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RESEARCH ARTICLE

Changes in the trophic state of Lake Niegocin based on physical, chemical, biological, and commercial fisheries data

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Abstract. Changes in the trophic state of Lake Niegocin were characterized based on physical, chemical, and commercial fisheries data. Analysis of nitrogen and phosphorus influx data has shown that the trophic state of the lake can be described as polytrophic for the time period of interest. A significant reduction in the influx of biogenic substances occurred following the construction of a mechanical-biological wastewater treatment plant employing chemical phosphorus precipitation technology. Shortly after the treatment plant went on line, a reduction in the amount of phosphorus and nitrogen was recorded along with an increase in lake water transparency. The changes in physical and chemical parameters presented herein correspond in general with changes in commercial fish catches. Special attention is paid to pikeperch whose yield had increased along with increasing trophic states but then declined once the treatment plant went on line. The paper emphasizes the fact that this species is one of the best indicators of eutrophication in vendace-type lakes.

Keywords: lake trophic state, physical, chemical and biological data, commercial fisheries

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Introduction

The eutrophication of water is a process caused by an increase in mineral nutrients, mainly phosphorus, which regulates biological production and limits the development of algae (Vollenweider 1968, Schindler 1977, Kajak 1979), thus stimulating lake eutrophication, ranging from oligotrophy to eutrophy (Vollenweider 1968, 1976, Carlson 1977, Hickman 1980). In polytrophic and hypertrophic lakes, the key factors are nitrogen and light (Zdanowski 1982).

It is a process that causes far reaching changes within all trophic states, strongly affecting fish populations that grow successively along with higher trophic states from Salmonidae to Cyprynidae (Colby et al. 1972, Hartmann 1977, 1979, Leach et al. 1977, Persson 1991, Zdanowski 1995, Bnińska 1996). Commercial fisheries data can be used to assess the trophic state of lakes and identify the effects of other factors associated with human pressure (Leopold et al. 1986, Bnińska 1985, 1991, Mickiewicz et al. 2003, Wołos and Falkowski 2007).

The aim of the paper is to show changes in lake trophic states and to test the hypothesis that trophic changes, both negative (increases) and positive (decreases), can appreciably influence commercial fish catches and the distribution of fish species considered to be good indicators of particular trophic states. The hypothesis was tested based on multi-year changes in physical, chemical, and biological parameters of Lake Niegocin water as well as commercial fisheries data.

Materials and methods

Study area

Lake Niegocin is part of the Great Masurian Lake System, which has been described in more detail in Wołos et al. (2009). For the purpose of this paper, it is important to remember that a drainage divide runs along the southern edge of Lake Kisajno, which is connected with Lake Niegocin (Mikulski 1966). The location of the divide can change during periods of drought from Lake Przystań to Lake Śniardwy (Bajkiewicz-Grabowska 2008). Lake Niegocin is a large glacial lake with diverse bottom topography including a large number of depressions and expansive mid-lake shallows (Table 1).

Table 1
Limnological characteristics of Lake Niegocin (unpublished Inland Fisheries Institute (IFI) data)

Parameter	
Surface area (ha)	2,600.0
Maximum depth (m)	39.0
Average depth (m)	9.9
Average depth x maximum depth^{-1}	0.25
Volume (thousands m^3)	258,521.6
Maximum length (km)	10.8
Maximum width (km)	4.8
Area of direct basin (km^2)	61.9
Area of total basin (km^2)	323.3
Average annual runoff rate (mln m^3 year^{-1})	69.9
Water exchange percentage per year (%)	27
Retention time (in years)	3.7
Hydraulic load (m year^{-1})	4.0

Lake Niegocin is connected in the north to Lake Kisajno via the Łuczański Canal and with Lake Tajty via the Niegocin Canal. To the south, it is connected to lakes Wojnowo and Boczne, while to the east, it is connected to Lake Grajewko. The lake's direct basin consists mainly of arable land. Its northern end includes the city of Giżycko. Many homes in the towns of Wilkasy and Strzelce and some homes in the towns of Rydzewo and Bystry are located along the lake's shoreline. Ten recreational facilities are also located around the lake as are four camp sites, four beaches with restaurants, and the Main Masurian Port Facility in Giżycko. The mean population density in the lake's direct basin is 26 people kilometer^{-2}; the population of Giżycko is about 31,000; and there is an average of 3,000 tourists day^{-1} (GUS Almanac 2001). For many years, Lake Niegocin served as a dumping site for untreated sewage from the city of Giżycko. In 1994, the city built a mechanical-biological wastewater treatment plant employing chemical phosphorus precipitation technology.

Data collection and treatment

Lake Niegocin's biogenic substance content was calculated using the Giercuszkiewicz-Bajtlik (1990) estimation method. Data on phosphorus and nitrogen sources were obtained from the following institutions: the Regional Inspectorate for Environmental Protection in Olsztyn and its branch in Giżycko, the county governments of Giżycko and Węgorzewo, the National Highway Authority, as well as the County Road Authority in Giżycko. Population and tourist data were obtained from the 2001 GUS Almanac. Calculations were performed using biogenic compound runoff coefficients produced by Giercuszkiewicz-Bajtlik (1990). The calculated content data was compared to results produced by a static model and a hydraulic model (Vollenweider 1968, 1976).

Data acquired at the deepest sampling site on the lake was used to test for changes in physical and chemical parameters. Four more sampling sites were added in 2001. Oxygen content was measured using an oxygen probe recording data every one meter from the bottom of the lake. A Secchi disk was used to assess the transparency of water. Chlorophyll and seston content was determined using water samples collected from the 0-10 m layer. Samples were filtered through glass filters (45 μm), dried in order to obtain a constant mass at 105°C, and then weighed. Information on chlorophyll content in the epilimnion was obtained from a paper by Napiórkowska-Krzebietke and Hutorowicz (2006). A Ruttner sampler was used to obtain water for physical and chemical testing purposes from the following three layers: subsurface (0.5 m), metalimnion (15 m), and bottom (0.5 m above the bottom). Standard analytical methods were then employed (Standard Methods 1992, Hermanowicz et al. 1999). The concentration of phosphate and total phosphorus as well as ammonia nitrogen, iron, and silicate was determined colorimetrically using a Schimadzu UV-1601 spectrophotometer. Total nitrogen and nitrite were determined using an Epoll ECO 20 spectrophotometer. Additional research conducted in the spring and autumn seasons produced even more nitrogen data.

The trophic state of the lake was determined for summer seasons based on measurements of Secchi disk visibility (SD), total phosphorus concentration (P_{tot}), and chlorophyll content (Chl). Carlson's Formula (Carlson 1977) was used to transform the results into the trophic state index (TSI). The oligo-mesotrophic state was characterized by TSI_{SD}, TSI_{Ptot}, TSI_{Chl} values below 40, while values between 40 and 60 were considered moderately trophic (mesotrophic), and eutrophic exceeding 60. The paper includes data obtained from the Institute of Hydrobiology and Water Protection at the Academy of Agriculture and Technology in Olsztyn. The data includes physical and chemical parameters of water for Lake Niegocin calculated in 1978 as well as archival materials from the Inland Fisheries Institute (IFI) in Olsztyn concerning research on lakes Mamry Północne and Niegocin from 1986-89 and 1990-99 (Zdanowski and Hutorowicz 1994, unpublished IFI data).

Commercial fisheries data obtained from Lake Niegocin fisheries logs for the 1967-2006 time period were used to analyze changes in the fish population. The Lake Niegocin commercial fishing was supervised by the Giżycko State Fisheries Cooperative until 1993. The Cooperative was renamed the Giżycko Fisheries Corporation in 1994. The paper makes a distinction between species and stocks indicative of eutrophication processes and those species, which can be described as "indifferent" in the face of environmental changes. Finally, the *Anguilla anguilla* (L.) eel mentioned herein comes exclusively from stocking (Wołos et. al. 2009). Commercial fisheries data (in %) were also analyzed for four consecutive decades (1967-1976, 1977-1986, 1987-1996, 1997-2006) based on the following classification of species: coregonids, littoral species, perch, "large" cyprinids, "small" cyprinids, pikeperch, eel, and others.

