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Reconstruction of Surface Water Temperature in Lakes as a Source for Long-Term Analysis of Its Changes

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Abstract: One of the key parameters of lakes is water temperature, which influences many physical and biochemical processes. In Poland, in situ temperature measurements are or have been conducted in only about 30 lakes, whereas there are over 3000 lakes with an area larger than 10 hectares. In many cases, the length of existing observation series is not always sufficient for long-term analysis. Using artificial neural networks of the multilayer perceptron network (MLP) type, the reconstruction of average monthly water temperatures was carried out for nine lakes located in northern Poland. During the validation stage of the reconstruction results, BIAS values were obtained in the range of −0.33 to 0.44 °C, the mean absolute error was 0.46 °C, and the root mean square error was 0.61 °C. The high quality of the reconstructed data allowed for an assessment of water temperature changes in the analyzed lakes from 1993 to 2022 using the Mann–Kendall and Sen tests. It was found that, on an annual basis, the water temperature increased by an average of 0.50 °C per decade, ranging from 0.36 °C per decade to 0.64 °C per decade for individual lakes. For specific months, the largest increase was observed in November, about 0.99 °C per decade, and the smallest in May, 0.07 °C per decade. The obtained results confirm previous studies in this field while adding new data from lakes, which are particularly significant for the western part of Poland—a region with a previously limited number of monitored lakes. According to the findings, the analyzed lakes have undergone significant warming over the past three decades, which is important information for water management authorities.

Keywords: inland water; global warming; thermal regime; Central Europe

Citation: Sojka, M.; Ptak, M. Reconstruction of Surface Water Temperature in Lakes as a Source for Long-Term Analysis of Its Changes. *Water* **2024**, *16*, 3347. https://doi.org/10.3390/w16233347

Academic Editor: Avi Ostfeld

Received: 8 October 2024
Revised: 18 November 2024
Accepted: 19 November 2024
Published: 21 November 2024

1. Introduction

Proper assessment of environmental changes requires long-term data records that represent their course and changes in interaction with other factors. In the case of hydrology, different regions of the world have more or less developed monitoring networks for various water parameters, and numerous studies indicate that these data relate to various timescales, including water levels [1,2], quality [3,4], ice phenomena [5,6], and temperature [7,8]. Moreover, remote sensing techniques are increasingly being used in hydrosphere studies [9,10], although they have certain limitations due to satellite revisit frequency or cloud cover [11]. For lakes, one of the key characteristics for their functioning is water temperature, which, as noted by Xu et al. [12], affects primary productivity, physical and biological properties, and, additionally, geochemical and ecological processes, which in turn influence water quality [13].

In Poland, water temperature observations have a tradition spanning several decades, with the first continuous measurements on lakes appearing in the late 1950s. The number of lakes monitored for water temperature has fluctuated over the years, reaching its peak at the end of the 1970s, with 39 lakes being observed at that time. At the turn of the 20th and 21st centuries, this number decreased to 30, only to increase by an additional 9 lakes between 2006 and 2011.

On a regional scale, general patterns of water temperature changes in lakes are similar, but local specifics and morphometric features of the lakes can result in varying degrees of these changes [14]. This is important, for instance, due to the amount of dissolved oxygen in the water [15], which in turn affects the lake's self-purification capacity and water quality [16]. Warming of lakes could potentially lead to stronger fluctuations in the internal nutrient load, extending the duration of cyanobacteria blooms [17]. Climate change is also expected to result in the emergence of new species due to the disappearance of low temperatures or oxygen deficits during the winter [18]. Therefore, the rise in lake water temperature forms the basis for taking remedial actions (e.g., lake restoration) by agencies responsible for water management and environmental protection.

In long-term climate studies, a period of 30 years is considered the classical standard [19]. This, in turn, translates into assessing how other components of the natural environment respond to changes over this timescale. A good example of this approach is found in numerous hydrological studies [20–23]. Collados-Lara et al. [24], in relation to the impact of climate change on meteorological and hydrological droughts, emphasize that conducting such an analysis requires a sufficiently long dataset, typically covering a period of 30 years or more. This time frame has been deemed appropriate in studies of surface water temperature, both for artificial reservoirs and natural lakes [25,26].

In light of the above methodological assumptions, it is necessary to have a set of information as broad and reliable as possible, understood as a period that allows for statistical assessment and interpretation of changes in this characteristic. Therefore, two research objectives were set: the first is to reconstruct the water temperature of selected lakes in Poland, and the second is to determine the direction and magnitude of temperature change trends from 1993 to 2022. Importantly, the objects for which reconstruction analyses were performed are mainly located in the western part of Poland, which has previously been characterized by a low number of monitored lakes in this regard.

2. Materials and Methods

2.1. Materials

The research material consists of daily water temperatures from 13 lakes in northern Poland (Figure 1). Water temperatures were obtained from hydrological stations where measurements were taken 0.4 m below the water table.

