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RESEARCH ARTICLE

Effects of eutrophication on vendace, *Coregonus albula* (L.). I. Limnological characteristics of selected lakes in Wielkopolska

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Abstract. The aim of the study was to characterize the abiotic environmental factors influencing the occurrence and biology of vendace, *Coregonus albula* (L.). The analyses covered four lakes in the Wielkopolska region – lakes Dominickie, Gorzyńskie, Lubikowskie, and Strzeszyńskie. The most important natural characteristics of the lakes were analyzed, and their current trophic states were determined. Moreover, two trophic state indicators were also used – the HB index and the Carlson index. Parameters differentiating the lakes most strongly included area, depth, area-depth index, shoreline development, and fish yield index. In terms of morphometry, lakes Gorzyńskie and Lubikowskie are most suitable for optimal vendace fishery management. The least developed stratification was observed in Lake Dominickie, while the most marked stratification was noted in Lake Gorzyńskie, which had the shallowest epilimnion depth, the highest thermocline temperature gradient, and a deep, cool hypolimnion. Considerable deoxygenation was observed in the summer in the hypolimnions in all the lakes; however, oxygen deficits were also detected in the metalimnion of Lake Strzeszyńskie. Based of the analysis of physicochemical factors and trophic state indexes, good water quality was noted in all the analyzed lakes. The trophic state of Lake Gorzyńskie was designated as on the border between the mesoeutrophic and eutrophic states, while lakes Dominickie, Lubikowskie, and Strzeszyńskie were designated as eutrophic.

Keywords: environmental factors, habitat, lakes, stratification

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Introduction

Vendace, *Coregonus albula* (L.), populations across Europe have declined recently, and the most frequently cited reason for this phenomenon is lake eutrophication (Nőges et al. 2008, Haberman et al. 2010, Elliot and Bell 2011). In Poland this fish is still one of the most economically valuable pelagic species because of its advantageous biological characteristics with a short period of two to three years required to achieve commercial weight (Ciepielewski 1974, Czerniejewski et. al. 2002a), as well as its premium quality meat with excellent taste and high nutritional value. Vendace is found in lakes with waters characterized by relatively low trophic states and high oxygen contents, which is why this species also serves as a water quality bioindicator.

Studies concerning vendace populations in lakes in western Poland are scarce. The first data on the occurrence of this species in lakes of the Wielkopolska region were published in studies by Thienemann (1922) and Kulmatycki (1928), while Walczak (1956) and Budych (1957) published studies after the Second World War. Investigations on vendace populations in the Wielkopolska region in the 1960s, 1970s, and 1980s were conducted by Budych (1971), Mastyński (1974, 1978, 1985), and Iwaszkiewicz (1981). Since then, similar studies have not been undertaken, as evidenced by the fact

Table 1
Morphometric data of studied lakes

Parameter	Lake Dominickie	Lake Gorzyńskie	Lake Lubikowskie	Lake Strzeszyńskie
Altitude above sea level (m)	61.7	45.8	54.6	76.75
Surface area (ha)	343.9	79.6	314.7	34.9
Maximum depth G (m)	17.1	34.4	35.5	17.8
Capacity (thousand of m^3)	22230	10109.2	34842.1	2847.1
Maximum length (m)	3830	1400	3820	1210
Maximum width (m)	1660	940	1780	540
Mean width (m)	898	569	824	288
Length of shoreline (m)	10575	5000	13875	4550
Elongation	2.3	1.5	2.15	2.2
Vulnerability to degradation	II	I	I	II

that in the available literature there are only two publications containing contemporary data on the biological and biometric characteristics of vendace in a single Wielkopolska lake (Tuczno Wielkie) from the so-called Gorzyń group (Czerniejewski et al. 2002a, 2002b). The lack of current data characterizing vendace populations in the lakes of the Wielkopolska region prompted the authors to undertake a study of this issue. This information is of great importance for fishery practice, as it is required when making rational economic decisions and designating the the most appropriate breeding concepts.

