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Hydroacoustical parameters of fish in reservoirs with contrasting levels of eutrophication

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Abstract

Hydroacoustical estimation of fish abundance and distribution is performed in three reservoirs that are characterised by different levels of eutrophication. The Biosonics 101 dual beam echosounder with a frequency of 420 kHz and the ESP software for acoustical data analyses are used. A clear dependence between fish density and the level of eutrophication is observed. In the mesotrophic Solina reservoir, fish abundance is over an order of magnitude lower than that in the eutrophic Dobczyce and Sulejów reservoirs. Fish length distributions have different shapes in the three reservoirs, which indicates the changes in fish size structure due to eutrophication; however, the mean target strength of fish does not differ significantly. These results suggest that hydroacoustically collected data may help to assess the ecological state of inland waters and may be used together with other methods in monitoring the water quality.

Keywords: Hydroacoustics; Eutrophication; Fish stocks; Reservoirs; Water quality

1. Introduction

Eutrophication of inland waters, which leads to fast deterioration of water quality and to the commonly observed phytoplankton blooms (Tarczyńska et al., 2001), is a worldwide problem for the managers of water resources. If sustainable management and restoration of aquatic ecosystems is to be successful, it is important to have cost-effective methods for reliable, large scale monitoring of water quality. New technology has an increasing role to play in the classification and management, and methodologies for classification and evaluation of lake state should be developed (see requirements of the new Water Framework Directive).

Classification schemes for standing waters have been a subject of research for over a century. The major focus of most research has been the trophic status, which is principally determined by phosphorus and nitrogen. However, it is well known that the concentrations of nutrients in reservoirs undergo natural fluctuations dependent on the physical, chemical and biological characters of their watersheds. This leads to significant difficulties in sampling, measurement, evaluation and classification of lakes. One of the major problems is that the trophic parameters are determined from point measurements, while in fact they are changing within the water body both horizontally and vertically. Thus, point measurements are not always representative of the trophic state of the whole ecosystem of reservoir or lake. Carlson (1977) has attempted to develop a universal trophic state index for lakes that could be calculated on the basis of any of several parameters, such as Secchi disk transparency, chlorophyll *a* or total phosphorus, thus, that would retain the expression of the diverse aspects of the trophic state, yet still could have the simplicity of a single parameter index. However, comparatively high fluctuations of the index, which are dependent on the parameter used for calculations, and high seasonal sensitivity have limited its routine application.

Changes in nutrient loading result in changes in community structure at each trophic level including fish. To quantify such changes, numerous indices have been developed, see review by Washington (1984), but their validity has been questioned, as contrasting results have been obtained for relationships between species richness and trophic state. Classification using various taxonomic groups, or assemblages from specific habitats have encountered difficulties, because such indices often reflect local conditions rather than

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Table 1
Characteristics of the reservoirs under study

Reservoir	State of eutrophication	Total phosphorus (µmg dm^{-3})	Retention time (month)	Area (ha)	Volume (10^6 m^3)	Mean depth (m)	Maximum depth (m)
Solina	Mesotrophic	6	6	2105	472	22	65
Dobczyce	Eutrophic	93	4	1120	127	11	35
Sulejów	Highly eutrophic	366	1	2200	75	3	10

the quality of the water as a whole. Classification schemes based upon phytoplankton and zooplankton, or zoobenthos, while offering probably the most directly relevant information to water managers as related to the whole water column, have limited usefulness due to the complexity of interpretation and difficulties in separating natural variation from those caused by the impact of man. The classification of standing water state using macrophytes (Melzer, 1999; Ozimek and Kowalczewski, 1984) is also limited by the fact that macrophytes may obtain their phosphorus from long accumulation in sediments and therefore may be largely independent of the current water column concentrations.

The existing different measures of the ecological state of the ecosystem, based on chemical, physical and biological parameters (Carlson, 1977; Washington 1984) are as yet not sufficient for the effective monitoring and management of a lake, and leave a considerable room for improvement. New methods for evaluation and assessment of a lake state should be developed. In this respect, hydroacoustical methods deserve more attention than that they have been given so far. In contrast to conventional point measurements, the hydroacoustical methods provide high resolution area-based synoptic data that are collected on a regular basis adequate for GIS presentation. Thus, they enable to visualise, evaluate and compare the outcome resulting from different reservoirs, or different moments in time (daily, seasonally, annually). The digital format of remotely sensed data makes it easy to retrieve and analyse large amounts of information at low cost and in a short period of time.