The length of the water temperature time series for the analyzed lakes varies from 12 to 23 years (Table 1). Additionally, isolated data gaps were identified within the data series. To reconstruct the missing data in nine lakes (No. 1, 2, 3, 6, 7, 8, 9, 11, and 13), daily water temperature from four lakes (No. 4, 5, 10, and 12) was used. Moreover, the daily air temperature data from six meteorological stations were used (Figure 1). The meteorological stations were assigned to the nearest lakes based on their locations (Table 1). The air and water temperature data used to reconstruct the data gaps covered the period from 1993 to 2022. The air temperature refers to the daily average and is measured in standard monitoring, conducted in a meteorological shelter 2 m above the ground surface.

The daily air and water temperature data used in this study were provided by the Institute of Meteorology and Water Management–National Research Institute. Furthermore, in the supplementary material for this analysis are the morphometric parameters of the lakes, including surface area, average depth, maximum depth and volume (Table 2).

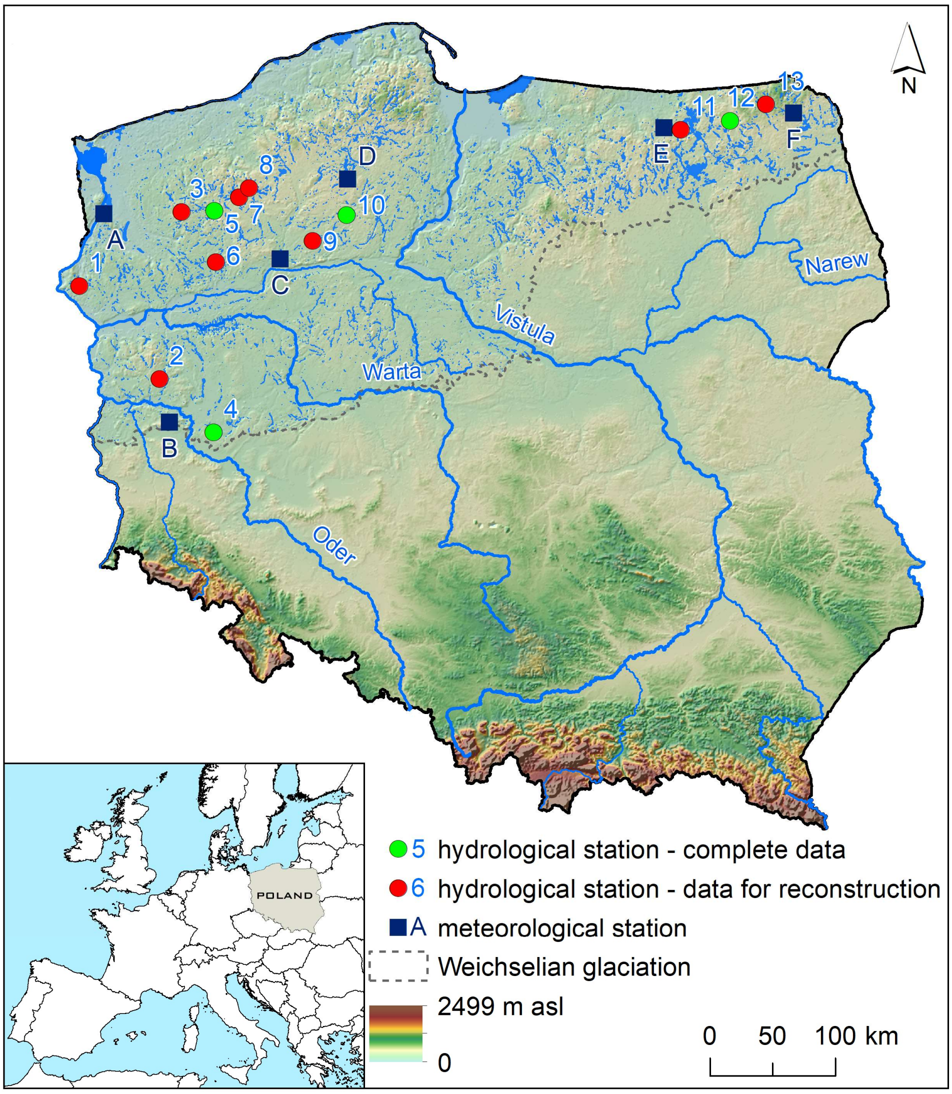

Figure 1. Location of study sites.

Table 1. Range of water and air temperature data used in this study.

No.	Lake	Period	No.	Meteorological Station	Period
1	Morzycko	2006–2022	A	Szczecin	
2	Niesłysz	2008–2022	B	Zielona Góra	
3	Ińsko	2011–2022	A	Szczecin	
4	Sławskie	1993–2022	B	Zielona Góra	
5	Lubie	1993–2022	C	Piła	
6	Ostrowite	2007–2022	C	Piła	
7	Drawsko	2000–2022	C	Piła	1993–2022
8	Komorze	2006–2022	C	Piła	
9	Sławianowskie	2007–2022	C	Piła	
10	Sępoleńskie	1993–2022	D	Chojnice	
11	Dejguny	2005–2022	E	Kętrzyn	
12	Litygajno	1993–2022	E	Kętrzyn	
13	Rospuda Filipowska	2005–2022	F	Suwałki	

Table 2. Morphometric parameters of the analyzed lakes [27].

