

# Bulletin

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**of the Sea Fisheries Institute**

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## Maria Kosior

01.01.1933 – 20.11.2006

Along with the last issue of the *Bulletin of the Sea Fisheries Institute* we sadly bid farewell to Dr. Maria Kosior, Professor of the Sea Fisheries Institute in Gdynia and for many years the journal's scientific editor. From 1993, she was the editor responsible for publications from the fields of oceanography and fishery biology, and from 2001 she was the journal's scientific editor. Thanks to her dedication and tireless efforts, the Polish language version of the *Bulletin* became an English language publication of international reach. This provided foreign authors an opportunity to publish in the journal, and the articles published often focused on areas outside of the Baltic Sea region.



Although it would not be an exaggeration to state that for more than a decade the *Bulletin* played an important role in Dr. Kosior's professional life, this was not at the cost of her scientific pursuits, to which the whole of her career was dedicated. Her work in the fields of science and fisheries commenced in 1957 at the Sea Fisheries Institute in Gdynia after she had graduated from the Department of Fisheries of the Higher School of Agriculture in Olsztyn.

The primary focus of her research was Baltic Sea cod, which is the most important species to Polish fisheries. Both her doctoral dissertation, defended in 1976, and her post-doctoral *habilitacja* dissertation, for which she received the title of *doktor habilitowany* in 1993, focused on the state of cod resources and their management. In the Department of Ichthyology (currently the Department of Fish Resources), Dr. Kosior also held directorial positions in research groups including Coastal Fisheries and Ecology and Genetics. She also participated in and led many research tasks and grants, including doctoral dissertation grants.

Her numerous significant scientific publications formed the foundation for elevating her to the position of contract professor at the Sea Fisheries Institute in Gdynia. Dr. Kosior was the first woman to earn all of her scientific titles at the SFI and to achieve such a high position in the hierarchy of the institute's scientific staff. She remained dedicated to the Sea Fisheries Institute until the end of her life.

Maria Kosior was acknowledged repeatedly for her service to marine science by both the director of the SFI and the Ministers responsible for Fisheries and in 1973 and 1978 she received the Silver and Gold Badges of Merit for Marine Workers. She received the Golden Cross of Merit in 1989.

For the younger generation of scientists, Dr. Kosior was the embodiment of competence in both the preparation and presentation of research results as well as in providing guidance to those in need. The older generation of institute scientists remembers her as a kind person who maintained a friendly working relationship with all employees of the institute regardless of their position and one who always provided assistance discreetly when necessary. As a scientist, Dr. Kosior was characterized not only by reliability with regard to the duties she undertook but also by her ability to stimulate the scientific ambitions of younger colleagues and by her co-operation with all those who valued her knowledge, professionalism, and organizational talents.

The Editorial Board

Dear Readers and Authors,

Regrettably, I must inform you that, due to too few papers being submitted to the editorial office of the Bulletin of the Sea Fisheries Institute, publication of this periodical will be suspended for an indefinite period. Although it has been a difficult decision, I had no alternative.

I would like to take this opportunity to offer my sincere thanks to the members of the editorial team for many years of hard work editing and publishing the Bulletin. I would also like extend my gratitude to all of the Scientific Advisors who, despite their own numerous professional commitments, repeatedly assisted the Bulletin editorial office in choosing reviewers.

Subscriptions for 2007 will not be renewed, and I would kindly request the recipients of our periodical, either through interlibrary exchange or subscription, for their understanding.

Yours faithfully,

Tomasz B. Linkowski  
Editor-in-Chief, SFI Director

# Bulletin

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## Zooplankton-based assessment of the trophic state of three coastal lakes – Łebsko, Gardno, and Jamno

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**Abstract.** The qualitative and quantitative analysis of the zooplankton of three coastal lakes, Łebsko, Gardno, and Jamno, was based on materials collected in the 1985-1997 period from June to September. It was found that the number of zooplankton species, their abundance, and their biomass varied greatly and were dependent on abiotic factors and lake trophic. An analysis of the structure characteristics of zooplankton as bioindicators of eutrophication in lakes Łebsko, Gardno, and Jamno revealed the presence in the zooplankton community of numerous species of rotifers and crustaceans, which are considered to be good indicators of lake trophic. The progressing eutrophication of the lakes was accompanied by a constant increase in the numbers and biomass of Rotifera and Crustacea. In all three lakes the zooplankton abundance was determined by rotifers and biomass by crustaceans. The zooplankton-related trophic state indices permitted classifying the lakes examined as meso-eutrophic or eutrophic, with symptoms of polytrophic.

**Key words:** coastal lakes, estuaries, brackish waters, trophic, zooplankton, zooplankton-related trophic state indices

### INTRODUCTION

In Poland there are between ten and twenty lakes that are in the immediate vicinity of the Baltic Sea; these are referred to as coastal lakes or estuarine water bodies due to their location and the values of their abiotic and biotic indices (Żmudziński *et al.* 2002). Key ecological factors affecting the biocenosis of estuarine waters include salinity (Remane 1934, Guttowa 1956, Różańska 1964, 1972, Hall *et al.* 2002), water temperature (Różańska 1966, Adamkiewicz-Chojnacka *et al.* 1985, Różańska *et al.* 1985, Żmudziński *et al.* 1990, Szlauer 1996, Paturej *et al.* 2000), and trophic status (Gliwicz 1969, 1974, 1977, Hillbricht-Ilkowska 1977, Matveeva 1991, Rogozin 2000). These factors cause changes in the qualitative and quantitative composition of zooplankton and influence their densities (Rotifera and Crustacea) and the occurrence of indicator species. The zooplankton community is a dynamic system that responds promptly to environmental changes. The abundance of nutrient salts and water reaction stimulate the development of forms typical of eutrophic waters, whereas thermal conditions, due to rapid changes in water temperature and salinity, have a selective effect that inhibits biocenosis development (Chojnacki 1984, Irvine *et al.* 1990). This is why organisms colonizing brackish lakes must show

high ecological plasticity (Hall *et al.* 2002, Telesh 2004). The fauna of brackish waters is usually characterized by species poverty and is dominated by those resistant to changing environmental conditions. Communities of euryhaline species of marine, freshwater, and brackish-water origins are formed, and such species exhibit a broad range of salinity tolerance (Remane 1934, Remane and Schlieper 1971, Elliott and McLusky 2002).

Although all coastal lakes undergo eutrophication, the degree of the process can vary greatly. On the one hand, flow-through lakes are liable to eutrophication (from large amounts of suspended solids, waterborne deposits, the eroded materials carried by rivers and the sands of migrating dunes), soil erosion, the discharge of municipal, domestic and agricultural sewage, and tourist traffic and recreation. The catchment areas of such lakes have an average nutrient retention capacity, and excessive oxygen levels are observed in surface waters in the summer, which are accompanied by oxygen deficits in bottom waters (Bajkiewicz-Grabowska 1987, 1990, Kubiak 2003). On the other hand, periodic intrusions of marine waters to estuaries inhibit eutrophication (Trojanowski 1990, Trojanowski *et al.* 1991, Cieśliński 2003a,b).

The morphometric and catchment characteristics of lakes Łebsko, Gardno, and Jamno, as well as the concentrations of biophilous compounds in the water, indicate their eutrophic character. These lakes are flow-through water bodies and their catchments are used for agricultural and recreational purposes, so they are exposed to factors that accelerate eutrophication. The trophic status of a lake is also reflected by the species composition, densities, and biomass of its zooplankton, as well as the relations between particular ecological groups and biocenotic indices. Zooplankton are good bioindicators of the physical and chemical conditions of aquatic environments (Gliwicz 1974, Radwan 1973, 1976, Hillbricht-Ilkowska 1977, Karabin 1985a, Matveeva 1991).

