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Fish Species Richness in Polish Lakes

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Abstract: Global warming, eutrophication, fisheries overexploitation, species invasions, and habitat loss are the major threats to freshwater biodiversity. The aim of this study was to determine the species richness and diversity of fish in 535 Polish lakes of different morphometry (area of more than 50 ha and a maximum depth ranging from 0.4 to 108.5 m) and trophic status (from oligotrophy to hypereutrophy). A total of 39 fish species were found in the studied lakes, among which eight species were alien invasive. The Shannon diversity index varied between 0 and 2.04.The most common and frequent species were *Rutilus rutilus* (99.8% frequency) and *Perca fluviatilis* (99.6% frequency). Ten fish species, including five alien ones, were characterized by a very low frequency (<1%). The number of fish species in single lakes ranged from 1 to 19. In most of the studied lakes, 11 and 12 species (104 and 108 lakes, respectively) were caught. The richest taxonomic composition (19 species) was recorded in the meso-eutrophic lake with an area of 80 ha and a maximum depth of 34.4 m, slightly poorer (18 species) in the hypereutrophic lake with an area of 168 ha and a maximum depth of 2.7 m. The poorest taxonomic composition (one species) was found in a lake with low conductivity and circumneutral pH. Statistical analysis showed that the number of fish species decreased with increasing eutrophication conditions of the studied lakes, while it increased with an increasing area and the maximum depth of these lakes.

Keywords: biodiversity; ichthyofauna; alien fish species; morphometry; trophy

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1. Introduction

Fish, especially some species and/or groups of species, are defined by the term "keystone species" [1] or "strong interactor" [2]. The role of these organisms in the matter and energy flow in the trophic food web is disproportionate to their numbers and contribution to the total biomass of the biotic components of aquatic ecosystems [3]. Species richness and diversity of local fish in lakes are regulated by morphometric and (bio)geographic/climatic parameters [4]. Among the morphometric parameters, lake area and maximum depth are the most important [5–7]. Larger and deeper lakes in warmer regions are usually the richest in species and diversity [4]. The species composition and structure of fish in lakes and rivers of the northern hemisphere undergo substantial changes due to eutrophication [8,9]. The increase in lake trophic status is accompanied by a decrease in the number of fish species inhabiting the lakes [10]. Fish species characteristic of low productive waters (salmonids) are replaced by cyprinid fishes (mainly *Rutilus rutilus*, *Abramis brama*, *Blicca bjoerkna*, and *Alburnus alburnus*) in highly productive lakes [2,11]. The result of eutrophication and disturbances in the functioning of the aquatic environment is also a decrease in the numbers of *Esox lucius*, *Tinca tinca*, and *Perca fluviatilis*, which are particularly sensitive to adverse environmental changes [10,12].

Literature data show that inland waters (lakes, rivers, ponds) of Poland are inhabited by 86 fish species [13]. While the composition of the fish of most rivers has been quite well determined by the electrofishing method [14–16], the species richness of lakes is less known [17]. The study of fishes in lakes is more time-consuming and labour-intensive due to the much larger area and depth of the lakes, and the need to use a greater fishing effort [18]. For this reason, most of the current literature data on the number of fish species occurring in various lake systems are based mainly on the effects of commercial and/or experimental catches [10,18]. It should be emphasized that the experimental studies focus primarily on the description of the biological or ecological characteristics of individual fish species [19,20], and not on the qualitative and quantitative assessment of the entire fish community [21,22]. Little information is available on fish in a single lake or many lakes in one lake system [17]. Different methods of fish caught are applied to estimate the species richness of fish in lakes [23]. The most effective method is the Nordic gillnets set used to monitor fish to assess the ecological status. This method allows the catching of the largest number of individuals and species of fish [23]. Knowledge about fish species richness and diversity is important for ecosystem functioning and fisheries management [4,5]. In addition, data on fish community composition can be useful for the conservation strategies of rare and endangered species.

The aim of this study was to determine the species richness and diversity of fish fauna in lakes of different morphometry and trophic status in Poland.

2. Materials and Methods

The studies were carried out in 535 lakes located in northern and central parts of Poland (Figure 1). Fishing was conducted once in each lake during the summer–autumn period (from the end of June until the middle of October) in 2014–2021. Water temperature, dissolved oxygen concentration, oxygen saturation, pH, and conductivity were measured in situ at 1.0 m depth intervals with a YSI multiparameter probe (Yellow Spring Instruments, USA). Water transparency was measured with a Secchi disc. The trophic state index (TSI) of lakes was calculated from Secchi disc depth according to Carlson [24]. It was assumed that lakes with TSI < 40 are oligotrophic, 40–45—mesotrophic, 45–50—meso-eutrophic, 50–70—eutrophic and those with TSI > 70—hypereutrophic. Taking into account the maximum depth, the lakes were divided into four categories: <6.0 m, 6.0–12.0 m, 12.0–20.0 m, and >20.0 m [25].

Fishing was carried out using Nordic multi-mesh gillnets according to European standard protocol (EN 14757). Benthic gillnets were 1.5 m deep and 30 m long and composed of 12 mesh sizes from 5 mm to 55 mm. Pelagic gillnets were 6 m deep and 27.5 m long and composed of 11 mesh sizes from 6.25 mm to 55 mm. Nets' time exposition was 12 h (between 18:00 and 6:00). All of the caught species were identified [13] and counted. CPUE (catch per unit effort) was determined using the number of individuals (NPUE) per 100 m^2 of gillnet. The Shannon–Weaver diversity index [26] in each lake was calculated based on the fish numbers (NPUE).

Data were statistically analysed using the STATISTICA software (StatSoft, Inc., St Tulsa, OK, USA). The linear regression model was applied to determine relationships between fish (the number of species and Shannon Index) and morphometric and trophic parameters (n = 535).