Lake	Area (ha)	Volume (10^6 m^3)	Mean Depth (m)	Max Depth (m)
Morzycko	317.5	49.8	14.5	60.7
Niesłysz	526	34.4	6.9	34.7
Ińsko	529	65.1	11	41.7
Sławskie	822.5	42.6	5.2	12.3
Lubie	1487.5	169.8	11.6	46.2
Ostrowite	387.6	36.4	9.4	28.5
Drawsko	1797.5	331.4	17.7	82.2
Komorze	386	49.3	11.8	34.7
Sławianowskie	269	18.3	6.6	15
Sępoleńskie	157.5	7.5	4.8	10.9
Dejguny	762.5	92.6	12	45
Litygajno	154.5	9.7	6	16.4
Rospuda Filipowska	323.5	49.7	14.5	38.9

2.2. Methods

In the first stage of the analysis, the average monthly temperature values were calculated for each lake and meteorological station. In the second stage, the missing data were reconstructed to obtain a 30-year data series for each lake, covering the period from 1993 to 2022. For the reconstruction and extension of the measurement series, an artificial neural network (ANN) of the multilayer perceptron network (MLP) type was applied. This method of data reconstruction provided the best results during the reconstruction of river water temperatures [28]. The MLP network training was conducted using approximately 70% of the measurement data, while about 30% of the data was used for validation (Table 3).

Table 3. Division of data into training and validation sets, and range of data reconstruction.

Lake	Series		Scope of Data Reconstruction
	Learning	Validation	
Niesłysz	2012–2022 (n = 132)	2008–2011 (n = 48)	1993–2007 (n = 180)
Morzycko	2011–2023 (n = 142) Without Jun. and Aug. 2011	2006–2010 (n = 60)	1993–2005 With Jul. and Aug. 2011 (n = 158)
Ostrowite	2012–2022 (n = 132)	2007–2011 (n = 60)	1993–2006 (n = 168)
Komorze	2011–2022 (n = 143) Without May 2019	2006–2010 (n = 60)	1993–2005 (n = 157) With May 2019
Drawsko	2008–2022 (n = 180)	2000–2007 (n = 92) Without Nov. 2011 and Mar., Apr., and May 2006	1993–1999 (n = 88) With Nov. 2011 and Mar., Apr., and May 2006
Insko	2014–2022 (n = 108)	2011–2013 (n = 36)	1993–2010 (n = 216)
Sławianowskie	2012–2022 (n = 132)	2007–2011 (n = 60)	1993–2006 (n = 168)
Dejguny	2010–2022 (n = 156)	2005–2009 (n = 60)	1993–2004 (n = 144)
Rospuda Filipowska	2010–2022 (n = 156)	2005–2009 (n = 60)	1993–2004 (n = 144)

Note: n—number of months.

To extend/reconstruct the data series, a three-layer MLP model was selected, with the second hidden layer containing between 3 and 20 neurons. The input (independent) variables were the average monthly air temperatures from the nearest meteorological station and the average monthly water temperatures from the nearest lake with a complete observation series. Additionally, qualitative data, such as the month index, were used when creating the MLP. The output variable was the average monthly water temperature for lakes with incomplete data series. An automatic search scheme was applied to build the MLP network. Activation functions during training for hidden and output neurons included linear, logistic, tanh, exponential, and sinusoidal functions. An automatic network design method was used, testing 100 different network architectures and retaining the 5 best ones. The MLP models were created using Statistica ver. 13.1 (TIBCO Software Inc., Palo Alto, CA, USA). The validation of the results, as well as the selection of the best network, was based on validation data through the calculation of commonly used statistical measures, such as standard deviation (SD) for the measurement data and modeling results, mean prediction error (MPE), mean absolute error (MAE), root mean square error (RMSE), correlation coefficient (R), and Nash–Sutcliffe model efficiency coefficient (NSE).

The developed models enabled the reconstruction of missing average monthly water temperatures. Ultimately, the data prepared for the period 1993–2022, which included average monthly and annual water temperatures for 13 lakes and air temperatures for six hydrological stations, were analyzed for long-term trends. For this purpose, non-parametric Mann–Kendall and Sen tests were used. The Mann–Kendall test allows for the identification of significant temporal changes in water and air temperatures, as well as the direction of these changes. The analysis was conducted at significance levels of 0.1, 0.05, and 0.001. Sen's test, on the other hand, was used to determine the magnitude of water and air temperature changes from 1993 to 2022. The Mann–Kendall and Sen tests were conducted using the modifiedmk package in the R program, developed by Patakamuri and O'Brien [29]. The results of data reconstruction quality and the magnitude of water temperature changes were analyzed in the context of the morphometric parameters of the lakes.