The paper presents the results of studies on the dynamics of the species composition, abundance, and biomass of summer zooplankton in lakes Łebsko, Gardno, and Jamno as dependent upon variable abiotic environmental factors. The aim of the study was to test the hypothesis that changes in the zooplankton communities of coastal lakes, recorded over an eight-year period, may provide a basis for determining the trophic state of these lakes.

## RESEARCH AREA

In the 1985-1997 period, ecological surveys were conducted in lakes Łebsko, Gardno, and Jamno (Majewski 1972), the three largest estuaries situated in the Koszalin Coastland (Kondracki 2002) (Fig. 1). The morphometric characteristics of these lakes are presented in Table 1.

**Lake Łebsko**, the largest coastal lake on the Polish Baltic Coast, is the remnant of a lagoon that comprised the neighboring lakes Gardno and Sarbsko. It is connected to Lake Gardno by a channel in the western part, and the Łeba River flows into this lake on the southern side. Lake Łebsko is permanently connected to the sea by a stretch of the Łeba River. Due to the inflow of sea waters, a reverse delta has formed at the river mouth.

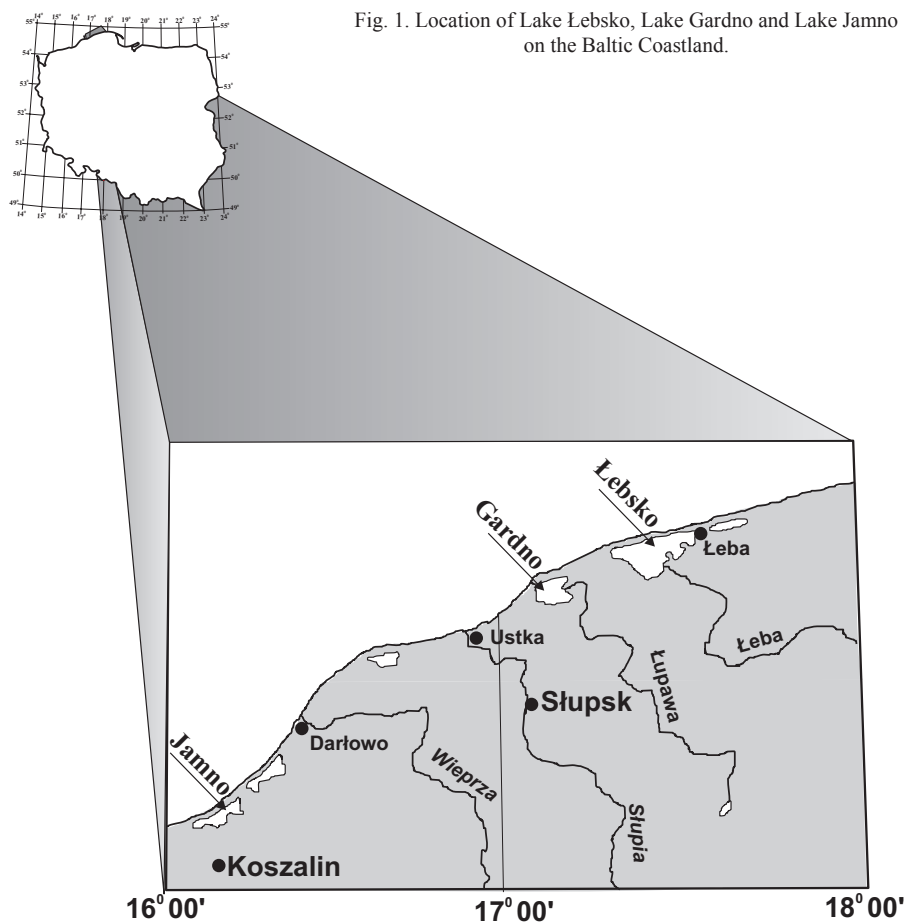


Fig. 1. Location of Lake Łebsko, Lake Gardno and Lake Jamno on the Baltic Coastland.

**Lake Gardno** forms an estuary in the course of the Łupawa River, which flows into this lake in the east and flows out into the Baltic Sea in the northwest near the village Rowy. The northeastern part of Lake Gardno is connected to Lake Łebsko by a channel (about 9.8 km in length). Waters from smaller rivers and drainage ditches flow into the lake in the south.

**Lake Jamno** is connected to the Baltic Sea by a channel known as the Nurt Jamneński (about 500 m in length). The movement of coastal debris periodically blocks the outflow, and water levels in the lake rise. On the southern side there are two peninsulas which divide the deep waters of the lake into three parts. Waters from a drainage ditch and the Strzeżenica River flow into the western part, waters from the Dzierżęcinka River—the most polluted river in Western Pomerania—flow into the central part, and waters from the Unieść River, which receives effluents from the Sianów region, flow into the eastern part.



Table 1. Morphometric characteristics of the coastal lakes Łebsko, Gardno, and Jamno\*

Parameters	Lake		
	Łebsko	Gardno	Jamno
Latitude	54°43'	54°39'	54°17'
Longitude	17°25'	17°07'	16°08'
Height above sea-level (m)	0.30	0.30	0.10
Area:			
Water-table surface (ha)	7140	2468	2239
Island area (ha)	0.22	0.06	
Catchment area (km <sup>2</sup> )	1594.0	964.4	510.6
Direct catchment area (km <sup>2</sup> )	320	126	–
Depth:			
maximum (m)	6.3	2.6	3.9
mean (m)	1.7	1.3	1.4
Volume (mln m <sup>3</sup> )	117.5	30.9	31.5
Dimensions:			
maximum length (m)	16370.0	6850.5	10100.0
maximum width (m)	7600.0	4730.0	3400.0
Main tributaries (rivers)	Łeba	Łupawa	Dzierżęcinka Strzeżenica Unieść

\*Unpublished data, Inland Fisheries Institute in Olsztyn (1958-1963)

**The water balance** in lakes Łebsko, Gardno, and Jamno is affected by the inflow of fluvial waters rather than that of marine waters (Szmids 1972). The intensity of the supply of sea water to the lakes is reflected by differences in water levels (Table 1). According to Szmids (1972), marine waters play a significant role in the water balance in lakes Łebsko and Jamno, whereas their contribution to the water balance in Lake Gardno is minor. This was confirmed by Cieśliński (2004), who determined the hydrochemical type of these lakes based on the ion concentrations in their waters. Lakes Łebsko and Jamno were classified as chloride-sodium (with the strong impact of marine waters) and Lake Gardno as bicarbonate-calcium (with the strong impact of fresh waters).