The aim of the first part of the study was to characterize the abiotic environmental factors that modify vendace habitats and influence its biology to a considerable degree. The lakes selected for the study are typical of Wielkopolska region lakes inhabited by vendace. Thus, one of the assumptions adopted by the authors was that the results of this study would be applicable to other vendace lakes in the Wielkopolska region.

Study area

The analyses were conducted in four lakes of the Wielkopolska region, i.e. lakes Dominickie, Gorzyńskie, Lubikowskie, and Strzeszyńskie. Lake Dominickie is located in the drainage basin of the Obrzyca and Obra rivers in the district of Leszno within the Przemęcki Landscape Park that was established in 1991. It is a flow-through lake that receives inflow from Lake Krzywce in the southwest, while waters are discharged into Lake Wielkie in the northeast through the Boszkowski Canal. Hydrological balance results indicate that Lake Dominickie is fed by ground waters by as much as 50%. Precipitation accounts for 44% of the water balance, while surface inflow from Lake Krzywce accounts for only 6%. The total catchment area of the lake is 20.4 km^2, while that of the direct catchment is 17.1 km^2. The land use structure in this small catchment area is as follows: forests 37.62%; built-up areas 7.93%; meadows 13.98%; arable land 40.47%. Lake Dominickie is a typical postglacial ribbon lake, and the basin of the lake is elongated in a northwest-northeast direction and has relatively gentle slopes, an irregular bottom surface, and a marked pothole with a maximum depth of 17.1 m. Detailed morphometric data are presented in Table 1. The lake's vulnerability to degradation was designated as category 2. The only disadvantageous indicator is the low percentage of water stratification that is expressed as the low share of the hypolimnion in the entire volume of the lake. To date, the waters of this lake have been subjected to relatively weak eutrophication, and they are in a beta-mesotrophic state. Vendace is not an autochthonous species in Lake Dominickie; it was introduced for the first time in 1951.

Lake Gorzyńskie is one of the clusters of the Gorzyń lakes located in the western part of the Międzychód-Sieraków Lake District. This water body is located in a series of lakes, which fill a postglacial channel stretching from the southeast to the northwest at a distance of 3-4 km south of Międzychód. The Struga Dormowska, a left-bank tributary of the Warta River, the spring of which is located in the village of Łowyń, flows in from the south. Lake Gorzyńskie is a deep water body. Detailed morphometric data regarding this lake are presented in Table 1. The most important potential source of pollution for Lake Gorzyńskie is sewage from the Experimental Agricultural Farm in Gorzyń as well as surface run-off from fields located along the north shore. Another important nutrient load is delivered by the outflow from two fish farms located near the shore.

Lake Lubikowskie is a postglacial water body located on out-wash deposits on the boundary of the two macro regions of the Lubuskie and Wielkopolskie lake districts. The catchment of Lake Lubikowskie constitutes a sub-catchment of the Struga Lubikowska, a small, left-bank tributary of the Warta River. Most of the lake catchment is covered by coniferous forests, while arable land is located only to the northwest. Lake Lubikowskie is a flow-through lake, the main inflow of which is from the Struga Lubikowska flowing from Lake Szarcz. Apart from the Struga Lubikowska, this lake is fed periodically by waters discharged by seven short ditches. Lake Lubikowskie has an irregular shape that is elongated in a west-easterly direction. It has two basins separated by an isthmus, and the waters in the middle of the lake are shallow. These two basins differ considerably in terms of depth, thermal and oxygen conditions, and with regard to flora. Detailed morphometric data concerning Lake Lubikowskie are presented in Table 1. At present, there are no point sources of pollution in the catchment area of the lake, and the recreation resorts located near it have cesspools. The Struga Lubikowska, as well as run-off from the arable lands in the catchment area, are the greatest suppliers of nutrients.