Eutrophication leads to undesirable changes in fish species composition, size distribution and abundance (Colby et al., 1972; Kubecka, 1993). Salmonids characteristic of oligotrophic conditions are replaced by cyprinids with rapidly decreasing share of predatory fish. The density of fish at the beginning increases, then falls dramatically with the number of species and their body lengths continuously decreasing (Bachmann et al., 1996; Jeppesen et al., 2000a, b). Fishery methods can give us detailed information about the population structure of fish, which is an important indicator of the water quality, but to assess fish biomass these methods are very tedious, time and labour consuming and not always applicable. By contrast, fish abundance can be easily estimated using acoustics. The length distributions of fish populations, measured acoustically, have lower precision than traditional fishery methods, but for comparison purposes, it is probably sufficient. In spite of the advantages of acoustical methods, they are as yet seldom used to study freshwater ecosystems.

Application of hydroacoustics for ecological studies is very promising and rapidly developing nowadays. Echo sounding techniques can provide the basic information not only on fish stocks, sizes and spatio-temporal distribution patterns (Świerzowski et al., 2000), but also on zooplankton (Stanton and Chu, 1998; Stanton et al., 2001), bottom characteristics (LeBlanc et al., 1992; Anderson et al., 2002) and macrophytes coverage (Sabol and Burczyński, 1998). Thus, acoustical methods can integrate several of the quality indices that have been used so far, in addition offering the scale and accuracy not available with other methods. Knowledge of the relationships between fish, macrophytes and zooplankton that can be assessed using acoustics is of great importance for the conservation of high water quality.

The paper presents the preliminary results, whose aim was to check which of the fish parameters derived from hydroacoustical monitoring of the reservoir can be used as indices of its trophic state. For this purpose, the hydroacoustical data concerning fish abundance and size distribution are compared with the environmental parameters for three reservoirs, which differed substantially as regarding their condition and water quality.

2. Materials and methods

2.1. Study sites

Three reservoirs with contrasting levels of eutrophication (total phosphorus loadings in each of them differed roughly by one order of magnitude) were studied: the montane mesotrophic Solina reservoir, the submontane eutrophic Dobczyce reservoir and the lowland highly eutrophic Sulejów reservoir. Their principal morphometric and trophic characteristics are summarised in Table 1.

The largest reservoir, Solina, situated in the Carpathian Mountains, comprises about 15% of the total water storage in Poland. Due to the power station activity, the fluctuation of the water level is up to 10 m, which leads to the absence of littoral area. Concentrations of phosphorus and nitrogen compounds in the reservoir correspond to mesotrophy. The most frequent fish species are: bream (*Abramis brama*) 57.8%, crucian carp (*Carassius carassius*) 16.1%, roach (*Rutilus rutilus*) 9.2%, pike-perch (*Stizostedion lucioperca*) 4.5% and perch (*Perca fluviatilis*) 4.8% (Bieniarz and Epler, 1993). Information on the physical, chemical and biological characteristics of the reservoir is available (Godlewska et al., 2000).

The Dobczyce reservoir supplies the drinking water for Kraków, one of the largest cities in Poland. Hence, the quality of water is the main concern for both the authorities and the inhabitants. The fish management applied in the reservoir is based on a biomanipulation, which is directed to an increase in the number of predatory fish by stocking and by prohibition of angling, and the limitation of planktivorous fish by regular catches. These practices ensure a good quality of water, in spite of a fairly high loading of nutrients. The most frequent species are the same as in the Solina reservoir, i.e. bream, roach, pikeperch and perch, but they are present in different proportions (Jelonek and Godlewska, 2000).

