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Review

History of Environmental and Climatic Changes Recorded in Lacustrine Sediments—A Wigry Lake Case Study

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Abstract: Wigry Lake represents one of the most beautiful and valuable postglacial lakes that is located in the north-eastern part of Poland. It has been an object of scientific interest for over a century, but the most intense period of research started in 1997 and resulted in the production of numerous papers of a multidisciplinary range. The lake is especially well analyzed in terms of its sediments, which were studied using geophysical methods and using traditional lake cartography based on the sampling of sediments and their geochemical characterization. Nearly two decades of research has resulted in the extraction of over 1200 sediment samples, which facilitated the analysis and the description of five main sediment types that can be found at the bottom of Wigry Lake, i.e., carbonate gyttja, lacustrine chalk, clastic sediment, fluvial-lacustrine sediment, and organic gyttja. A very thorough vertical as well as spatial examination of Wigry Lake sediments, together with paleobiological research and isotopic dating, allowed researchers to analyze the history of environmental changes in the lake and its immediate vicinity, including anthropogenic changes. Wigry Lake had been preserved as a pristine lake for a long time, and, despite the significant growth of anthropopressure, which began in the 17th century and intensified in the 20th century, it retained its natural character to a large extent. This was possible mainly due to the favorable morphometry of the lake (large depth and capacity of the reservoir) and different forms of active and passive protection, introduced mainly after the establishment of the Wigry National Park in 1989.

Keywords: Wigry National Park; Wigry Lake; paleobiology; paleoclimatology; plaeoceology; palelimnology; lacustrine sediments; carbonate gyttja; lacustrine chalk; trophic status

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1. Introduction

Lakes constitute diverse water bodies of a great environmental importance, as they play a vital role in the water cycling process, represent a source of freshwater for living creatures, also including humans, provide a habitat for various living organisms, are an important element of the landscape and local climate, and are also essential to many branches of the economy and industry [1–3]. Lakes, and, in particular, lacustrine sediments, are also considered to be a good archive of climate changes, due to the susceptibility of freshwater ecosystems to climatic conditions. Climate changes influence physical characteristics of lakes, such as water temperature, rate of evaporation, or stretch of ice cover, which, in turn, modify lake mixing regimes, and these impact chemical parameters (pH, ionic composition, electrical conductivity, nutrient concentration, etc.) and effectively biological indicators (e.g., diversity and abundance of plankton species) of lake environments [4–7]. Freshwater bodies cover just over 3% of the Earth's surface [8], whereas they cover only 1% in Poland [1], which represents one of the factors that place Poland at the forefront of European countries with the lowest freshwater resources [9]. Furthermore, these are anthropogenically affected, mainly due to urbanization, mining, industry, wastewater discharge and agriculture [10–12], which is another reason why Polish freshwater resources deserve special attention and protection.

Polish lakes are in the vast majority of postglacial origin and are located mostly in the northern part of the country, creating three largest lake districts: the Mazurian Lakeland, the Pomeranian Lakeland, and the Wielkopolska Lakeland, as well as some other smaller lake districts, with several thousands of lakes with an area of more than 1 ha [1,13]. One of them is Wigry Lake, located in the NE part of Poland and representing one of the most interesting, important, and beautiful water bodies in the country that has been an object of scientific interest for decades [14]. Wigry Lake was "discovered for science" in the second half of the 19th century [15], and, since then, it has been an object of scientific interest for researchers from many fields. Its research intensified with the establishment of a Hydrobiological Station led by Alfred Lityński in the first half of the 20th century. The Station, firstly primitive, quickly became a relatively modern scientific facility, also being one of the few in Europe at the time. Its scientific achievements were highly appreciated also beyond Poland, e.g., in Sweden [16], and resulted in numerous publications, e.g., [17–28]. After the Second World War, the interest in the lake and its surroundings faded somewhat, although it did not cease, e.g., [29–33], only to increase again in the 1980s [34]. In 1975, the International Union for Conservation of Nature (IUCN) included Wigry Lake in the list of the most valuable water reservoirs in the world [35], the Landscape Park was created in order to prevent the degradation of the Wigry Lake environment in 1976, then the protection of this area was strengthened by the establishment of the Wigry National Park (WNP) in 1989 [16,36,37], and the lake was "adopted" (as the first in the world) by the International Association of Theoretical and Applied Limnology in 1998 [38]. In 2002, the WNP was recognized as a wetland of special international importance (Ramsar Convention), and it became a part of the Natura 2000 network as a bird protection area in 2004. More contemporary studies started in 1997 and lasted nearly two decades, thanks to the extraordinary passion of Professor Jacek Rutkowski [14,39,40], as well as his numerous colleagues and "scientific friends", which resulted in dozens of publications (many of which are quoted below), numerous master's theses, and several Ph.D. theses, e.g., [41,42].

What additionally makes Wigry Lake especially unique is the scale of research carried out on its sediments, which have been identified in particular detail. Lake deposits are a remarkably important element of freshwater environments, as they affect biological life, accumulate contaminants and other substances (both organic and inorganic), affect the silting of water bodies, etc. [43–46]. Although aqueous deposits are quite often closely studied and described, e.g., [47–50], research is usually based on a relatively small number of samples. In the case of the Wigry Lake, however, over 1200 sediment samples have been obtained since 1997, allowing for the development of a reasonably accurate map of the bottom sediments of the lake, which represents a unique result in itself. Although such maps are sometimes developed, e.g., [51–56], it is not a common area of research, especially nowadays. One of the reasons for this is that the geological cartography of aqueous sediments, unlike that of land areas, is a much more complicated and problematic issue [45].

The main purpose of this review paper is to summarize several decades of interdisciplinary research carried out on Wigry Lake and to compile the extensive information on the lake that is currently scattered across a remarkably wide range of papers, published mostly in Polish. Special attention is paid to Wigry Lake sediments as a very good archive of environmental changes.

2. Specification of the Study Area

Wigry Lake is nowadays protected as a part of the Wigry National Park (Figure 1), which has a territory of 148.4 km^2 and partly covers the area of two physical–geographical mesoregions: the Suwałki Lakeland and the Augustów Plain, which both represent parts of the Lithuanian Lakeland macroregion. The geomorphology of this area is clearly bifid and was shaped by Weichselian (Vistulian, Baltic) glaciation. The northern part of the WNP is characterized by frontal moraines made of glacial till, gravels, and rocks, as well as numerous kames and eskers, whereas its southern part is covered by extensive sandur [16,57–63].