Statistical analysis

Change patterns in the physical and chemical parameters of lake water were tested using the nonparametric Mann-Whitney and Kruskal-Wallis statistical tests. A significance level of $P < 0.05$ was used for each test. Two methods were used in the analysis of commercial fisheries data. The first method was used to analyze the catches of selected species. In the case of bream and roach fish body size was also taken into consideration via the use of time series (trends) including polynomials up to the fourth degree with a threshold significance level of $P < 0.05$. Statistically significant polynomials were graphed. In the absence of such polynomials, raw data was graphed instead. The arrows found on commercial fisheries diagrams indicate the year of the construction of the wastewater treatment plant in Giżycko.

Results

Basin influence on the lake

The direct basin of Lake Niegocin was capable of delivering a phosphorus load (0.67 g P m^{-2} $year^{-1}$) three times the critical level and a nitrogen load (4.30 g N m^{-2} $year^{-1}$) twice the critical level in 2000-2001. Its total basin, on the other hand, was capable of delivering a phosphorus load five times the critical level and a nitrogen load four times the critical level (Table 2). The phosphorus and nitrogen loads, however, were three times smaller than that predicted, mainly as a result of reductions in the amount of pollutants being pumped directly into the lake following the

Table 2
Estimated potential phosphorus and nitrogen influx to Lake Niegocin from its direct basin and total basin in 2001-2002

Source	Annual phosphorus load (kg P year^{-1}) direct basin	Annual phosphorus load (kg P year^{-1}) total basin	Annual nitrogen load (kg N year^{-1}) direct basin	Annual nitrogen load (kg N year^{-1}) total basin
Point				82 399
Spatial	3,387	7,437	57,982	148,147
Dispersed (animal husbandry)	12,276	14,985	45,745	56,579
Atmospheric precipitation	1,773	2,297	7,720	38,600
Swimming areas	16	33	314	651
Linear	6	8	16	21
Lake's actual phosphorus and nitrogen loads (g m^{-2} year^{-1})	0.671	1.058	4.299	12.554
Lake's critical nitrogen and phosphorus loads (g m^{-2} year^{-1})	0.098-0.198[1] 0.101-0.205[2]		1.580-3.170[1]	

[1]Vollenweider (1968) based on average depth criteria
[2]Vollenweider (1976) based on hydraulic criteria

construction of a wastewater treatment plant. Phosphorus loads entering the lake as part of sewage decreased almost twentyfold to 0.11 g P m^{-2} year^{-1} in 2000-2001, while nitrogen loads decreased threefold to 3.17 g N m^{-2} year^{-1} relative to forecasts produced for the 1990s. The actual phosphorus and nitrogen loads were 10% and 25% of the lake's total pollution load, respectively.

Oxygen conditions

Lake Niegocin is a dimictic lake where waters mix twice during the year – in the spring and autumn. It is a third degree static-type lake, highly susceptible to the mixing of epilimnion waters during the summer stagnation period. Oxygen content ranged from 6.2 to 16.2 mg dm^{-3} in the surface layer and from 0 to 14.6 mg dm^{-3} in the bottom layer. Reduced oxygen content was observed in the lower strata of the epilimnion and throughout the hypolimnion. Trace amounts of oxygen were always detected in the metalimnion and the hypolimnion. Oxygen content variability along the vertical cross section of the lake was described by a clinograde curve, typical for lakes in an elevated state of eutrophication (Fig. 1).

Supply of biogenic substances

The epilimnion of Lake Niegocin was characterized by a steady supply of phosphorus of approximately 0.200 mg dm^{-3}. The average supply of phosphorus in the bottom layer was 0.360 mg dm^{-3} (Table 3). The largest concentrations of phosphorus in the surface layer (0.456 mg dm^{-3}) and the bottom layer (0.870 mg dm^{-3}) were recorded in Lake Niegocin prior to the construction of the wastewater treatment plant. Phosphate in the epilimnion constituted, on average, 70% of total phosphorus, and in the bottom layer, 90%. An appreciable reduction in phosphorus supply in the surface layer of Lake Niegocin was detected following the construction of the wastewater treatment plant (Kruskal-Wallis Test, H=14.6204, P = 0.0056). Decreasing phosphorus concentrations in the bottom layer were also detected throughout the entire growing season.

Lake Niegocin's supply of nitrogen has normally been high, especially prior to the construction of the wastewater treatment plant (Table 3). The highest levels were recorded between 1986 and 1989, reaching 4.20 mg dm^{-3} in the surface layer and 6.06 mg dm^{-3} in the bottom layer. Once the treatment plant went on line, total nitrogen content decreased more than 50% in both layers. Most of the nitrogen in the

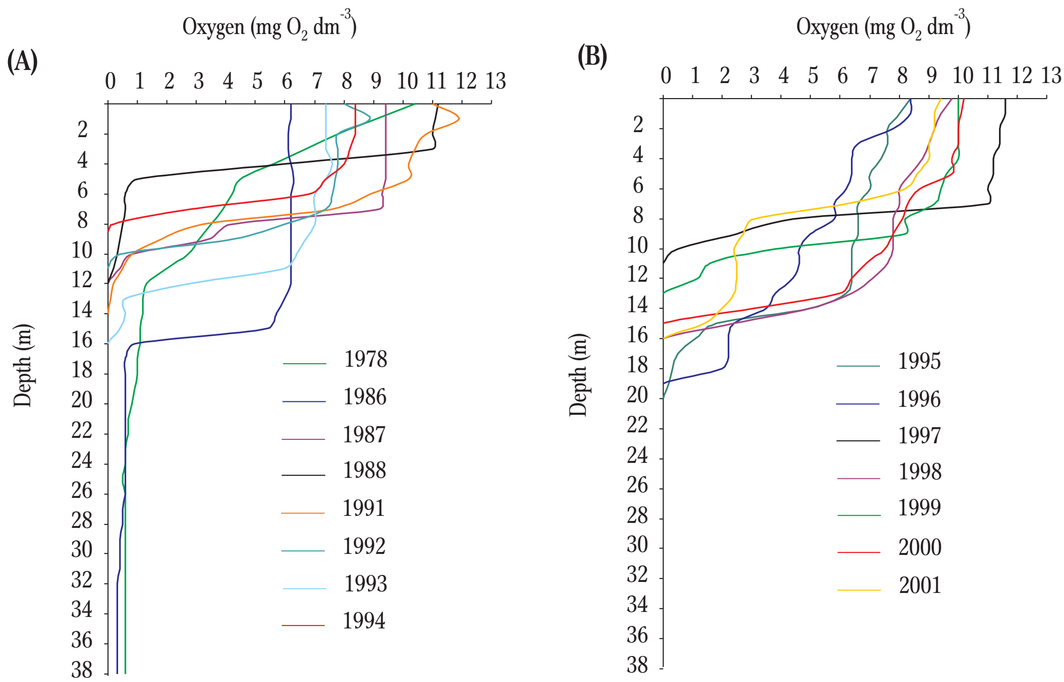

Figure 1. Oxygen conditions during the summer stagnation period from 1978 to 1994 (A) and from 1995 to 2001 (B).

Table 3

Changes in the trophic parameters of water in the surface layer (a) and the bottom layer (b) of Lake Niegocin (sampling site 1)

Parameter		Time period				
		1978[1] (n=7)	1986-1989[2] (n=24)	1991-1994[3] (n=13)	1995-1999[3] (n=15)	2000-2001 (n=13)
Total-P (mg dm^{-3})	a	0.148-0.327	0.184-0.368	0.164-0.456	0.071-0.315	0.057-0.154
	b	0.218-0.521	0.200-0.870	0.244-0.680	0.124-0.560	0.095-0.470
PO_4-P (mg dm^{-3})	a	0.112-0.320	0.057-0.330	0.052-0.411	0.012-0.196	0.009-0.108
	b	0.185-0.550	0.114-0.840	0.052-0.658	0.074-0.449	0.054-0.422
Total-N (mg dm^{-3})	a	1.45-2.18	1.56-4.20	0.81-2.59	0.53-0.79	0.89-2.15
	b	1.54-2.80	1.46-6.06	0.87-3.84	0.49-2.39	1.20-3.27
NO_3-N (mg dm^{-3})	a	0.10-0.34	0.03-0.40	0.06-0.29	0.0-0.11	0.0-0.13
	b	0.12-0.61	0.05-0.57	0.06-0.32	0.0-0.43	0.0-0.63
NO_2-N (mg dm^{-3})	a	0.002-0.108	0.0-0.022	0.0-0.023	0.001-0.023	0.0-0.031
	b	0.0-0.020	0.0-0.180	0.0-0.021	0.0-0.023	0.0-0.035
NH_4-N (mg dm^{-3})	a	0.0-0.80	0.04-0.57	0.04-0.45	0.06-0.41	0.05-0.13
	b	0.08-1.27	0.04-2.96	0.02-1.97	0.06-2.40	0.09-1.71
Secchi disk visibility (m)		1.7-3.5	0.5-4.0	0.9-3.7	1.5-5.0	1.8-4.5
Seston content (mg d.m. dm^{-3})		-	0.2-11.1	0.4-9.9	0.6-6.6	1.2-6.0
COD_{Mn} (mg O_2 dm^{-3})		16.0-19.2	9.0-24.9	6.4-15.4	1.6-19.2	10.4-14.1
Chlorophyll content (mg m^{-3}) [4]		-	1.3-62.3	2.9-93.9	1.7-36.2	3.8-46.5