3. Results

The analysis of long-term thermal changes in lake waters requires data spanning at least 30 years. However, not all lakes in Poland meet this condition, as available measurement series are often too short and also contain gaps. Given these requirements and limitations, it was decided to reconstruct the average monthly water temperatures in the studied lakes using MLP-type neural networks. The results obtained were validated using commonly applied statistical measures. The standard deviations of the measurement data from the validation subset for the studied lakes ranged from 6.67 °C in Lake Drawsko to 7.76 °C in Lake Niesłysz, with an average of 7.32 °C. Meanwhile, the SD values for the modeled data in the validation subset ranged from 6.90 °C (Drawsko) to 7.55 °C (Niesłysz), with an average of 7.26 °C. A comparison of the SD values for the measurement and modeled data using the Student *t*-test showed no significant differences at a significance level of 0.05. The mean prediction error (MPE) values for individual lakes ranged from −0.33 °C to 0.41 °C, with an average of 0.06 °C. Negative MPE values were obtained for Lakes Morzycko, Sławianowskie, and Ińsko, indicating that the model results were higher than the measurement data. Positive MPE values were observed for the remaining lakes, suggesting that the modeling results were lower than the measurement data. MPE values within the range of ± 0.1 °C were achieved for Lakes Komorze and Dejguny, indicating the best data reconstruction results. The mean absolute error (MAE) values ranged from 0.33 °C for Lake Sławianowskie to 0.66 °C for Lake Rospuda Filipowska, with an average MAE of 0.46 °C for the analyzed lakes. The root mean square error (RMSE) values for the lakes ranged from 0.40 °C to 0.85 °C, with an average of 0.61 °C. Additionally, the correlation coefficient and NSE (Nash–Sutcliffe efficiency) values were both higher than

0.992 and 0.986, respectively. The validation results of the MLP models are illustrated in the Taylor diagram (Figure 2).

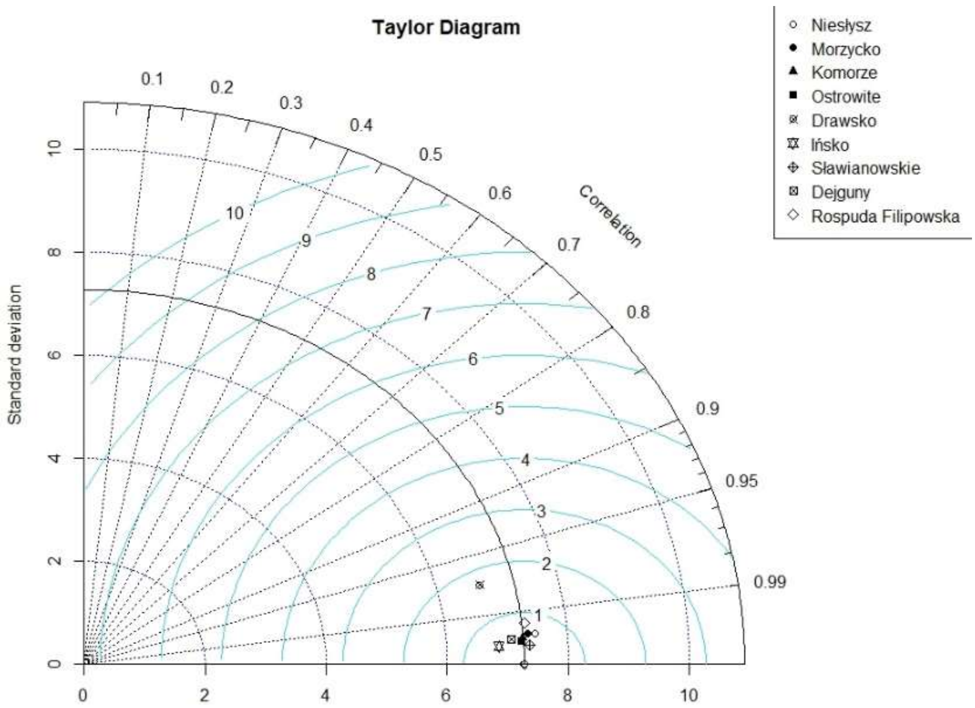

Figure 2. Validation results of MLP-type neural networks presented in a Taylor diagram.

The results demonstrate that MLP-type neural networks are highly effective for reconstructing average monthly water temperatures in lakes. The analysis of the relationships between the statistical indicators used to assess the quality of the modeling results revealed the following patterns: lakes with larger surface area and volume had lower standard deviations (SD) in water temperature; higher MAE (mean absolute error) and RMSE (root mean square error) values were observed in lakes with greater average depth; and lakes with greater average depth exhibited lower correlation coefficients (R) and Nash–Sutcliffe efficiency (NSE) values. These data allowed for the determination of values of monthly water temperature variability in the studied lakes, both those subject to data reconstruction and those with complete data (Figure 3).

The average annual water temperatures in the analyzed lakes during the period from 1993 to 2022 ranged from 9.8 °C in Lake Dejguny to 11.6 °C in Lake Sławskie. The lake with the highest variability in average annual temperatures was Lake Rospuda Filipowska (range of 1.9 °C), while the greatest variability was found in Lake Litygajno (range of 3.5 °C). When considering monthly temperatures, it was shown that the water in the lakes is coldest in January and February, averaging around 2.0 °C, and warmest in July and August, around 21.0 °C. In general, there is spatial variation in average annual temperatures, with lakes in western Poland having higher water temperatures than those in the east. The variability of average monthly water temperatures in Lake Morzycko (located farthest to the west) and Lake Rospuda Filipowska (located farthest to the east) is shown in Figure 4. Overall, of all the lakes studied, the smallest variability in average monthly temperatures occurred in February, ranging from 2.3 °C to 4.4 °C with an average of 3.2 °C. In contrast, the greatest variability occurred in July, averaging 6.7 °C with a minimum value of 5.7 °C and a maximum of 7.3 °C.