The degree of eutrophication in lakes Łebsko, Gardno, and Jamno depends primarily on the inflow of fluvial waters. Periodical inflows of sea waters reduce eutrophication in the estuaries. The rivers Łeba, Łupawa, and Dzierżęcinka supply over 90% of waters to these lakes and constitute a serious threat to them as the waters they supply to the lakes are polluted. In the Łeba River the total nitrogen concentration is  $4.4 \text{ mg} \cdot \text{dm}^{-3}$ , total phosphorus is  $0.46 \text{ mg} \cdot \text{dm}^{-3}$ , and  $\text{BOD}_5$  is  $6.2 \text{ mg O}_2 \cdot \text{dm}^{-3}$ . In the Łupawa River these values are  $4.9 \text{ mg} \cdot \text{dm}^{-3}$ ,  $0.51 \text{ mg} \cdot \text{dm}^{-3}$ , and  $7.3 \text{ mg O}_2 \cdot \text{dm}^{-3}$ , respectively, while in the Dzierżęcinka River they are  $6.8 \text{ mg} \cdot \text{dm}^{-3}$ ,  $0.54 \text{ mg} \cdot \text{dm}^{-3}$ , and  $11.4 \text{ mg O}_2 \cdot \text{dm}^{-3}$ . In Lake Gardno total nitrogen concentration is  $3.6 \text{ mg} \cdot \text{dm}^{-3}$  and total phosphorus concentration is  $0.39 \text{ mg} \cdot \text{dm}^{-3}$ . The levels of these elements in lakes Łebsko and Jamno are  $3.3 \text{ mg} \cdot \text{dm}^{-3}$  and  $0.28 \text{ mg} \cdot \text{dm}^{-3}$ , and  $5.2 \text{ mg} \cdot \text{dm}^{-3}$  and  $0.44 \text{ mg} \cdot \text{dm}^{-3}$ , respectively (Trojanowski 1990, Trojanowski *et al.* 1990, 1991). It follows that a considerable pollutant load is brought to

the lakes from the land, which disturbs the chemical, biochemical, and biological equilibrium in these water bodies.

## MATERIALS AND METHODS

Studies of the zooplankton of lakes Łebsko, Gardno, and Jamno (Fig. 1) were conducted in the 1985-1997 period from June to September. In the 1985-1989 period, zooplankton samples were collected in the water column with a 5-liter Ruttner sampler at intervals of every meter from the surface to the bottom or at intervals of 0.5 m at shallow sites. In the 1994-1997 period, the sampler was towed vertically from the water surface to the bottom, and from 25 to 50 liters of water were collected at each sampling site. The zooplankton samples were concentrated by pouring through a 60  $\mu\text{m}$  mesh plankton net, preserved with Lugol's solution, and then with 2-4% formaldehyde or 40% ethyl alcohol solutions. Samples were collected at sites representing three habitat types: the zone with low salt concentrations due to fresh water inflow (1-2 sampling sites), the central part of the lake (4 sites), and the zone where fresh and marine waters mix (1-2 sites). Water temperature and Secchi disc visibility were determined at each site, and water was collected for hydrochemical analysis (chlorides, oxygen concentration, nitrogen, phosphorus, chlorophyll *a*). The analyses were performed with Standard Methods (1976). The number of samples collected over the experimental period was as follows: Lake Łebsko – 40; Lake Gardno – 43; Lake Jamno – 37 (Table 3).

The abundance of zooplankton (individuals  $\cdot \text{dm}^{-3}$ ) was estimated using the Hensen formula (Starmach 1955). The biomass of rotifers and crustaceans ( $\text{mg} \cdot \text{dm}^{-3}$ ) was estimated indirectly using reference data and the relationship between body weight and body length (Starmach 1955, Hillbricht-Ilkowska and Patalas 1967, Čislenko 1968, Bottrell *et al.* 1976).

The Shannon indicators of species diversity and the uniformity of species distribution were calculated according to Odum (1982) and Krebs (1996). Zooplankton-related trophic state indices were taken from Radwan (1976) and Karabin (1985a, b). Table 4 presents the detailed criteria used as eutrophication indicators in the zooplankton community for lakes of different trophic status. The classification of the trophic status of the lakes in Table 5 was based on the classical physicochemical criteria in Carlson (1977) and Hillbricht-Ilkowska and Kajak (1986).

The results of the study, in the form of measurable indices, were analyzed statistically using Statistica PL 6.0 software, and interpreted as recommended by Stanisław (1998). The normal distribution of data was assumed. In cases when the variables did not show normal distribution, the data were  $\log(y + 1)$  transformed. The quantitative parameters of the zooplankton were determined with principal component analysis (PCA) performed on data arranged in a correlation matrix. The aim of the analysis was to verify the statistical significance of correlations between the occurrence and abundance of zooplankton species and environmental variables. In order to determine significant sources of variation ( $p < 0.05$ ), the means were compared with the HSD-based Tukey test.

Table 2. List of Rotifera and Crustacea species found in zooplankton in the summer in lakes Lebsko, Gardno, and Jamno

Year	1985			1986			1987			1988			1989			1994			1996			1997		
	L	G	J	L	G	J	L	G	J	L	G	J	L	G	J	L	G	J	L	G	J	L	G	J
<b>Rotifera:</b>																								
<i>Asplanchna priodonta</i> Gosse	*			*			*			*			*			*			*			+	*	+
<i>Brachionus angularis</i> Gosse				*			+			*			*			+			*			*	*	*
<i>Brachionus calyciflorus</i> Pallas				+															+					
<i>Brachionus diversicornis</i> Daday			+																					
<i>Brachionus urceolaris</i> Linnaeus																								
<i>Colurella colurus</i> Ehrenberg																								
<i>Euchlanis dilatata</i> Ehrenberg	*			*			*			*			*			*			*			+	+	+
<i>Filinia longiseta</i> Ehrenberg																						*	*	*
<i>Kellicottia longispina</i> Kellicott																								
<i>Keratella cochlearis cochlearis</i> Gosse	+	+		+	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
<i>Keratella cochlearis f. tecta</i> Gosse	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
<i>Keratella quadrata</i> O.F.Müller	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
<i>Lecane closterocerca</i> Schmarda																								
<i>Lecane luna</i> O.F.Müller	+	+		+	+		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
<i>Polyarthra dolichoptera</i> Idelson																								
<i>Pompholyx sulcata</i> Hudson																								
<i>Proales</i> sp.																								
<i>Synchaeta balitica</i> Ehrenberg																								
<i>Synchaeta kiitina</i> Rousselet																								
<i>Synchaeta littoralis</i> Lauterborn																								
<i>Trichocerca pusilla</i> Lauterborn	*			*			*			*			*			*			*			*		*
<b>Crustacea:</b>																								
<i>Alona quadrangularis</i> O.F.Müller				+			+			+			+			+			+			+		*
<i>Bosmina coregoni</i> Baird	*			*			*			*			*			*			*			*		*
<i>Bosmina longirostris</i> O.F.Müller				*			*			*			*			*			*			*		*
<i>Chydorus sphaericus</i> O.F.Müller				*			*			*			*			*			*			*		*
<i>Daphnia cucullata</i> Sars				*			*			*			*			*			*			*		*
<i>Daphnia longispina</i> O.F.Müller				*			*			*			*			*			*			*		*
<i>Diaphanosoma brachyurum</i> Liévin				*			*			*			*			*			*			*		*
<i>Lepidodora kindtii</i> Focke				*			*			*			*			*			*			*		*
<i>Acanthocyclops vernalis</i> Fischer																								
<i>Cyclops strenuus</i> Fischer																								
<i>Cyclops vicinus</i> Ulfjanin	+	+		+			+			+			+			+			+			+		+
<i>Mesocyclops leuckartii</i> Claus																								
<i>Copepoda</i> juv.	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
<b>Total</b>	10	11	12	12	14	7	18	17	16	17	10	10	11	13	11	15	14	15	16	16	15	19	22	10

(number of samples: Lebsko – 40; Gardno – 43; Jamno – 37). L – Lebsko, G – Gardno, J – Jamno, \* – indicator species of trophic state