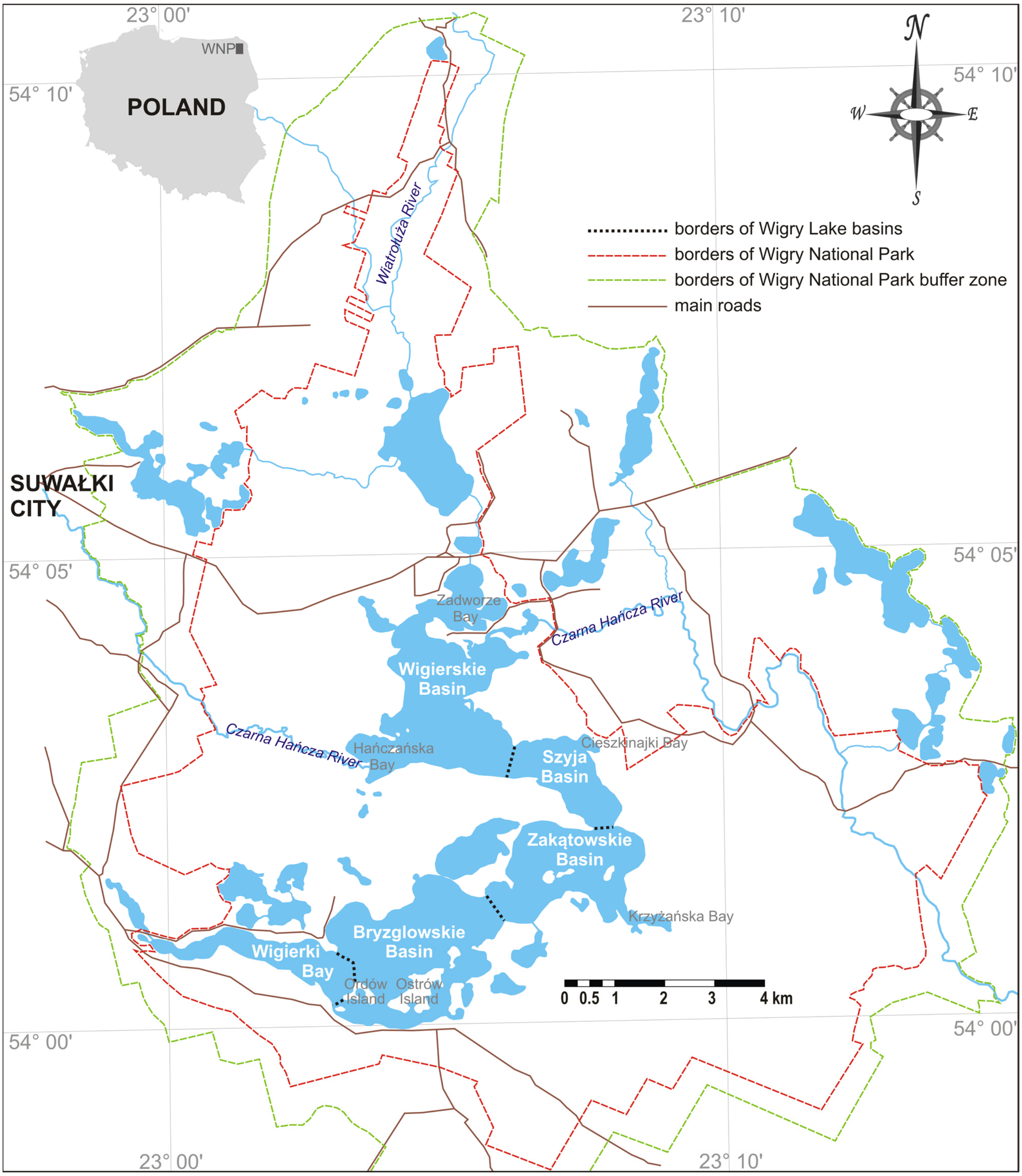

Figure 1. Study area: Wigry Lake within the borders of the Wigry National Park (WNP) (according to [64], modified).

The climate of this area is moderate and transitional between continental and maritime, with the advantage of the former. The mean multiannual year temperature is approx. 6.4 °C (4.3–8.2 °C), with the highest monthly average in July and the lowest monthly average in January, wherein the mean temperatures for the WNP area increase over time. The average annual precipitation is about 600 mm, fluctuating from approx. 330 mm to 830 mm, with a maximum in summer and minimum in winter. Winter comes quite early and is relatively long, with several dozen days of snow cover and ice cover on lakes [61,65–69].

The Wigry National Park lies in the middle part of the catchment of Czarna Hańcza River (which represents a part of the Neman River catchment), which flows from the western direction into the Wigry Lake in its northern part (Hańczańska Bay in the Wigierskie Basin) and flows out of the lake in its north-eastern part. The second important river of the WNP is Wiatrołuża, which flows into the lake from the north (Zadworze Bay in Wigierskie Basin) as a left tributary of the Czarna Hańcza River (Figure 1). Other important elements of the hydrographic system of WNP and the Wigry Lake include nearby lakes, small streams, springs, groundwater, and precipitation. The average water change rate in the lake is about 3 years and is different for each of the main parts (basins) of the lake, due to their diversified morphometry [16,70–77].

The name "Wigry" probably comes from the Lithuanian word *vingrùs*, which means tortuous or squiggly [36,78], and reflects the complicated structure, morphometry (Table 1), and characteristic shape of the lake basin resembling the letter "S". The lake is divided into five (sometimes six) major parts, separated by narrowings and shallows (Figure 1). The Wigierki Bay has the characteristics of a tunnel valley and stretches out to Ordów Island in the Bryzglowskie Basin. The Bryzglowskie Basin and the Zakątowskie Basin are genetically glacidepressions, transformed during deglaciation into melting basins. Furthermore, the Szyja Basin, the deepest part of the lake (Figure 2A) with the steepest slopes, represents a tunnel valley. Finally, the Wigierskie Basin is partly of morainic and partly of furrow type and may be subdivided into three different parts: southern, middle and northern ones. The most northern part of this basin—the Zadworze Bay—is sometimes treated as a separate, sixth main part of the Wigry Lake [59,60,73,79–85]. The contemporary shape of the lake basin was established between Younger Dryas and Holocene, about 14,000 years BP [67,86,87], and the initial lake area was larger than it is nowadays [84,88–90]. Wigry is a dimictic lake, characterized by typical thermic stratification of water in the summer (epilimnion, metalimnion, and hypolimnion), winter stagnation, and mixion, observed in the spring and in the autumn [67,73,91–93].

Table 1. Morphometry of the Wigry Lake.