Lake Strzeszyńskie is located in the northwestern part of the city of Poznań in the Bogdanka-Warta--Oder Basin. The direct catchment of this lake is 132.6 ha in area, of which approximately 61% comprises forests, approximately 20% is arable land, and 16% is meadows. Lake Strzeszyńskie is located on the watershed and has two outlets: one in the direction of Lake Rusalka and the second is in the opposite direction towards the Samica River. Lake Strzeszyńskie is a natural flow-through water body that was formed by sub-glacial waters. Detailed morphometric data concerning this lake are presented in Table 1. The lake is irregular in shape and consists of two parts; Lake Strzeszyńskie proper and a smaller area called Strzeszyn Mały are separated markedly by emergent vegetation and shrubs. These two reservoirs are connected by a short channel. Based on an analysis of morphometric, hydrographic, and catchment characteristics, Lake Strzeszyńskie can be classified as relatively highly resistant to human impact, and the general vulnerability of this lake was designated as category 2. Lake Strzeszyńskie is a recreation and leisure area for the inhabitants of Poznań.

Materials and methods

In order to realize the aim of this study, analyses of the most important natural characteristics of the lakes that influence all processes occurring in the lake ecosystems and current trophic states were determined as they are reflected in the ichthyocenotic relationships, including the occurrence and condition of vendace.

Based on the morphometric parameters presented in Table 1, the following indexes that are linked with the potential productivity of the waters were calculated: the depth index (Szczerbowski 1993); theoretical epilimnion depth (Patalas 1960); the theoretical epilimnion depth to the maximum depth ratio (Patalas 1960); the area-depth ratio (Bajkiewicz-Grabowska 1987); the shoreline development index (Bajkiewicz-Grabowska 1987); the morphoedaphic index (Szczerbowski 1993).

Samples for physicochemical and biological analyses of water were collected in the summer period (August 2005). The following parameters were determined: BOD_5; total phosphorus; total nitrogen; chlorophyll “a” content; seston dry matter content; Secchi depth. The thermal and oxygen depth profiles during the summer stagnation period were also determined. The temperature and oxygen conditions were measured in situ with a YSI 556 MPS device. Water samples for analyses were collected from the deepest sites and the epilimnion (at a depth of 1.0 m) with a 5 l water sampler. All analyses were performed according to Polish Standards.

The data from these analyses were used to evaluate water quality in accordance with the guidelines of Poland’s National Lake Monitoring program (Kudelska et al. 1994), which are proposed in simplified form by Bnińska (2000). Moreover, two trophic state indexes were used to more accurately determine the trophic state of the investigated water bodies:

- Carlson’s index (Carlson 1977), which is the mean value derived from three equations calculated using data on Secchi depth, chlorophyll-a concentration, and total phosphorus concentration;
- the HB index (Hakanson and Boulion 2001), which is calculated using the mean concentration of chlorophyll “a”.

Results

Morphometric characteristics

According to the morphometric data, Lake Dominickie is not a very deep lake, and it is the shallowest water body of those analyzed in this study both in terms of the maximum and mean depth. The depth index that describes the inclination of slopes and the lake basin factor is 0.4, which indicates a diverse bottom surface and relatively steep slopes (Table 2).

On the other hand, Lake Domnickie is the largest of the lakes analyzed with the highest area-depth index of 54 which means it is most exposed to wind action and thus to wave motion. This obviously influences its water mixing capacity. The theoretical depth of the epilimnion, i.e. the mixing zone, calculated with the formula by Patalas (1960), in combination with the relatively limited depth, yields the third degree of lake water statics that is low for dimictic lakes. This means that even in the summer period the water can be mixed to a depth of more than 7 m, which is nearly half of the maximum depth. Shoreline development is moderate, and the value of the morphoedaphic index is the lowest among the analyzed lakes.

Lake Gorzyńskie differs considerably from Lake Dominickie (Table 2). With an area that is over four times smaller, its maximum and mean depths are two times greater; thus, this lake can be classified as deep. The depth index indicates a varied bottom and considerable slope inclination. The area-depth ratio

Table 2
Morphometric index of studied lakes

Parameter	Lake Dominickie	Lake Gorzyńskie	Lake Lubikowskie	Lake Strzeszyńskie
Mean depth	6.4	12.7	10.9	8.2
Depth index	0.37	0.37	0.31	0.46
Depth of epilimnion E	7.3	4.8	7.4	4.1
Area depth index	53.7	6.3	28.9	4.2
Shoreline development index	1.61	1.58	2.19	2.17
Morphoedaphic index	30.8	62.8	44.1	130.4
$E/G_{max.}$ ratio	0.42	0.14	0.21	0.23

is only 6.3, which, together with the small theoretical mixing depth of 4.8 m, means that the waters are not susceptible to mixing. The high water statics degree of 4-5 in this lake is confirmed by the lowest value of the E/G ratio at 0.14. The shoreline is moderately developed, and the value of the morphoedaphic index of 63 indicates that this lake offers relatively good living and development conditions for ichthyofauna in the littoral zone.