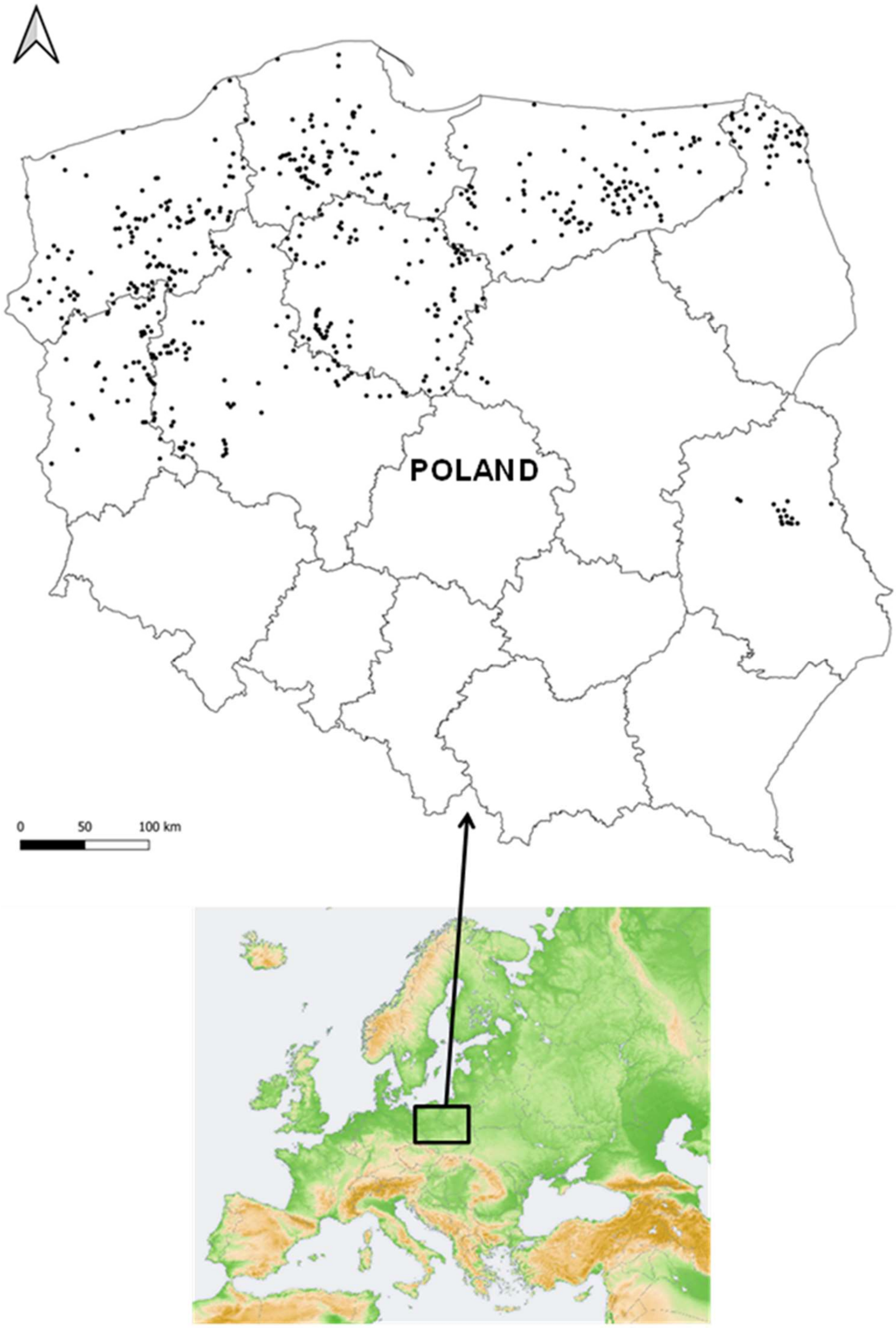

Figure 1. Map of Europe (**below**) and Poland (**above**) showing the geographical distribution of the 535 lakes sampled during the study.

3. Results

The area of the studied lakes ranged from 50 to 1446 ha. Most of the lakes (277 lakes, 52% of all of the studied lakes) were less than 100 ha. The maximum depth of the lakes was between 0.4 and 108.5 m. The largest group of lakes was the one with a maximum depth of less than 10 m (227 lakes, 42% of all of the studied lakes). Water transparency and TSI varied in a wide range from 0.08 to 7.52 m and from 30.9 to 96.4, respectively.

A total of 39 fish species were found in the studied lakes, among which eight species were alien invasive ones (Table 1). These were: *Carassius gibelio*, *Cyprinus carpio*, *Ameiurus* *nebulosus*, *Neogobius fluviatilis*, *Acipenser baerii*, *Pseudorasbora parva*, *Hypophthalmichthys molitrix*, and *Ctenopharyngodon idella*. The number of specimens caught in the studied lakes ranged from 162 to 13,548. The most common and frequent species were *R. rutilus* (99.8% frequency) and *P. fluviatilis* (99.6% frequency). *Rutilus rutilus* was only absent in one lake (maximum depth of 23.1 m and area of 61 ha) of extreme environmental condition (Secchi depth of 0.3 m, pH of 6.0, conductivity of 36 µS cm^{-1}). It should be underlined that *P. fluviatilis* was the only species of fish caught in this lake. Four other species (*Gymnocephalus cernua*, *A. brama*, *A. alburnus*, and *B. bjoerkna*) were present in more than 90% of the studied lakes. Additionally, *Scardinius erythrophthalmus* (87.3% frequency), *T. tinca* (72.2%), *E. lucius* (70.7%), and *Rhodeus amarus* (64.9 % frequency) were noted quite often. Ten fish species, including five alien ones, were characterized by a very low frequency (<1%) (Table 1).

Table 1. List of caught fish species, their status, and frequency in 535 Polish lakes.

Species	Status	Frequency (%)
Rutilus rutilus (Linnaeus, 1758)	native	99.8
Perca fluviatilis Linnaeus, 1758	native	99.6
Gymnocephalus cernua (Linnaeus, 1758)	native	96.6
Abramis brama (Linnaeus, 1758)	native	94.4
Alburnus alburnus (Linnaeus, 1758)	native	92.7
Blicca bjoerkna (Linnaeus, 1758)	native	91.8
Scardinius erythrophthalmus (Linnaeus, 1758)	native	87.3
Tinca tinca (Linnaeus, 1758)	native	72.2
Esox lucius Linnaeus, 1758	native	70.7
Rhodeus amarus (Bloch, 1782)	native	64.7
Leucaspius delineatus (Heckel, 1843)	native	47.5
Cobitis taenia Linnaeus, 1758	native	47.3
Carassius carassius (Linnaeus, 1758)	native	44.1
Sander lucioperca (Linnaeus, 1758)	native	42.6
Gobio gobio (Linnaeus, 1758)	native	35.7
Coregonus albula (Linnaeus, 1758)	native	24.9
Carassius gibelio (Bloch, 1782)	alien	17.9
Silurus glanis Linnaeus, 1758	native	15.3
Gasterosteus aculeatus Linnaeus, 1758	native	9.0
Coregonus maraena (Bloch, 1779)	native	6.2
Cyprinus carpio Linnaeus, 1758	alien	5.2
Leuciscus aspius (Linnaeus, 1758)	native	4.5
Leuciscus idus (Linnaeus, 1758)	native	4.5
Ameiurus nebulosus (Lesueur, 1819)	alien	4.3
Misgurnus fossilis (Linnaeus, 1758)	native	3.4
Squalius cephalus (Linnaeus, 1758)	native	3.2
Osmerus eperlanus (Linnaeus, 1758)	native	2.8
Lota lota (Linnaeus, 1758)	native	2.1
Anguilla anguilla (Linnaeus, 1758)	native	1.9
Neogobius fluviatilis (Pallas, 1814)	alien	0.9
Acipenser baerii Brandt, 1869	alien	0.6
Vimba vimba (Linnaeus, 1758)	native	0.4
Pseudorasbora parva (Temminck & Schlegel, 1846)	alien	0.4
Leuciscus leuciscus (Linnaeus, 1758)	native	0.4
Hypophthalmichthys molitrix (Valenciennes, 1844)	alien	0.4
Ctenopharyngodon idella (Valenciennes, 1844)	alien	0.2
Cottus poecilopus Heckel, 1837	native	0.2
Ballerus ballerus (Linnaeus, 1758)	native	0.2
Salmo trutta Linnaeus, 1758	native	0.2