## RESULTS

The zooplankton of the three coastal lakes, Łebsko, Gardno, and Jamno, was comprised of 20 rotifer species and 12 crustacean species, including individuals in the juvenile stage (Table 2). The taxonomic structure of the zooplankton varied widely over the experimental period, depending on environmental conditions (Fig. 2). Among those analyzed, factors 1 and 2 (the correlation between the occurrence and abundance of zooplankton species and environmental parameters) explained 35.8% of the variation. The analysis of environmental variables showed that the occurrence of zooplankton species in particular years of the study was correlated negatively with water transparency, water oxygen content, and concentrations of chloride ions and correlated positively with temperature. The relationships between the occurrence and densities of zooplankton species, and abiotic environmental factors were differentiated. The diagram of PCA results (Fig. 2) shows that among the zooplankton groups examined in the study, the occurrence of rotifers depended on water temperature ( $p = 0.000$ ) while that of crustaceans was dependent on water transparency and the concentrations of oxygen and chloride ions ( $p = 0.000$ ). A significant positive correlation (values approaching 1.0) was observed for the rotifer indicator species of high trophic levels – *Brachionus angularis*, *Trichocerca pusilla*, and *Filinia longiseta*, and a negative correlation (values approaching –1.0) was recorded for crustaceans of the same indicatory group – *Bosmina coregoni*, *Chydorus sphaericus*, and *Bosmina longirostris*, and two rotifer species – *Pompholyx sulcata* and *Keratella quadrata*. The results of an analysis of the occurrence and abundance of zooplankton species in particular years of the study and in the various lakes (Fig. 3) indicated that in Lake Jamno they were negatively correlated with influencing variability factors, while in lakes Gardno and Łebsko they were positively correlated. These relationships were statistically significant ( $p = 0.000$ ).

Numerous species of rotifers and crustaceans considered good indicators of the trophic state of lakes were found in the zooplankton community (Table 2). *Keratella cochlearis* f. *tecta* and *Keratella quadrata* were present in all lakes throughout the experimental period. *Brachionus angularis* occurred only in lakes Łebsko and Gardno, as did *Trichocerca pusilla* (in the 1990s, this species played a decisive role in trophic states of all three lakes). The occurrence of *Filinia longiseta*, *Pompholyx sulcata*, and *Proales* sp. varied widely. Among the crustaceans which comprised ecological group II (species whose proportion in the total biomass of a given community is very high and are indicators of high trophicity and typical of eutrophicated water bodies; their domination and percentage in the plankton increased along with increasing trophic levels), there were five species that are indicators of high trophic status. *Chydorus sphaericus* was recorded throughout the experimental period, whereas *Bosmina coregoni*, *Bosmina longirostris*, and *Diaphanosoma brachyurum* showed high variation in occurrence, and *Mesocyclops leuckarti* was found only once.

In lakes Łebsko and Gardno, zooplankton abundance was determined by rotifers and biomass by crustaceans. Both the densities and biomass of the zooplankton in Lake Jamno depended upon crustaceans (Table 3). In Lake Łebsko, the greatest numbers and biomass of Rotifera and Crustacea were observed in 1994 (2409 and 1188 individuals · dm<sup>-3</sup>, respectively), while in the 1985-1986 period both values were much lower. High

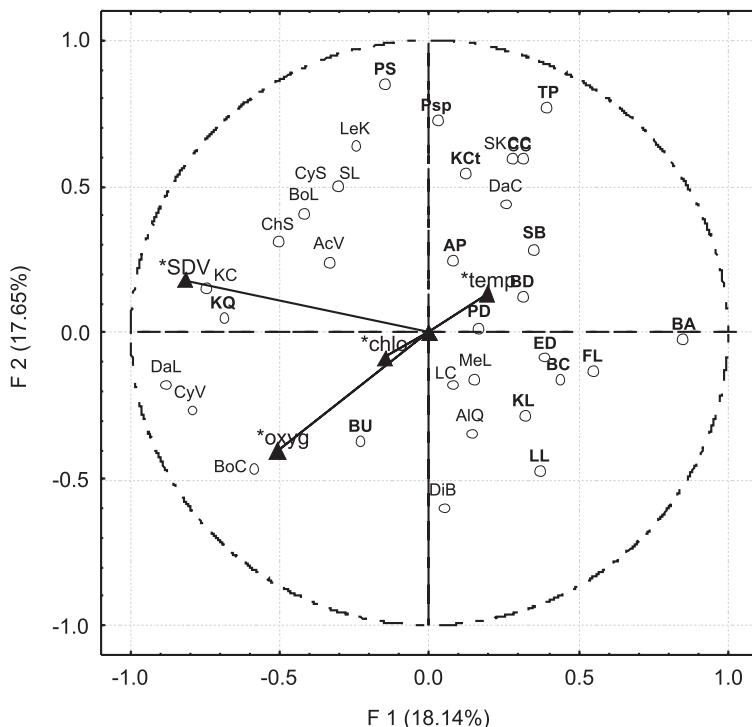


Fig. 2. Diagram of PCA results – zooplankton species occurrence in lakes Łebsko, Gardno, and Jamno in the 1985-1997 period depending on environmental factors.

Taxa abbreviations/Active variables: \**Asplanchna priodonta* (AP); *Brachionus angularis* (BA); *Brachionus calyciflorus* (BC); *Brachionus diversicornis* (BD); *Brachionus urceolaris* (BU); *Colurella colurus* (CC); *Euchlanis dilatata* (ED); *Filinia longiseta* (FL); *Kellicotia longispina* (KL); *Keratella cochlearis* (KC); *Keratella cochlearis f. tecta* (Kt); *Keratella quadrata* (KQ); *Lecane closterocerca* (LC); *Lecane luna* (LL); *Polyartha dolichoptera* (PD); *Pompholyx sulcata* (PS); *Proales* sp. (Psp); *Synchaeta baltica* (SB); *Synchaeta kittina* (SK); *Synchaeta littoralis* (SL); *Trichocerca pusilla* (TP); *Alona quadrangularis* (AIQ); *Bosmina coregoni* (BoC); *Bosmina longirostris* (BoL); *Chydorus sphaericus* (ChS); *Daphnia cucullata* (DaC); *Daphnia longispina* (DaL); *Diaphanosoma brachyurum* (DiB); *Leptodora kindtii* (LeK); *Acanthocyclops vernalis* (AcV); *Cyclops strenus* (CyS); *Cyclops vicinus* (CyV); *Mesocyclops leuckartii* (MeL)

Environmental variables: temperature (temp); oxygen (oxyg); chlorides (chlo); Secchi Disk Visibility (SDV)

\* Rotifera in bold

densities of rotifers were recorded in Lake Gardno from 1994 to 1996 (1171 – 1548 individuals · dm<sup>-3</sup>), whereas crustaceans were present in large numbers in 1996 only (1050 individuals · dm<sup>-3</sup>), although they still dominated the zooplankton biomass. A different ecological community structure was observed in Lake Jamno; rotifers occurred at very high densities in 1994 only (3046 individuals · dm<sup>-3</sup>), while in the other years their abundance ranged from 31 to 539 individuals · dm<sup>-3</sup>. The dominant ecological group was comprised of crustaceans, and both their numbers and biomass were high in all years.

