

Abiotic factors as a long-term stressor for the vendace fisheries in Lake Ińsko (European Central Plains Ecoregion, Poland)

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Abstract: The population of vendace (*Coregonus albula* L., 1758) in many European lakes, especially in Central Europe, have declined recently as a result of lake eutrophication. The aim of the study was to (i) determine many years' changes in the volume of vendace catches and specific physicochemical parameters of water, (ii) determine correlations between particular physicochemical parameters, and (iii) indicate hydrochemical parameters which show the greatest impact on the volume of vendace catches on the example of Lake Ińsko located in the European Central Plains Ecoregion. Principal Component Analysis (PCA) was applied to indicate the most important hydrochemical variables impact on vendace fisheries. Among them, after redundancy analysis, 6 were taken into account (total nitrogen, N-NO₃, N-NO₂, total phosphorus, oxygen concentration, temperature). Time series analysis revealed an increasing trend in nutrients concentration in lake. Analyses showed that fish catches were mostly negatively connected to nitrogen and phosphorus concentration. Trend analysis, based on the above-mentioned parameters, can provide prediction of vendace catches for further years with the predictability at the level of around 60% accuracy. The results of this study are very crucial to the vendace fisheries and for formulating fisheries management policies in the future in the changing hydrochemical condition of lakes.

Keywords: biogens, fish yield, hydrochemical condition, Lake Ińsko, vendace

INTRODUCTION

A large number of lakes located in northern Europe are related to the activity of the Baltic Sea glaciation [HEINE *et al.* 2015]. These reservoirs are characterised by diversified habitat conditions (hydromorphological and physicochemical), due to the phenomenon of accelerated eutrophication caused by human activity [HILLBRICHT-ILKOWSKA 1997]. The number of lakes in Poland is about 7,000 reservoirs with an area of more than 1 ha [CHOIŃSKI 2006], which play an important role in the protection of water resources and biodiversity, but at the same time have economic importance [KAISER *et al.* 2014]. As a result of increased anthropopressure in lakes, they show high variability of physicochemical and hydrological conditions, which has an effect on water organisms [WOOLWAY *et al.* 2020; YANG *et al.* 2018]. The rate of these processes may be different and basically depends on morphometric features of the lake, size and type of the basin use,

and climate conditions [JEPPSEN *et al.* 2014, ZHOU *et al.* 2022]. These processes are important not only due to environmental effects, but also due to economy (e.g. deterioration of the water quality, reduced water resources) [SIMA *et al.* 2013], which causes changes in the ichthyofauna structure and resources [JAPPESEN *et al.* 2010; SZCZERBOWSKI 2008]. Although some fish species (e.g. cyprinid fish) are adapted to low oxygen levels, especially at low or high temperatures [SOARES *et al.* 2006], many of them reveal reduced resources in the case of more advanced trophic processes and reduced oxygen content [JAPPESEN *et al.* 2010].

One of such species is vendace (*Coregonus albula* L., 1758), which is a typical pelagic fish, with a small body size, living in schools, and preferring cold water [KARJALAINEN *et al.* 2021; NYBERG *et al.* 2001; OREHA, ŠKUTE 2022; SARVALA *et al.* 1999]. In lakes, this species avoids areas where the temperature exceeds 18–19°C, or the oxygen level is below 2 mg·dm⁻³ [ELLIOTT *et al.* 2010]. The natural habitat of this species are lakes located around

the Baltic Sea: from Germany and Denmark in the west, through Poland, and to Estonia, Lithuania, Latvia and Russia in the east [CZERNIEJEWSKI, RYBCZYK 2008; SZCZERBOWSKI 2008]. Special economic importance is associated with vendace in cold, clean and oxygen-rich lakes in Norway [MUTENIA, SALONEN 1992; SANDLUND *et al.* 1985], Sweden [SVÄRDSON 1976; 1979] and Finland [AUVINEN 1987; HELMINEN, SARVALA 1994]. According to WINFIELD *et al.* [1996], this species also occurs in a few lakes of Ireland, England and Wales. In recent decades, the resources of this species have decreased in most lakes, and the causes of this phenomenon are assigned to changes resulting from waterbody eutrophication [ELLIOTT *et al.* 2010; MARJOMÄKI *et al.* 2004; 2014; 2021].

In Poland, vendace is considered one of the most precious component of ichthyofauna of Polish lakes with regard to economy [CZERNIEJEWSKI, RYBCZYK 2008; CZERNIEJEWSKI, WAWRZY- NIAK 2006], although it is characterised by high phenotypic variability, and its status of endangerment is VU (vulnerable) [WITKOWSKI *et al.* 2009]. Therefore, prior to taking up any activities related to restoration of the fish population, it is necessary to conduct detailed studies of not only the fish, but also of hydrochemical changes in its habitats, in order to determine which environmental parameters have the greatest impact on the condition of the fish resources, and at the same time on catches of the fish. It seems essential to indicate these parameters in order to make conclusions on the possibility to restore the population. In research papers, authors most often assign the cause of the reduced vendace catches to high water temperatures and low oxygen content caused by climate changes and progressive eutrophication [ELIOT *et al.* 2010; NYBERG *et al.* 2001], overfishing [AUVINEN 1994, COWX 2015], long period of ice presence [NYBERG *et al.* 2001]. They do not indicate, however, which of the hydrochemical parameters responsible for the phenomenon of eutrophication has the greatest influence on the condition of resources and volume of vendace catches.