Parameter	Value [1]	Value [2]
Degree of coastline development	4.35	–
Water surface (km^2)	21.2	21.7
Bottom surface (km^2)	–	21.9
Islands surface (km^2)	0.68	0.67
Capacity (mln m^3)	336.7	335.4
Max length (km)	17.5	–
Max width (km)	3.5	–
Max depth (m)	73	72.3
Mean depth (m)	15.8	–
Basin shoreline length (km)	59.8	63.9
Islands shoreline length (km)	12.4	–
Total catchment (km^2)	453.7	–

[1] Data presented in the table are official and reprinted in many papers (here according to [73,79,91,94]), but Rutkowski et al. [83] suggests that some of them need to be updated; [2] some updated data (according to [85]).

The analysis of a water reservoir's depth is very important in most aspects of limnological research, as it affects water temperature, insolation, oxygenation, circulation, etc. [95,96]. The bathymetry of the Wigry Lake has been quite thoroughly analyzed, but still insufficiently due to it being highly complicated, with numerous wide shallows and considerable depths, which it has long been known for [22]. The first depth measurements were carried out over a century ago but covered only a small part of the lake [97]. Subsequently, the bathymetry of certain selected parts of Wigry Lake was examined in the 1920s [17–19].

The first, and currently the only official depth map of the entire lake area, was developed in 1950s–1960s by Inland Fisheries Institute in Olsztyn [94]. In the 2000s, the range of shallows was determined using panchromatic aerial photographs [92,96]. Numerous depth measurements were made during the performance of several dozen seismoacoustic sections with the use of an echosounder [98–101], as well as during sediment sampling [96]. Additionally, a part of the Bryzglowskie Basin has been very precisely analyzed in terms of the bathymetry and the lake bed type with the use of the RoxAnn system [95]. All these studies confirmed the high complexity of the Wigry bottom structure and bathymetry (Figure 2A).

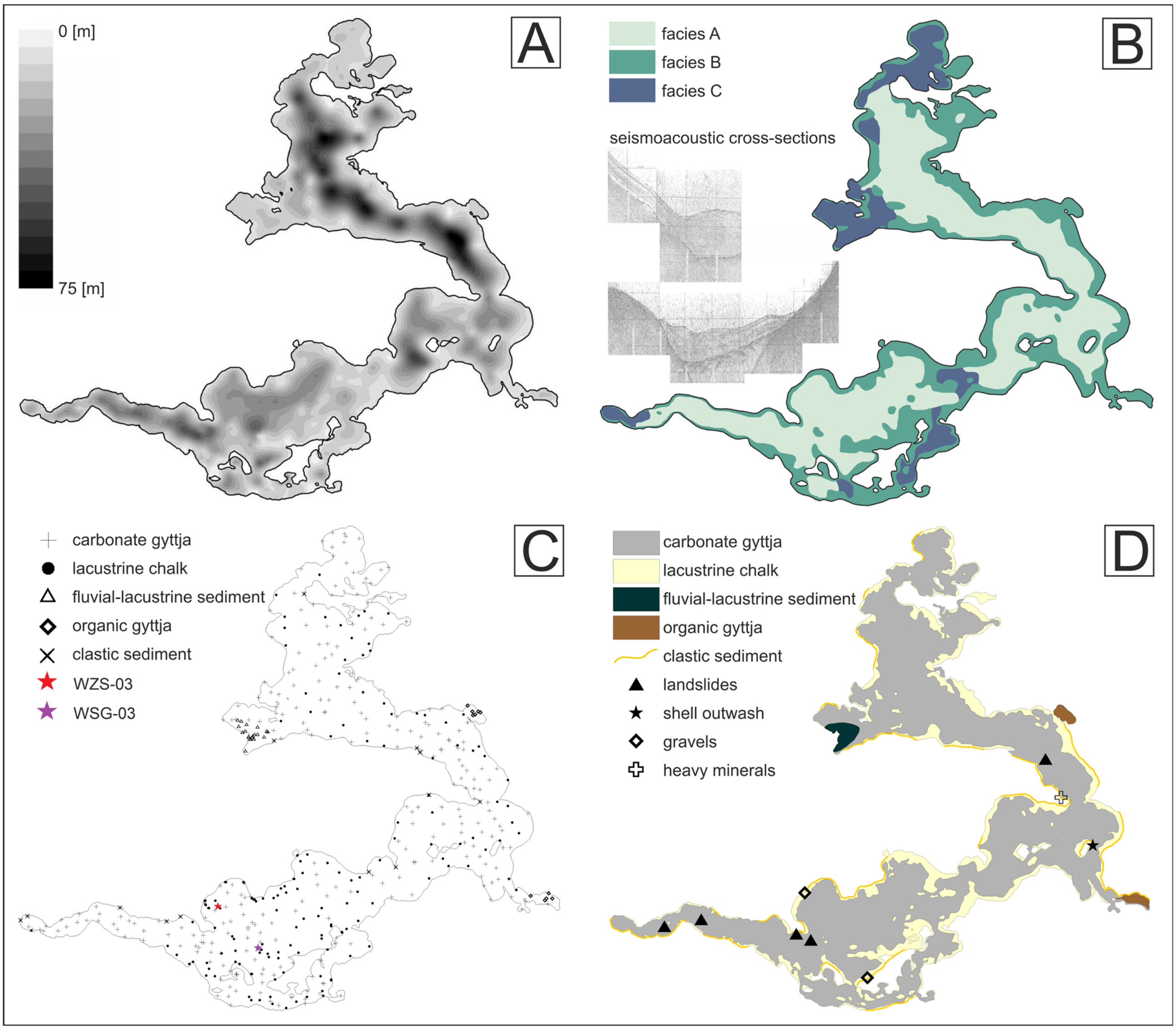

Figure 2. Spatial characterization of the sediments of Wigry Lake: (**A**) a bathymetry sketch of the bottom (according to [102]); (**B**) a map of the extent of individual facies and fragments of exemplary seismoacoustic cross-sections (according to [92,103], modified); (**C**) sampling map; (**D**) map of the extent of individual sediment types and other sedimentological phenomena (according to [89,92,96,104,105] *vide* [42], modified).

Shallows and strong bottom depressions are situated next to each other at short distances; therefore, the slope of the lake is heavily inclined in many places. About 23.5% of the lake bottom consists of shallows having a depth of less than 5 m; depths between 5 and 10 m cover 19.4% of the bottom; depths between 10 and 20 m cover 26.4%; and between 20 and 40 m cover 25.8%; whereas the remaining area of approx. 5% of the total lake bed area constitutes depths of more than 40 m. The Wigierki Bay and the Szyja Basin, being typical tunnel valleys, are relatively deep, and shallows constitute a negligible element here. However, landslides may be observed in these parts of the lake (Figure 2D), as the slopes here are relatively steep. The Bryzglowskie and Zakątkowskie Basins, being of a typical melt-out origin, are characterized by numerous and expansive shallows and islands, and their depths are relatively lower. The Wigierskie Basin, together with the Zadworze Bay (sometimes treated as a separate part of the lake) of mixed origin (partly morainic and partly furrow), are defined by significant variability, both in terms of its bathymetry, as well as in the nature of its shoreline, with quite numerous bays, islands, and shallows [83,85].