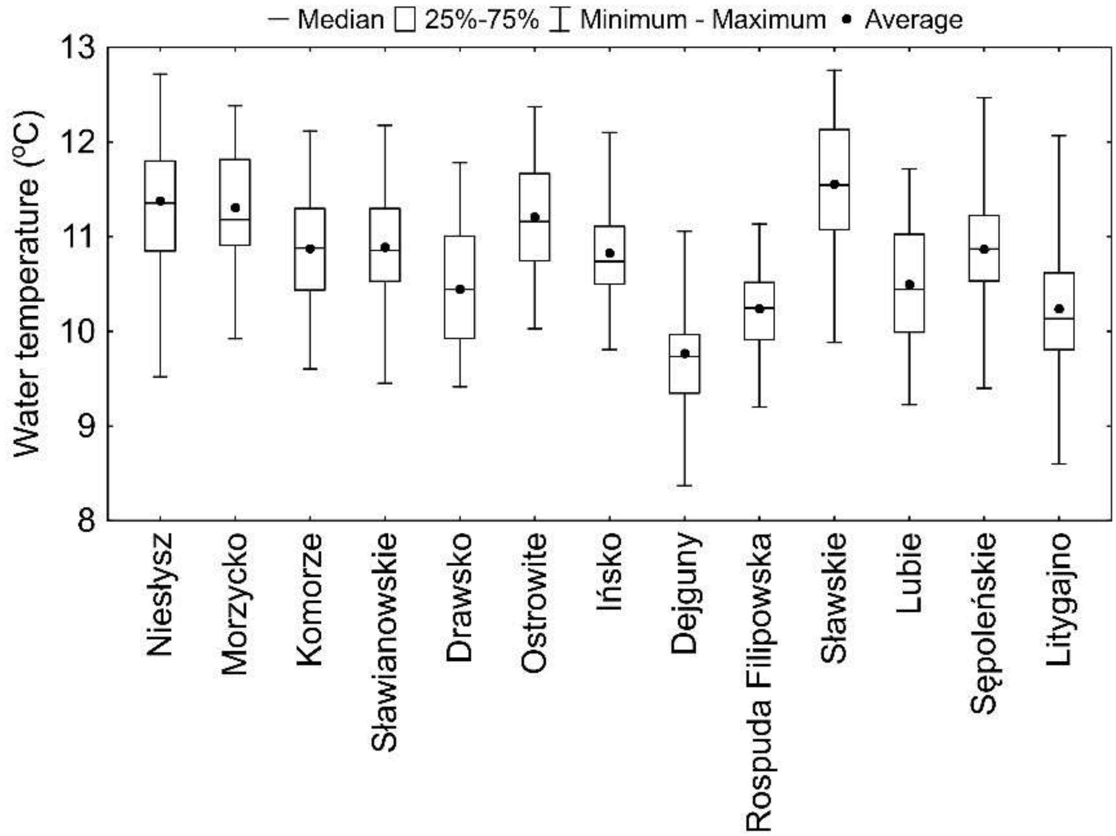

Figure 3. Variability of mean annual water temperatures in lakes in the period 1993–2022.

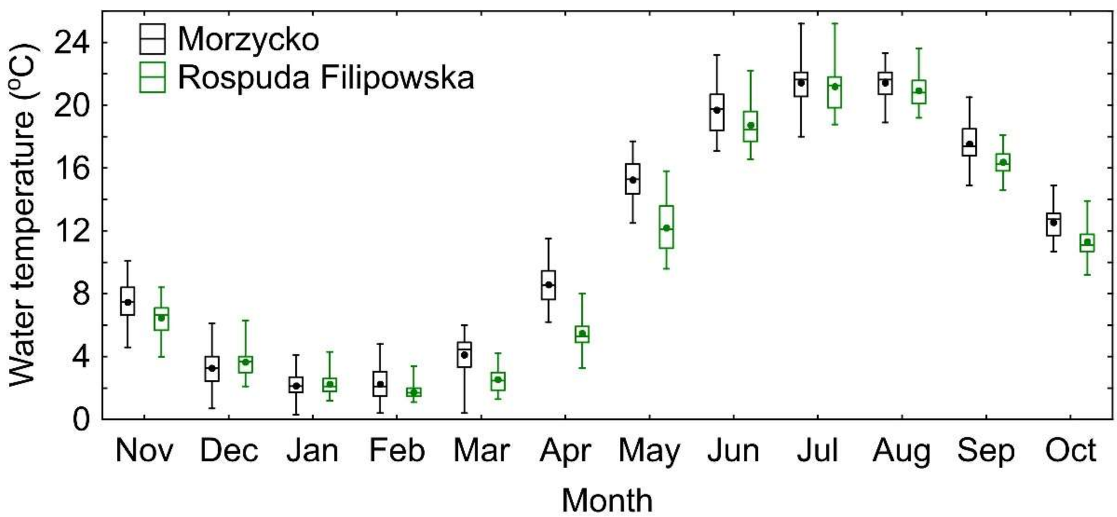

Figure 4. Variability of average monthly water temperatures in Lakes Morzycko and Rospouda Filipowska.