The species diversity of the zooplankton community, determined using the Shannon index based on abundance and biomass, was low (Table 3) and typical of eutrophic

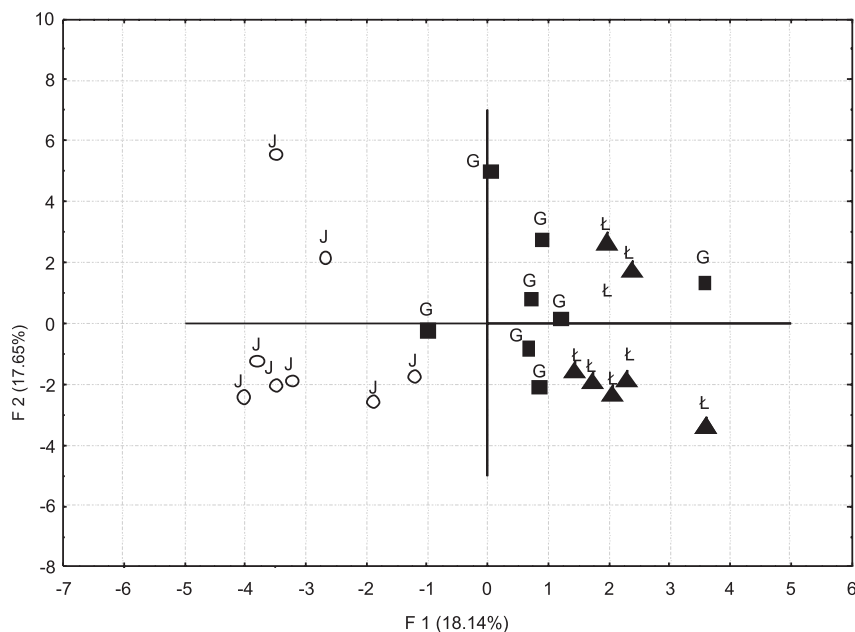


Fig. 3. Diagram of PCA components – ordering of zooplankton samples collected in the 1985-1997 period in lakes Łebsko (Ł), Gardno (G), and Jamno (J).

waters (Karabin 1985a). Low species diversity was recorded in lakes Łebsko and Gardno in years when the zooplankton community was comprised of a small number of species (Łebsko –  $H_N = 1.17 - 10$  species; Gardno –  $H_N = 1.5 - 11$  species), and high species diversity was observed when the number of species was the highest (Łebsko –  $H_N = 2.08 - 18$  species; Gardno –  $H_N = 2.21 - 22$  species). A similar relationship was found in the case of the index of biomass species diversity. In the biocenosis of Lake Jamno lower values of the biomass species diversity index indicated a more advanced trophic state and the domination of single species accompanied by low proportions of other taxa.

Generally speaking, high numbers and biomass of rotifers and crustaceans were accompanied by low species diversity of the biocenosis. In all lakes the greatest abundance of Rotifera was observed in 1994. Crustacea were present in the highest numbers in 1994 in Lake Łebsko, in 1996 in Lake Gardno and in 1996 and 1997 in Lake Jamno. The biomass of these two ecological groups was also high in these years. These parameters were accompanied by low values of the species diversity index, which indicated eutrophication in these water bodies.

The trophic state of lakes Łebsko, Gardno, and Jamno was assessed based on **basic** and **supplementary** zooplankton-related trophic state indices (Table 4). One of the key indices that permits estimating the degree of lake eutrophication is the trophic state index based on Secchi disk transparency. The values of this index indicated the polytrophic character of the lakes studied.

The biomass of indicator species of high trophic status (ecological group II which includes eight taxa of Rotifera – *Brachionus angularis*, *Brachionus diversicornis*, *Filinia*

Table 3. Mean numbers (indv. · dm<sup>-3</sup>, N), biomass (mg · dm<sup>-3</sup>, B), and species diversity in the numbers (H<sub>N</sub>) and biomass (H<sub>B</sub>) of Rotifera and Crustacea in lakes Łebsko, Gardno, and Jamno

Lake	Year	Number of samples	Rotifera				Crustacea				H <sub>N</sub>	H <sub>B</sub>
			N	sd*	B	sd*	N	sd*	B	sd*		
Łebsko	1985	4	321	206.0	0.036	0.028	100	84.8	1.197	1.473	1.17	0.98
	1986	5	267	101.2	0.128	0.049	251	161.2	1.204	0.766	1.94	1.34
	1987	6	529	83.4	0.2	0.067	397	118.8	4.409	1.759	2.08	1.69
	1988	6	264	124.2	0.153	0.137	168	30.2	1.96	0.489	1.9	1.58
	1989	6	506	158.6	0.083	0.034	247	109.7	1.593	0.463	1.55	1.48
	1994	4	2409	607.4	0.268	0.067	1188	356.0	7.905	2.322	1.7	1.35
	1996	4	542	224.1	0.131	0.113	516	186.9	6.175	3.355	1.77	1.4
	1997	5	492	286.7	0.095	0.043	450	152.7	4.138	1.603	1.58	1.4
Gardno	1985	3	785	615.6	0.085	0.067	163	144.8	1.409	0.534	1.5	1.29
	1986	6	434	375.7	0.073	0.068	396	131.0	9.926	5.690	1.89	1.49
	1987	6	789	245.8	0.136	0.048	370	119.9	5.764	2.315	2.06	1.5
	1988	6	638	437.4	0.099	0.051	191	40.6	4.119	1.754	1.72	1.14
	1989	6	942	553.9	0.118	0.074	342	77.5	4.471	1.161	1.48	1.5
	1994	5	1548	361.3	0.132	0.032	331	131.1	4.983	2.242	1.71	0.71
	1996	5	1171	624.4	0.129	0.104	1050	925.4	8.576	7.013	1.65	1.06
	1997	6	583	355.4	0.091	0.048	238	88.9	3.278	1.194	2.21	1.44
Jamno	1985	5	201	157.2	0.085	0.058	694	283.3	17.381	6.208	1.58	1.1
	1986	2	217	88.9	0.183	0.106	488	104.2	7.826	2.153	1.89	1.62
	1987	5	200	167.8	0.195	0.048	607	286.9	15.213	7.912	1.77	1.72
	1988	5	48	51.9	0.022	0.020	657	219.8	11.076	3.107	1.75	1.69
	1989	5	174	56.1	0.056	0.017	679	214.2	15.979	4.434	1.88	1.68
	1994	5	3046	1376.7	0.268	0.088	920	166.2	11.289	3.504	1.78	1.29
	1996	5	539	140.5	0.1	0.032	1065	513.4	11.752	4.000	1.76	1.42
	1997	5	31	13.6	0.016	0.011	1287	706.1	19.413	9.323	1.15	1.51

\* - standard deviation

*longiseta*, *Keratella cochlearis* f. *tecta*, *Keratella quadrata*, *Pompholyx sulcata*, *Proales* sp., *Trichocerca pusilla*; Table 2) made a high contribution to the biomass of rotifers, which indicated the meso-eutrophic character of the lakes. Particular attention should be paid to the situation observed in the 1986-1989 period in Lake Gardno when the proportion of eutrophy-indicating species was very high (almost 100% of the *tecta* form in the *Keratella cochlearis* population) and revealed the polytrophic character of this water body. Analogous situations were recorded in 1985 in Lake Łebsko and in 1994 in Lake Jamno. A distinct improvement in the environmental state took place in the 1990s in lakes Gardno and Jamno, while in Lake Łebsko the situation was unstable.

One of the most reliable trophic state indices is the proportion of the *tecta* form in the biomass of one of the most common rotifers – *Keratella cochlearis* (Karabin 1985a). In lakes Łebsko and Gardno, the percentage of the *tecta* form was typical of polytrophic waters in all years. Lake Jamno was classified as polytrophic or meso-eutrophic in particular years during the experimental period, and in 1997 this form was absent, which suggested an improvement in the state of the aquatic environment.