Therefore, the aim of the present study was to: (i) determine many years changes in the volume of vendace catches and specific physicochemical parameters of water, (ii) determine correlations between particular physicochemical parameters, and (iii) indicate hydrochemical parameters which show the greatest impact on the volume of vendace catches on the example of Lake Ińsko located in the European Central Plains Ecoregion.

MATERIALS AND METHODS

STUDY AREA

As the study area, Lake Ińsko located on the Ińsko Lake Region in north-western Poland was selected. The surface area of this waterbody is 589.9 ha, and the area of the island located in the north-eastern part – 22.3 ha. As a post-glacial lake formed as a result of local crossing of several glacial valleys, it is highly fragmented. This is reflected in the values of shoreline development index (WL = 3.65) and elongation index (2.61). The maximum depth of the lake is 41.7 m, but due to its large surface area, the relative depth of the lake is quite low (0.0181). Ińsko is characterised by highly varied bottom, with a concave lake basin, which is assumed from the low depth index (0.32) (Tab. 1).

Table 1. Morphometric characteristics of Lake Ińsko

Trait	Unit	Value
Area	ha	589.9
Volume of waters	thous. m ³	65182.0
Maximum length	m	5400
Maximum width	m	2100
Elongation	–	2.61
Shoreline length	m	31450
Shoreline development index	–	3.65
Maximum depth	m	41.7
Mean depth	m	11.1
Relative depth	–	0.0181
Depth index	–	0.32

Source: JANCZAK [1996], modified.

DATA ON VENDACE CATCHES

Data characterising the fishing industry in 1950–2020, with special regard to vendace catches in this reservoir, were obtained from the economic book of Lake Ińsko containing information on catches and fishing capacity with regard to vendace and other fish species, on the type and dose of stocking material, and fishing tools used for vendace utilisation. This book was provided by ichthyologists of Fisheries Enterprise in Ińsko (Mr. Marek Pietrucha and Mateusz Gzyl).

HYDROCHEMICAL DATA

The study uses results of many years of research conducted by the Department of Hydrochemistry and Water Protection of the West Pomeranian University of Technology in Szczecin in 1970, 1971, 1978, 1982, 1987, 1992, 1996, 1997, 1998, 1999, 2002, 2006 and 2010 (1970–2010). These long-term researches were funded by Agricultural University in Szczecin, West Pomeranian University of Technology in Szczecin, Provincial Inspectorate of Environmental Protection in Szczecin, Fisheries Enterprise in Ińsko and other institutions.

Water samples were vertically collected from three study sites located at the deepest points of the lake (every 1 m), at a frequency of 6–8 times per year (Fig. 1). During sampling, additional measurements were performed, also vertically, every 1 m, including the temperature (to the nearest ±0.1°C) and oxygen content (thermal oxygen probe YSY Digital Professional Series). During field studies, also visibility of the Secchi disk was assessed. Biogenic substances were measured, including particular forms of nitrogen: ammoniac, total nitrogen, nitrite nitrogen, nitrate nitrogen, mineral nitrogen, organic nitrogen and forms of phosphorus: total phosphorus, mineral phosphorus, organic phosphorus. Colorimetric analysis were made using a Perkin Elmer Lambda 10 spectrophotometer. The measurements also included the level of organic matter and water mineralisation by determining biological oxygen demand (BOD_5), chemical oxygen demand (COD), and specific electrolytic conductivity. Chemical

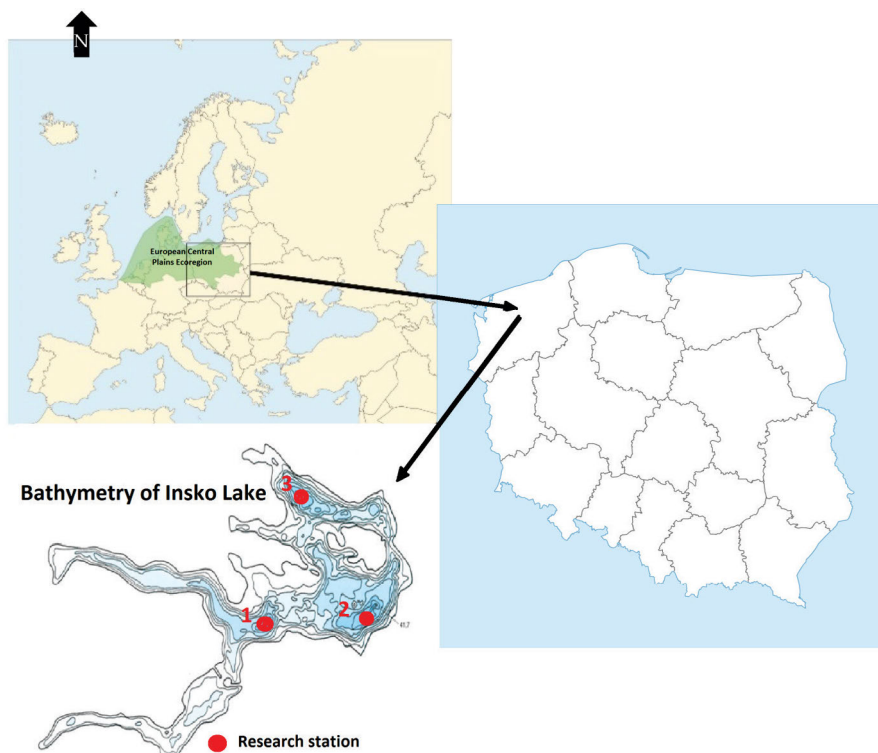


Fig. 1. Location of research stations on Lake Ińsko (European Central Plains Ecoregion); source: own elaboration

analyses of water parameters were performed at the laboratory using widely accepted methods for this kind of tests [EATON *et al.* (eds.) 2005].

