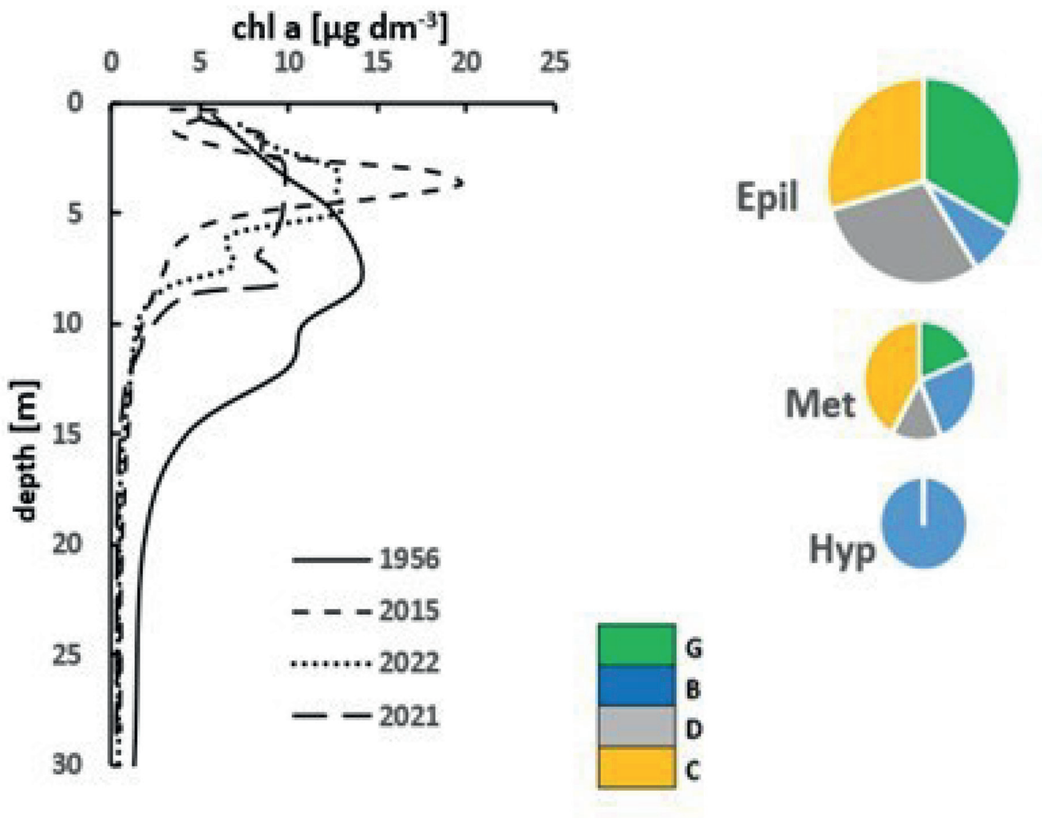

Figure 13.
Vertical differentiation of chlorophyll "a" concentration in the deepest part of Wigry Lake (station 3 in **Figure 1***) in years 1956–2022 and phytoplankton structure (% chloropyll) in years 2015–2022; G - green algae, B - cyanobacteria, D – Diatoms, C- Cryptophytes (in situ measurement results).*

The history of hydrochemical transformations of the river flowing into Wigry Lake presented above changed the fertility of the lake to the greatest extent during the period of maximum inflow of nutrients (in 1990s).

Since the beginning of the twenty-first century, the level of trophy expressed by the Carlson index oscillates around the border between meso- and eutrophy in most parts of the lake, except for small bays and its northern part (**Figure 14**). Thanks to the natural hydrological features of the lake and the existing in-lake biogeochemical and biotic systems, the anthropogenic eutrophic impulse did not lead to a meaningful change in the trophic state. This proves that a properly functioning river-lake biogeochemical continuum is maintained in the catchment and is resistant to stress factors that disintegrate the system [7]. Protection activity taken in the lake by the administration of the national park is significant here.

5.4 Recent ecological state of the Wigry Lake

So far, various forms of active and passive protection of the lake and the immediate catchment area of the lake ecosystem have been carried out, which were included in the statutory tasks of the Wigry National Park.

Thanks to this, the current ecological status of Wigry Lake can be considered good, despite the unfavorable catchment conditions.