[1]archival data from the ART Institute of Hydrobiology and Water Protection in Olsztyn
[2]Zdanowski and Hutorowicz (1994)
[3]archival material from the IFI Department of Hydrobiology in Olsztyn
[4]Napiórkowska-Krzebietke and Hutorowicz (2006)

epilimnion came from organic compounds. In the summer, inorganic nitrogen (nitrate, nitrite, ammonia) constituted about 25% of total nitrogen content. The key driver of changes in total nitrogen content in the bottom layer was ammonia nitrogen, which made up about 80% of total nitrogen content (Table 3). Prior to the construction of the wastewater treatment plant, ammonia nitrogen content did not exceed 2.96 mg dm^{-3} while in recent years it has been at 1.71 mg dm^{-3}. A high concentration of ammonia in the bottom layer indicates a high level of eutrophication of the lake. The same is true of phosphate being released from lake bottom deposits.

The open water zone across Lake Niegocin is rather uniform in terms of nitrogen and phosphorus supply with the exception of the sewage influx site. In 1978, total phosphorus, phosphate, total nitrogen, and ammonia nitrogen levels in the surface layer were much higher before the wastewater treatment plant went on line (data from 1995-1999 and 2000-2001).

Water transparency

Lower water transparency was recorded in the lake during the summer period with an average of 1.5 m. The water had been much less transparent (1 m or less) prior to the construction of the wastewater treatment plant compared to transparency measured after the year 2000 (at least 1.8 m). Suspended material content reached 6.0 mg d.m. dm^{-3} and chemical oxygen demand (COD_{Mn}) reached 14.1 mg O_2 dm^{-3} after the year 2000. It has been shown that water transparency has increased over 1.0 m in recent years (Kruskal-Wallis, H=15.3566, P = 0.0040). Changes in water transparency have corresponded with less expansive algal blooms and decreased concentration of chlorophyll (46.5 mg m^{-3}) during the same period of time (Table 3). Appreciable differences in water transparency, seston content, and chemical oxygen demand were not detected between the various sampling sites. Changes in water transparency in the lake tended to be more related to seston content than chlorophyll content. Seston content in the epilimnion of Lake Niegocin explained 71% of changes in transparency ($r^2 = 0.706$, $P < 0.001$), while chlorophyll content explained 46% of changes in transparency ($r^2 = 0.456$, $P = 0.001$). No correlation between phosphorus supply and chlorophyll content was determined.

Trophic state

The value of TSI_{SD} ranged from 42 to 62 and was characteristic of mesotrophic and eutrophic waters. The phosphorus index TSI_{TP} ranged from 67 to 90 and the chlorophyll index TSI_{Chl} ranged from 67 to 71, and were both characteristic of an eutrophic state. The lake's water has been shown to be less fertile in recent years, that is following the construction of the wastewater treatment plant.

Trends of commercial fish catches

Commercial fisheries data indicates that the following species of fish were present in the lake from 1967 to 2006: vendace, *Coregonus albula* (L.), common whitefish, *Coregonus lavaretus* (L.), pike, *Esox lucius* L., tench, *Tinca tinca* (L.), crucian carp, *Carassius carassius* (L.), perch, *Perca fluviatilis* (L.), bream, *Abramis brama* (L.), roach, *Rutilus rutilus* (L.), white bream, *Abramis bjoerkna* (L.), pikeperch, *Sander lucioperca* (L.), eel, smelt, *Osmerus eperlanus* (L.), and bleak *Alburnus alburnus* (L.). The highest catches – over 80 tons – were recorded in 1967, 1975, 1977, 1980, 1984, and 1988. The lowest catch was recorded in 2006 – under 20 tons. The lake's commercial fish catch across all species is on the decline, reaching its lowest level towards the end of the time period of interest (Fig. 2). Vendace catch indicates a complete disappearance of this species from the lake at the very beginning of the research period (Fig. 3). Catch of common whitefish has fluctuated quite a lot, however, a marked increase has been observed following the construction of the wastewater treatment plant (Fig. 4). Pike catch has been on the decline in Lake Niegocin since the 1970s with just a small spike since 1997 (Fig. 5). This may

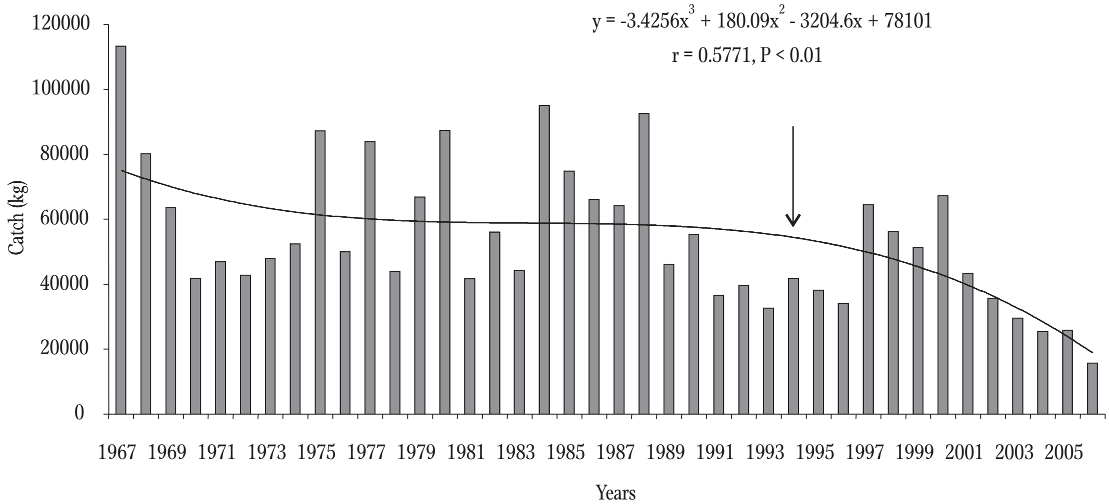

Figure 2. Total commercial fish catches from 1967 to 2006 in Lake Niegocin. The arrow denotes wastewater treatment plant going on line.

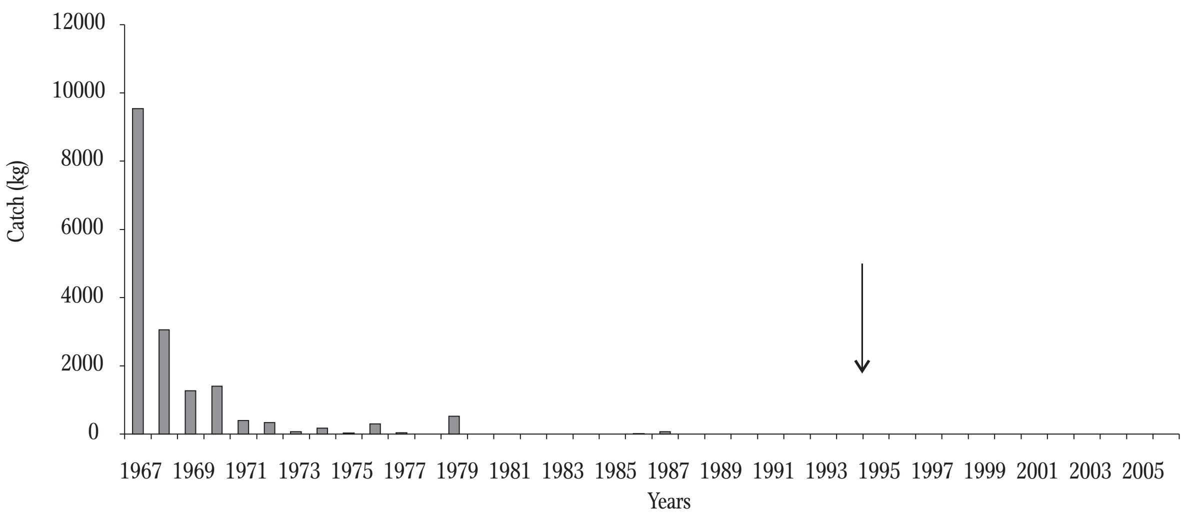

Figure 3. Commercial vendace catches from 1967 to 2006. The arrow as in Fig. 2.