The Sulejów is a shallow lowland reservoir situated in central Poland. The reservoir is eutrophic due to high nutrient loads. Total phosphorus concentrations (TP) of about 150-500 µg dm^{-3}, and total nitrogen (TN) of 1500-2500 µg dm^{-3} are maintained throughout the year (Tarczyńska, 2001). This leads to the occurrence of toxic algal blooms during periods of mean water temperatures exceeding 18 °C. Since the Sulejów reservoir is one of the important freshwater resources for the city of Łódź (over one million people) the utilisation of water may be highly dangerous.

2.2. Field measurements

Hydroacoustical records of fish distribution were obtained along closely separated zigzag transects covering the whole area of the reservoirs with depths exceeding 3 m. Surveys were performed during summer seasons of 1999-2002 on day and night bases: three surveys in the Solina reservoir, three in the Dobczyce reservoir and one survey in the Sulejów reservoir. The echosounder used was a Biosonic 101 dual beam, 420 kHz, with a narrow beam width of 6° and a wide beam width of 15°. To estimate fish abundance and size distribution, the echo counting method was applied with the TVG set to 40 log *R*. Due to time limitations and the fact that the echosounder used did not allow for the simultaneous recording of 20 log *R* and 40 log *R*, the echo integration was not performed. The echo sounding results were analysed using the ESP software system supplied by the manufacturer. The instrument settings for data acquisition were the following: pulse length τ = 0.4 ms, single target criteria $0.8 < \tau < 1.2$, repetition rate 0.1 or 0.5 s, threshold -65 dB (200 mV), The parameters settings in the post-processing software were the same for all three reservoirs The maximum half-angle for processing targets was set to three and the beam pattern factor > zero had threshold 3 dB. The acoustic system was routinely calibrated with a -43.2 dB tungsten carbide sphere before each measurement series (Foote et al., 1987).

In the Solina reservoir, water samples for the analysis of chlorophyll *a*, nutrients, and zooplankton were taken at nine stations at which temperature, oxygen concentration and Secchi disk visibility were also measured. The stations were situated in the main basin near the dam, as well as in the two branches of the reservoir; the Solinka and San supply rivers, which were characterised by different trophic levels. For the Dobczyce and Sulejów reservoirs, environmental data were taken from one monitoring station during the year when acoustical data were collected (M. Tarczyńska and E. Wilk-Woźniak, personal communications).

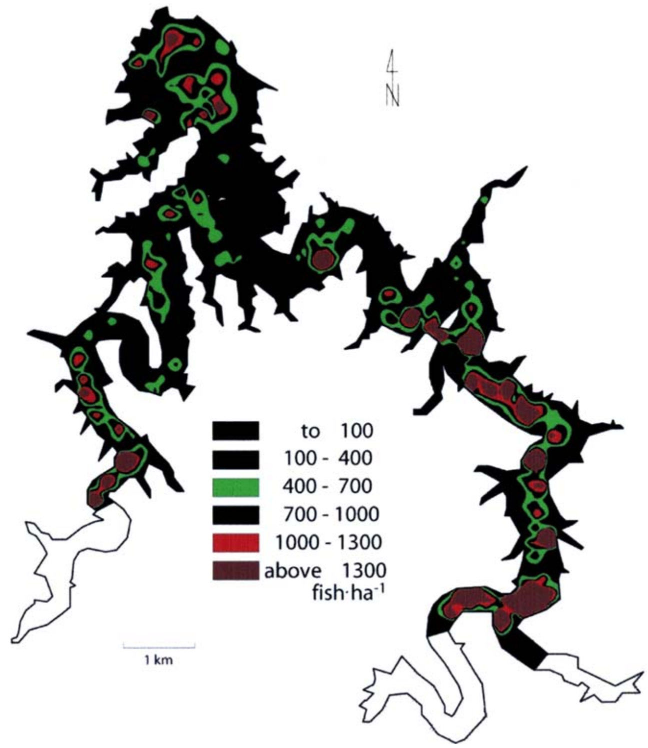

Fig. 1. Fish spatial distribution in the Solina reservoir (Poland).

3. Results

3.1. The Solina reservoir

Fish spatial distribution in the Solina reservoir (Fig. 1) exhibits a typical longitudinal pattern with higher concentrations in shallow areas close to the river discharge, and lower concentrations in a deep part near the dam. The fish density gradient corresponds to the enhancement in the productivity of the reservoir. Patchiness in fish distribution also clearly reveals the locations of agricultural and tourist pollution (source of nutrients).