3. Methods Applied to the Research of Wigry Lake Sediments

The sediments of Wigry Lake have been comprehensively analyzed using different techniques. Next to traditional lake cartography and sediment sampling, several geophysical methods, as well as isotope-based dating, were applied. A wide range of paleobiological research was also carried out.

The geophysical analysis of sediments is considered to be a very helpful preliminary step to the actual lithological research [99]. One of such methods is a seabed discrimination system with a 28/200 kHz echosounder (RoxAnn Groundmaster Stereo System by SONAVISION). This method enables the collection data on the so-called "acoustic roughness" and "acoustic hardness" of the bottom, which may be interpreted to determine the appropriate type of sediment [95,106]. However, the collected data covered only a small part of the lake bed and was not decisive enough for the precise discrimination of sediments. The other geophysical method used to examine Wigry Lake sediments was a high-resolution seismic survey, also known as seismoacoustic, which was conducted with the use of a Seabed Oretech sub-bottom profiler with a frequency of 5 kHz (model 3010B and 1030P by ORETECH) [98–101,103,107]. This method provides data on stratification, stratigraphy, and sedimentation, due to the emission of acoustic signals. Those signals are reflected by the bottom and by some of the strata under the bottom, and their intensities depend on the acoustic impedance of the analyzed deposits. Reflected signals are recorded, appropriately processed, and visualized in the form of sections that clearly demonstrate the geological boundaries (Figure 2B).

In the case of Wigry Lake, the geophysical and lithological analysis of its bottom was conducted simultaneously. Sediments were sampled during the summer months (starting from 1997) in various ways, depending on the depth and region of the lake. Sediments present in the shallows (up to the depth of about 2 m) were collected into transparent plastic tubes that were pressed manually into the bottom, then filled with water, sealed tightly at the top using a rubber stopper (to prevent the material from slipping out of the pipe), and pulled out. The tubes containing sediments and water were then plugged at the bottom and at the top using a piece of rubber and clamping rings. Sediments from the deeper parts of the lake were collected using a gravitational sampler designed by Rutkowski [108] and constructed specifically for the research of Wigry Lake sediments. The sampler was made of two concentric tubes; the outer one was metallic, and its role was to shield the inner plastic pipe, which constituted the actual sampling tube. Both pipes were connected by a head that contained a mechanism for plugging the sampling pipe. The sampler was suspended on a rope, dropped from a boat and embedded into the bottom of the lake. The plastic sampling tube was then plugged at the top using a rubber stopper installed within the sampler head and with the use of a "messenger"—a weight travelling along the rope. Its role was to stick the stopper into the sampling tube using its own weight and gravity. After the sampler was pulled out, the inner plastic pipe was removed and sealed in the same way as described above. A new sampling tube was then installed in the sampler, and the whole procedure was repeated. Both methods of collection of sediments were considered to be simple, safe, and suitable for the sampling of plastic and semi-liquid material [109]. They enable the acquisition of sediment cores with an undisturbed structure, of several cm in diameter and up to about 1.5 m long. Sediment cores were transported to the laboratory of the Wigry National Park in Krzywe (Poland) in plastic tubes and then analyzed further. In this way, over 1200 sediment samples (Figure 2C) were collected in the form of cores of different lengths (Figure 3A), over the course of more than a decade of research. Each sampling location was determined using a GPS system and consequently plotted on a map. Sampling depths were measured using an echo-sounder (model 381/382 by FURUNO) or using a multiparameter water quality monitor (model 6920 by YELLOW SPRINGS INSTRUMENT), whereas they were measured in shallow areas using a calibrated pole [89]. In 2003, two long profiles, both located in the Bryzglowskie Basin (Figure 2C), were also taken using a Więckowski probe. A WZS-03 core of a length of 5.26 m was taken from profundal area of the lake bottom, from a depth of 18.2 m [67,110], whereas a WSG-03 profile of a length of 6.55 m was taken from the littoral zone, at the depth of 3.6 m, and at the top of an underwater hillock, called "Sielawna Górka" [89,111].