Numbers of rotifers characteristic of eutrophy ( $400\text{--}2000$  individuals  $\cdot \text{dm}^{-3}$ ) (Karabin 1985a) were recorded throughout the experimental period in Lake Gardno, and in the 1996–1997 period in Lake Łebsko. A meso-eutrophic water state was reflected by rotifer densities ( $< 400$  individuals  $\cdot \text{dm}^{-3}$ ) in Lake Jamno and also in Lake Łebsko at the beginning of the 1980s. The abundance of rotifers in lakes Łebsko and Jamno in 1994 was 2409 and 3046 individuals  $\cdot \text{dm}^{-3}$ , respectively, which indicated the polytrophic character of these water bodies. The high densities of rotifers corresponded to the almost 100% proportion of the *tecta* form in the *Keratella cochlearis* population (Karabin 1985a). The other basic indices based upon the structural characteristics of the crustacean population can be applied primarily to stratified lakes; however, they may also be a useful tool in confirming the trophic state of non-stratified lakes, even though their role as bioindicators is less important in such lakes. In lakes Łebsko, Gardno, and Jamno, ecological group II of Crustacea was represented by five species in the biomass of the indicator community, namely *Bosmina coregoni*, *Bosmina longirostris*, *Chydorus sphaericus*, *Diaphanosoma brachyurum*, and *Mesocyclops leuckarti* (Table 2). The contribution of indicator species to the total biomass of the zooplankton population in Lake Gardno suggested mesotrophy, and a eutrophic state was recorded only in 1996. The zooplankton community in Lake Łebsko was unstable. During the 1996–1997 period in Lake Jamno, the proportion of indicator species in the total biomass of Crustacea (over 60%) suggested a eutrophic state, whereas in the previous years the lake was classified as meso-eutrophic. If the contribution of Cyclopidae to Crustacea biomass is below 15%, a lake is classified as mesotrophic; such a situation was observed at the end of the 1990s in the lakes studied, while eutrophic states (over 30%) were recorded in the 1980s. The ratio between Cyclopidae to Cladocera biomass partly confirmed the conclusions formulated on the basis of rotifer-related indices.

The other components of the zooplankton structure, referred to as supplementary indices, can be used to a limited extent to determine certain stages of water eutrophication. The results of long-term studies conducted on lakes Łebsko, Gardno, and Jamno, as well as the above basic zooplankton-related trophic state indices, suggest that an increase in a lake's trophic status is accompanied by an increase in the numbers of rotifers, whereas the abundance of crustaceans increases only between mesotrophy and meso-eutrophy, following which it exhibits a decreasing tendency (Table 4). The mean numbers of zooplankton indicated the meso-eutrophic state of waters and permitted ordering the lakes as follows: Łebsko ( $1081$  individuals  $\cdot \text{dm}^{-3}$ ); Gardno ( $1246$  individuals  $\cdot \text{dm}^{-3}$ ); Jamno ( $1357$  individuals  $\cdot \text{dm}^{-3}$ ). Zooplankton densities above  $2000$  individuals  $\cdot \text{dm}^{-3}$  indicate polytrophy (Karabin 1985a), which was recorded in 1994 in lakes Łebsko and Jamno, and in 1996 in Lake Gardno. The polytrophic character of these water bodies in these years was conditioned by all of the trophic state indices discussed.

Another trophic state index, i.e., the ratio between the biomass and numbers of rotifers, has a lower bioindicatory value. Karabin (1985a) found that a value of this index lower than  $0.000150$  mg indicates eutrophy and polytrophy. Such a value, resulting from the B:N ratio of Rotifera, was recorded in 1994 in lakes Łebsko and Jamno, and nearly throughout the experimental period in Lake Gardno. Progressing lake eutrophication is reflected by an increase in the numbers of crustaceans, which was noted especially in Lake Jamno. The trophic status of the lakes was confirmed by the ratio between the bio-



Tab. 4. Zooplankton-based indices of the trophic state of Lake Lebsko, Lake Gardno and Lake Jamno: TSI<sub>SD</sub> (Carlson 1977), proportion of ecological group II in the biomass of the indicator rotifer community (%), group II - Rotifera), proportion of *Keratella cochlearis* (%), TECTA), abundance of rotifers (indiv·dm<sup>-3</sup>, Rotifera N), proportion of ecological group II in the biomass of the indicator crustacean community (%), group II – Crustacea), proportion of Cyclopidae in the biomass of Crustacea (%), Cyclopidae in B Crust.), ratio between Cyclopidae biomass and Cladocera biomass (mg·dm<sup>-3</sup>, B<sub>CY</sub>:B<sub>CL</sub>), total zooplankton abundance (indiv·dm<sup>-3</sup>, Zoopl. N), ratio between rotifer biomass and rotifer numbers (mg, B:N Rotifera), abundance of Crustacea (indiv·dm<sup>-3</sup>, Crust. N), ratio between crustacean biomass and crustacean numbers (mg, B:N Crustacea), biomass of Cyclopidae (mg·dm<sup>-3</sup>, Cyclop. B), Crustacea – indicator of the species diversity of biomass H<sub>B</sub>, uniformity of species distribution e and ranges of values for trophic types of lakes (Karabin 1985a).

Lake	Year	TSI <sub>SD</sub>	Basic indices				Supplementary indices							
			II group - Rotifera	TECTA	Rotifera N	II group Crustacea	Cyclopidae in B Crust.	B <sub>CY</sub> :B <sub>CL</sub>	Zoopl. N	B:N Rotifera	Crust. N	B:N Crustacea	Cyclop. B	Crustacea - H <sub>B</sub> , e
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Łebsko	1985	69	97.2	100	321	2.47	97.5	0.440	421	0.000112	100	0.011970	0.986	0.65; 0.94
	1986	67	42.2	100	267	64.4	32.0	0.470	518	0.000479	251	0.004797	0.227	0.72; 0.52
	1987	70	72.5	83.3	529	47.7	13.5	0.156	926	0.000378	397	0.011106	0.532	1.47; 0.71
	1988	70	34.6	0.001	264	57.7	33.7	0.509	432	0.000580	168	0.011667	0.609	1.39; 0.78
	1989	69	75.9	100	506	58.0	42.0	0.723	753	0.000164	247	0.006449	0.498	1.06; 0.96
	1994	70	60.4	100	2409	67.6	23.7	0.310	3597	0.000111	1188	0.006654	1.685	1.19; 0.57
	1996	70	46.6	100	542	39.0	5.04	0.053	1058	0.000242	516	0.011967	0.264	1.29; 0.80
Gardno	1997	70	68.4	100	492	62.3	12.0	0.136	942	0.000193	450	0.009196	0.421	1.28; 0.72
	1985	73	89.4	88.2	785	24.9	47.2	0.895	948	0.000108	163	0.008644	0.548	1.06; 0.76
	1986	73	100	100	434	15.9	44.0	0.785	829	0.000168	396	0.025066	4.038	1.44; 0.69
	1987	73	99.3	100	789	36.7	24.3	0.321	1159	0.000172	370	0.015578	1.357	1.35; 0.65
	1988	73	100	100	638	7.78	20.0	0.250	829	0.000155	191	0.021565	0.800	1.02; 0.57
	1989	73	99.2	97.8	942	22.0	44.6	0.805	1284	0.000125	342	0.013073	1.850	1.39; 0.78
	1994	73	75.8	100	1548	1.91	8.00	0.087	1879	0.000085	331	0.015054	0.384	0.57; 0.41
	1996	73	59.7	95.5	1171	71.9	6.79	0.073	2221	0.000110	1050	0.008168	0.573	0.94; 0.53
	1997	73	56.0	76.9	583	17.8	23.4	0.305	821	0.000156	238	0.013773	0.731	1.13; 0.51