This is confirmed by the assessments carried out using the provisions and indicators of the EU Water Directive [28]. During the state monitoring of rivers and waters,

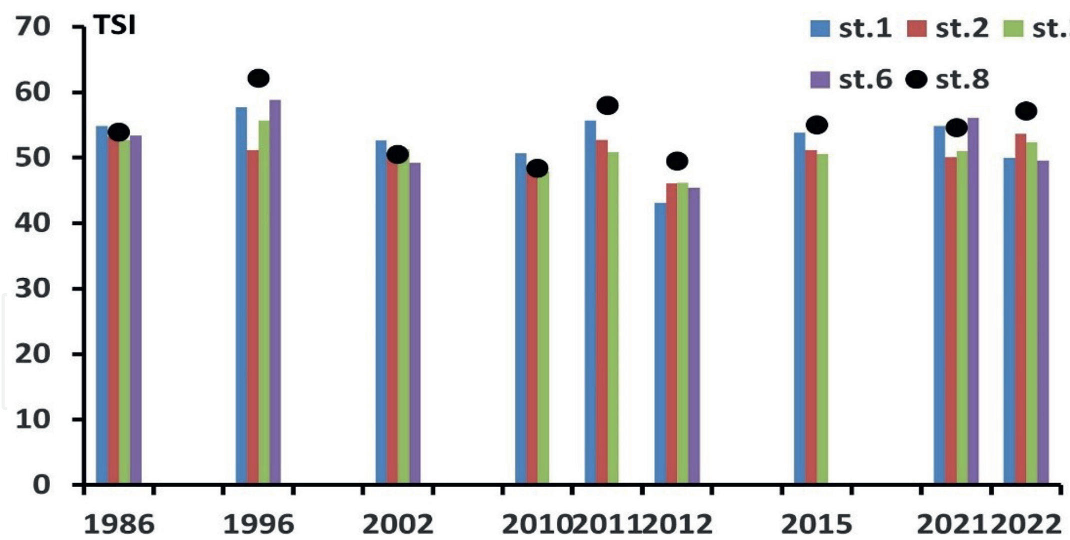

Figure 14.
Long-term and spatial changes of trophic state index (TSI) for Wigry Lake in years 1986–2022.

periodic presence of several hazardous substances specified in the list of the EU Water Directive is found in the water of lakes. In a shallow bay (stage 8 in **Figure 1**), substances were identified in the bottom sediments, formerly deposited during the period of strong eutrophication, and considered a dangerous environment. They are chemically inactive with the natural deposit of lacustrine chalk constantly present at the bottom. There is a high habitat potential in the lake, ensuring the presence of a variety of crustacean zooplankton described at the beginning of the twentieth century [29, 30]. On over 125 hectares of the Wigry Lake, there are charophyte underwater meadows with 10 species of the genera *Chara* and *Nitell*a. Four fish species and two species of mollusks from Natura 2000 list are present in the lake. The existing natural values of the lake enable the presence of 175 species of birds (found in the WNP), i.e., over one third of the list of Polish birds, of which 90 species can be found in Wigry Lake [31].

6. Conclusion

The Hydrobiological Station on Wigry, founded by Dr. A. Lityński in 1920, thanks to the exceptional commitment of the entire staff, played a significant role in learning about the aquatic environment of northern Poland and contributed to the development of limnology in Poland and in the world. Wigry Lake belongs to the flow-through, deep, polymictic, with a long time of water exchange, with underground supply constituting more than one third of the amount of water in annual circulation, with a general tendency to decrease. This trend has been disturbed in the last decade by the effects of climatic changes, and in particular by the increase in the intensity of vertical water exchange in the lake. Despite climate changes, no significant long-term changes in the annual amount of river water supply to the lake have been recorded. On the other hand, the slowly increasing amount of treated sewage, especially in dry years and periods, may account for over 12% of the total river flow, which is almost twice as much as at the beginning of the second half of the twentieth century. A potential threat to the functioning of the lake and its ecological status are the effects of more frequently heavy rainfall. The investment activities undertaken in the catchment area with increasing urbanization reduced the load of phosphorus and nitrogen to the level acceptable according to the Vollenweider criteria. Reduction of catchment eutrophication load in the lake lasted much longer for phosphorus than for nitrogen. Recovery of lakes after nutrient loading reduction may be confounded by concomitant global warming effects.

Conflict of interest

The authors declare no conflict of interest.

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