Acoustical fish characteristics, such as mean density and mean target strength (TS) along the longitudinal axis (Fig. 2) are correlated with the nutrient gradient represented by such

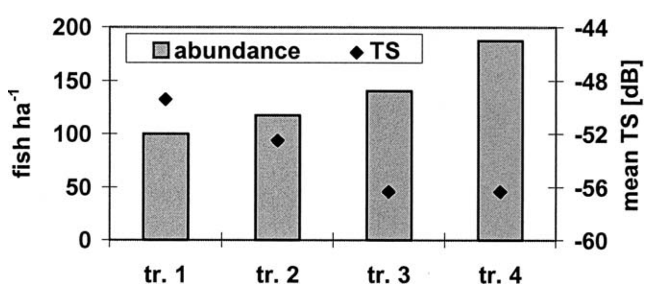

Fig. 2. Fish densities and their mean TSs in four transects in the Solinka branch of the Solina reservoir along the increasing trophic level (from the dam towards the river discharge).

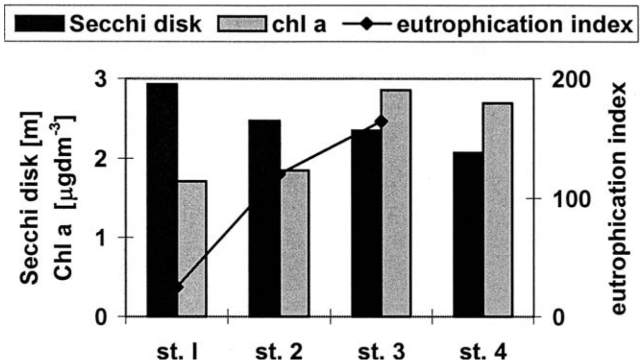

Fig. 3. Environmental parameters at four stations along the Solinka branch of the Solina reservoir. Secchi disk visibility and chlorophyll *a* concentration are taken as mean for the season, from May to October (T. Półtorak, personal communications) and eutrophication index based on the *Oligochaeta* to Chironomidae ratio in benthos was determined by T. Prus et al. (personal communications).

environmental characteristics as Secchi disc visibility, chlorophyll *a* concentration and eutrophication index based on the *Oligochaeta* to Chironomidae ratio in benthos (Fig. 3). Comparison of the Figs. 2 and 3 shows that fish abundance increases with increased eutrophication level, while the mean size of fish represented by its TS decreases.

3.2. Comparison of dam reservoirs

As expected, the three reservoirs with the contrasting levels of eutrophication also differed strongly in the levels of fish densities and fish length distributions. Similar to the Solina reservoir alone, fish abundance first increased with an increased concentration of chlorophyll *a* in the Dobczyce reservoir, then dropped in the Sulejów reservoir, although the chlorophyll *a* was further increasing (Fig. 4). Using the echo counting method, instead of echo integration, could lead to some underestimation of fish abundance, especially in the shallowest Sulejów reservoir. This makes it impossible to decide whether the observed drop in fish density was caused by the bias in the acoustical fish density estimate or was the real one and caused by eutrophication. In the Solina and Dobczyce reservoirs, fish were fairly well dispersed at night and the bias due to multiple targets was negligible. The seasonal and year-to-year fluctuations of fish densities within a given reservoir were much smaller than the variations between the reservoirs (Table 2).

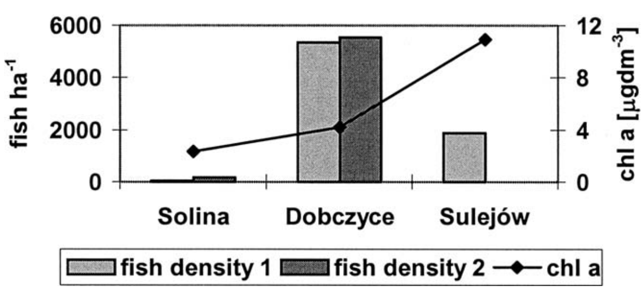

Fig. 4. Fish density estimates (night only, threshold -65 dB) in three reservoirs with different levels of eutrophication. Fish density 1: the Solina reservoir surveyed on 14 July 2000, the Dobczyce reservoir surveyed on 19 June 2000, the Sulejów reservoir surveyed on 16 July 2002. Fish density 2: the Solina reservoir surveyed on 23 August 2001, the Dobczyce reservoir surveyed on 1 August 2002 (see Table 2).