STATISTICAL ANALYSES

Correlations between consecutive hydrochemical parameters were tested with R-Spearman's test due to non-linearity and non-normality of the variables. Changes in trends in time were tested with linear correlation analysis both for all the parameters measured. To reveal the connection between environmental conditions, an ordination method – Principal Component Analysis (PCA) was used to summarize and visualize the information contained in large multivariate data sets. Since Principal Factor Analysis (PFA) is used to assume or wish to test a theoretical model of latent factors causing observed variables, PCA was applied to reduce the correlated observed variables to a smaller set of important independent composite variables. In order to avoid data redundancy (multicollinearity), variance inflation factor (VIF) was first calculated.

R-Spearman's correlation, trend analyses and PCA were performed in Statistica software (ver. 13.3), while VIF was calculated in R-software using the `vif` function (ver. 4.03).

RESULTS

ANALYSIS OF VENDACE CATCHES

Vendace catches were analysed in 1950–2020. During this period the fishing economy of Lake Ińsko was focused on regular commercial catches of 11 fish species, which constituted 85.96% weight of all fish caught in this period. The mean long-term fish

yield from this lake was $15.88 \text{ kg}\cdot\text{ha}^{-1}$ (range $3.72\text{--}41.1 \text{ kg}\cdot\text{ha}^{-1}$), wherein the mean share of vendace (in 1950–2020) was 33.14%. The highest proportion of vendace was observed in 1960–1975 (more than 50% of the caught fish), while from the 80's of the 20th century to the beginning of the 21st century, except for a few years, a decrease in the vendace share in fish catches was observed. Figure 2 shows the dynamics of vendace catches over many years. The mean yield of this species in 1950–2020 was $5.64 \text{ kg}\cdot\text{ha}^{-1}$, and the mean biomass of vendace catches was $2784.4 \text{ kg}\cdot\text{yr}^{-1}$. However, the yields and sizes of the catches showed high variability (range $0\text{--}19.27 \text{ kg}\cdot\text{ha}^{-1}$, and $0\text{--}9379 \text{ kg}\cdot\text{yr}^{-1}$). In the years 1964, 1973 and 2011, the yield was about $15 \text{ kg}\cdot\text{ha}^{-1}$ (19.21, 19.27 and $18.21 \text{ kg}\cdot\text{ha}^{-1}$, respectively), while a value of $5.0 \text{ kg}\cdot\text{ha}^{-1}$ was recorded for the period of 35 years of fishing activity in this reservoir.

Lake Ińsko was stocked with 4 forms of vendace material: fertilised fish eggs, eyed eggs, hatchlings and fry. The last two juvenile stages of the vendace development were used most often and with greatest effect, which in the years after stocking resulted in increased catch sizes of this species. This correlation was not observed in 1998–2000, when, despite regular annual stocking in the mean amount of 4800 pcs. of hatchlings per ha, a rapid decline in the vendace catch sizes was observed, down to a minimum level of $0.71 \text{ kg}\cdot\text{ha}^{-1}$ in 2000. However, the stocking conducted in 2008–2020, mainly with vendace hatchlings at a dose above 5000 hatchlings per ha caused a significant increase in the catch sizes of this fish. It must be emphasised that the stocking had a significant effect on the volumes of vendace catches in Lake Ińsko ($p < 0.05$), although the value of the correlation coefficient $r = 0.45801$ (Fig. 3) demonstrates that aside to stocking, there are also other factors determining the amounts of vendace.

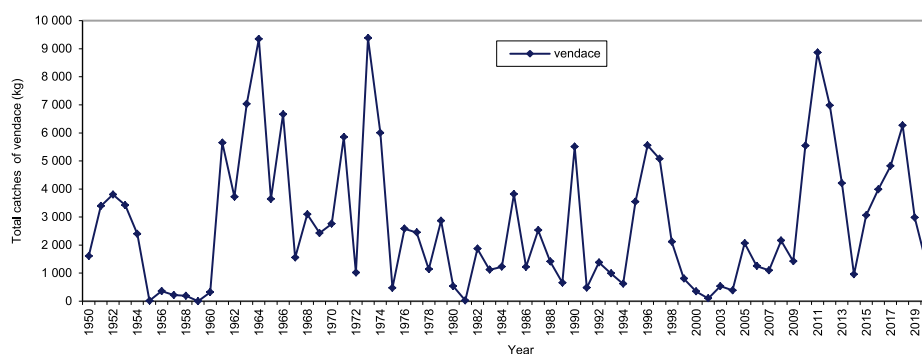


Fig. 2. Yield of vendace in Lake Ińsko in 1950–2020; source: own study

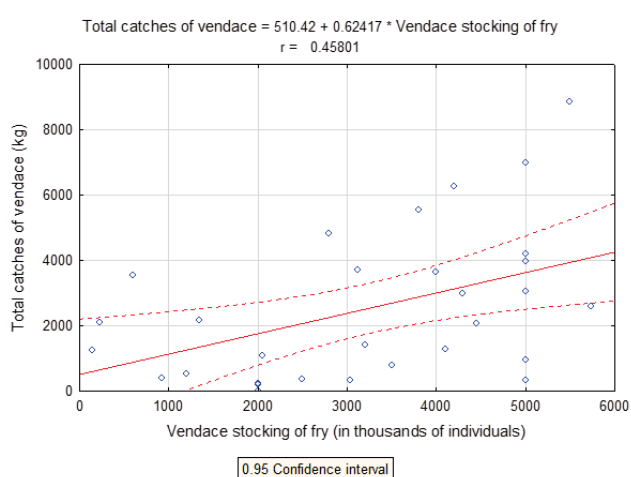


Fig. 3. Relationship between stocking material quantity and vendace catch yield in 1950–2020 period from Lake Ińsko; source: own study