table 4 continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Jamno	1985	77	63.5	50.0	201	57.8	25.2	0.337	895	0.000423	694	0.025045	4.316	1.05; 0.50
	1986	77	72.1	66.2	217	48.0	22.8	0.295	705	0.000843	488	0.016037	1.766	1.60; 0.99
	1987	77	84.6	65.9	200	55.4	18.2	0.223	807	0.000975	607	0.025063	2.757	1.70; 0.77
	1988	77	50.0	9.1	48	40.7	49.8	0.991	705	0.000458	657	0.016858	5.393	1.68; 0.86
	1989	77	82.1	9.1	174	35.8	42.6	0.743	853	0.000322	679	0.023533	6.634	1.66; 0.80
	1994	83	91.4	89.0	3046	35.3	24.0	0.315	3966	0.000088	920	0.012271	2.650	1.17; 0.56
	1996	83	57.0	70.0	539	61.7	31.6	0.462	1604	0.000186	1065	0.011035	3.591	1.36; 0.70
	1997	83	50.0	0.0	31	75.1	10.3	0.115	1318	0.000516	1287	0.015084	1.974	1.51; 0.84
Ranges of values														
Trophic types														
Mesotrophy	<45	<10	0-5	<400	<25	<15	<0.2	-	-	-	<180-200	>0.05-0.06	<0.4-0.5	2.2-2.3
	45-55	10-90	5-20		25-60	15-30	0.2-0.8	-	-	-	-	-	-	-
Meso-eutrophy	55-65	>90	20-60	400-2000	>60	>30	>0.8	-	<0.00015	-	-	-	-	-
Eutrophy	>65		>60	>2000	-	-	-	<2000	-	-	-	-	-	-
Polytropy														

Table 5. Classification of coastal lakes (1985-1989) according to their trophic state, determined by Secchi Disk Visibility, water concentrations of total phosphorus (TP), total nitrogen (TN) and chlorophyll *a* (Chl. *a*) (Hillbricht-Ilkowska and Kajak 1986) in the summer, and by the Carlson index (1977)

Index	Lake					
	Lebsko	Class	Gardno	Class	Jamno	Class
SDV (m)	0.66 (0.4- 0.65)	II	0.33 (0.3-0.4)	III	0.2 (0.3-0.35)	III
TP (mg P·dm <sup>-3</sup> )	0.256 (0.171-0.393)	II/III	0.370 (0.145-0.600)	III	0.414 (0.235-0.691)	III
TN (mg N·dm <sup>-3</sup> )	3.46 (1.05-6.24)	II	3.62 (1.51-5.94)	III	5.16 (3.82-6.48)	III
Chl. <i>a</i> (mg·m <sup>-3</sup> )	68.5	II	85.3	III	128.4	III
Carlson	74.5	III	79.0	III	82.2	III

mass and numbers of crustaceans, as well as by the biomass of Cyclopidae. In almost all years in Lake Łebsko and in 1994 in Lake Gardno the contribution of Cyclopidae to crustacean biomass indicated that these water bodies were mesotrophic. The much higher values of Cyclopidae biomass (above 1 mg) recorded in Lake Jamno and, in some years, in Lake Gardno, confirmed the eutrophic state of these lakes.

The index of species diversity of crustacean biomass ( $H_b$ ) showed low values in lakes Łebsko and Gardno, where from two to eight species were identified, and slightly higher values in Lake Jamno, where the number of species was higher (5-9) as were their abundance and biomass. The index of uniformity of Crustacea distribution approached unity only in some years in lakes Łebsko and Jamno, which indicated comparable densities of taxa. In the other years the values of this index were low, which suggested the domination of single species in the zooplankton community. According to the above indices, the lakes were classified as mesotrophic.

According to Hillbricht-Ilkowska & Kajak (1986), taking into account the classical, non-zooplankton-related criteria of trophic state assessment (Table 5), the lakes studied should be classified as follows: Lake Łebsko – class II; lakes Gardno and Jamno – class III. According to the values of the trophic state index (TSI) proposed by Carlson (1977), all of the lakes represent class III (eutrophy to polytrophy).

## DISCUSSION

The majority of rotifers and crustaceans are tolerant to changes in the environment, and may constitute reliable indices of the trophic state of lakes (Lityński 1925, Patalas 1954, Radwan 1973, 1976, Karabin 1985a). However, attempts to determine the relationships between the trophic state of lakes and the zooplankton species inhabiting them based solely on faunal analysis were unsuccessful. This problem was investigated by Bowkiewicz (1938) and Patalas (1954). From the point of view of bioindication, it is not only necessary to perform faunal analysis; the relationships between the trophic state of lakes and the number of structural characteristics of zooplankton must also be determined based on numerical data. The results of long-term research carried out on lakes Łebsko, Gardno, and Jamno showed that progressing lake eutrophication was accompanied by a constant increase in the numbers and biomass of rotifers and crustaceans (Table 3), as well as by a decrease in the number of species and species diversity of zooplankton. Rogozin (2000), who studied selected structural parameters of zooplankton in lakes that differed in trophic status, also confirmed the hypothesis that an increase in trophic status is followed by structural simplification. Numerous authors (Gliwicz 1969, 1974, 1977, Karabin 1985a, b, Radwan 1976, Hillbricht-Ilkowska 1977, Matveeva 1991, Szlauer 1996) share the opinion that trophic relations in lakes are the main factors determining the abundance, biomass, and species structure of zooplankton.

Many other structural characteristics of zooplankton, i.e., bioindicators of eutrophication, were also determined to assess the trophic states of lakes Łebsko, Gardno, and Jamno. Zooplankton densities in these lakes varied widely ( $421 - 3966 \text{ individual} \cdot \text{dm}^{-3}$ ). Zooplankton-related trophic state indices (basic and supplementary) were used to determine the relationships between the numbers and biomass of crustaceans and rotifers

and the trophic status. According to Karabin (1985a), the abundance of rotifers increases along with an increase in lake trophic status, whereas the abundance of crustaceans increases only between mesotrophy to meso-eutrophy. Changes of a different nature can be observed in zooplankton biomass; the biomass of rotifers increases in the mesotrophy to eutrophy range but there is no correlation between crustacean biomass and lake trophic status. These relationships were partially confirmed by the results of the current study on coastal lakes. Straile and Geller (1998) studied crustacean zooplankton in Lake Constance where trophic status changed from oligotrophic to meso-eutrophic. These authors found that the biomass of crustaceans increased several times over this period, as in the present study. The numbers of rotifers increased in lakes Łebsko and Gardno but decreased in Lake Jamno, where crustaceans dominated both in terms of abundance and biomass. Based on the total numbers of zooplankton, the numbers of crustaceans, and the ratio of Rotifera biomass to number, the lakes can be classified as eutrophic with symptoms of polytropy, whereas crustacean-based indices indicated eutrophy. One of the most reliable indices, which permits determining precisely the trophic state of lakes, is the proportion of the *tecta* form in the *Keratella cochlearis* population. In mesotrophic lakes this form only occurs sporadically, while in polytrophic water bodies it accounts for 70% to 100% of the biomass (Hillbricht-Ilkowska 1977, Karabin 1985a). This situation, namely the polytrophic character of waters, was observed in coastal lakes.

Karabin and Ejsmont-Karabin (1993, 1996), who analyzed zooplankton-related trophic state indices and the values of other parameters of the community structure in lakes situated in the Suwałki District and the Masurian Lakeland, reported that advanced eutrophication can be observed primarily in shallow, polymictic lakes (coastal lakes are characterized by this morphometry), whereas deep, stratified lakes are more resistant to eutrophication. The process of eutrophication in lakes Łebsko, Gardno, and Jamno was subject to considerable fluctuation.