The number of fish species in individual lakes ranged from 1 to 19, but the most common were 11 species (104 lakes) or 12 species (108 lakes) (Figure 2). Both the lowest and the highest number of species were recorded in individual lakes. The highest species richness was recorded in the meso-eutrophic lake (TSI 48.96) with an area of 80 ha and a maximum depth of 34.4 m, slightly poorer (18 species) in the hypereutrophic lake (TSI 73.22) with an area of 168 ha and the maximum depth of 2.7 m. Shannon diversity index ranged from 0 to 2.04. The lowest value of this index and the lowest number of species (one species) was noted in the mentioned above the soft-water lake. The maximum value of the Shannon index was noted in the highly eutrophic (TSI 80.0), shallow (7.5 m) and relatively large lake (area of 219 ha).

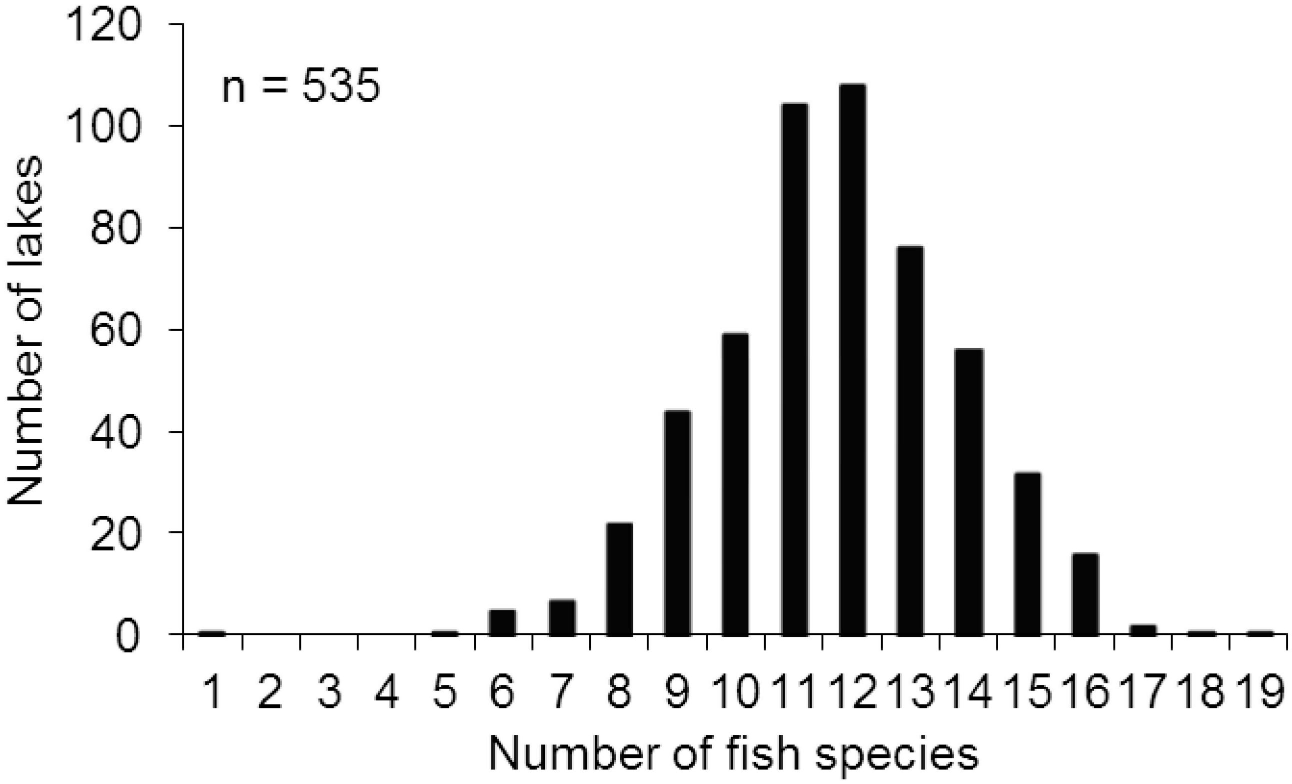

Figure 2. The number of fish species and the assigned number of lakes (in total *n* = 535 lakes).

The ranges of fluctuations in the number of fish species in oligotrophic and eutrophic lakes were very similar (Table 2). A much higher range of fluctuations was observed in hypereutrophic lakes (1–18 species). However, the mean number of fish species, in particular trophic groups of lakes, was similar (12 species in oligo- to eutrophic lakes, 11 in hypertrophic lakes). The smallest range of fluctuation in the Shannon diversity index was recorded in oligotrophic lakes, while the highest was in hypereutrophic lakes (Figure 3).

Table 2. The number of lakes and the number of fish species in different trophic types. Trophic conditions of the studied lakes were based on the trophic state.index (TSI) of lakes, calculated from Secchi discvisibility according to Carlson [24]. SD = standard deviations.