HYDROCHEMICAL CONDITIONS

Analysis of hydrochemical condition were made in 1970–2010. R-Spearman's rank correlation analysis indicated relationships between the hydrochemical parameters (Tab. 2). The results show positive correlation between oxygen content and COD ($R = 0.48$), BOD_5 ($R = 0.21$) and the concentration of organic nitrogen (N_{org} , $R = 0.19$). Furthermore, COD and BOD_5 was strongly negatively correlated with phosphorus ($P-PO_4$, $R = -0.67$) and nitrogen ($N-NO_3$, $R = -0.45$; $N-NO_2$, $R = -0.47$). Most of the fractions of nitrogen are significantly positively correlated with phosphorus fractions except for $N_{org}-P-PO_4$ ($R = -0.28$) and $N_{org}-P_{tot}$ ($R = -0.23$). Visibility showed to be connected negatively with total nitrogen ($R = -0.47$), organic nitrogen ($R = -0.49$) and phosphorus ($R = -0.36$). As for conductivity, the strongest negative relationship occurred to be with COD ($R = -0.46$) but it increased with phosphorus concentration (total and organic).

Time-series analysis indicated trends in changes for temperature (Fig. 4), oxygen content (Fig. 5), COD (Fig 6),

Table 2. Spearman's rank correlation values between consecutive hydro-chemical parameter for Lake Ińsko

Variable	Spearman's rank correlation values												
	O ₂	COD	BOD ₅	N _{tot}	N _{org}	N-NH ₄	N-NO ₂	N-NO ₃	P-PO ₄	P _{tot}	P _{org}	visibil-ity	conduct-ivity
O ₂	1.00	0.48	0.21	-0.04	0.19	-0.27	-0.15	-0.38	-0.29	-0.17	0.28	-0.13	-0.24
COD	0.48	1.00	0.50	0.28	0.44	-0.49	-0.47	-0.45	-0.67	-0.39	0.40	0.17	-0.46
BOD ₅	0.21	0.50	1.00	0.13	0.23	-0.50	-0.10	-0.30	-0.51	-0.34	0.22	0.16	-0.06
N _{tot}	-0.04	0.28	0.13	1.00	0.91	-0.18	-0.25	-0.08	-0.09	-0.11	0.11	-0.47	-0.37
N _{org}	0.19	0.44	0.23	0.91	1.00	-0.45	-0.26	-0.29	-0.28	-0.23	0.18	-0.49	-0.42
N-NH ₄	-0.27	-0.49	-0.50	-0.18	-0.45	1.00	0.21	0.39	0.66	0.41	-0.26	-0.26	0.39
N-NO ₂	-0.15	-0.47	-0.10	-0.25	-0.26	0.21	1.00	0.24	0.52	0.36	-0.40	0.09	0.11
N-NO ₃	-0.38	-0.45	-0.30	-0.08	-0.29	0.39	0.24	1.00	0.46	0.35	-0.31	-0.06	0.12
P-PO ₄	-0.29	-0.67	-0.51	-0.09	-0.28	0.66	0.52	0.46	1.00	0.75	-0.35	-0.36	0.32
P _{tot}	-0.17	-0.39	-0.34	-0.11	-0.23	0.41	0.36	0.35	0.75	1.00	0.25	-0.34	0.37
P _{org}	0.28	0.40	0.22	0.11	0.18	-0.26	-0.40	-0.31	-0.35	0.25	1.00	-0.22	0.05
Visibility	-0.13	0.17	0.16	-0.47	-0.49	-0.26	0.09	-0.06	-0.36	-0.34	-0.22	1.00	0.13
Conductivity	-0.24	-0.46	-0.06	-0.37	-0.42	0.39	0.11	0.12	0.32	0.37	0.05	0.13	1.00

Explanations: significant values ($p < 0.05$) are marked in red.
 Source: own study.

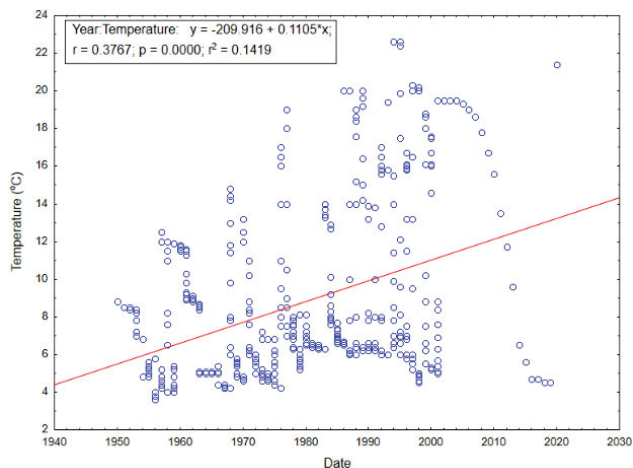


Fig. 4. Time series analysis for water temperature in Lake Inisko; source: own study