Lakes Lubikowskie and Dominickie are the largest water bodies in the Wielkopolska region; however, the former, with a mean depth of 10.9 m, is much deeper than the latter. The slopes of the lake basin are relatively steep, and the bottom is varied, as indicated by the depth index (Table 2). The area-depth index is 28.9, and the theoretical water mixing depth in the lake during the summer stagnation period is as high as 7.4 m. Despite the similar epilimnion depth to that of Lake Dominickie, Lake Lubikowskie is characterized by much higher water statics and the E/G ratio is 0.21. The shoreline development index is the highest of the four lakes analyzed, and the morphoedaphic index is 44, indicating that the littoral zone is not well developed and its role is limited.

Lake Strzeszyńskie is the smallest lake with relatively shallow waters at a mean depth of 8.2 m (Table 2). The value of the depth index of 0.5 indicates a poorly varied bottom and relatively gentle slopes. The lake is sheltered from wind, which is confirmed by the very low area-depth ratio. The theoretical depth of the epilimnion is 4.1, and it is the lowest of all the analyzed lakes. Despite its limited depth, because the lake is sheltered from wind, it has a relatively high water statics degree of 4, which is expressed in the E/G ratio of 0.23. This lake is characterized by a well-developed shoreline (2.17), and the value of the morphoedaphic index at 130, which

Table 3
Temperature and oxygen content in water of studied lakes during summer stagnation

	Lake Dominickie		Lake Gorzyńskie		Lake Lubikowskie		Lake Strzeszyńskie	
Depth (m)	Temperature (°C)	Oxygen content ($mgO_2\ dm^{-3}$)	Temperature (°C)	Oxygen content ($mgO_2\ dm^{-3}$)	Temperature (°C)	Oxygen content ($mgO_2\ dm^{-3}$)	Temperature (°C)	Oxygen content ($mgO_2\ dm^{-3}$)
0	18.2	7.33	19.0	9.65	18.8	8.40	18.3	8.82
1	18.2	7.30	19.0	9.07	18.8	8.50	18.3	8.60
2	18.3	7.23	19.0	9.30	18.8	8.44	18.3	8.70
3	18.2	7.16	18.9	9.18	18.8	8.60	18.3	8.46
4	18.3	7.18	18.9	9.21	18.8	8.38	18.3	8.60
5	18.2	7.20	18.8	9.21	18.8	7.60	18.2	8.40
6	18.2	7.10	15.2	6.82	18.8	8.16	17.0	4.80
7	18.2	7.11	10.6	4.48	18.7	8.33	11.7	2.34
8	18.2	7.12	8.0	2.40	16.5	9.25	8.9	3.22
9	18.0	6.95	6.5	2.55	11.4	9.54	7.6	0.45
10	12.3	0.17	5.9	2.52	9.4	8.93	6.4	0
11	10.9	0.12	5.5	2.88	8.0	6.63	5.8	0
12	9.9	0.13	5.4	2.90	7.2	2.65	5.6	0
13	9.5	0.16	5.2	2.60	6.7	1.16	5.3	0
14	9.5	0.19	5.1	1.60	6.4	0.58	5.3	0
15	9.4	0.15	5.0	0	6.3	0.45	5.3	0
16	9.3	0.12	5.0	0	6.0	0.15	5.0	0
17	8.7	0.11	5.0	0	5.7	0	5.0	0
18			5.0	0	5.5	0		
19			4.9	0	5.4	0		
...			...	...	...	...		
35			4.9	0	5.4	0		

is the highest of the lakes analyzed, indicates it has a very well-developed littoral zone that plays a significant role in the functioning of this ecosystem.