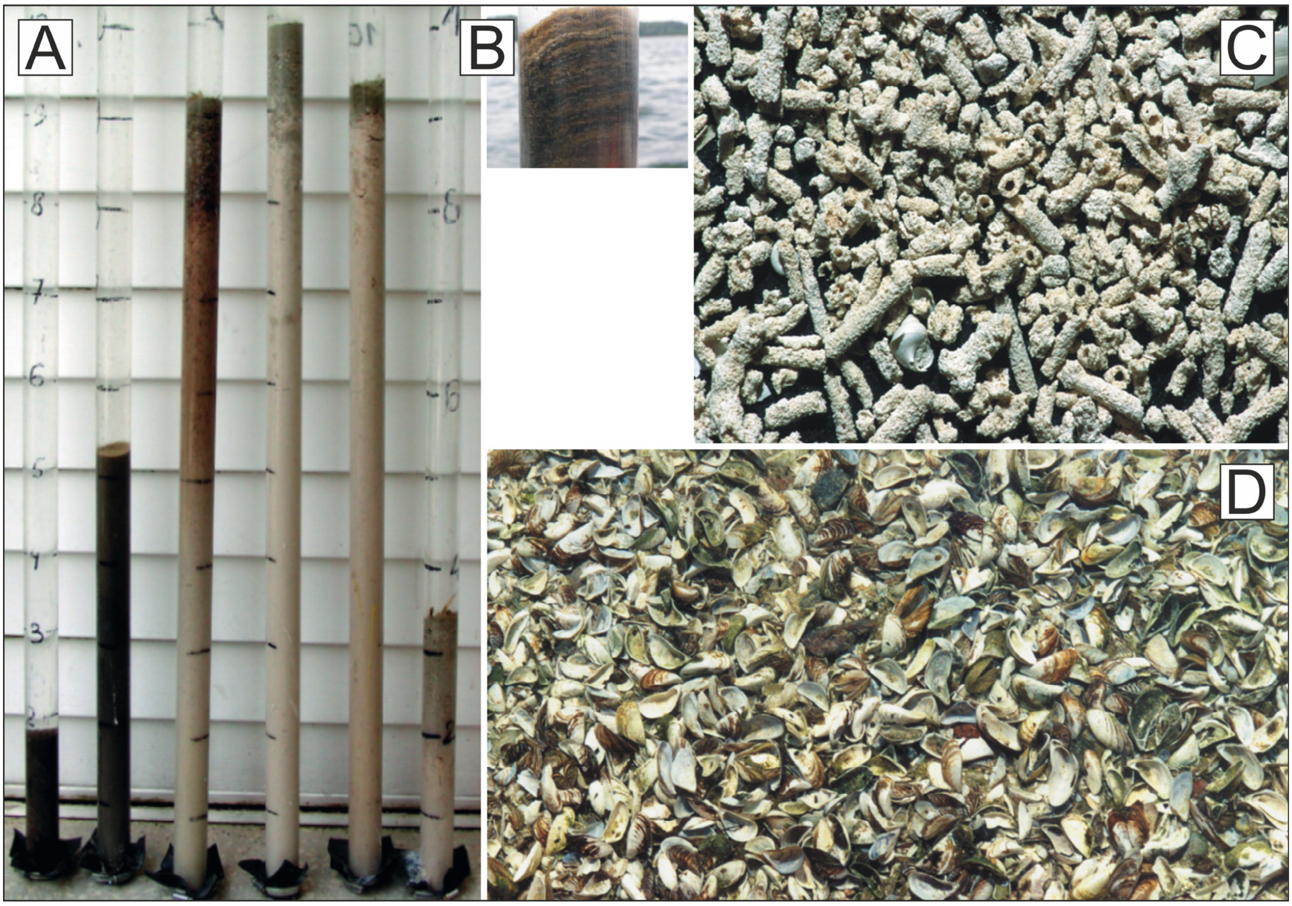

Figure 3. Lithological characterization of the sediments of Wigry Lake: (**A**) examples of sediment core profiles of various lengths, from about 20 cm to 100 cm (according to [14]) (from left to right: two organic gyttja cores; core consisting of lacustrine chalk in the bottom, turning gradually into carbonate gyttja in the upper part; three cores of lacustrine chalk enriched with organic matter in their upper parts); (**B**) upper part of carbonate gyttja with lamination; (**C**) calcareous tubes and clumps washed out from lacustrine chalk (according to [92], photo: L. Krzysztofiak); (**D**) shell outwash (according to [92], photo: J. Rutkowski).

The WZS-03 core was used to prepare an absolute timescale for Wigry Lake, and radiocarbon dating (also known as isotope dating) was performed to this end. This method is based on the measurement of proportions between the radioactive isotope of carbon ^{14}C and the stable isotopes ^{12}C and ^{13}C in natural material. Carbon isotopes enter the cycle of this element in the process of photosynthesis and food chains, and this exchange stops when a given organism dies. From that moment, the relative amount of ^{14}C (in relation to stable isotopes ^{12}C and ^{13}C) in a given material decreases, as ^{14}C is unstable (its half-life is 5740 years). Sediment samples extracted from the WZS-03 core were dated using Gas Proportional Counting (GPC), following decomposition with 2% hydrochloric acid in order to obtain pure CO_2. Purified plant residues (wood pieces, twigs, roots, reed pieces, peat, leaf fragments, seeds, pollen) were identified using the Accelerator Mass Spectrometry (AMS), following combustion and graphitization according to standard procedures. The final timescale for Wigry Lake was obtained after its calibration by Bayesian analysis using OxCal v 3.10 software and the IntCal04 calibration curve, also with the consideration of the reservoir effect and with the support of stratigraphic data [86,87,112]. The results of radiocarbon dating were supported and supplemented with isotopic investigations, based on ^{13}C, ^{14}C, ^{18}O, ^{137}Cs, and ^{210}Pb, which were carried out also on younger Wigry Lake sediments, as well as adjoining peat bogs and sub-peat sediments [87,113–116].

The WZS-03 core was also used for paleobiological, paleolimnological, paleoclimatic, and paleoecological studies, including the analysis of pollen, Cladocera, Ostracoda, and diatoms. Palynological analysis was based on the determination of the percentage of pollen of individual taxa in subsequent layers of sediment, following the preparation of sediment samples using Erdtman's acetolysis method. Mineral fraction was removed using hydrofluoric acid. The obtained pollen diagram allowed for the separation of local pollen levels that reflected subsequent stages of vegetation development in the vicinity of Wigry Lake as well as particular settlement stages [117–121]. Cladocera studies were based on the microscopic analysis of their remains (headshields, shells, postabdomens, postabdominal claws, and ephippia) extracted from sediment samples after pretreatment with HCl (in order to eliminate carbonates) and boiling in a 10% solution of KOH (in order to remove humic matter). The determination of the affiliation of species of Cladocera provided information on temperature, hydrological conditions, and trophy status of the water reservoir during the deposition of sediment [122–124]. Ostracoda research plays a similar role in paleolimnological studies, and it was based on the analysis of shells extracted from sediment samples. Taxonomic composition and the abundance of particular species allowed for the separation of Ostracoda assemblages related to subsequent stages of Wigry Lake development [125–127]. Diatoms, very well known as an excellent bioindicators (especially in terms of such parameters like pH, conductivity, salinity, trophic status, oxygen conditions, etc.), also helped to recreate the conditions prevailing during sediment accumulation. Their silicon shells are well-preserved in the sediment and are usually quite abundant, therefore the microscopic analysis of diatoms is relatively easy and very useful. Sediment samples of the WZS-03 core for diatom analysis were treated with 10% HCl (in order to remove carbonates) and 37% H_2O_2 (in order to remove organic material) [128,129]. All these comprehensive areas of research, combined with mollusc studies [130–132] as well as peat bogs and sub-peat sediments studies [90,133–137], have facilitated a detailed reconstruction of the evolution of Wigry Lake and its surroundings.

4. The Sediments of Wigry Lake

The first characterization of Wigry Lake sediments was carried out in the first half of the 20th century, e.g., [20,22,28], and the lake deposits were subsequently studied, e.g., by Rybak [30], Czeczuga and Gołębiewski [31], and, finally, more recently (beginning with 1997) by Professor Jacek Rutkowski and his collaborators [14,40]. It is also notable that Stangenberg has already pointed out in 1938 [28] that the chemical composition of lake sediments cannot be analyzed without the consideration of the morphometry of the lake basin, or the nature of the catchment and its geology; however, Wigry Lake has been well analyzed in this way. The basin of the contemporary lake is mainly filled with sediments of chemical and biochemical origin, although deposits of other two groups (clastic and organic) have also been observed. This is typical of the so called "young" lakes (formed at the end of the last ice age, about 14,000–16,000 years ago) present in Poland [46].