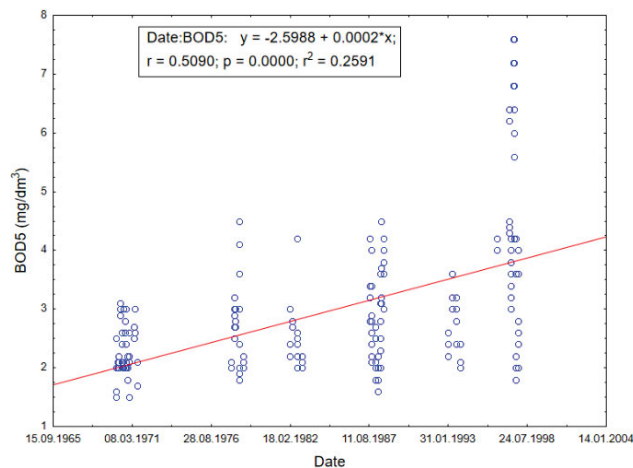


Fig. 7. Time series analysis for BOD₅ in Lake Inisko; source: own study

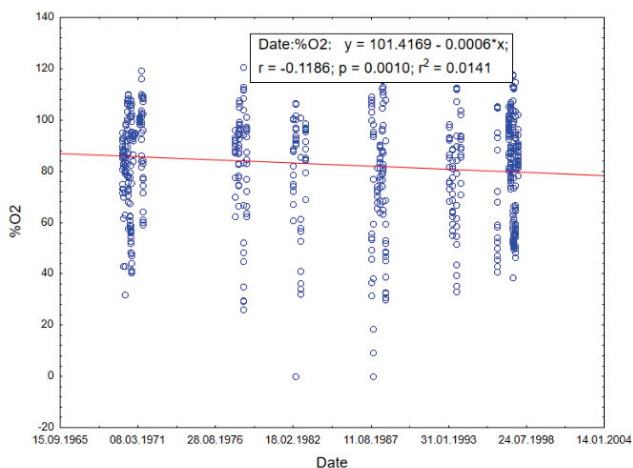


Fig. 5. Time series analysis for oxygen content in Lake Inisko; source: own study

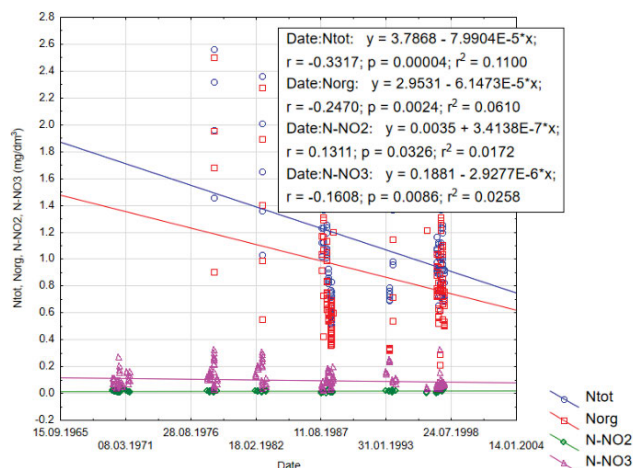


Fig. 8. Time series analysis for nitrogen content in Lake Inisko; source: own study

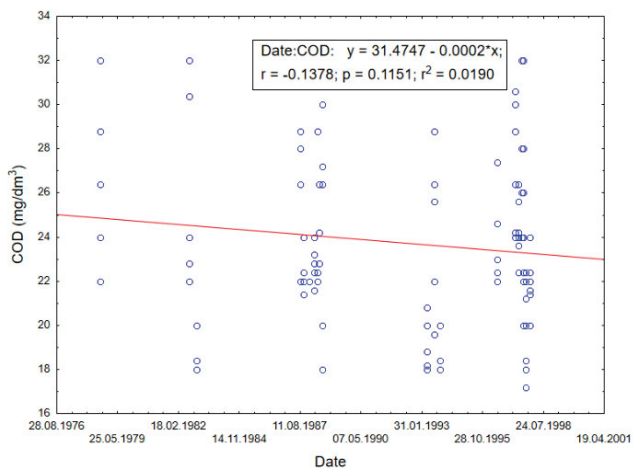


Fig. 6. Time series analysis for COD in Lake Inisko; source: own study

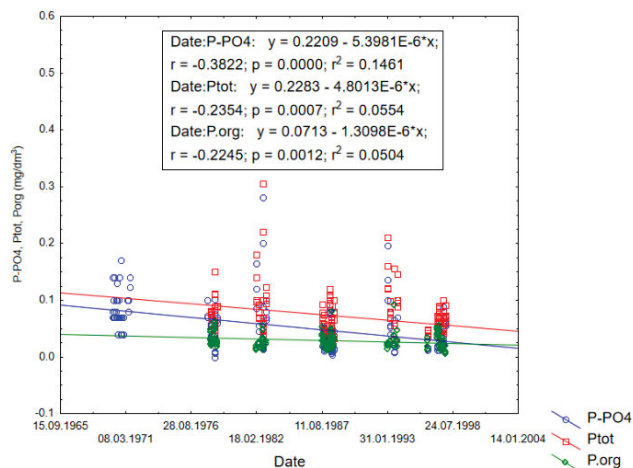


Fig. 9. Time series analysis for phosphorus content in Lake Inisko; source: own study

BOD₅ (Fig. 7), nitrogen forms (Fig. 8), phosphorus (Fig. 9), visibility (Fig. 10) and conductivity (Fig. 11). The analysis showed significant ($p < 0.05$) increase in water temperature in the research period. The accuracy of the fitting was moderate ($r = 0.3767$, $r^2 = 0.1419$). Oxygen content significantly slightly decreased throughout the research period of time ($r = -0.1186$,