Trophy	Number of Lakes	Number of Fish Species	
		Min.–Max.	Mean ± SD
Oligotrophy	37	7–15	12 ± 2
Mesotrophy	66	9–16	12 ± 2
Meso-eutrophy	68	7–19	12 ± 2
Eutrophy	281	6–17	12 ± 2
Hypereutrophy	83	1–18	11 ± 3

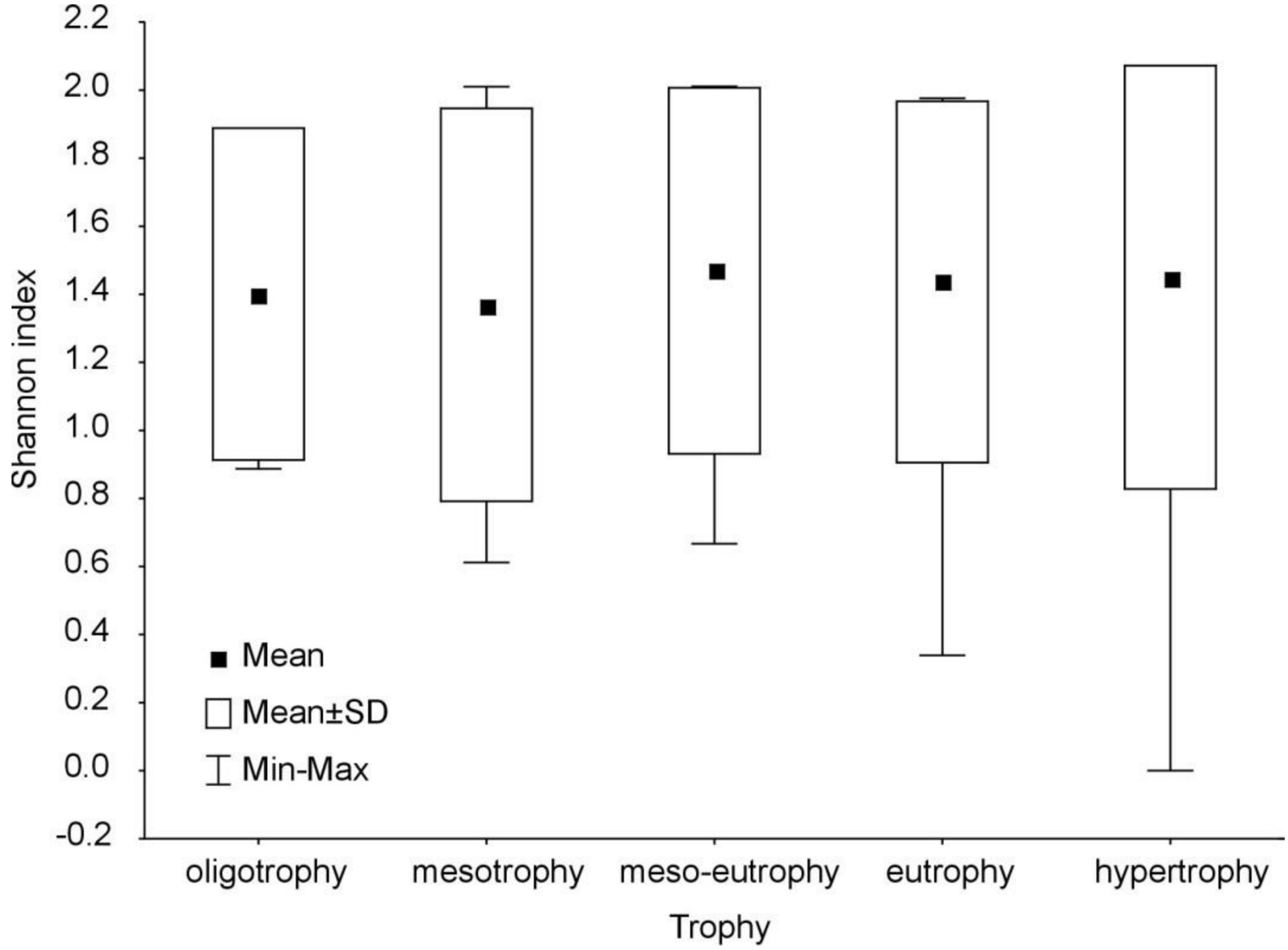

Figure 3. The Shannon index in 535 Polish lakes of different trophic status. Trophic conditions of the studied lakes were based on the trophic state index (TSI) of lakes, calculated from Secchi disc visibility according to Carlson [24]. SD = standard deviations.

Taking into account fisheries categories of lakes (Table 3), the highest range of fluctuations in fish species was recorded in deep lakes (>20 m). The mean number of species (11 species) in shallow lakes (<6 m) was only slightly lower than in the other categories of lakes (12 species each). The mean values of the Shannon diversity index were very similar in all categories of lakes, while the ranges of fluctuations of this index differed among lakes (Figure 4). It should be noted that the number of lakes in each trophic group of lakes varied widely from 37 (oligotrophic lakes) to 281 lakes (eutrophic lakes) (Table 2), while the number of lakes in all fisheries categories of lakes was very similar and ranged from 120 to 150 lakes (Table 3).

Table 3. The number of lakes and the number of fish species in lakes of different maximum depth. SD = standard deviations.

Maximum Depth (m)	Number of Lakes	Number of Fish Species	
		Min.–Max.	Mean ± SD
<6	120	5–18	11 ± 2
6–12	143	6–16	12 ± 2
12–20	122	8–16	12 ± 2
>20	150	1–19	12 ± 2

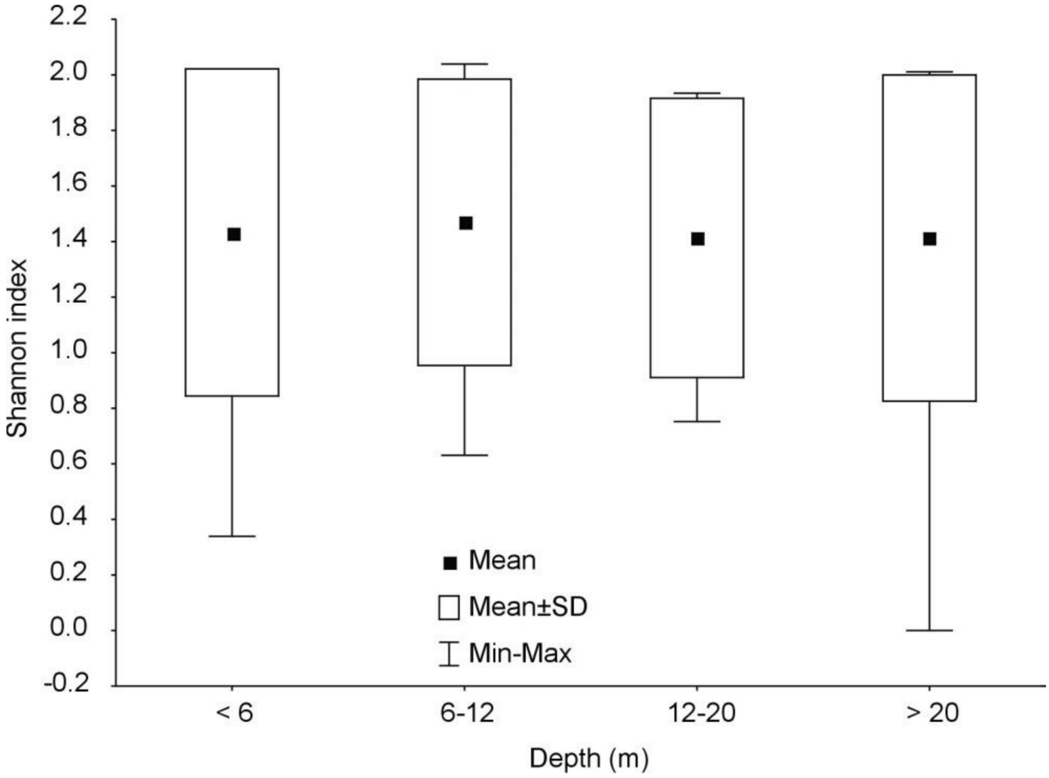

Figure 4. The Shannon index in 535 Polish lakes of different maximum depth. SD = standard deviations.