The thicknesses of sediments observed during contemporary research (conducted after 1997) vary between 2–6 m (mostly 4–6 m), only rarely reaching 7 or even 10 m, whereas they may reach 10–12 or even 14 m at the foot of underwater slopes (which may be observed, e.g., in the Szyja Basin or the Wigierki Bay—Figure 2D) [89]. There are also areas with a nearly "naked" rock bottom as a result of landslides. Older papers [31,138] reported slightly higher sediment thicknesses, reaching 7–12 m and even 30 m or more at the foot of underwater slopes [139,140].

The sedimentation rate (SR) of lacustrine deposits is usually calculated with the consideration of the age and thickness of the sediments [89]. The examination of the WZS-03 sediment core of a length of 5.26 m [110] using radiocarbon dating indicated that SR varied in the course of the development history of Wigry Lake and ranged from 0.08 to 1.12 mm/year [89]. The sedimentation rate for older deposits varies between 0.24 and 0.33 mm/year, whereas it is approx. 0.68 mm/year for the youngest deposits [112–114], and the average SR was observed at 0.45 mm/year [87]. Comparable results (up to 0.67 mm/year) were obtained by Poręba and Sikorski [115] using ^{137}Cs and ^{210}Pb measurements. In some parts of the lake, the bottom lake sediment layer contains peats dated at the end of the last glaciation (about 14,000 years BP) and the sedimentation rate, calculated on the basis of the thickness of the adjacent deposits, is between 0.50 and 0.86 mm/year [92]. SR estimated on the basis of the thickness and the lithological characteristics of the WSG-03 core [111] amounts to 0.46 mm/year. Taking into account various published data, the sedimentation rate in Wigry Lake can be estimated at 0.19–0.93 mm/year, 0.4–0.5 mm/year on average [89]. The sedimentation rate of younger, more recent deposits may also be based on mollusk, which appeared relatively recently in the lake environment, e.g., *Patomopyrgus antipadarum* or *Dreissena polymorpha* [130,131]. The sedimentation rate calculated this way was 11–16 mm/year and 10–13 mm/year, respectively [92].

A high-resolution seismic survey revealed four seismic facies within the Wigry Lake bottom sediments [100,101,103]. Facies A reveals parallel stratification and is the most widespread, covering the majority of bottom areas of the depth of more than a dozen or so meters (Figure 2B). It is substantially thick (up to a dozen or so m, 4–6 m on average). Facies B demonstrates the absence of stratification, occurs at low depths, and is limited to near-shore areas or central shallows. Facies C can mainly be found in the Wigierskie Basin and demonstrates stratification only in a thin top layer, whereas its lower part is devoid of reflections. It can be observed in the areas of bottom depths between several to more than ten meters, and its thickness can reach up to 12 m (in the area of the Czarna Hańcza mouth) (Figure 2B). Facies D can be found locally (especially in the Wigierki Bay and in the Szyja Basin) and probably consists of slump deposits, as its reflections are mixed [98–101,103,139,141,142]. This interpretation was confirmed by lithological studies [104].

Carbonate sedimentation is predominant in the contemporary Wigry Lake basin, whereas clastic and organic deposits appear only locally [28,96,143]. The main chemical component of sediments is $CaCO_3$, whereas the second one is organic matter [92], composed mainly of humic and fulvic acids and humins [144]. Approximately 60–75% (about 16.2 km^2) of the lake bed, which corresponds with the profundal zone, is very consistent in terms of sedimentation and is covered by carbonate gyttja. It corresponds with facies A and C, but facies D (landslide collapses) of the area of about 0.07 km^2 can be observed in the depths area. Littoral zones that cover approximately 25–30% of the lake bed (about 5.4 km^2) are more diverse in terms of sedimentation and correspond with facies B. Shallows are mainly covered by lacustrine chalk, but other types of deposits may be also found here. These include clastic sediments (sands and gravels in the form of narrow belts; about 0.2 km^2 of the lake bed) or highly organic fluvial-lacustrine sediment located in the mouth of the Czarna Hańcza River (about 0.04 km^2), whereas organic gyttja can be found in the Cieszkinajki Bay and in the Krzyżańska Bay (Figure 2D). Other deposits, e.g., shell outwash composed of *Dreissena polymorpha* mussels (Figure 3D), are of little importance and represent more of a natural curiosity [89,92,104,105,145]. During sampling, the release of gases from the sediments may be observed, wherein it was established that they are composed mainly of methane, carbon dioxide, and nitrogen of microbiological origins [139,146].

It is notable that there are no sharp boundaries between the various types of sediments [139,140]. For example, 80% content of calcium carbonate is assumed as the "geochemical boundary" between lacustrine chalk and carbonate gyttja [46,84,89], but chalk in Wigry Lake gradually turns into gyttja with depth, and it is sometimes problematic to assign a given sample to a specific type of sediment. Moreover, deposits typical of littoral may be sometimes found at considerable depths, and carbonate gyttja may be observed in the shallows, especially in lake areas exposed to eutrophication or overgrown with reeds. The top layer of sediments may also be disturbed by the activities of fishermen [89,111]. The assignment of a given sample to a specific type of sediment was carried out in situ and then verified in a laboratory, in the course of a physio-chemical analysis, including color, density, and contents of $CaCO_3$, organic matter, and water (Table 2). The following characteristics of five main types of Wigry Lake sediments (carbonate gyttja, lacustrine chalk, clastic sediment, fluvial-lacustrine sediment, and organic gyttja) refer to typical ones.

Table 2. Wigry Lake sediments characterized in terms of selected physio-chemical parameters (according to [67,92,139,142,147–150] *vide* [151]).

	Carbonate Gyttja	Lacustrine Chalk	Clastic Sediment	Fluvial-Lacustrine Sediment and Organic Gyttja
$CaCO_3$ content (as dry) [1] (%)	54–87	52–98	7–16	3–14
Organic matter content (as dry) [2] (%)	8–30	2–7	<1	10–51
Water content [3] (%)	74–95	45–85	17–51	80–98
Density (10^3 kg/m^3)	1.05–1.24	1.12–1.62	nd *	1.01–1.06
Silty and clayey granulation content (%)	95–99	41–72	<1	nd

[1] Scheibler method (according to [152]); [2] LOI (550 °C, 4 h; according to [153]); [3] 105 °C; * nd—not determined.