$p < 0.05$, $r^2 = 0.0141$). COD non-significantly decreased over the time ($p > 0.05$). Trend for BOD₅ is significantly and highly positive ($r = 0.509$, $p = 0.00$, $r^2 = 0.2591$). Total and organic nitrogen decreased significantly ($p < 0.05$) in their concentration, nitrate nitrogen decreased slightly, and nitrite nitrogen remained relatively similar. All the forms of phosphorus showed negative

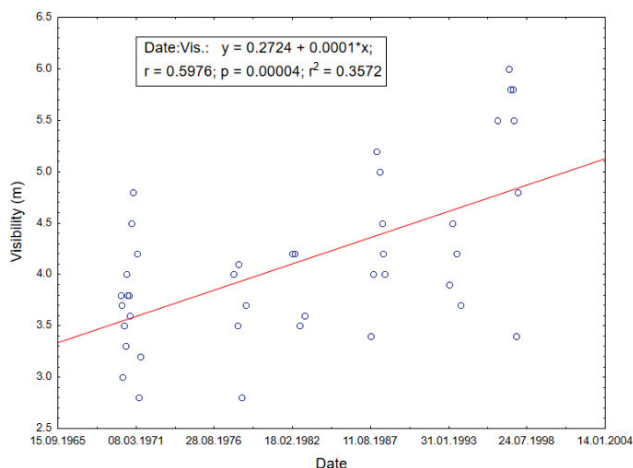


Fig. 10. Time series analysis for visibility in Lake Ińsko; source: own study

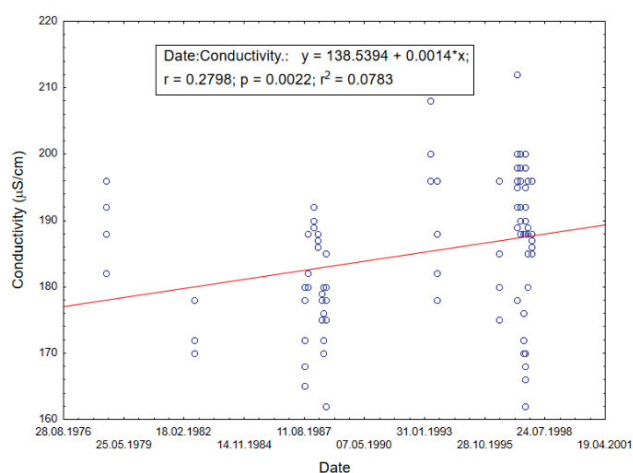


Fig. 11. Time series analysis for conductivity in Lake Ińsko; source: own study

trends ($p < 0.05$). The level of the decrease was the highest for P-PO₄ ($r = 0.3822$). As for total phosphorus and organic phosphorus lowered their contents ($r = -0.2352$ and $r = -0.2245$, respectively). The analysis showed, that visibility increased significantly over the research period ($r = 0.5976$, $p < 0.05$, $r^2 = 0.3572$). Conductivity showed a slight increasing trend in the research period ($r = 0.2796$, $p < 0.05$, $r^2 = 0.0783$).

THE EFFECT OF PHYSICOCHEMICAL PARAMETERS ON THE VOLUME OF VENDACE CATCHES

The analysis of variance inflation factor (VIF) was applied to indicate the more important parameters influencing fish catch, avoiding collinearity between the explaining environmental factors. The following were chosen for PCA analysis: total nitrogen (N_{tot}), N-NO₃, N-NO₂, total phosphorus (P_{tot}), oxygen content and temperature (Fig. 12).

Analysis of the eigenvalues showed that two first axes should be taken into account, since the percent of the variation explained was sufficient (Tab. 3).

The vendace catches during the analysed period were negatively correlated with the total nitrogen content, and, to a lesser extent, with the total phosphorus content, and were also positively correlated with the N-NO₂ and N-NO₃ content.

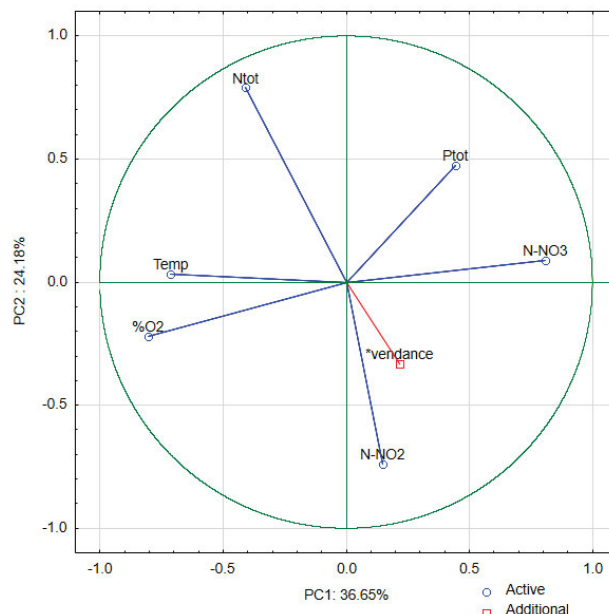


Fig. 12. Biplot of PCA analysis of the data for Lake Ińsko; source: own study

Table 3. Results of PCA analysis

PC no	Eigenvalues	% of the total variance	Cumulated eigenvalues	Cumulated (%)
1	2.199	36.65	2.199	36.6
2	1.451	24.18	3.650	60.8
3	0.910	15.16	4.559	76.0
4	0.786	13.11	5.346	89.1
5	0.404	6.74	5.750	95.8
6	0.250	4.17	6.000	100.0

Source: own study.