In the mesotrophic Solina reservoir, fish concentrations were over one order of magnitude lower than that in the other two eutrophic reservoirs, independently of the threshold applied for the analysis (Table 2). This was true for both day and night estimates. In the Solina reservoir, the day estimates were regularly slightly higher than those of the night ones, probably due to diurnal vertical migrations of fish (Godlewska et al., 2000). On the other hand, in the Dobczyce and Sulejów reservoirs, which are shallower, night estimates were usually higher than the estimates during the day, probably due to predominance of the horizontal over the vertical migrations, from the littoral during the day to open water at night (Godlewska, 2002).

The fish length distributions represented by their TS differed markedly in all three reservoirs. The distributions presented were based on all echoes considered as independent samples (Fig. 5). Since the different number of fish was registered in each of the reservoirs, the frequency of every TS class was shown as the percentage of total number of fish. In the Solina reservoir, all but very large sizes (in dB) were present in similar proportions. In the Dobczyce reservoir, pressure of the predatory fish was demonstrated by a little contribution of small specimens into the population structure (due to biomanipulation the predatory pike-perch and perch made over 30% of fish population and efficiently eliminated small specimens). In the Sulejów reservoir, the situation was opposite, the smallest sizes dominated and larger fish were entirely absent.

In spite of clear differences in the shape of fish length distributions in the three reservoirs, the mean values of fish acoustical lengths did not differ significantly (Table 2). It was to be expected, as the TS values varied greatly, and in this case the mean value was almost meaningless. To characterise the fish size distributions, instead of the mean value, one should rather use the percentage of fish belonging to a certain size classes.

4. Discussion

By studying systems at the extremes of the trophic gradient (low trophy Solina reservoir and highly eutrophic Sulejów reservoir), we hoped to obtain a more clear picture of the relationship between lake productivity and fish parameters in a broad spectrum of the reservoir ecosystems. The reservoirs, as expected, differed strongly in the levels of fish density. Fish concentrations in the two eutrophic reservoirs were more than an order of magnitude higher than that in the mesotrophic reservoir. It is obvious, that for the purpose of comparison, measurements should be taken at the same time of the season—preferably at the end of summer, and the same time of day—preferably at night, when a majority of fish are dispersed in the pelagial. The TS threshold is very important, although its proper choice may be difficult at the present,