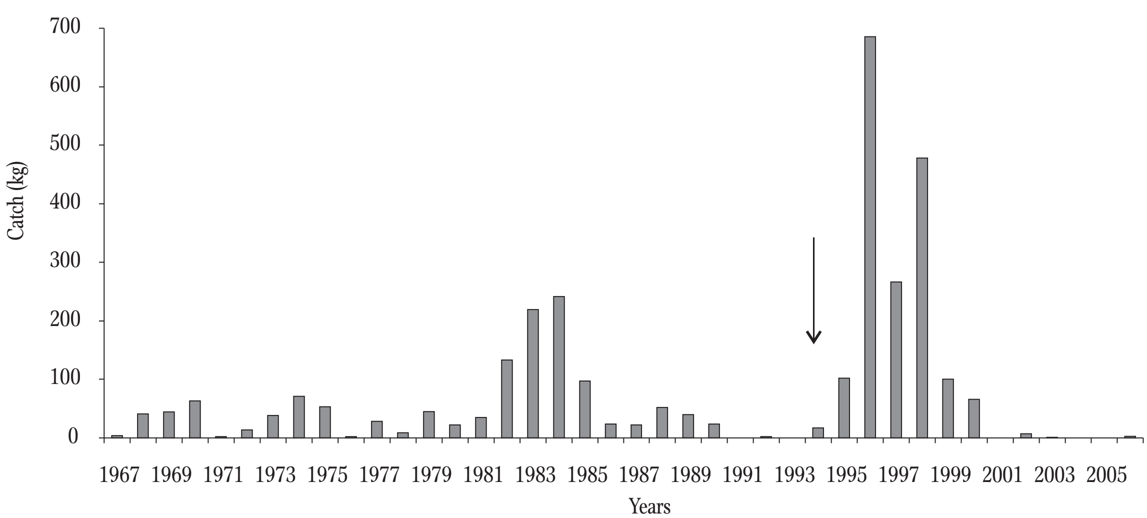

Figure 4. Commercial common whitefish catches from 1967 to 2006. The arrow as in Fig. 2.

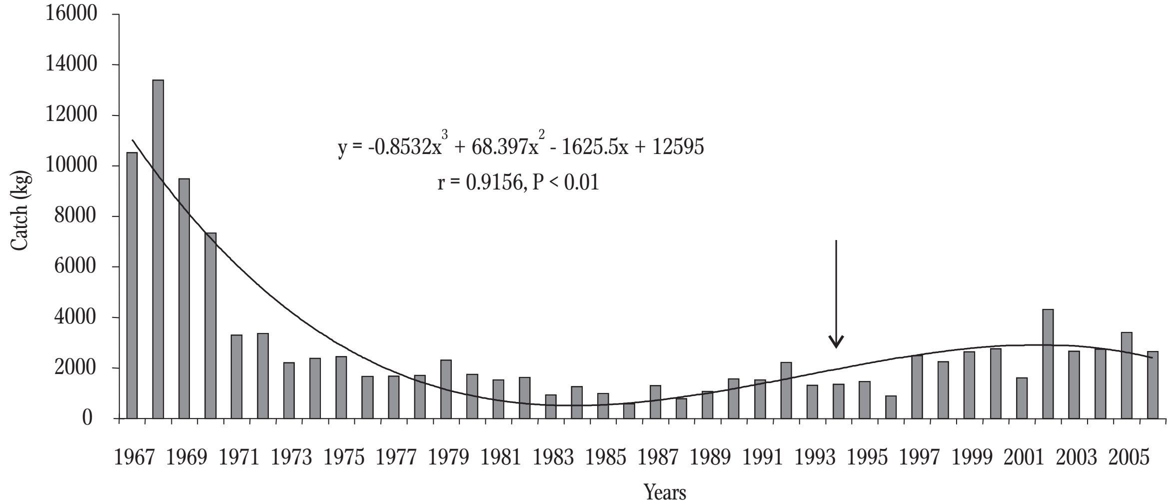

Figure 5. Commercial pike catches from 1967 to 2006. The arrow as in Fig. 2.

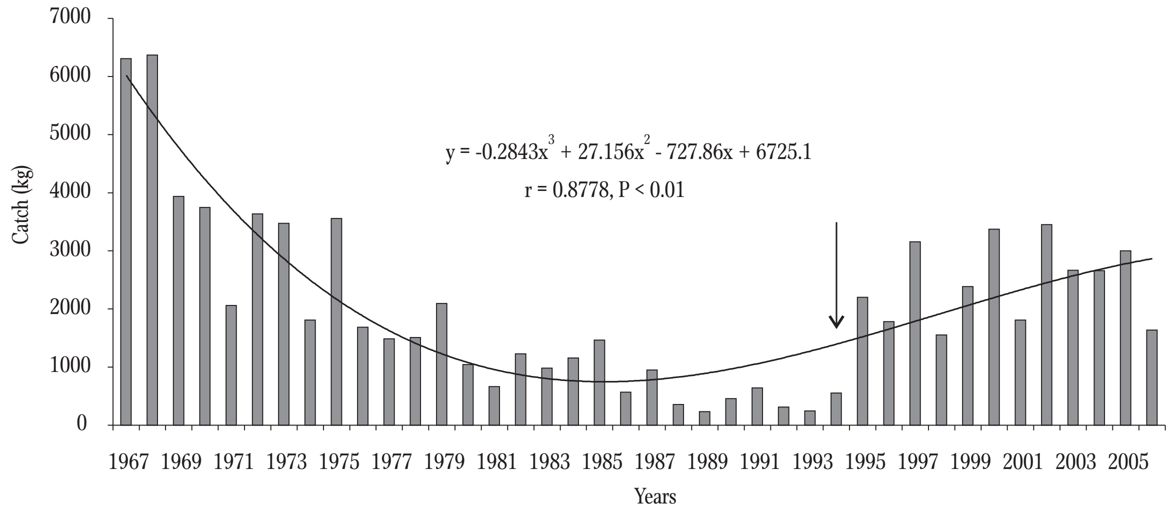

Figure 6. Commercial perch catches from 1967 to 2006. The arrow as in Fig. 2.

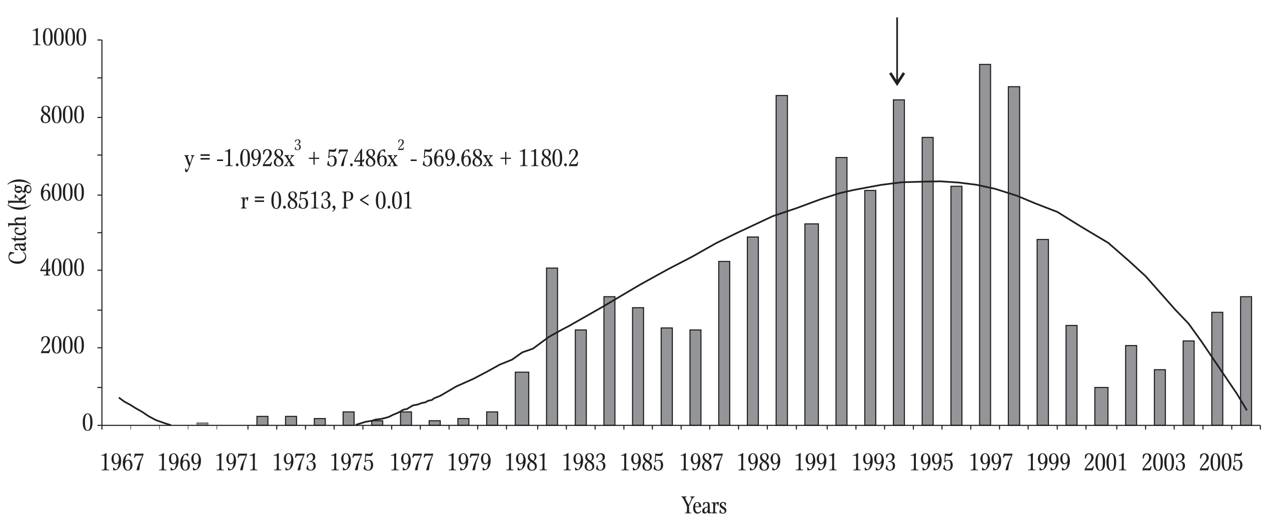

Figure 7. Commercial tench catches from 1967 to 2006. The arrow as in Fig. 2.