Together with the other variables, they accounted for over 60% variability. The information which parameters are the most correlated with the catch volume enables for a new, large set of hydrochemical data with numerous analysed variables, to select those which will be sufficient to create a model of correlations of a satisfactory quality at a lower cost of statistical analyses.

DISCUSSION

Vendace catches recorded in various European lakes are characterised by high fluctuations, which may be related to environmental conditions in the period of reproduction and during stocking [MARJOMÄKI *et al.* 2004], course of annual temperatures [TAPANINEN *et al.* 1998], pressure of predators [HEIKINHEIMO 2001], as well as by the size of spawning school and amount of the stocking material [CZERNIEJEWSKI, WAWRZYŃIAK 2006]. In Lake Ińsko, a significant effect of stocking with this species on vendace catches was observed, as well, although the value of the correlation coefficient ($r = 0.45801$) indicates that aside to stocking, other factors related to the water environment are also important for vendace management in lakes. Due to

varied progression of trophic processes in lakes, currently the vendace yields are typically between 3 and 10 kg·ha⁻¹ [KANGUR *et al.* 2020; SCHMIDT *et al.* 2005]. Also the mean many year vendace yield from waters of Lake Ińsko amounting to 5.64 kg·ha⁻¹ falls in this range. With regard to the classification of vendace lakes in Poland developed by CZERNIEJEWSKI and WAWRZYŃIAK [2006], Lake Ińsko belongs to “good” lakes with the vendace yield in the range of 5.0–10.0 kg·ha⁻¹. It must be emphasised, however, that fishing yields of this species in more than 3/4 reservoirs in Poland (75.4%) are low (up to 5 kg vendace from 1 ha of water surface) [CZERNIEJEWSKI, WAWRZYŃIAK 2006]. High variability of vendace catches over the years in Lake Ińsko (range 0–19.27 kg·ha⁻¹) may result not only from irregular and varied amount of the stocking material of this species introduced in the lake, but first of all from observed changes in the vendace habitat conditions. For example, as reported by MARJOMÄKI *et al.* [2004], changes in the environmental conditions of numerous Finnish lakes resulted in a reduced fishing yield of vendace. Also in Lake Ińsko, significant habitat changes were observed over the years, which were the consequences of eutrophication. Studies revealed that Lake Ińsko, initially mesotrophic, showed an increased trophy in the 80’s and at the beginning of the 21st century, the reservoir is again in the state of mesotrophy.

Generally, lakes are distributed in agricultural plain, which are subjected to intense human activities [ZHOU *et al.* 2022]. Nutrients are emitted from both point and diffuse sources in the human environment and enter aquatic systems via surface runoff, as well as groundwater and atmospheric deposition [PAERL 1997]. The catchment area of Lake Ińsko is partially covered by forests, but also used by agriculture. Intensive agriculture in the 1970s and 1980s contributed to the transport of large loads of nutrients into the lake and the increase of lake trophy [KUBIAK *et al.* 2021]. In addition, in the years 1977–1982, in the lake was intensively caged rainbow trout farming, and the production was about 27 Mg. The load of organic pollution from this farm was estimated at 10–15 thous. of equivalent inhabitants. Moreover, the trophic state of water was undoubtedly affected by the introduction of raw (untreated) municipal waste from the city of Ińsko to the lake [KUBIAK 1996].

Climate change may undoubtedly affect the quality of Lake Ińsko and biomass of vendace. It has been observed that global warming in European lakes may cause an increase in water temperature and the content of nutrients and decrease in oxygen [MOSS *et al.* 2017; STROCK *et al.* 2013]. In oligotrophic whitefish lakes in Sweden, this leads to an increase in the production of vendace [NYBERG *et al.* 2001]. In lakes with more advanced trophies, this may lead to oxygen depletion at the bottom and a significant decrease in recruitment [KARJALAINEN *et al.* 2021; MARJOMÄKI *et al.* 2021] and decrease in vendace catches [ELLIOTT, BELL 2010; KANGUR *et al.* 2020].

Changes of Lake Ińsko trophy may effected on the level of vendace catches. Following high vendace catches in the 60s, a decline in the catches and resources of this fish was observed in 70s and 80s, which lasted even when stocking was performed in the first years of the 21st century. For example, in 2003–2004, vendace represented only 6–7% of total weight of commercial catches on Lake Ińsko. Gradually improving abiotic conditions and stocking performed in subsequent years caused an increase in the proportion of this species above 50% of the fish caught in 2010–2015 [BIERNACZYK *et al.* 2012; authors’ own data]. Similar

impact of eutrophication was noted in some Europeans lakes. In Peipsi Lake (Estonia/Russia), vendace was the main target of commercial fishery until the end of the 1980s, but it dramatically declined thereafter [KANGUR *et al.* 2020]. Similarly, the same decrease in catches of vendace was noted in Finnish lakes: Pyhäjärvi and Puulavesi [HELMINEN, SARVALA 1994; MARJOMÄKI *et al.* 2004], in Swedish lakes (e.g. Lake Mälaren, NYBERG *et al.* [2001]) and English lakes (e.g. Lake Bassenthwaite, ELLIOTT and BELL [2010]). In addition unfavourable environmental conditions in lakes affect the recruitment of subsequent generations of fish [MARJOMÄKI *et al.* 2004; 2021]. This is due to the very low survival of vendace eggs and larvae in spawning grounds, not exceeding 5% in many lakes [KARJALAINEN *et al.* 2021].