The number of fish species decreased with increasing eutrophication conditions of the studied lakes (Figure 5), while increased with an increased maximum depth of these lakes (Figure 6) and lake area (Figure 7). However, there were no significant correlations between the Shannon index and the above parameters ($p > 0.05$).

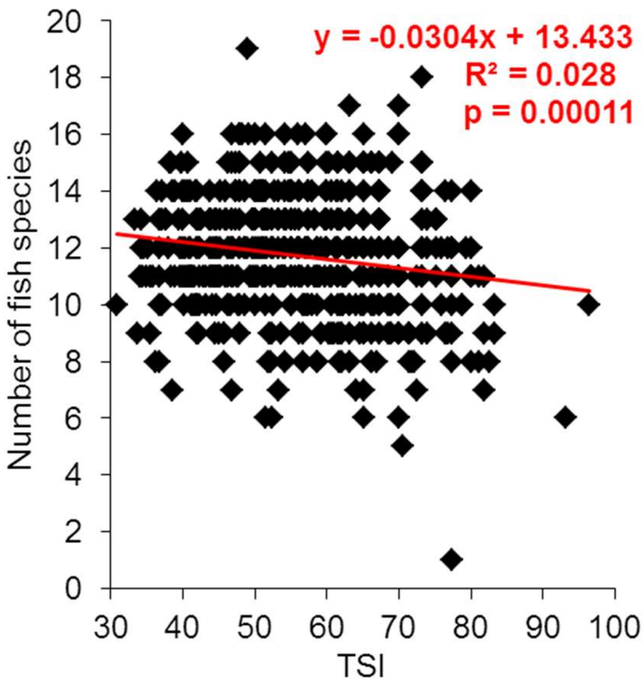

Figure 5. The relationship between the lake trophic state index (TSI) and the number of fish species in 535 Polish lakes.

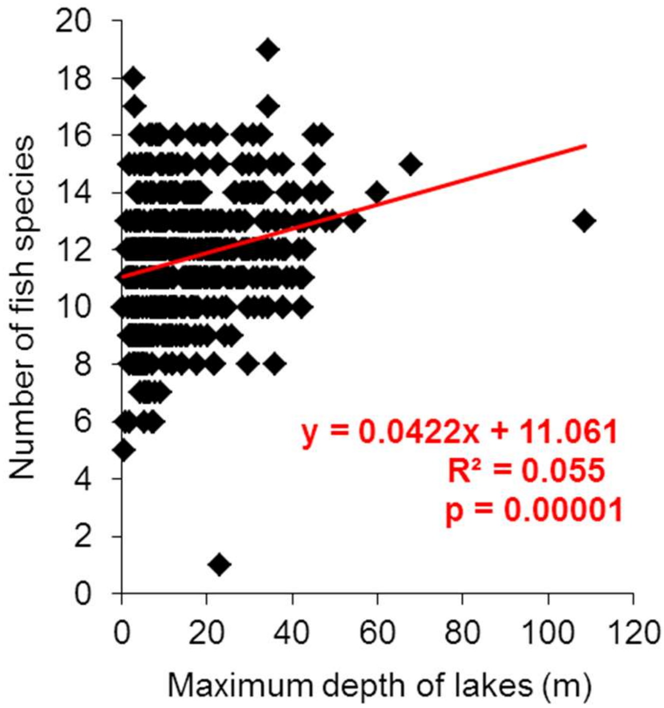

Figure 6. The relationship between the maximum depth of lakes and the number of fish species in 535 Polish lakes.

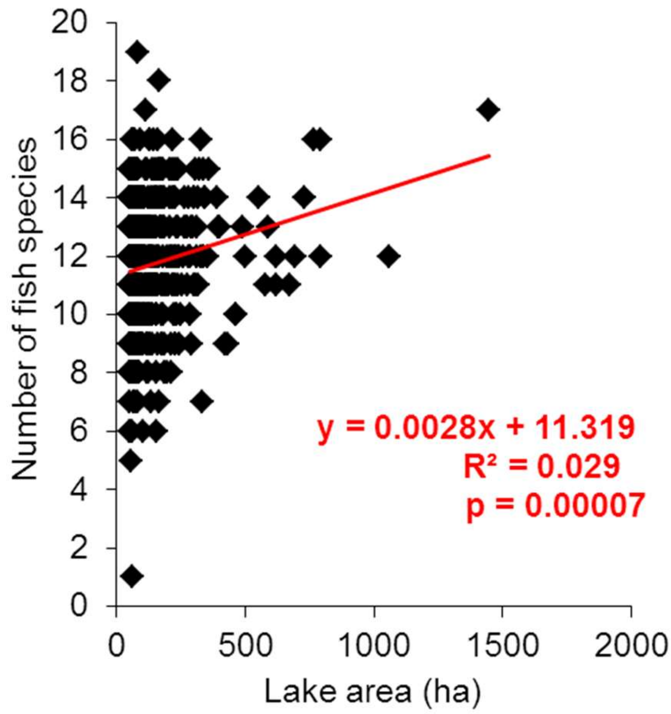

Figure 7. The relationship between the lake area and the number of fish species in 535 Polish lakes.

4. Discussion

The studies carried out in 535 lakes, located mainly in northern Poland, showed the presence of 39 fish species. A much lower number of species (27) were recorded in the lakes of the Wigry National Park [10], or the waters (20 lakes and one watercourse) of the Bory Tucholskie National Park (20 species) using various fishing gear [27]. A similar number of species (34) was found in 67 lakes in north-eastern Germany [28] and in eight large and deep Italian subalpine lakes [29]. Although the number of identified fish species in the waters of the Masurian Landscape Park was slightly higher (42 species), the species composition of fish was combined for lakes and rivers [17].