The most interesting results from the perspective of lake functioning and aquatic ecosystems are the changes in water thermal conditions between 1993 and 2022. An analysis of changes in the average annual water temperatures for four lakes—Sławskie, Lubie, Sępoleńskie, and Litygajno—for which complete data were available revealed a significant increasing trend at a significance level of 0.01. The slope values of the trend line, according to Sen's test, ranged from 0.36 °C per decade to 0.64 °C per decade (Table 4). A significant increase in water temperatures, ranging from 0.36 °C to 0.61 °C per decade, was also observed in the other lakes.

Table 4. Results of trend analysis of average annual water temperatures in lakes.

Lake	S	Z-Value	*p*-Value	Sen's Slope °C per Decade
Lubie	252	4.71	0.000	0.64
Sępoleńskie	186	3.47	0.001	0.36
Sławskie	252	4.71	0.000	0.59
Litygajno	236	4.41	0.000	0.63
Sławianowskie	178	3.32	0.001	0.38
Ostrowite	236	4.41	0.000	0.55
Niesłysz	226	4.22	0.000	0.61
Morzycko	224	4.18	0.000	0.49
Komorze	226	4.22	0.000	0.53
Ińsko	212	3.96	0.000	0.42
Drawsko	150	2.79	0.005	0.43
Dejguny	218	4.07	0.000	0.48
Rospuda Filipowska	216	4.03	0.000	0.36

Considering the average monthly water temperatures in the lakes, significant changes in thermal conditions most frequently occurred in November (significant change in 13 out of 13 lakes); March, June, and December (change in 12 out of 13 lakes); September (change in 9 of the lakes studied); and October (change in 8 out of 13 lakes) (Figure 5). Although temperature increases were also recorded in other months, these changes were not always statistically significant. In May, water temperature changes between 1993 and 2002 were not statistically significant. However, in July and in January and February, a significant increase in water temperatures was observed only in two and three lakes, respectively.

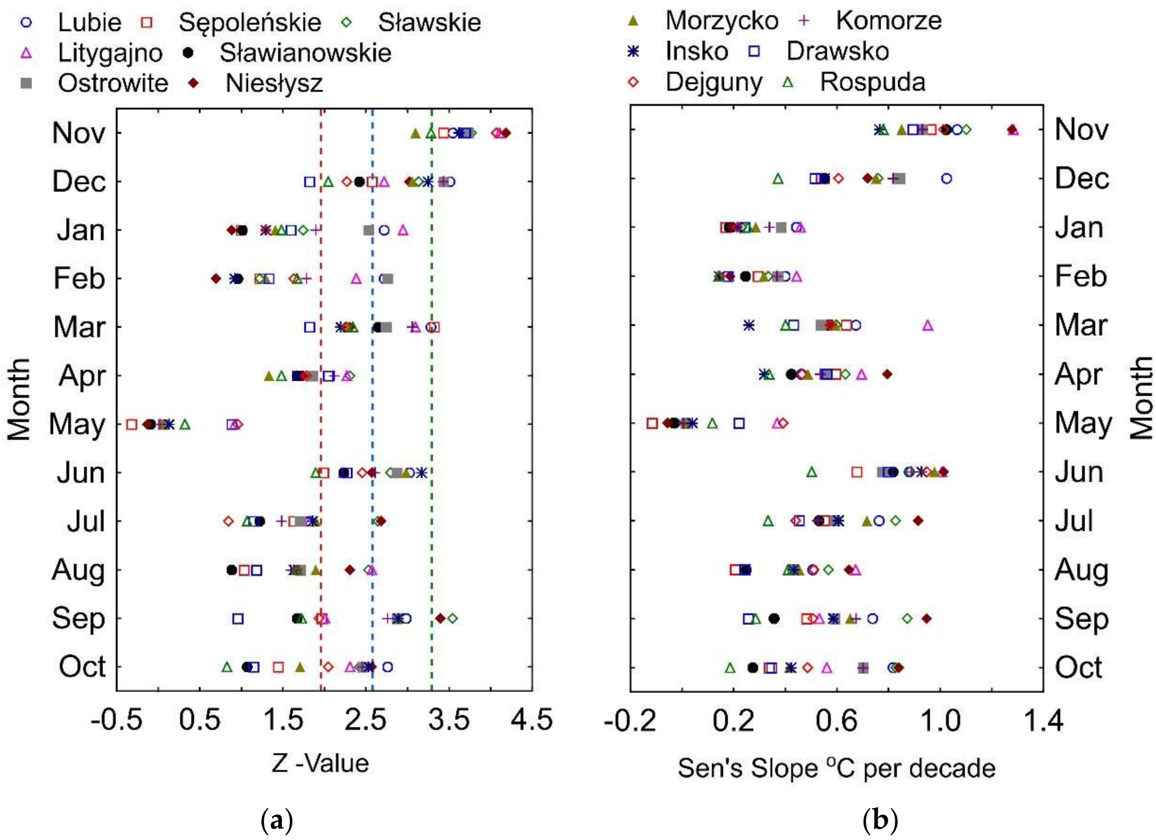

Figure 5. Changes in average monthly water temperatures in lakes: (**a**) significance of changes; and (**b**) value of changes.