Temperature and oxygen conditions

Lake Dominickie is divided into three layers in the summer stagnation period (Table 3). This is closely connected with the natural characteristics of the lake as described above. The empirically established depth of the epilimnion is 9 m, which is almost 2 m greater than that calculated using the formula by Patalas. This confirms the low water statics of this lake. The water temperature in the epilimnion fluctuated around 18°C. This temperature dropped rapidly by almost 6°C in the 9-10 m layer. Further decreases in temperature were not that marked, but the thermocline was still 3 m thick. Starting from 12 m the temperature decreased slowly until it reached a value of 8.7°C at the bottom. Oxygen conditions in this lake were not very advantageous with good water oxygen concentration recorded to a depth of 9 m, while below the thermocline rapid oxygen depletion was observed in the water to 0.17 $mgO_2\ dm^{-3}$ at the bottom.

Three well-marked layers were noted in Lake Gorzyńskie, which is typical of dimictic lakes with a high degree of water statics (Table 3). With a temperature of approximately 19°C, the epilimnion extended to a depth of 5 m, which was slightly deeper than the calculated value. Below the depth of 5 m there was a rapid temperature change characteristic of thermoclines. The strongly-marked metalimnion was 4 m thick, and the temperature differences between the highest and lowest points was as much as 12.3°C. The temperature gradient in the hypolimnion below 9 m was only 1.6°C, while the bottom water temperature was 4.9°C, which is typical of dimictic lakes with a water statics degree of 4-5. Oxygen conditions in the epilimnion were advantageous, with an oxygen content to a depth of 5 m that fluctuated around 9.3 mg $O_2\ dm^{-3}$. The water oxygen content in the metalimnion decreased to 2.6 $mgO_2\ dm^{-3}$. A successive decrease in oxygen content was recorded in the hypolimnion, where starting from a depth of 15 m to the bottom complete oxygen depletion was noted.

In Lake Lubikowskie the temperature throughout the epilimnion to a depth of 7m was approximately 18.8°C; thus, the calculated value was close to that obtained from measurements (Table 3). Similarly to that in Lake Gorzyńskie, the metalimnion was 4 m thick, and the temperature gradient in this layer was 10.7°C. The hypolimnion began at 11 m, and the temperature in this layer decreased slowly to as little as 5.4°C. The oxygen profile of the lake is characterized by a positive heterograde, which means that, in contrast to the lakes described previously, the metalimnion oxygen content increases slightly instead of falling. Advantageous oxygen conditions are noted to a depth of much as 11 m; below this, the oxygen content in the hypolimnion decreases to a value of zero at a depth of 17 m.

Despite its shallow depth, a thermal profile formed in Lake Strzeszyńskie that is typical of dimictic lakes with considerable statics (Table 3). The depth of the epilimnion was 6 m, which was 2 m more than the calculated value. The water temperature within this layer fluctuated around 18°C. The 4-m-thick thermocline was characterized by a considerable temperature gradient of 10.6°C. The temperature in the hypolimnion below 10 m decreased gradually to 5°C. The oxygen conditions in this lake were highly disadvantageous; good oxygen supply was only noted in the epilimnion, while complete oxygen depletion was observed in the metalimnion at a depth of 10 m.

Water quality and trophic state

The waters of Lake Dominickie were classified as quality class II based on the simplified formula of quality evaluation using eight water indexes (Table 4). This lake was ranked third among the analyzed lakes as its total score was 1.88. The values of five indexes were in class I, but the indexes that lowered the final score were for mean oxygen saturation in the hypolimnion and total phosphorus content in