Data from the literature show that the number of fish species in lakes varies in a wide range. There are also lakes without fish [30]. Such fishless water bodies are, for example, small bog lakes with naturally low pH and conductivity, while with high content of humic substances [27,31]. Until recently, fishless lakes were considered to have limited value and were therefore sometimes referred to as "barren" [32]. Fishless lakes provide a unique habitat for many groups of aquatic fauna and therefore increase regional species diversity. Until now, fishless lakes in Poland have been known from mountainous areas [33] and as bog lakes [30,31]. Therefore, it was interesting to verify whether fishless lakes also occur among the larger water bodies of the lakes district area. There were no fishless lakes in our study, and the number of fish species ranged from 1 to 19. However, both the lowest and the highest number of species were observed in individual lakes. In lakes of the "Bory Tucholskie" National Park, the number of fish species in single lakes ranged from 1 to 15 [27] or even up to 23 [30]. In Italian subalpine lakes, the number of fish species ranged from 13 to 26 [29]. Relatively high species richness of fish (28 species) was found in the mesotrophic Lake Wigry [12], which is one of among the ten largest lakes (area of 2118.3 ha) and among the five deepest lakes (maximum depth of 74 m) in Poland. In the oligotrophic Lake Hańcza (the deepest lake in Poland with a maximum depth of 108.5 m), the presence of 24 native species of fish was found in the years 1999–2007 [8]. In addition to species typical of whitefish lakes (*Coregonus maraena*, *Coregonus albula*, *Osmerus eperlanus*), rare fish taxa such as the lake form of *Salmo trutta* and *Cottus poecilopus* have been recorded in the lake [8]. Lake Hańcza is the only lake in the North European Plain inhabited by a population of *C. poecilopus*, which is a glacial relict here [34]. It is documented that these species are characteristic of rivers, and Lake Hańcza is the only lake in Poland with its presence [8,35]. Our study showed that the species composition of fish in this lake was much poorer (13 species) than in Lake Wigry. The characteristic species of this lake were *Salmo trutta* and *C. poecilopus* caught in the number of one and two individuals, respectively. In turn, *C. maraena* was not found. The above data confirm that the composition and species structure of fish in the Polish lakes undergo natural and anthropogenic changes [9]. In this study, the level of diversity (Shannon index) fluctuated in the wide range of 0–2.04 and was comparable to the values calculated for European lakes [4]. According to Brysiewicz et al. [36], the Shannon index in small watercourses of Central European fluctuated in the narrower range from 1.2 to 2.6.

In our study, no fish species occurred in all of the studied lakes. However, *R. rutilus* and *P. fluviatilis* were not present in only one and two lakes, respectively. Thus, we found their high frequency. There were no lakes without fish, but one lake was inhabited by one species only (*P. fluviatlis*). In this lake, low electrolytic conductivity (<40 µS cm^{-1}) and circumneutral pH value (about 6), indicating the humic nature of the lake, probably restricted the species richness of fish fauna. The frequency of other species, such as *G. cernua*, *A. brama*, *A. alburnus*, and *B. bjoerkna* was also relatively high. Similar results were found in 67 German lakes where *R. rutilus*, *A. brama*, *P. fluviatilis*, and *G. cernua* were the only four species found in all lakes, while *Carassius auratus*, *Carassius gibelio*, *H. molitrix*, *Squalius cephalus*, and *Oncorhynchus mykiss* were recorded only in individual lakes [28]. In turn, Søndergaard et al. [37] studying 796 Danish lakes found that fish were absent mainly in lakes smaller than 0.1 ha and the most common species were *R. rutilus*, *P. fluviatilis*, *E. lucius*, *S. erythrophthalmus*, *A. brama* and *Anguilla anguilla*. In this study, the number of lakes in which the presence of *A. anguilla* was found (10 lakes out of 535 of all the studied lakes, frequency 1.9%) seems to be underestimated because this species is usually caught by electrofishing and traps [23]. It should be underlined that some individuals of large-sized fish were probably also underestimated due to the use of only one method of catching.

In the studied lakes, the presence of four protected (*C. poecilopus*, *Cobitis taenia*, *Misgurnus fossilis*, and *R. amarus*) and 8 alien species of fish (*C. carpio*, *C. idella*, *N. fluviatilis*, *P. parva*, *A. baerii*, *C. gibelio*, *A. nebulosus*, and *H. molitrix*) were found. More data on these species will be presented elsewhere (Traczuk, in prep.). It should be emphasised that much more alien invasive fish species (15) than in our study were recorded in rivers at 1639 sites in 2011–2018 with the use of electrofishing method [38]. Volta et al. [29] recorded 14 alien fish species out of 34 species recorded in Italian subalpine lakes.

In lakes located in different parts of Europe, the fish species richness is shaped by different sets of variables. For example, in 161 Swedish lakes, productivity, lake area and maximum depth were important factors in determining the benthic fish communities [39]. In 796 Danish lakes, area, mean depth, and TP content contributed significantly and positively to the species richness of fish [37]. In 67 lakes in north-eastern Germany, fish community composition was mainly determined by maximum and mean depth, chlorophyll *a* concentration and lake volume [28]. In 1632 lakes from 11 European countries, productivity had a strong positive effect on fish species richness and diversity [4]. In 71 shallow Danish lakes [5] and 36 south Finnish lakes [6], fish species richness was unimodally related to total phosphorus and positively related to the lake area and/or mean depth. Other factors, such as habitat loss and degradation, species invasions, overharvesting and pollution [2], global warming [40], habitat modification, exploitation by fisheries, acidification, and the use of lakes for recreation [41,42] may also influence the local fish communities in lakes. In Polish lakes, species richness decreased with decreasing depth and trophic status of lakes. In deeper lakes, from 15 to 27 species of fish, while in the shallow eutrophic lakes 2 to 12 species or no fish are usually recorded [10]. Studies carried out in the lakes of the Bory Tucholskie National Park showed that 12 to 15 species of fish were present in the low-productive lake and the high-productive lakes where salmon fish (*C. maraena* and *C. albula*) can still live, while in other lakes of this type from 7 to 10 species, in shallow lakes from 0 to 4 species of fish were found [27]. In our study, lake area and maximal depth had a positive effect on fish species richness, but not on the species diversity (Shannon Index). We also found that species richness decreased with increasing trophic conditions of lakes. It is documented that the species richness of fish in lakes tends to increase with lake size and depth, probably due to the higher spatial complexity and habitat stability in large lakes than in small lakes [4,5,41].

Our study, performed with the use of multi-mesh gillnets, showed that lakes are inhabited by 39 fish species. However, data from the Polish literature [8,17,30] also indicated the presence of five other species of fish, such as *Coregonus peled*, *Cottus gobio*, *Hypophthalmichthys nobilis*, *Phoxinus phoxinus*, and *Pungitius pungitius*, in the lakes of northern Poland.