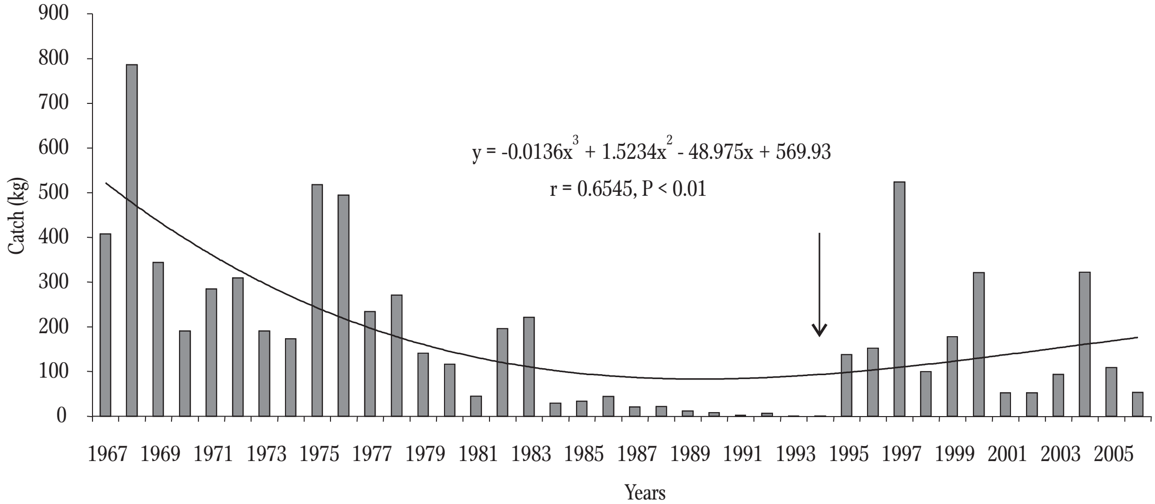

Figure 8. Commercial pikeperch catches from 1967 to 2006. The arrow as in Fig. 2.

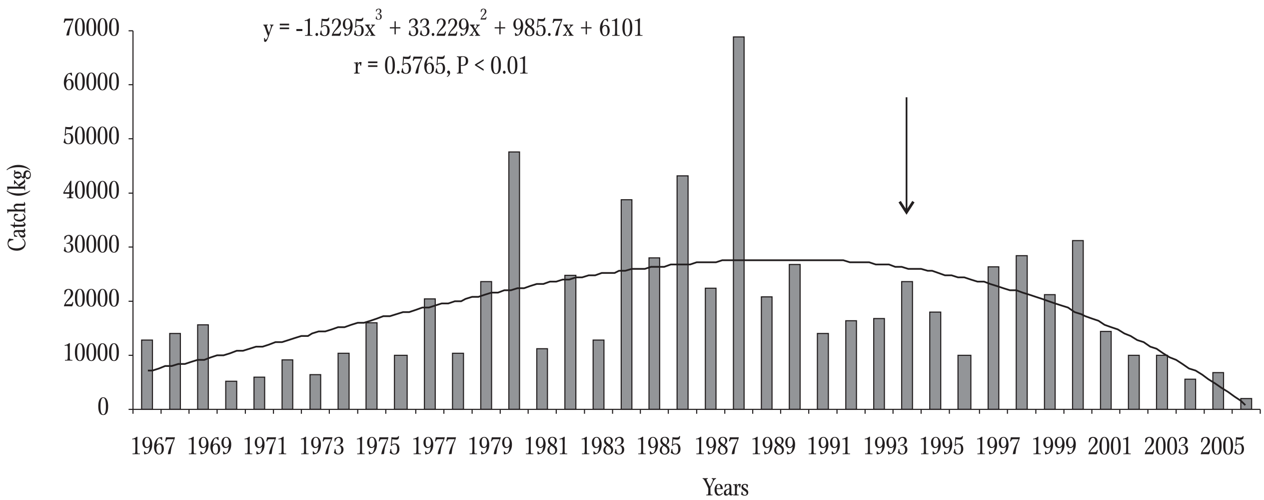

Figure 9. Total commercial bream catches from 1967 to 2006. The arrow as in Fig. 2.

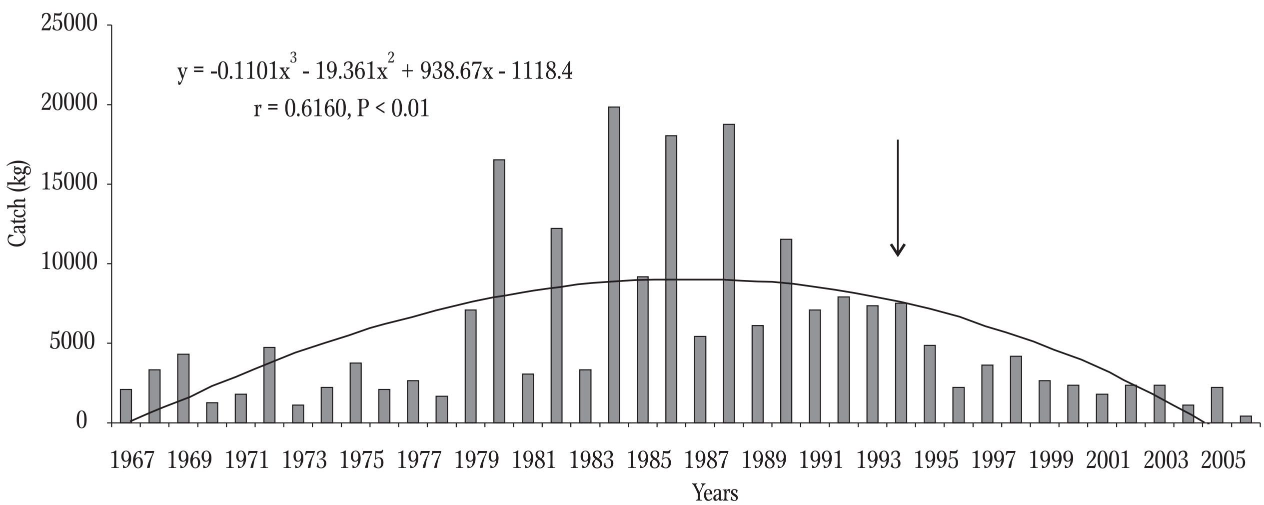

Figure 10. Commercial large bream catches from 1967 to 2006 (large bream – fish with body weight above 1.0 kg). The arrow as in Fig. 2.

be partly the result of improved water quality since the construction of the wastewater treatment plant but another factor may be the fact that the lake has been systematically stocked with pike since 1995. Perch catch has mirrored pike yield. Both species of fish experienced a decrease in catches in the 1970s and an increase since 1995 (Fig. 6). The increase has been more clear cut in the case of pike. On the other hand, pikeperch catch increased beginning in the 1980s and then began to decrease in 1998 (Fig. 7). Tench catches decreased throughout the time period in question until 1994 when it began to resurge (Fig. 8). Bream catches in Lake Niegocin tended to rise in the 1980s and then began to drop, reaching a minimum in 2006 (Fig. 9). The catch of both large and midsize bream (Figs. 10, 11) has been on the decline since the early 1990s. Small bream catch (Fig. 12), however, has increased in recent years. Roach catch has been steadily decreasing (Fig. 13) with the exception of large roach catch, which does not exhibit a meaningful trend (Fig. 14). Small roach catch has been decreasing and remained in decline at the end of the time period of interest (Fig. 15). White bream yield in Lake Niegocin peaked in the late 1990s, only to be followed by another decline in the years since (Fig. 16).