4.1. Carbonate Gyttja

Carbonate gyttja (also called calcareous gyttja) is a type of sediment that covers profundal lake zones almost entirely and may be sometimes observed also within the littoral (Figure 2C,D). It is the most fine-grained sediment, composed mainly of $CaCO_3$ of silty and clayey granulation (<0.06 mm), precipitated chemically and with the participation of phytoplankton [105,154], but organic matter is also a significant component. Water content is high, and density is low (Table 2). Carbonate gyttja is a sediment of grey color, sometimes almost black (it becomes lighter during drying, which indicates the oxidation of Fe-complexes, probably hydrotroilite), which is related to organic matter content (Figure 3A). Sometimes very fine, color-marked lamination (Figure 3B) may be observed [89,92,139,140,142,145,148]. The mean level of mineralization of carbonate gyttja interstitial waters is 717.7 mg/L [155].

4.2. Lacustrine Chalk

Typical lacustrine chalk (sometimes also called lake chalk) is light in color, whitish, yellowish, greyish, or creamy (Figure 3A), and its main component is a silty and clayey $CaCO_3$ (<0.06 mm). Nevertheless, sandy and even gravel fraction can be also observed, and it often consists of clumps and tubes (Figure 3C) formed by the precipitation of $CaCO_3$ with the participation of algae, mainly Charophyta [105,156] and plants, as well as crushed mussels of shellfish. The other component of chalk is organic matter, and sometimes a small admixture of sand may be observed. Water content is relatively low, and density is the highest among other deposit types (Table 2). Lacustrine chalk found in various parts of the lake (Figure 2C,D) usually varies in terms of its consistency, color, granulation, and $CaCO_3$ content. For example, chalk overlying coastal shallows seems to be more fine-grained than that found on in-lake shallows, has higher water content on average, slightly lower $CaCO_3$ content, and is richer in organic matter and clastic material [89,92,111,139,140,143,148]. The mineralization of lacustrine chalk interstitial waters is the lowest among all sediment types and is on average 544.5 mg/L [155].

4.3. Clastic Sediment

Clastic sediments are represented mainly by sands and gravels (>0.06 mm, Table 2), which can be found near lake shores (Figure 2C,D) in the form of narrow belts (10–15 m wide), and which turn into carbonate sediments further away from the shore. Clastic sediments usually appear at the foot of cliffs, with most of them being inactive nowadays, and the only known active cliff can be found in the NW part of Ostrów Island. Deposits of this type can also be found in the vicinity of the estuaries of some streams into the lake. Two types of rocks (of comparable quantities) dominate in the petrographic composition of sands and gravels found in the Wigry Lake: carbonate rocks (mainly limestones and dolomites, which are the main source of $CaCO_3$ for carbonate sedimentation in the lake) and igneous and metamorphic rocks. Both come mainly from Scandinavia and were transported by glaciers [89,92,139,140,148,157,158]. The effect of gravel segregation was observed on one of the beaches [159], and the presence of heavy minerals (due to the activity of waves) was observed in the Szyja Basin (Figure 2D) [139]. Both of these phenomena are characteristic of Baltic environments [89,96].

4.4. Fluvial-Lacustrine Sediment and Organic Gyttja

Fluvial-lacustrine sediment can be found in the estuary of the Czarna Hańcza River (Figure 2C,D). It is almost black, heavy-watered, poor in $CaCO_3$ and relatively rich in organic matter (Table 2), which is mainly coarse-grained due to the substantial abundance of poorly decomposed plant residue [89,92,96,105]. This sediment resembles detritus gyttja, and its pore water mineralization is the highest among all examined sediments and amounts to 1670.9 mg/L on average [155]. Fluvial-lacustrine sediment also contains the highest amounts of gases [89,146].

Somewhat similar characteristics are demonstrated by sediments found at the bottom of the moderately eutrophic Cieszkinajki Bay and Krzyżańska Bay, called organic gyttja (Figure 2C,D) [89,92,96]. It is worth noting, however, that these sediments are more fine-grained and lighter in color (which is related to the organic matter content). Additionally, research related to seven metals (Cd, Cr, Cu, Fe, Mn, Pb, and Zn) present in Wigry Lake sediments [41,42,64,102,151] has revealed that mean element concentrations in organic gyttja and carbonate gyttja do not differ significantly (except for iron, and to a lesser extent manganese). This may suggest that organic gyttja is genetically more related to carbonate gyttja than to fluvial-lacustrine sediment, although the small amount of organic gyttja samples being studied prevents an unambiguous conclusion.

5. Ecological State of Wigry Lake—Past and Present

Wigry Lake is believed to be subject to relatively minor anthropopressure when compared to other Polish lakes. Its catchment is not affected by heavy industry; the Wigry National Park is located within one of the least populated provinces in Poland [160] and, together with the Białowieża National Park, constitutes the so-called "green lungs of Poland", which are considered to be one of the most pristine regions of Europe [161–163]. Nowadays, the morphometric characteristics of Wigry Lake (especially its significant depth, capacity and high proportion of hypolimnion) make it relatively resistant to adverse changes [1,164,165]. On the other hand, however, regeneration (re-oligotrophication) of such reservoirs is generally slower than in the case of shallow lakes [16]. Contemporary Wigry is a typical harmonic lake of mesotrophic–eutrophic character [73,166–169].

Research carried out on long sediment profiles [67,110,111,150,170] has revealed that Wigry was subject to natural evolution typical of Holocene postglacial lakes in the Polish Lowland. Gravels, sands, and sandy mud found in the bottom of sediment cores gradually turn into lacustrine chalk (very pure in its middle part), which is characteristic for oligotrophic environments. In the case of littoral, chalk becomes enriched in plant detritus in the upper part, whereas chalk turns gradually into carbonate gyttja in the case of profundal (Figure 3A). That indicates progressive deterioration of aerobic conditions and the increase in temperature and trophy of the lake throughout its evolution history. Sedimentological data stay in line with paleobiological analyses, which demonstrates that the vegetation in the area of Wigry Lake in the postglacial period has long retained its natural character and has remained almost natural up to the present day [117–121,171]. The main factors affecting the biological development of the Wigry Lake include natural climatic changes [122–124] because the development of human settlement has never been intensive in this area [172], and agricultural activity did not intensify until the 17th century [89]. Archeological and paleobiological data, however, are not strictly convergent on the matter, which prevents its unambiguous interpretation [121]. The rather significant deterioration of the trophic state of Wigry Lake began in more or less the 17th century. It was mostly associated with the beginning of the activity of the Camaldolese Order, which accelerated the development of settlement and agriculture, increased deforestation, influenced local water conditions, and started the period of intensive extraction and processing of materials such as bog ores, wood, charcoal, tar, turpentine, and glass [16,36,84,121].