Table 4
Physicochemical water quality variables during summer stagnation

Parameter	Lake Dominickie	Lake Gorzyńskie	Lake Lubikowskie	Lake Strzeszyńskie
Mean oxygen saturation of hypolimnion (%)	1.2 (non)	5.2 (III)	5.1 (III)	0 (non)
BOD5 (mg O_2 dm^{-3})	1.9 (I)	0.55 (I)	1.0 (I)	1.9 (I)
Total phosphorus (mg P dm^{-3})	0.25 (non)	0.12 (III)	0.11 (II)	0.15 (III)
Total nitrogen (mg N dm^{-3})	0.74 (I)	1.12 (II)	1.19 (II)	1.026 (II)
Chlorophyll "a" (μg dm^{-3})	2.8 (I)	1.29 (I)	3.8 (I)	3.33 (I)
Seston dry weight (mg dm^{-3})	2.4 (I)	0.6 (I)	0.8 (I)	1.4 (I)
Fecal coliform titer	2 (I)	>100 (I)	>100 (I)	4 (I)
Secchi disc visibility (m)	3.0 (II)	5.0 (I)	5.3 (I)	1.7 (III)
Final evaluation of water quality	1.88 (II)	1.63 (II)	1.50 (II)	2.00 (II)

Table 5
Indicators describing the trophic status of lakes surveyed

Indicator	Lake Dominickie	Lake Gorzyńskie	Lake Lubikowskie	Lake Strzeszyńskie
TSI (SD)	44.2	36.8	35.9	52.3
TSI (Chl)	40.7	33.1	43.7	51.4
TSI (TP)	83.8	73.2	72.0	76.4
TSI Mean	56.2	47.7	50.5	60.0
HB	36.2	27.8	39.5	39.9

the surface layers. Based on Carlson's index, Lake Dominickie was designated to be in an early eutrophic state. The value of this index was 56.2, which ranks this lake third among those analyzed. According to the HB index, which was better, this lake is mesotrophic (Table 5).

The water quality of Lake Gorzyńskie was also classified as class II with a total score of 1.63 (Table 4). Similarly to Lake Dominickie, the indexes that decreased the final score included the oxygen and total phosphorus contents. Lake Gorzyńskie had the lowest values of both the Carlson's and HB indexes, which indicates that it can be classified, according to the former, as on the border between mesotrophic and eutrophic states, and according to the latter as in a mesotrophic state (Table 5).

Based on physicochemical analyses, Lake Lubikowskie was also classified as quality class II, while the total score of 1.50 ranks this lake first (Table 4). The only index that lowered the final score was that of the mean oxygen saturation in the hypolimnion. The content of nutrients, particularly phosphorus, was the lowest among the lakes analyzed. In terms of the trophic state, similarly to Lake Gorzyńskie, the Carlson's index indicates that the lake can be classified as in transition between the mesotrophic and eutrophic states, while the HB index indicated it was in an advanced mesotrophic state.

The water quality of Lake Strzeszyńskie was the least advantageous of all the lakes analyzed; however, the waters were classified as quality class II based on physicochemical analyses. The total score was 2, which is the worst value from among the analyzed lakes (Table 4). The decline in water quality was influenced primarily by the low oxygen content in the hypolimnion and the high content of total phosphorus. Lake Strzeszyńskie was classified as eutrophic based on the trophic state indexes.

Discussion

The natural characteristics of the analyzed lakes differ considerably, and the greatest differences are noted with regard to area and depth. Moreover, other parameters that differentiate these lakes include area-depth index, shoreline development, and morphoedaphic index. The variable morphometry of these lakes influences numerous processes that occur with varying intensity, which, in turn, is reflected in the productivity of these ecosystems. Christianus (1995) stated that the highest growth rates are usually noted for vendace inhabiting small reservoirs (28-120 ha) ranging in depth from 21 to 42.5 m and with high water transparency.

The lakes were divided according to fishery typology into two categories: bream (Lakes Dominickie and Strzeszyńskie) and vendace (Gorzyńskie and Lubikowskie). In their investigation of the species composition of the ichthyocenoses of German lakes, Mehner et al. (2005) reported that, depending on the morphometry and trophic state of lakes, two types of lakes are distinguishable: deep lakes with cold waters and vendace and perch and shallower lakes with higher water temperatures and cyprinids as the dominant species. The species composition of the communities depended mainly on maximum and mean depths, chlorophyll "a" content, and volume.