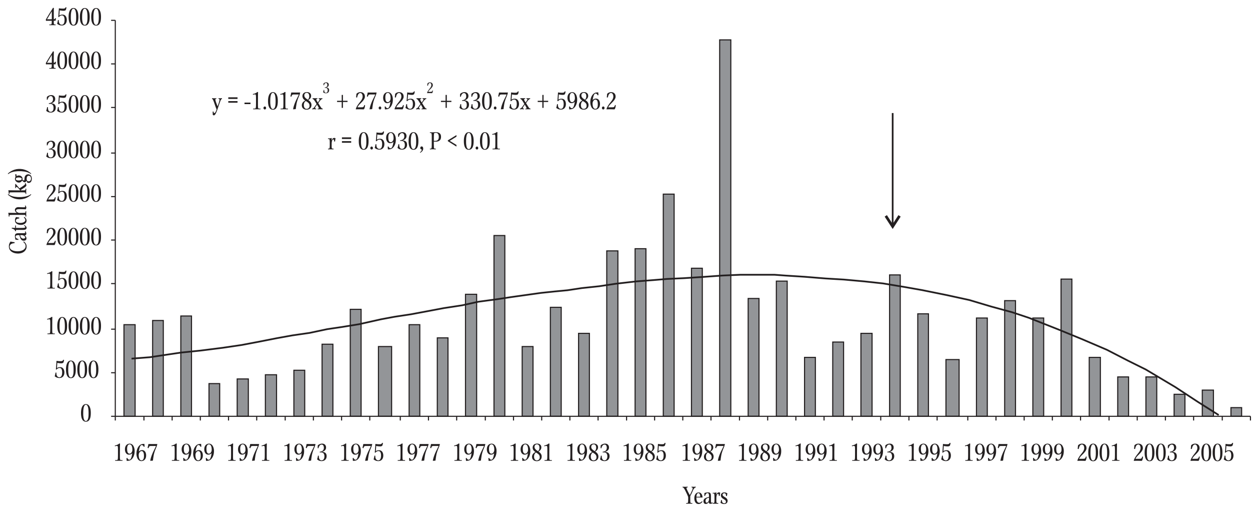

Figure 11. Commercial medium-size bream catches from 1967 to 2006 (medium-size bream – fish with body weight 0.5-1.0 kg). The arrow as in Fig. 2.

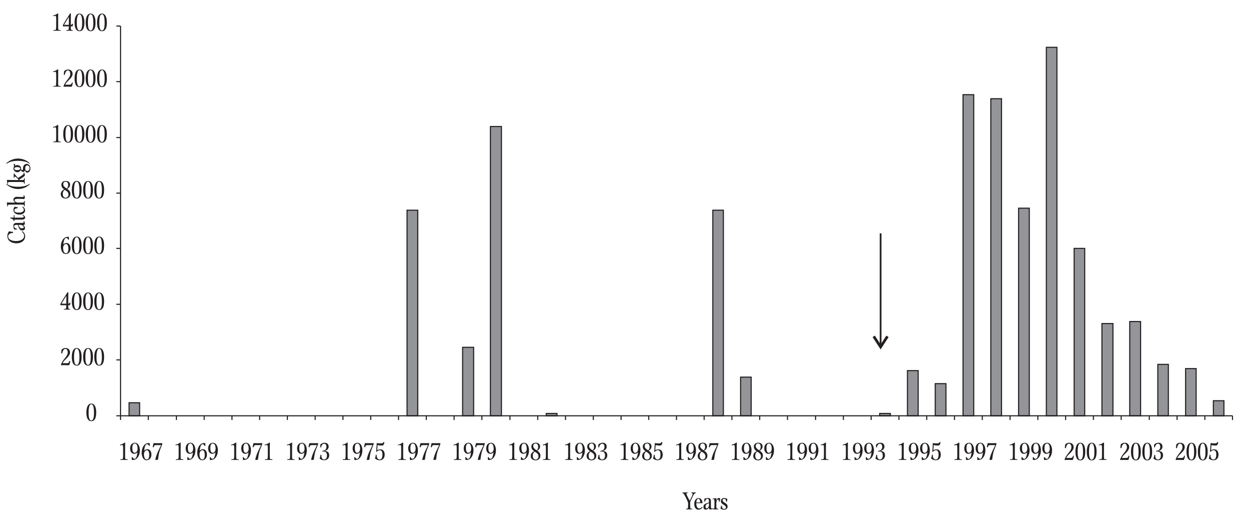

Figure 12. Commercial small bream catches from 1967 to 2006. The arrow as in Fig. 2.

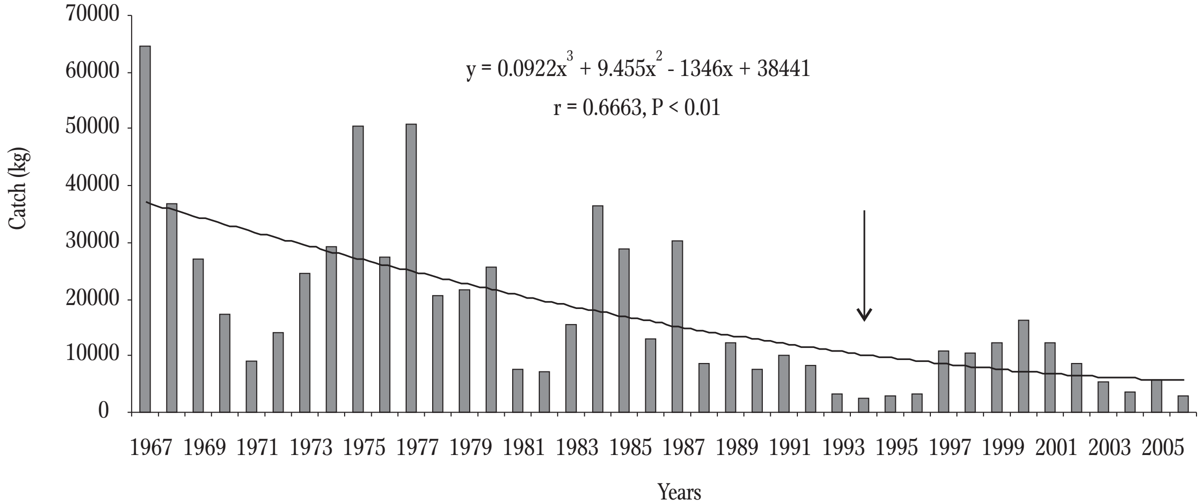

Figure 13. Total commercial roach catches from 1967 to 2006. The arrow as in Fig. 2.

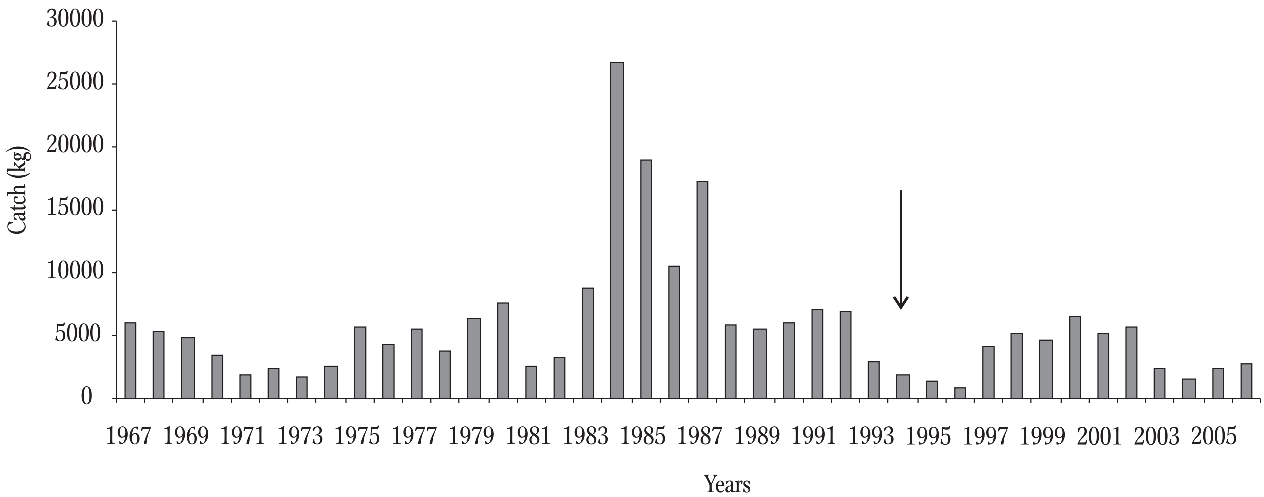

Figure 14. Commercial large roach catches from 1967 to 2006. The arrow as in Fig. 2.