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References

1. Power, M.E.; Tilman, D.; Estes, J.A.; Menge, B.A.; Bond, W.J.; Mills, L.S.; Daily, G.; Castilla, J.C.; Lubchenco, J.; Paine, R.T. Challenges in the quest for keystones: Identifying keystone species is difficult—But essential to understanding how loss of species will affect ecosystems. *BioScience* **1996**, *46*, 609–620. [CrossRef]
2. Carpenter, S.; Frost, T.; Persson, L.; Power, M.; Soto, D. Freshwater ecosystems: Linkages of complexity and processes. In *Functional Roles of Biodiversity: A Global Perspective*; Mooney, H.A., Cushman, J.H., Medina, E., Sala, O.E., Schulze, E.-D., Eds.; John Wiley & Sons: Hoboken, NJ, USA, 1996; pp. 299–325.
3. Kopylov, A.I.; Kosolapov, D.B.; Lazareva, V.I.; Mineeva, N.M.; Pryanichnikova, E.G. Structure, biomass and production of the biotic component of the ecosystem of an growing eutrophic reservoir. *Biosyst. Divers.* **2018**, *26*, 117–122. [CrossRef]
4. Brucet, S.; Pédron, S.; Mehner, T.; Lauridsen, T.L.; Argillier, C.; Winfield, I.J.; Volta, P.; Emmrich, M.; Hesthagen, T.; Holmgren, K.; et al. Fish diversity in European lakes: Geographical factors dominate over anthropogenic pressures. *Freshw. Biol.* **2013**, *58*, 1779–1793. [CrossRef]
5. Jeppesen, E.; Jensen, J.P.; Søndergaard, M.; Lauridsen, T.; Landkildehus, F. Trophic structure, species richness and biodiversity in Danish lakes: Changes along a phosphorus gradient. *Freshw. Biol.* **2000**, *45*, 201–218. [CrossRef]
6. Olin, M.; Rask, M.; Ruuhljärvi, J.; Kurkilahti, M.; Ala Opas, P.; Ylönen, O. Fish community structure in mesotrophic and eutrophic lakes of southern Finland: The relative abundances of percids and cyprinids along a trophic gradient. *J. Fish Biol.* **2002**, *60*, 593–612. [CrossRef]
7. Mehner, T.; Holmgren, K.; Lauridsen, T.L.; Jeppesen, E.; Diekmann, M. Lake depth and geographical position modify lake fish assemblages of the European 'Central Plains' ecoregion. *Freshw. Biol.* **2007**, *52*, 2285–2297. [CrossRef]
8. Kozłowski, J.; Chybowski, Ł.; Poczyczyński, P. Ichtiofauna jeziora Hańcza. In *Środowisko i Ichtiofauna Jeziora Hańcza*; Kozłowski, J., Poczyczyński, P., Zdanowski, B., Eds.; IRS: Olsztyn, Poland, 2008; pp. 121–124.
9. Kapusta, A.; Bogacka-Kapusta, E.; Czarkowski, T.K.; Czarnecki, B.; Duda, A.; Hutorowicz, J.; Jarmołowicz, S.; Napiórkowska-Krzebietke, A.; Prusińska, M.; Stawecki, K.; et al. Czy typ użytkowania rybackiego ma wpływ na strukturę zespołów ryb w jeziorach północnej Polski? In *Działalność Podmiotów Rybackich i Wędkarskich w 2020 Roku w Świetle Uwarunkowań Gospodarczych, Ekonomicznych i Środowiskowych*; Kowalska, A., Wołos, A., Eds.; IRS: Olsztyn, Poland, 2021; pp. 99–109.
10. Białokoz, W.; Krzywosz, T. Struktura ichtiofauny w jeziorach Wigierskiego Parku Narodowego. In *Jeziora Wigierskiego Parku Narodowego. Stan Eutrofizacji i Kierunki Ochrony*; Zdanowski, B., Ed.; Ossolineum: Wrocław, Poland, 1992; pp. 153–162.
11. Colby, P.J.; Spangler, G.R.; Hurley, D.A.; McCombie, A.M. Effects of eutrophication on salmonid communities in oligotrophic lakes. *Can. J. Fish. Aquat. Sci.* **1972**, *29*, 975–983. [CrossRef]
12. Chybowski, Ł.; Białokoz, W. Dynamika zespołów ichtiofauny jeziora Wigry. In *Funkcjonowanie i Ochrona Ekosystemów Wodnych na Obszarach Chronionych*; Zdanowski, B., Kamiński, M., Martyniak, A., Eds.; IRS: Olsztyn, Poland, 1999; pp. 521–526.
13. Brylińska, M. *Ryby Słodkowodne Polski*; PWN: Warszawa, Poland, 2000; p. 521.
14. Penczak, T.; Kruk, A.; Marszał, L.; Zięba, G.; Galicka, W.; Tszydel, M.; Tybulczuk, S.; Pietraszewski, D. Monitoring ichtiofauny systemu rzeki Gwdy: Trzecia dekada badań. *Rocz. Nauk. PZW* **2008**, *21*, 61–89.
15. Witkowski, A.; Kotusz, J. Stan ichtiofaunistycznych badań inwentaryzacyjnych rzek polski. *Rocz. Nauk. PZW* **2008**, *21*, 23–60.
16. Witkowski, A.; Popiołek, M.; Kotusz, J.; Wawer, K.; Stefaniak, J. Ichtiofauna Dzikiej Orlicy (dorzecze Łaby, Polska)—dziesięć lat później. *Rocz. Nauk. PZW* **2015**, *28*, 5–25.
17. Kapusta, A.; Chybowski, Ł.; Bogacka-Kapusta, E. Ichtiofauna Mazurskiego Parku Krajobrazowego. In *Mazurski Park Krajobrazowy, Różnorodność Biologiczna i Kulturowa*; Wittbrodt, K., Janecki, T., Eds.; Labrita: Kętrzyn, Poland, 2019; pp. 116–125.
18. Kapusta, A.; Morzuch, J.; Bogacka-Kapusta, E.; Pająkowski, J. Ichtiofauna jeziora Mukrz w rezerwacie przyrody „Cisy Staropolskie im. Leona Wyczółkowskiego" w Wierzchlesie. *Chrońmy Przyr. Ojczystą* **2012**, *68*, 435–442.
19. Czarkowski, T.K.; Martyniak, A.; Kapusta, A.; Wójcik, A.; Bowszys, M.; Wziątek, B.; Szymańska, U.; Kozłowski, J. Feeding ecology of vendace, *Coregonus albula* (L.), in Lake Wigry (Northeastern Poland). *Arch. Pol. Fish.* **2007**, *15*, 117–128.
20. Kozłowski, K.; Kozłowski, J.; Poczyczyński, P.; Martyniak, A. Age and growth of vendace, *Coregonus albula* (L.), from Lake Wigry (northeast Poland). *Arch. Pol. Fish.* **2010**, *18*, 239–245. [CrossRef]
21. Hutorowicz, A.; Kapusta, A.; Krzywosz, T.; Hutorowicz, J. The ichthyofauna of the dystrophic Lake Smolak (northern Poland) in light of selected physical and chemical water conditions thirty years after conclusion of liming and fertilization. *Arch. Pol. Fish.* **2005**, *13*, 207–225.
22. Rechulicz, J.; Płaska, W.; Tarkowska-Kukuryk, M. The ichthyofauna of littoral of two shallow lakes on background of fishery management and angling pressure. *Teka Kom. Ochr. Kszt. Środ. Przyr.* **2014**, *11*, 163–172.
23. Kapusta, A.; Perkowski, J.; Traczuk, P.; Heese, T.; Woźniak, J.; Strzałkowski, Ł.; Dobrowolski, M. Porównanie różnych metod połowu ryb do określenia składu gatunkowego oraz struktury ilościowej ichtiofauny jezior. In *Działalność Podmiotów Rybackich i Wędkarskich w 2018 roku. Uwarunkowania Ekonomiczne i Środowiskowe*; Mickiewicz, M., Wołos, A., Eds.; IRS: Olsztyn, Poland, 2019; pp. 65–73.
24. Carlson, R.F. A trophic state index for lakes. *Limnol. Oceanogr.* **1977**, *22*, 361–369. [CrossRef]
25. Rudnicki, A.; Waluga, J.; Waluś, T. *Rybactwo Jeziorowe*; PWRiL: Warszawa, Poland, 1971; p. 403.
26. Shannon, C.E.; Weaver, W. *The Mathematical Theory of Communication*; University of Illinois Press: Urbana, IL, USA, 1949; p. 125.
27. Robak, S.; Białokoz, W.; Chybowski, Ł. Ichtiofauna. In *Ekosystemy Wodne Parku Narodowego "Bory Tucholskie"*; Zdanowski, B., Hutorowicz, A., Białokoz, W., Eds.; IRS: Olsztyn, Poland, 2004; pp. 233–240.