Among Polish researchers, Leopold et al. (1998a, 1998b) investigated the effect of lake morphometry on the efficiency of vendace management. Their studies clearly indicate that among the parameters analyzed mean depth had the strongest effect on species yield and stocking efficiency. In view of the data presented in this paper, lakes Gorzyńskie and Lubikowskie are morphometrically most suitable for optimal vendace management.

Factors affecting the productivity of lakes with regard to mineral content can include the degree of water mixing, which is linked to morphological parameters (Patalas 1960). Lakes differ in matter cycling dynamics depending on the degree of water statics (Kajak 1998). The highest theoretical epilimnion depth according to the area-depth index was noted in lakes Dominickie and Lubikowskie, which have the greatest surface areas. The considerable thickness of the epilimnion in Lake Lubikowskie did not manifest in high mixing potential because of the lake's considerable depth. The lowest statics expressed as the E/G ratio were noted in Lake Dominickie, in turn, the highest water mass stability was noted in Lake Gorzyńskie. Despite its limited depth, Lake Strzeszyńskie had relatively high statics despite its limited depth and because it was sheltered from the wind. According to Szczerbowski (1993), the morphoedaphic index, which ranges from 0 to 200, provides information about littoral development and its use by many communities of aquatic organisms, as well as potential threats from internal nutrient loading. The morphoedaphic index of Lake Strzeszyńskie was particularly distinguished, as it was at least two times higher than in the other lakes analyzed, which indicates it offers the best conditions for hydrobiont development in the shoreline zone.

Fluctuations in epilimnion range and the sharpness of the temperature gradient in the thermocline can accelerate or delay the transport of nutrients from deeper layers (Filipiak et al. 1995). Moreover, the temperature of the hypolimnion and the temperature gradient in the metalimnion can also be considered to be measures of water exchange intensity in lakes. Relatively high hypolimnion temperatures together with slight decreases in thermocline temperatures indicate high intensity exchange, and thus an increased inflow of mineral nutrients to the epilimnion (Filipiak et al. 1995). In lakes with similar nutrient contents higher primary production is observed when the exchange of water between the bottom and the surface is more intense (Vollenweider 1971).

The distribution of temperature values throughout the water columns in summer made it possible to distinguish layers in the lakes analyzed. The analyzed lakes were characterized by varied epilimnion depths, which were most frequently higher in relation to calculated values. This could have been influenced by the period in which the measurements were taken at the end of the summer stagnation period.

The least-developed stratification was observed in Lake Dominickie. The epilimnion was 2 m deeper in comparison to the theoretical value, and the water in the hypolimnion was the warmest (fluctuating around 9°C). In turn, typical, well-defined stratification was noted in Lake Gorzyńskie, where the shallowest epilimnion depth, the highest thermocline temperature range, and a deep, cool hypolimnion were noted.

Prusik et al. (1989), who investigated six dimictic lakes in the Mazurian Lakeland, reported interesting findings that the theoretical mixing capacity in lakes was higher than the actual range of the epilimnion. This was because the lake was shielded from wind. Water mixing was an important factor that determined the intensity of internal nutrient supply. After stratification had been established and water blooms ceased, sedimentation increased and the concentration of phosphorus in the epilimnion decreased. On the other hand, as the epilimnion deepened towards the end of the stagnation period, the epilimnion began to become enriched with nutrients.

Oxygen regime is a good, well-recognized trophic state index, and oxygen condition analysis during summer stagnation periods is highly suitable for evaluating lake trophic status (Kajak 1998, Pernaravičiűtë and Balkuvienë 2000, Lampert and Sommer 2001). Eutrophic lakes exhibit hypolimnion oxygen deficits in the summer and early fall periods. During this period, waters that provide adequate habitat conditions for vendace are reduced (Muller and Stadelmann 2004). In turn, excessive oxygen contents in surface water layers that results from intense photosynthesis can cause gas disease in vendace fry. Considerable deoxygenation was noted in the summer in the hypolimnions of all of the lakes analyzed. In Lake Strzeszyńskie, oxygen deficits were also evident in the metalimnion. The low oxygen content noted in the lakes analyzed can be disruptive, and, at a higher intensity, could also prevent the occurrence of vendace. Muller and Stadelmann (2004) reported that vendace require a minimum of 4 mgO_2 dm^{-3}, which is considered essential to support natural reproduction. Szczerbowski (1993) reported that 2 mg O_2 dm^{-3} to a depth of at least 6 m is sufficient. It must be stressed at this point that oxygen content of over 2 mg in the benthic zone prevents iron phosphate reduction and the release of orthophosphates from sediments, which play key roles in decelerating of eutrophication. The eutrophication of surface waters is a very serious problem, as it leads to water quality deterioration and disturbs the equilibrium of aquatic ecosystems (Kubiak 2003).