A dominant opinion presented in the literature is that oxygen plays the most important role in the formation of ichthyofauna complexes in lakes [PENCZAK 2000; SZCZERBOWSKI 2008], especially for growth of oxygen-loving species [CZERNIEJEWSKI, RYBCZYK 2008]. In Lake Ińsko, however, oxygen was not the main parameter significantly affecting the population size and catches of vendace in this waterbody. This may have been caused by the fact that waters of Lake Ińsko were characterised, in the summer, during intensive vendace growth, by permanent presence of oxygen in bottom waters in the amount of above 4.0 mg O₂·dm⁻³, and water oxygenation was over 30%. This means that Lake Ińsko had good oxygen conditions for vendace growth during the whole study period [CZERNIEJEWSKI, RYBCZYK 2008; ELIOT, BELL 2010].

Temperature is one of important factors of the water environment, which plays a crucial role in ensuring normal course of physiologic processes in the fish body, affecting their behaviour, including their distribution in the reservoir [KEEN *et al.* 2016; MCBRYAN *et al.* 2013]. The maximum water temperature for adult vendace should not exceed 18–19°C [ELLIOTT, BELL 2010]. Vendace has a cold-water thermal window characterised by a metabolic optimum approximately 7–9°C. In Polish waters, intensive feeding of vendace in observed between May and September [CZERNIEJEWSKI, RYBCZYK 2008], although the intensity of feeding and metabolism is reduced at a temperature exceeding 20°C [OHLBERGER 2008]. With regard to this parameter in Lake Ińsko, it may be indicated that it is not a factor limiting the size of vendace population over the years. This may result from high water depth (41.7 m) and volume of this reservoir (65182 thous. m³) (unpublished data IRS Olsztyn) and high oxygen content at the bottom for this species, which makes the fish omit those parts of reservoirs with higher water temperature.

PCA demonstrated that the highest impact in Lake Ińsko on the size of vendace catches was exerted by nitrogen, mainly total nitrogen, and to a lesser extent total phosphorus. A negative effect of various components of total nitrogen is well known. For example, CAMARGO *et al.* [2005] show a negative effect of concentrations of these ions with long-term exposure of susceptible water animals. The major toxic effect of nitrates on fish is conversion of oxygen-carrying pigments (haemoglobin, haemocyanin) to forms unable to carry oxygen (methaemoglobin, methaemocyanin), which may cause higher mortality and a decline in the resources of sensitive organisms [CAMARGO, ALONSO 2006; CHENG *et al.* 2002]. Whereas, RUSSO [1985] indicates that nitrite ions in water are not so very toxic to fish. Higher toxicity seems to be caused by ammonia, whose excess may cause reduced growth of fish and tissue degeneration, immune

suppression and high mortality of water animals [LEMARIE *et al.* 2004; LI *et al.* 2014; SINHA *et al.* 2012]. Thus, knowledge of current changes in total nitrogen in water, including particular nitrogen components, is an important element in the proper use of vendace resources and conducting stocking with this sensitive species.

Also total phosphorus is a factor regulating biological productivity in waters [SCHINDLER *et al.* 2008; WEIGELHOFER *et al.* 2018], which may affect biodiversity and concentration of fish [CHENG *et al.* 2016; SZCZERBOWSKI 2008]. JEPPESEN *et al.* [1997] pointed out that the total fish biomass in lake water increases with an increased level of total phosphorus. However, when total phosphorus reaches the value of 140 µg, the total fish biomass may become reduced [GRIFFITHS 2006]. As for waters in Lake Ińsko, although the above value was not reached in any of the study years, the biomass of the caught vendace was negatively correlated with total phosphorus, which confirms the information of MARCIAK [1970] and MARJOMÄKI *et al.* [2014], that the species is sensitive to increased levels of biogenic elements. This affects not only the state of the fish resources, but also has a significant effect on the vendace body features [CZERNIEJEWSKI, FILIPIAK 2002], and also on the biological and population features of the species [CZERNIEJEWSKI, RYBCZYK 2008; MARJOMÄKI *et al.* 2014].

CONCLUSION

Lake Ińsko belongs to vendace reservoirs, in which the fishing economy according to the fisheries books kept in 1950–2020 was based on fishing vendace, whose share in the catches in some years exceeded 70% of the total fish catches. However, high variability of the vendace catches was recorded (range of fishing yield 0–19.27 kg·ha⁻¹), which results from irregular and varied amount of the stocking material of this species introduced in the lake, and also from progressive changes in the habitat conditions of this fish. Hydrochemistry of Lake Ińsko was analysed in 1970–2010. Waters of this reservoir, initially mesotrophic, were characterised by high vendace catches. Then, in the 80's and 90's, the trophy level increased (eutrophy), and the catches declined. In the last 2 decades, an improvement in the habitat conditions (mesotrophy) has occurred, and the volume of vendace catches increased. As shown by the conducted studies, hydrochemical parameters which have the largest influence on the fish resources and catches include the concentrations of biogenic compounds, mainly total nitrogen, and to a lesser extent total phosphorus. Therefore, development of a vendace plan of fishing management for lakes, based on intensive support in the form of stocking, requires physicochemical studies of water, so as to make the undertaking reasonable from the ecological and economic point of view, and the stocking could give the assumed effect.

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