Based on Sen's statistic, the highest changes in water thermal conditions in the lakes occurred in November, with an average increase of 0.99 °C per decade in the analyzed lakes, while the lowest changes occurred in May, averaging 0.07 °C per decade. To illustrate the pattern of changes in the thermal regime of the lakes, they were grouped using hierarchical cluster analysis. The lakes most similar in terms of average monthly water temperatures are Komorze, Morzycko, Sławianowskie, and Ostrowite (Figure 6). Therefore, these lakes were used to demonstrate how the thermal regime has changed over the 30 years analyzed. The starting point for this analysis is the average monthly water temperatures from these lakes in 1993 (blue line), along with the values from Sen's statistic. Sen's statistic helped determine the average temperature at the end of the analysis period, and the red and orange lines were used to indicate the range of possible changes.

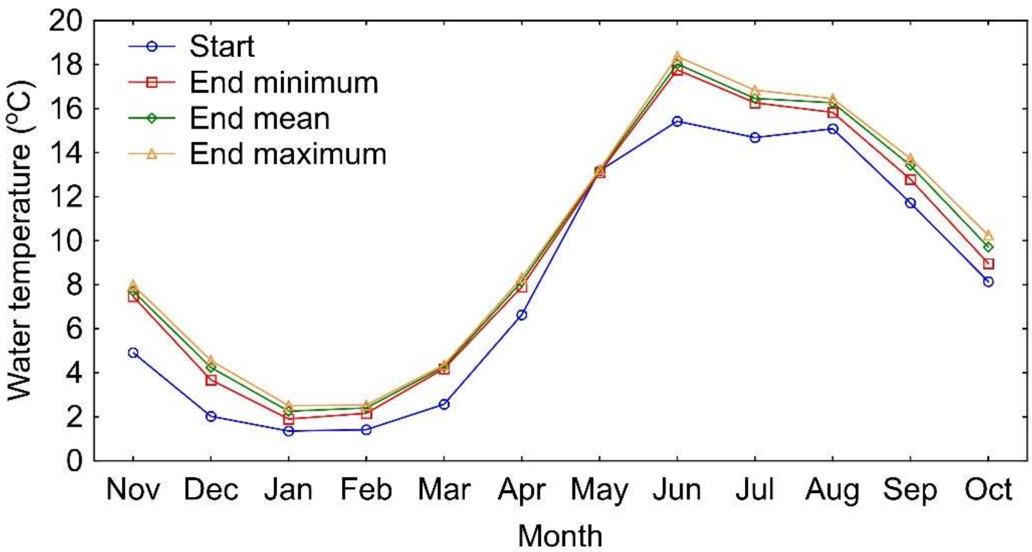

Figure 6. Average change of water temperature regime in Lakes Komorze, Morzycko, Sławianowskie, and Ostrowite.

4. Discussion

Contemporary climate change necessitates actions aimed at gaining increasingly comprehensive knowledge about individual environmental components and their responses to global warming. This approach is being implemented through both the ongoing development of measurement techniques and analytical–statistical methods. As previously indicated, a proper and reliable assessment of atmosphere–hydrosphere interactions requires certain preliminary assumptions, including those related to the length of the study period. The increasing use of models in hydrology allows, among other things, for filling in missing data. The reconstruction of water temperature for over 600 lakes has shown that in most cases, the RMSE was less than 1.5 °C [30]. In the case of Poland, the extension of water temperature data has so far focused on rivers. The daily water temperature reconstruction for several dozen rivers was carried out using the air2stream model [31], where the calibration period RMSE was 1.21 °C and the validation was 1.32 °C. For five rivers, a reconstruction was performed using a multilayer perceptron network, random forest, and linear regression. The first method yielded the best results [28], with an RMSE of 1.52 °C. Therefore, the results obtained in this study are generally consistent with previous approaches aimed at reconstructing inland water temperatures. The use of a single explanatory variable (air temperature) with the optimal model selection allows for a simple yet accurate reconstruction of lake water temperatures. This is an important consideration in water resource management, especially with the emergence of new observation stations and the need for sufficiently long data records.

With a 30-year data set (the minimum period according to widely accepted methodological assumptions), it was possible to assess the long-term changes in the thermal regime of the analyzed lakes. In all cases, the average annual water temperature from 1993 to 2022 showed an upward trend, amounting to a total increase of 0.50 °C per decade. This information aligns with earlier findings, where such a situation is common across Europe. The surface water temperature of Lake Lugano (Italy/Switzerland) experienced warming between 1972 and 2013, ranging from 0.2 to 0.9 °C per decade, depending on the season [32]. Lake Konnevesi, located in Northern Europe (Finland), exhibited clear warming of surface temperatures during the summer period, with an increase of 0.41 °C per decade from 1984 to 2021 [33]. Poland's largest lake has warmed by more than 2 °C since the early 1970s [34].