The water quality determined in all of the analyzed lakes according to physicochemical and trophic state indexes was good; however, the lakes still differ from each other within one class or trophic level. Lake Strzeszyńskie proved to be of inferior quality to the other three lakes. The highly adverse oxygen conditions posed the greatest threat to water quality, and, thus, to vendace populations. Moreover, elevated amounts of total phosphorus were noted, but this problem concerns all the lakes, particularly Lake Dominickie, in which phosphorus content exceeded permissible limits. This is linked to the increased nutrient cycle dynamics in the ecosystem. In most lakes, phosphorus is a key element that regulates phytoplankton production, while the interrelation between phosphorus and chlorophyll is the most important element in lake eutrophication theory (Hakanson and Boulion 2001). Vollenweider (1976) identified two critical trophic thresholds: when total phosphorus of approximately 10 μg dm^{-3} occurs regularly there is a high probability of lakes transitioning from an oligotrophic state to a mesotrophic state, but at a level of approximately 20 μg dm^{-3} a transition to the eutrophic state is anticipated.

The highest water quality based on physicochemical parameters was noted in Lake Lubikowskie, while that based on trophic state indexes was noted in Lake Gorzyńskie. The trophic state of these reservoirs was designated as being on the border between mesotrophic and eutrophic states, while lakes Dominickie and Strzeszyńskie were designated as eutrophic. Mastyński and Szeląg-Wasielewska (1989) and Bnińska (2000) observed higher *Coregonidae* management efficiency in vendace lakes with a higher trophic state than in those lakes in which a lower amount of fry was sufficient for the production of 1 kg of commercial fish.

This was probably because of the better weight increments in eutrophic water bodies. Completely different conclusions were drawn when analyzing stocking efficiency. This author stated that the chlorophyll index was the quality index that was most negatively correlated with stocking efficiency. The higher the production of reservoirs is, then the lower fry survival rates are. The content of chlorophyll "a" is closely linked to both primary production and trophic state (Hakanson and Boulion 2001). This means that in eutrophic lakes losses of fry might be so high that natural spawning cannot ensure adequate recruitment and the effects of stocking are very often negligible.

Hakanson and Boulion (2001) developed a classification system for lake waters based on primary parameters including estimated fishery production and dominant fish species. This classification could be suitable for basic assessments of lake productivity or for fishery management planning. According to these criteria, only Lake Gorzyńskie is mesotrophic, and whitefish and perch are the predominant species. The other lakes analyzed are eutrophic, where the dominant ichthyofauna are perch and roach. The analyzed lakes are also monitored by the Provincial Environmental Pollution Inspectorates in Leszno, Gorzów Wielkopolski, and Poznań, and basic monitoring conducted by them in the 1990 allowed designating all of the lakes analyzed in the present study as quality class II, but with certain fluctuations of indexes within this class.

Conclusions

1. The natural characteristics of the analyzed lakes differ which affects both their water quality and trophic states.
2. The best living conditions for vendace are found in the deep, static lakes Gorzyńskie and Lubikowskie.
3. The lakes are of good water quality and have relatively low trophic states, but the greatest threat to vendace noted in the reservoirs is summer oxygen deficiency, which can occur throughout the hypolimnion, and occasionally even in the metalimnion.
4. Regular oxygen deficits at the bottom can lead to elevated trophic states as a result of secondary water pollution from bottom deposits.
5. Without regular, intensive stocking programs, it will be impossible to maintain vendace populations in lakes Dominickie and Strzeszyńskie.

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