Table 2
Fish densities and the TS for the studied reservoirs

Reservoir name	Date	Fish (ha^{-1})	Mean TS [a]	S.D.	TS max	Mean s (in dB) [b]	Number of fish [c]	Day or night
Threshold 200 mV (TS = –65 dB)								
Solina reservoir	14 July 2000	48	–52.39	6.7	–35.8	–47.52	229	D
	14 July 2000	43	–53.76	6.1	–37.0	–46.64	107	N
	23 August 2001	178	–55.63	5.2	–34.3	–51.32	2287	N
Dobczyce reservoir	19 June 2000	3030	–54.34	4.8	–32.9	–51.33	5944	D
	19 June 2000	5340	–55.04	4.3	–29.0	–52.44	9200	N
	13 August 2001	2610	–53.23	5.6	–30.3	–49.75	13 074	D
	13 August 2001	3390	–53.74	5.2	–34.4	–50.97	16 355	N
	01 August 2002	5625	–55.48	5.2	–31.0	–52.10	7889	N
Sulejów reservoir	16 July 2002	1743	–56.47	4.8	–35.5	–53.13	1662	N
	16 July 2002	574	–56.58	5.9	–36.3	–50.38	80	D
Threshold 500 mV (TS = –57 dB)								
Solina reservoir	14 July 2000	35	–49.29	4.2	–35.8	–46.78	164	D
	14 July 2000	23	–49.03	4.4	–37.0	–46.27	58	N
	23 August 2001	43	–50.47	4.0	–34.3	–47.99	1176	N
	24 September 2002	58	–47.90	4.9	–30.6	–44.17	733	D
	24 September 2002	43	–48.84	4.4	–30.5	–45.91	535	N
Dobczyce reservoir	19 June 2000	1875	–50.87	3.3	–32.9	–49.06	3672	D
	19 June 2000	2865	–51.69	2.6	–29.0	–50.12	4939	N
	13 August 2001	1605	–49.34	3.4	–30.3	–47.70	8057	D
	13 August 2001	2055	–49.98	2.9	–34.4	–48.97	9930	N
	01 August 2002	2805	–50.67	2.9	–31.0	–49.24	3882	N
Sulejów reservoir	16 July 2002	151	–48.55	5.1	–35.5	–45.08	21	D
	16 July 2002	618	–51.00	3.3	–36.3	–49.00	431	N
Threshold 1000 mV (TS = –50 dB)								
Solina reservoir	14 July 2000	13	–45.18	3.0	–35.8	–43.99	58	D
	14 July 2000	8	–44.51	3.6	–37.0	–42.97	22	N
	23 August 2001	10	–46.10	3.3	–34.3	–44.57	314	N
	24 September 2002	28	–44.98	3.7	–30.6	–43.11	361	D
	24 September 2002	20	–45.33	3.3	–30.5	–43.87	239	N
Dobczyce reservoir	19 June 2000	345	–46.26	2.9	–32.9	–44.95	685	D
	19 June 2000	180	–46.33	3.9	–29.0	–43.24	321	N
	13 August 2001	690	–46.58	2.3	–30.3	–45.54	3485	D
	13 August 2001	735	–47.36	1.8	–34.4	–46.86	3549	N
	01 August 2002	690	–47.73	2.4	–31.0	–46.42	1164	N
Sulejów reservoir	16 July 2002	63	–44.02	4.4	–36.3	–42.01	9	D
	16 July 2002	98	–45.46	3.2	–35.5	–43.96	70	N

[a] Mean TS averaged in logarithmic domain.
[b] Mean TS averaged in linear domain and then recalculated to dB.
[c] Number of fish taken for statistics.

with a limited knowledge of the TS of inland fishes at different frequencies. The threshold used in this study (-65 dB) may seem to be low as compared with other investigations done at frequencies 120 and 200 kHz. The reason for this low threshold was that at frequency 420 kHz, the TS of fish is considerably smaller than at lower frequencies. According to Mason and Schaner (2001), who measured the TS of fish simultaneously by a few different echosounders, the 420 kHz system consistently had the lowest estimates of TS, with a 13 dB average deviation from other systems at -70 dB threshold, and 17 dB at -80 dB. In our observations (not published), the TSs of roach and perch were considerably lower than it would be expected from the commonly used Love's formula (1977). The TS distributions can be directly compared only if they were received with the same frequencies. Observed differences in fish density and fish length distributions, along the nutrient gradient, suggest that both parameters can be used as indices of the quality of the ecosystem.

We are aware of the fact that fish populations are subject to large fluctuations seasonally, and from year to year. These changes may arise through fish management (fishing pressure or stocking) or from natural causes, mainly affecting the survival of juveniles. This considerably weakens the strength of the fish abundance as an indicator of the quality of the ecosystem. Nevertheless, a relationship between fish densities and the eutrophication level has been demonstrated in the literature. Jeppesen et al. (1997) observed that the total catch of fish per net (CPUE) in multimesh gillnets placed in the