More contemporary adverse changes in the Wigry Lake environment are a result of the urban and industrial development of the nearby city of Suwałki (which held the status of the voivodeship capital in the years 1974–1999) [16,173], the development of tourism [16,174], and the relatively large load of nutrients (especially phosphorus) carried by the Czarna Hańcza River [37,91,164,175–178], as well as some other contaminants like polynuclear aromatic hydrocarbons [179] or metals, which have been extensively studied [41,42,64,102,147,149–151,163,180–187]. The analysis of long sediment cores [150,186] revealed that relatively high metal concentrations in the bottom part of profiles originate from crystalline rocks derived from glacial sediments, whereas the middle parts of cores are very pure, and the concentration of metals is higher in the upper part of the profiles. The highest levels of metals have been found in sediment layers dating back to the 1960s–1990s, which corresponds with the most intensive anthropopressure, including agricultural and industrial development. Studies based on short sediment cores [41,149,163,186] stay in line with these results. A detailed analysis of spatial distribution of metals in recent sediments of Wigry Lake [41,42,64,102,151], however, revealed that their origin is both natural and anthropogenic (with a diverse contribution of these sources in the case of individual elements), whereas two main factors affecting the spatial distribution of metals are of natural character, and they are the sediment type (generally the fluvial-lacustrine sediment is the most enriched in metals, whereas lacustrine chalk or clastic sediment is the least enriched) and lake depth (the concentration of metals is generally proportional to depth).

Symptoms of progressive eutrophication of the Wigry Lake environment include the dwining of charophytes (*Chara fragilis*), which were still dominant a century ago [97], and, even in the 1960s [111], the overgrowing of common reed (*Phragmites australis* (*communis*)) in shoreline areas (which is the most intense in the Zadworze Bay and in the northern part of the Wigierskie Basin) and the displacement of other species of vascular plants by hornwort (*Ceratophyllum demersum*) [89,111,188,189]. Other changes include the deterioration of oxygen conditions, including the decrease in oxygen saturation of hypolimnion [16,190], which is manifested in changes in crustacean species assemblages [125–127], changes in species compositions of algae [16], including diatoms [128,129], or in the more frequent occurrences of mollusk species tolerating eutrophic conditions [131,132] in the youngest sediment layers. Finally, the reduction in the precipitation of $CaCO_3$ can be observed, which leads to the displacement of carbonate sediments by organic ones [89,92,139,148].

Wigry Lake and its vicinity are also subject to changes resulting from contemporary climatic processes and especially from global warming. These changes, however, are slightly slower than in the case of other lakes in the Polish Lowland because Wigry Lake lies in the area of Poland with the most severe climate [93]—the area of Suwałki is often named as the coldest area in Poland. The increase in mean air temperatures is accompanied by the increase in mean lake water temperatures, especially in the summer period in the littoral zone [93,191]. Climate changes affect the hydrological balance of Wigry Lake, disrupting the proportions between the vertical and horizontal water exchanges [16]. The number of days with snow cover in the WNP area and with icing effects on the lake is also falling, although the trend for the period 1949–2007 has been considered as statistically irrelevant [192]. Global warming processes in general have caused the prolongation of the growing season up to about 200 days on average, but with significant variability over last years. They are also most probably responsible for the gradual disappearance of some plant species from the WNP area and for the propagation of other species, including invasive forms [69].

Finally, it must be said that the lowest quality of the Wigry Lake environment was observed in the 1980s and 1990s, and the ecological state of the lake is now considered to be relatively good and constantly improving. This is mainly the result of the construction of a sewage treatment plant in Suwałki in 1986 and its modernization in the 1990s, including dephosphatation, as well as the development of a sewage network in the catchment [16,37,69,73,174,176,193,194]. Additionally, some less fertile fields were abandoned in the middle of the 20th century, and some of them have been subject to spontaneous re-forestation [121]. Of great importance here were various forms of active and passive protection, carried out as part of the statutory activities of the Wigry National Park [16].

6. Conclusions

The concept of sustainable development has been adopted by the researchers and enthusiasts of Wigry Lake and its surroundings since the 1920s, when the uniqueness and beauty of the Suwałki area's landscape were discovered and appreciated. The different forms of protection implemented since that time, which culminated in the creation of the Wigry National Park, helped to preserve the natural character of this area and simultaneously allowed the local communities to develop. The WNP area is currently protected in three main forms: strict, active, and landscape protection. Nature protection is focused mostly on preserving the existing diversity of species and their habitats, as well as restoring those ecosystems that have been transformed under the influence of human activity. Protected forests and waters remain in use, but with attention being paid to the unique qualities of the natural and cultural landscapes.

The aim of sustainable management of forests, covering approximately 63% of the WNP area, is to facilitate and accelerate the return of natural forests consisting of tree species suitable for local soil and habitat conditions and to reduce the propagation of invasive species. Some trees of species associated with anthropogenic activity (pine and spruce) are removed, and, in their place, species typical of the natural oak-hornbeam forests here are planted (oak, hornbeam, linden, maple, ash, and elm). Forests are also protected against pests (like bark beetle) by removing infected trees and using pheromone traps. Non-forest ecosystems like peat bogs and marshy areas are also subject to active protection, which involves suppressing their overgrowth by mowing herbaceous vegetation (including reeds) and removing shrubs and woody species. These activities contribute to the preservation of biodiversity of valuable non-forest habitats, including many protected species.

The greatest threat to the quality of the WNP water bodies, which cover about 19% of the park's area, is their fertilization (eutrophication). It may lead to a decrease in water transparency due to an increase in the mass of algae suspended in the water column, deterioration of oxygen conditions, and consequently to the decrease in the diversity of aquatic organisms as well as disappearance of species suitable for low-trophic waters. Therefore, the main aim in terms of waters protection in WNP is to prevent the increase in their fertility by limiting the influx of phosphorus and nitrogen compounds into the water. This goal was achieved largely thanks to the construction and modernization of the sewage treatment plant in Suwałki as well as the development of a sewage network in the catchment. Also, the number of individual fish species is regulated in such a way as to decrease abundance of phytoplankton, which contributes to reducing water trophy.

The national park employees are also responsible for the organization of scientific research, environmental monitoring, or the development of tourism, and they perform these roles in cooperation with the local authorities, the residents of the WNP, as well as national institutions and European organizations. All of these integrated activities have contributed to the good environmental conditions of Wigry Lake and its surroundings. However, history preserved in the lake's settlements, which has been discovered in the course of interdisciplinary research, is a priceless source of knowledge on environmental changes connected both with natural processes, as well as with anthropogenic activity, and allows us to better understand their mutual interactions. It must be emphasized that many of the results presented above were achieved despite very little financial support and only due to the commitment and true passion of the participants of the "Wigry adventure". These results could be achieved also due to the personal and material support provided by the authorities of the Wigry National Park. Therefore, this paper is also a kind of tribute to people associated with the Wigry Lake studies in some way or another, in particular to Professor Jacek Rutkowski.

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