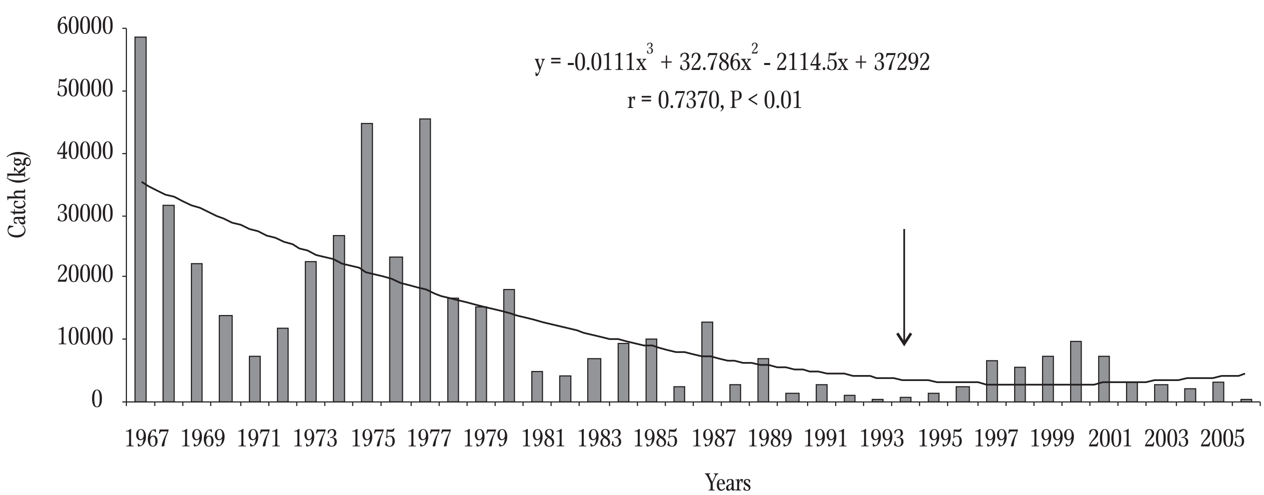

Figure 15. Commercial small roach catches from 1967 to 2006. The arrow as in Fig. 2.

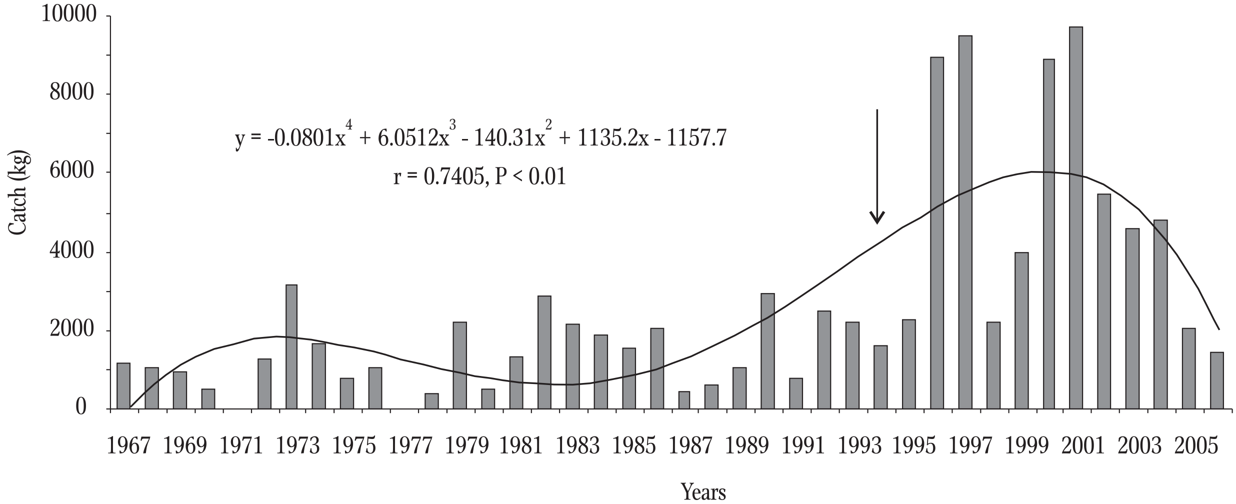

Figure 16. Commercial white bream catches from 1967 to 2006. The arrow as in Fig. 2.

Changes in composition commercial fish catches

Commercial fish catches were dominated by small cyprinids (Table 4) from 1967 to 1976 and then again from 1997 to 2006. The second most common type of fish caught were large cyprinids. From 1987 to 1996, such species made up as much as 58.7% of the lake's catches. The largest number of coregonids were caught from 1967 to 1976. However, their share of total catch was only 2.7% with pikeperch catch at only 0.2% of total catch. Pikeperch catches began to increase in the years that followed with a peak at 12.6% from 1987 to 1996. Perch and littoral species catches stood at 5.8% and 9.6%, respectively, from 1967 to 1976, and began to decline in the years that followed. Their catches rose again during the most recent study period to 6.2% (perch) and 7.1% (littoral species).

Discussion

Lake Niegocin has been the subject of ongoing hydrobiological, ichthyological, and fisheries research for a number of years (Gliwicz et al. 1980, Giercuszkiewicz-Bajtlik and Głąbski 1981, Zdanowski et al. 1984, Giercuszkiewicz-Bajtlik 1990, Zdanowski and Hutorowicz 1994, Czerwiński and Wołos 2001, 2004, Napiórkowska-Krzebietke

Table 4

Selected fish species and groups of species as a percentage of total catch from 1967 to 2006

Species/groups of species	1967-1976 (%)	1977-1986 (%)	1987-1996 (%)	1997-2006 (%)	1967-2006 (%)
Coregonids	2.7	0.2	0.2	0.2	0.9
Littoral species	9.6	2.4	2.9	7.1	5.5
Perch	5.8	1.9	1.6	6.2	3.8
"Large" cyprinids	22.9	50.6	58.7	32.9	41.1
"Small" cyprinids	43.9	25.5	14.1	38.8	30.8
Pikeperch	0.2	2.7	12.6	9.3	5.4
Eel	10.8	16.1	9.2	5.4	11.0
Other	4.1	0.6	0.7	0.1	1.5

and Hutorowicz 2006). Researchers observed mass vendace mortality (Zachwieja 1966), worsening hatching conditions, declining habitat quality of herbivorous fish, as well as increased brood and hatchling mortality of a number of species of fish (Zakęś and Pyka 1990). Other trends were also observed such as a general decline in fish catches including that of tench (Zakęś and Pyka 1990), pike (Wołos 1988), and perch (Wołos and Szlażyńska 1988), this being the result of progressive eutrophication and pollution.

Lake Niegocin was considered to be one of Poland's most polluted lakes, primarily because of the raw sewage that was being dumped into the open waters of the lake. The phosphorus (2.73 g P m^{-2} $year^{-1}$) and nitrogen (9.59 g N m^{-2} $year^{-1}$) loads delivered to the lake at the time by far exceeded acceptable levels for lake water (Giercurszkiewicz-Bajtlik and Głąbski 1981, Giercuszkiewicz-Bajtlik 1990, Zdanowski and Hutorowicz 1994). As a result, the lake became "saturated" with phosphorus and nitrogen with average spring concentrations of 0.300 mg P_{tot} dm^{-3} and 2.5 mg N_{tot} dm^{-3}, respectively. Based on criteria established by Zdanowski (1982), this classified the lake as polytrophic.