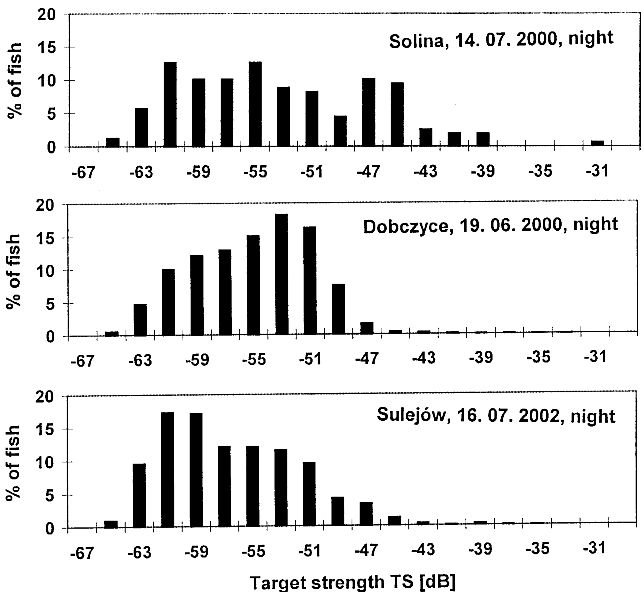

Fig. 5. Fish length distributions in three reservoirs with different trophic levels.

open water and the littoral zone of 42 north temperate Danish lakes was positively related to nutrient level. The relationships between fish abundance and nutrients and fish abundance and zooplankton/phytoplankton ratio and between chlorophyll *a* and total phosphorus measured in 25 New Zealand lakes (Jeppesen et al., 2000a) have largely followed the pattern obtained for Danish lakes. A similar pattern was observed in 65 Florida (USA) lakes, which were selected to range from oligotrophic to hypereutrophic. The total fish biomass per unit area was positively correlated with total phosphorus, total nitrogen, chlorophyll *a*, and inversely correlated with Secchi disc transparency. On an average, the standing crops increased about one order of magnitude from the oligotrophic to the hypereutrophic (Bachmann et al., 1996). According to these authors, there was a considerable unexplained variance (about 75%) in these relationships, due in part to other factors influencing fish stocks and the practical sampling problems of estimating the biomass of wild fish populations. It is apparent, that a large number of interlinking ecological factors operate, especially in shallow lakes, to make at present only a general guidance possible in which fish populations can be associated with lakes of different environmental conditions. The application of acoustics may lead to a better understanding of these linkages and a more precise estimation of fish stocks.

The changes in fish abundance and size distribution received in this study, using hydroacoustical methods, correspond well to the results received by traditional fishery methods for other lakes, both in temperate and tropical regions. Many factors may introduce biases in the fish density measured by acoustics (MacLennan and Simmonds, 1992), but other methods are not free of them either. Diurnal variation in fish behaviour affects the results of surveys, especially the ratio of apparent biomass measured by day and night (Godlewska, 2002). Among the different biases, the majority leads to underestimation rather than overestimation. During the day, factors leading to underestimation include: vessel avoidance (Olsen, 1990), the acoustic shadow in dense aggregations (Appenzeller and Leggett, 1992), daily horizontal migrations causing that fish are located in inaccessible area, littoral zone for instance (Godlewska, 2002), the decrease in TS associated with an increase in the tilt angle, when fish dive below the boat (Fréon et al., 1993), and the bottom blind area when during the day important part of the biomass is located very close to the bottom. During the night, the major underestimation, in measured acoustic density, is due to a subsurface blind area dependent on the depth of the transducer and its dead zone. This problem may be solved using additional horizontally looking transducer (Kubecka, 1996). In spite of all these difficulties, the use of hydroacoustics to estimate fish abundance, instead of traditional fishery methods, has many advantages, e.g. such as time and cost effectiveness, coverage of large areas, high spatial resolution. If additionally accompanied by control catches for species composition, acoustics can provide the basis for an integrated fish-oriented indicator of the ecosystem quality. The efforts of incorporating fish into lake quality measures should be supported because fish have both economic and aesthetic values, and thus help to raise awareness for the necessity of conserving aquatic habitats. Among the biological indices, fish should be considered as key organisms because they are present in nearly all water bodies, are indicative of habitat quality at various spatial scales, occupy variety of trophic levels, and play a central role in lake restoration and management (Lammens, 1999).

Acoustical methods need many more investigations before they can be used as a standard monitoring tool and a source of ecosystem quality indices, but the results so far justify efforts applied. A standard protocol, for the collection and processing of acoustic data, should be done before implementation of the new Water Framework Directive. Currently, there are at least 13 different scientific echosounders encompassing seven models and four frequencies (70, 120, 200 and 420 kHz), which make it very difficult to compare data between different hydroacoustic systems, lakes and individual users. The intercalibration of different acoustical systems should be encouraged.

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