In the monthly distribution, the highest increase occurred in November, and between 1993 and 2022 it amounted to 0.99 °C per decade. The lowest increase occurred in May and amounted to 0.07 °C per decade. When analyzing individual lakes, it was determined that the annual trends varied from 0.36 °C per decade to 0.64 °C per decade. Despite the relatively small area covered by the analysis, the variation in the course of changes is quite significant, which, as previous studies have shown, may depend on the morphometric parameters of individual lakes [14]. Richardson et al. [35] note that lakes provide a good reflection of climate change, but their characteristics influence the magnitude of these changes, which is crucial for the biology, ecology, and chemistry of the lakes.

Concerning the analyzed lakes, the last three decades have been characterized by a clear transformation of the thermal regime. Given the connection of water temperature with essentially every process (whether direct or indirect), this situation should be regarded as unfavorable. Assessing multistep reactions related to the interactions of hydrobiological conditions and water parameters is challenging. Analysis of the eutrophic Lake Peipsi showed that water temperature was crucial for the abundance and biomass of zooplankton, subsequently affecting the biomass of cyanobacteria, nitrogen concentrations, and water transparency [36]. Moreover, the emergence of invasive species disrupts the existing features of biocenoses. In Europe, the increase in the temperature of hydrosphere elements is beneficial for the spread of exotic species [37]. Grabowska et al. [38], describing seven invasive fish species in inland waters in Poland, stated that their colonization success is influenced by a high tolerance to unfavorable environmental conditions, such as oxygen deficits. Therefore, in a situation where water temperature increases, it will lead to a decrease in dissolved oxygen content and create less favorable conditions for native ichthyofauna. Additionally, it is important to note the different timescales of the fundamental biological processes of living organisms. A study involving three lakes in the Netherlands [39] showed that water temperature was the main factor influencing the hatching and growth of young fish.

An adequate amount of oxygen is also crucial for the mineralization of organic matter, thereby improving water quality in lakes. The overall classification of the status of uniform parts of surface water available from the analyzed set for seven lakes [40] showed poor status in all cases. Key indicators for assessment included nitrogen, phosphorus, and water transparency. The increase in water temperature may be a process that complicates achieving a specified status, even with the elimination of external threats. Research conducted in Sweden indicated that a longer residence time of water in Lake Erken led to greater sensitivity to climate change [41]. According to one of the accepted scenarios, the concentration of dissolved phosphorus in this lake for the epilimnion is nearly twice as high in the spring and autumn seasons. Higher temperatures in relation to shallow lakes may accelerate the development of planktonic algae and increase their dominance over benthic algae, thereby contributing to eutrophication [42]. The increase in water temperature in Lake Iseo (Italy) had a key impact on phytoplankton, resulting in increased volume and decreased diversity, as well as fostering the dominance of cyanobacteria [43].

The above examples clearly demonstrate the role of water temperature in the progression of selected limnological processes. In this context, the change in thermal regime observed in the analyzed lakes presents new challenges for institutions responsible for water resources. Considering the factors regulating water availability and quality, the risk associated with water scarcity should be regarded as higher than initially assumed, especially in the context of climate change [44]. In Poland, the institution responsible for water management is the State Water Holding–Polish Waters, which provides administrative decisions regarding water abstraction licenses for municipal, industrial, and agricultural purposes and licenses for the release of treated wastewater. Warmer waters have less capacity for self-purification; in order to maintain good water status as required by the Water Framework Directive, water abstractions will be limited, but limiting the discharge of treated wastewater or better sewage treatment should also be considered. Likewise, the use of water for cooling purposes will be less efficient due to warming waters. Also, the results of studies indicating warming water should be considered in lake restoration activities due to the fact that water temperature limits biological and physicochemical processes.

Another issue is the need for detailed (daily) information regarding the thermal layers of stratified lakes. Implementing such monitoring in Poland would allow for the understanding of changes in the extent of the epilimnion, the thermal gradient of the metalimnion, and the thermal conditions of the hypolimnion. These issues will be crucial for understanding biogeochemical changes and biodiversity in these ecosystems.

5. Conclusions

The water temperature of lakes is one of the key characteristics determining, on various scales, all processes occurring in these ecosystems. An accurate assessment of changes in their thermal regime requires sufficiently long data sets, which is not feasible in many cases. One solution is to utilize increasingly dynamic modeling methods that employ artificial intelligence, which have the advantage of requiring minimal input data. This study used an approach based on air temperature measurements and available water temperature observations to reconstruct water temperature for nine lakes in northern Poland. The best results were obtained using MLP-type neural networks, as indicated by the RMSE values. Based on the reconstructed and existing records, it was determined that, over the last three decades, there has been a significant increase in water temperature, averaging 0.50 °C per decade. These results align with similar findings in various regions around the world, simultaneously posing challenges for institutions managing water resources.

Author Contributions: Conceptualization, M.S. and M.P.; methodology, M.S.; software, M.S.; validation, M.S.; formal analysis, M.S. and M.P.; investigation, M.S. and M.P. resources, M.P.; data curation, M.S. and M.P.; writing—original draft preparation, M.S. and M.P.; writing—review and editing, M.S. and M.P.; visualization, M.S.; supervision, M.P.; project administration, M.P.; funding acquisition, M.S. and M.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: https://danepubliczne.imgw.pl/ (accessed on 1 October 2024).

Conflicts of Interest: The authors declare no conflicts of interest.

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