Poor water quality in Lake Niegocin was, first of all, the result of poor sanitary conditions: extensive bacterial plankton, heterotrophic bacteria including excrement bacteria *Escherichia coli* and excrement streptococci, as well as filiform and yeast-type fungi (Niewolak 1989). Other indicators of poor water quality were lack of oxygen in the metalimnion and the hypolimnion (Zdanowski et al. 1984, Zdanowski and Hutorowicz 1994), low transparency of water (approx. 1.0 m), extensive presence of phytoplankton including cyanophytes (Spodniewska 1978, 1979), lack of oxygen and the presence of hydrogen sulfide in the hypolimnion, rapid increases in the summertime concentrations of biogenic compounds (phosphate, ammonia nitrogen) in bottom strata, and increasing water salinity (Zdanowski et al. 1984, Zdanowski and Hutorowicz 1994).

A low nitrogen to phosphorus ratio (N/P) during the summer indicated that nitrogen was a limiting factor in the development of algae. The ratio had been roughly 7 prior to the construction of the wastewater treatment plant. This situation is characteristic of polytrophic and polluted lakes (Forsberg et al. 1978, Zdanowski 1982). At an N/P ratio of less than 10, an extensive presence of cyanophytes can be expected to develop, especially those adapted to binding free atmospheric nitrogen dissolved in water. A modern wastewater treatment plant was put on line in 1994, featuring chemical phosphorus precipitation technology. This significantly reduced the amount of phosphorus-bearing sewage flowing into the lake – by about 90% or 0.11 g P m^{-2} $year^{-1}$. Nitrogen load was reduced 75% or 3.17 g N m^{-2} $year^{-1}$. This reduction in the lake's phosphorus and nitrogen levels, as seen in the physical and chemical data tables presented herein, was able to cut the rate of eutrophication in the lake. The lower eutrophication rate can be discerned from decreasing phosphorus and nitrogen levels in the lake's epilimnion as well as increasing transparency of water.

Analysis of commercial fisheries data has shown unequivocally that these changes were generally in agreement with an eutrophication-based model of change described by Colby et al. (1972) and Hartmann (1977, 1979). Considering the entire 40-year period of interest (1967-2006), "large" and "small" cyprinids accounted for about 72% of commercially caught fish while coregonids accounted for only 0.9%, on average. Littoral species accounted for 5.5%, perch 3.8%, and pikeperch 5%. Any analysis of the types of species caught in Lake Niegocin must include the wastewater treatment plant built in Giżycko, which has had a clearly positive impact on selected physical, chemical, and biological characteristics of the lake. The plant has also had a positive impact on the actual number of fish present in the lake. While perch had accounted for only 3.8% over the 40 years in question, it increased to 6.2% during the last decade of the four decade research period. The same is true of littoral species, which increased to 7.1% during the same decade. The most symptomatic, however, was the trend exhibited by pikeperch. The fish accounted for only 0.2% during the first decade of the four decade research period, 2.7% during the second decade, 12.6% during the third decade, and

9.3% during the fourth decade. It was during the fourth decade that the wastewater treatment plant went on line.

Trends in commercial fish catches were consistent with the eutrophication model, which applies to vendace, pike, perch, tench, and pikeperch. Catches of less valuable fish such as bream and roach have tended to decrease, which may be explained primarily by lower fishing quotas driven by lower market prices. Another factor may be increased cormorant activity (Krzywosz 2003), something that affects commercial fish catches nationwide (Wołos et al. 2007). The recent increase in pike catches can be attributed to the combined effect of the new wastewater treatment plant as well as increased fish stocking. Perch catch has followed a similar trend with a sudden jump in 1996, which was most certainly a result of the wastewater treatment plant going on line. Water transparency also increased as measured using a Secchi disk. The most symptomatic trend is that of commercially harvested pikeperch, which made up as much as 12.6% of total fish catch at its peak. The construction of the wastewater treatment plant and the resulting increase in the transparency of water led to a gradual decrease in pikeperch catches. Persson et al. (1991) demonstrated that in the process of ecological succession, when affected by eutrophication, percids exhibit two maxima: 1) perch in lakes of average productivity, and 2) pikeperch in lakes of high productivity. Wołos and Bińska (1998) used 25 lakes to show a similar relationship between vendace and pikeperch. A symptomatic relationship between vendace and pikeperch was also noted by Wołos and Falkowski (2007) in the case of the vendace-type Lake Lubie. The lake is located along the Drawa River, which has for years served as a sewage dumping ground for two towns located upstream of the lake. This led to the complete disappearance of vendace in the lake and a significant increase in pikeperch catch. The construction of the wastewater treatment plant had a pronounced effect on water quality in Lake Lubie. The pikeperch population completely disappeared as a result of the lake's process of self-purification. It was replaced by a large population of vendace. Jeppesen et al. (2005a) used eight Danish lakes to show the positive effects of a reduced phosphorus load on the fish population in the lakes. The yield to effort ratio decreased in the case of cyprinids such as bream and roach fish and increased in the case of fish such as perch, pike, and rudd. These conclusions were confirmed by Jeppesen et al. (2005b) where 35 lakes were used to show the presence of the process of oligotrophication. In 82% of the lakes, total fish biomass decreased with decreasing phosphorus. In 80% of the lakes, the percentage of predatory species, characteristic of lower trophic levels, increased.

Lake Niegocin tends to retain pollutants much longer than Lake Lubie. For this reason, the process of reducing the amount of biogenic substances and the positive changes that normally follow, including the restoration of a large vendace population, will take much longer but are highly likely to occur.

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Streszczenie

Zmiany trofii jeziora Niegocin na podstawie wskaźników fizyko-chemicznych, biologicznych i rybackich

Jezioro Niegocin usytuowane w kompleksie Wielkich Jezior Mazurskich należy do zbiorników szczególnie cennych z przyrodniczego, rekreacyjnego i gospodarczego punktu widzenia, a jednocześnie przez wielolecia charakteryzowało się skrajnie niekorzystnymi warunkami środowiskowymi. W pracy założono, że zmiany troficzne wód jeziora można scharakteryzować zarówno na podstawie zmian wskaźników fizyko-chemicznych, biologicznych, jak i odłowów gospodarczych ryb. Przeprowadzone analizy dopływu azotu i fosforu do jeziora oraz zmian parametrów fizyko-chemicznych (tlen, przezroczystość wody, chlorofil, seston, utlenialność ($ChZT_{Mn}$), fosforany i fosfor całkowity, azot amonowy, azot całkowity i azotyny) wykazały, że w całym badanym okresie trofia jeziora Niegocin była bardzo wysoka, kwalifikując zbiornik jako politroficzny. W jeziorze Niegocin, które przez wielolecia podlegało procesowi przyspieszonej eutrofizacji, nastąpiła radykalna redukcja dopływu biogenów i innych związków chemicznych po oddaniu do użytku w listopadzie 1994 r. w Giżycku mechaniczno-biologicznej oczyszczalni ścieków z chemicznym strącaniem fosforu. W wyniku oddziaływania tej oczyszczalni w bardzo krótkim przedziale czasowym nastąpiła w wodach jeziora redukcja zawartości fosforu i azotu, przy jednoczesnym wzroście przezroczystości wody. Przedstawione w pracy zmiany parametrów fizyko-chemicznych i biologicznych na ogół korespondowały ze zmianami w odłowach gospodarczych gatunków, a także wyodrębnionych grup gatunków wskaźnikowych dla procesu eutrofizacji. Symptomatyczne były zmiany odłowów koregonidów, które zanikły całkowicie z odłowów gospodarczych już na początku analizowanego 40-letniego okresu (1967-2006). Modelowy przebieg miały także tendencje odłowów gatunków litoralowych, okonia, a także – na co zwrócono w pracy szczególną uwagę – sandacza, bowiem w przypadku jeziora Niegocin mieliśmy do czynienia z prawdziwą eksplozją populacji tego gatunku. Podkreślono, że w jeziorach sielawowych właśnie sandacz jest jednym z najlepszych gatunków wskaźnikowych dla zachodzącego procesu eutrofizacji, zwracając przy tym uwagę, że już w kilka lat po uruchomieniu w Giżycku oczyszczalni ścieków odłowy sandacza zaczęły gwałtownie spadać, głównie ze względu na wzrastającą przezroczystość wody.