28. Mehner, T.; Diekmann, M.; Brämick, U.; Lemcke, R. Composition of fish communities in German lakes as related to lake morphology, trophic state, shore structure and human-use intensity. *Freshw. Biol.* **2005**, *50*, 70–85. [CrossRef]
29. Volta, P.; Jeppesen, E.; Sala, P.; Galafassi, S.; Foglini, C.; Puzzi, C.; Winfield, I.J. Fish assemblages in deep Italian subalpine lakes: History and present status with an emphasis on non-native species. *Hydrobiologia* **2018**, *824*, 255–270. [CrossRef]
30. Kapusta, A.; Błoniarz, W. Fish. In *Animated Nature in the "Bory Tucholskie" National Park. Part I—Vertebrate Animals*; Winiecki, A., Lubińska, K., Eds.; Bogucki Wydawnictwo Naukowe: Poznań, Poland, 2021; pp. 25–49.
31. Kalinowska, K.; Napiórkowska-Krzebietke, A.; Ulikowski, D.; Bogacka-Kapusta, E.; Stawecki, K.; Traczuk, P. Under-ice environmental conditions, planktonic communities and ichthyofauna in dystrophic lakes. *Eur. Zool. J.* **2021**, *88*, 340–351. [CrossRef]
32. Schilling, E.G.; Loftin, C.S.; Degoosh, K.E.; Huryn, A.D.; Webster, K.E. Predicting the locations of naturally fishless lakes. *Freshw. Biol.* **2008**, *53*, 1021–1035. [CrossRef]
33. Galas, J. Pest fish in naturally fishless high mountain lakes of the national parks. *Chrońmy Przyr. Ojcz.* **2010**, *66*, 427–432.
34. Kotusz, J.; Krappe, M.; Kusznierz, J.; Propiolek, M.; Riel, P.; Waterstraat, A.; Witkowski, A. Distribution, density and habitat of *Cottus poecilopus* (Heckel, 1836) in Lake Hancza (North East Poland) as compared with the situation in the Luzin lakes (North East Germany). *Gesell. Ichtyol.* **2004**, *4*, 91–105.
35. Witkowski, A. Głowacz pręgopłetwy, *Cottus poecilopus* Heckel, 1836 w jeziorze Hańcza. *Prz. Zool.* **1975**, *19*, 224–227.
36. Brysiewicz, A.; Czerniejewski, P.; Dąbrowski, J.; Formicki, K.; Więcaszek, B. Fish diversity and abundance patterns in small watercourses of the Central European Plain Ecoregion in relation to environmental factors. *Water* **2022**, *14*, 2697. [CrossRef]
37. Søndergaard, M.; Jeppesen, E.; Jensen, J.P. Pond or lake: Does it make any difference? *Arch. Hydrobiol.* **2005**, *162*, 143–165. [CrossRef]
38. Szlakowski, J.; Adamczyk, M.; Buras, P.; Ligięza, J.; Prus, P.; Wiśniewolski, W. Gatunki obce w monitoringu ichtiofauny w rzekach Polski w latach 2011–2018. In *Działalność Podmiotów Rybackich i Wędkarskich w 2018 Roku. Uwarunkowania Ekonomiczne i Środowiskowe*; Mickiewicz, M., Wołos, A., Eds.; IRS: Olsztyn, Poland, 2019; pp. 89–105.
39. Holmgren, K.; Appelberg, M. Size structure of benthic freshwater fish communities in relation to environmental gradients. *J. Fish Biol.* **2000**, *57*, 1312–1330. [CrossRef]
40. Jeppesen, E.; Mehner, T.; Winfield, I.J.; Kangur, K.; Sarvala, J.; Gerdeaux, D.; Rask, M.; Malmquist, H.J.; Holmgren, K.; Volta, P.; et al. Impacts of climate warming on the long-term dynamics of key fish species in 24 European lakes. *Hydrobiologia* **2012**, *694*, 1–39. [CrossRef]
41. Jennings, M.J.; Bozek, M.A.; Hatzenbeler, G.R.; Emmons, E.E.; Staggs, M.D. Cumulative effects of incremental shoreline habitat modification on fish assemblages in north temperate lakes. *N. Am. J. Fish. Manag.* **1999**, *19*, 18–27. [CrossRef]
42. Allan, D.J.; Abell, R.; Hogan, Z.; Revenga, C.; Taylor, B.W.; Welcomme, R.L.; Winemiller, K. Overfishing of inland waters. *Biocience* **2005**, *55*, 1041–1051. [CrossRef]