The results of the analysis of the experimental materials collected in the study provided the basis for describing the dynamics of the structural systems of zooplankton used as bioindicators of the eutrophication process taking place in the three coastal lakes of Łebsko, Gardno, and Jamno in the 1985-1997 period. The most important conclusions formulated from the current study are as follows:

- the zooplankton communities in the lakes examined included numerous species of rotifers and crustaceans, which are good indicators of the trophic state of water bodies. They belong to so-called ecological group II comprised of eight taxa of Rotifera – *Brachionus angularis*, *Brachionus diversicornis*, *Filinia longiseta*, *Keratella cochlearis* f. *tecta*, *Keratella quadrata*, *Pompholyx sulcata*, *Proales* sp., *Trichocerca pusilla*, and five species of Crustacea – *Bosmina coregoni*, *Bosmina longirostris*, *Chydorus sphaericus*, *Diaphanosoma brachyurum*, and *Mesocyclops leuckarti*;

- progressing lake eutrophication was accompanied by a constant increase in the numbers and biomass of Rotifera and Crustacea. Zooplankton abundance was dominated by rotifers and zooplankton biomass by crustaceans in all three lakes;

- the increase in the trophic levels of lake waters and changes in the species structure of zooplankton were accompanied by a decrease in the number of species (7-22) and species diversity expressed by the Shannon index;

- the trophic state of lakes Łebsko, Gardno, and Jamno was assessed during the study period on the basis of zooplankton-related trophic indices, both basic and supplementary.

Based on the basic indicators, including rotifer-related indices such as ecological group II of Rotifera and the numbers of Rotifera, the lakes can be considered meso-eutrophic and eutrophic. Taking into account the proportion of the *tecta* form in the *Keratella cochlearis* population, the lakes should be classified as polytrophic. Crustacean-related indices differed significantly both in the individual lakes and in particular years of the study, but the results of analyses indicated that the character of these water bodies is meso-eutrophic.

According to the supplementary indices, such as the total numbers of zooplankton, the numbers of crustaceans, and the ratio of the Rotifera biomass to number, as well as crustacean-related indices, the lakes should be classified as eutrophic with symptoms of polytrophy.

Based on faunal analysis, the structural characteristics of zooplankton (Karabin 1985a, b), and classical, non-zooplankton-related criteria (Carlson 1977, Hillbricht-Ilkowska and Kajak 1986), the lakes can be ordered by increasing trophy as follows – Łebsko, Gardno, and Jamno.

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## Mechanical properties of twine and netting used in Baltic fisheries

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**Abstract.** This paper presents a method for determining the basic technical parameters of netting material impacting the selective and protective properties of fishing gear. It also permits obtaining the values of the elasticity modulus (Young's -  $E$ ) for several types of polyamide (PA) and polyethylene (PE) twines (studies performed in the dry state) used to manufacture codend netting. The results obtained were compared with those in the technical literature.

The proposed method of determining the technical parameters of netting material can be used to determine the ability of a given netting material to protect resources of various fish species in different marine basins prior to making netting constructions.

This paper also presents results of breaking tests of 90° turned meshes in comparison with those of standard mesh (diamond) netting used in the manufacture of trawl codends used in Baltic fisheries. The results obtained confirmed that the turned meshes are 10 to 25% more resistant to breaking force than are standard meshes.

**Key words:** selectivity, breaking strength, elasticity modulus, stiffness, netting material

## INTRODUCTION

Preserving living marine resources requires applying all possible measures in order to find the appropriate protective tools including technical solutions that do not require fishermen to cease fishing. One of these methods is to apply more effective fishing gear that allows juvenile and undersized fish to escape the gear in good condition.

The mechanical properties of the material used to manufacture netting constructions influence such characteristics of their utility features as resistance to breaking and selectivity. These characteristics are closely related. Increased strength in twine and netting material lowers selectivity while increasing the endurance of the product. The selectivity, for example, of a codend, is determined primarily by the degree to which meshes in the trawl codend open. Codends manufactured of stronger material are stiffer which means that the meshes of constructions currently in use are less capable of opening widely. Plastic and netting factories are currently producing materials that are increasingly strong. Such material is sought after by fishing vessels owners due to their increased durability.

The codends in common use are strong (too strong) but not selective enough. This refers primarily to standard codends manufactured from diamond netting, but it also refers to codends derived from this type, for example those with selective windows (not currently used in Baltic cod fisheries) and the Bacoma type. In this last instance, the low overall selectivity of the standard codend is improved by the highly selective window of square meshes that is placed in the rear upper section of the gear.

A decrease in selective properties, synonymous with increased, unnecessary fish mortality, depends on the mechanical properties of the twine used in the construction of trawl codends, *i.e.*, stiffness and breaking load.

The aim of the current paper was to determine the technical parameters of twine – the elasticity modulus ( $E$ ), and the moment of inertia of the mesh bar cross-section ( $J$ ). This is indispensable for estimating theoretically the stiffness of different twine constructions that are used in the construction of trawl codends. Knowledge of these values permits ranking the suitability of a given netting material for manufacturing selective fishing gear. The main goal, however, was to develop a technical measure for determining the degree of opening of netting meshes turned through  $90^\circ$  (T90), as this is necessary for designing gears with T90 netting.

## THEORETICAL BASIS

Based on the theory of material strength, specifically on bending theory, the process of the opening of netting meshes can be compared to the process of the opening of four equally long bars connected in a contained set that form, for example, a rhombus without articulated vertices. The possibility of meshes opening depends on the stiffness of their bars. Stiffness, according to the bending theory of beams, is described by the product of the elasticity modulus ( $E$ ) of the material which the beam is made of (in this instance – the mesh bar) and the value of the moment of inertia of the beam (mesh bar) cross-section – ( $J$ ). The value of the first parameter ( $E$ ) depends on the elastic properties of the material. The second parameter (except for elasticity modulus –  $E$ ) describes, simply stated, the resistance of the beam to bending. This refers to the quantification (determining quantifiably) of the impact of the cross-section shape on the ability of the beam to bend. This is because a beam with the same cross-sectional area gives in to bending at varying degrees depending on parameter  $J$ . The higher this value, the less bend there is in the beam. The  $J$  values for the typical shapes of cross-sections (circles, squares, etc.) depending on their parameters are widely available in the professional literature, *i.e.*, mechanics handbooks.

In bending theory, the elasticity modulus  $E$  (Young's modulus) is the value determined based on the tensile tests of a sample of a given material. During bending, a beam (bar) with a layered structure (fibrous) is characterized by a dual load: some layers (fibers) are stretched and others compressed. The exception is the layer which lies on the inert axis of the beam, which is neither stretched nor compressed. The layers (fibers) that, for example, lie above the inert axis of the beam are stretched while those below it are compressed. In the initial stretching stage, relative lengthening is proportional to stress, as is the case with compression; shortening (negative lengthening) is proportional to compres-

sion stress. From this point of view, the elasticity modulus  $E$  obtained during the tearing of material samples can and is applied in bending theory.

Since the structure of the twine used to manufacture netting material is very similar to that of fibrous (layered) materials such as those made of wood or metal, the principles of the science of material strength can be applied in the theory of the opening of netting meshes. The degree of similarity differs in the twine materials used in fisheries. All of the twines currently in use have a fibrous structure as they are all comprised of a number of single fibers that together form a twine of a determined thickness (diameter). The twines can be braided or twisted. Braided twines are comprised of an outer braided layer and a core of a certain number of parallel fibers. Twisted twine is usually comprised of three strands of a given number of technical yarn strands, which are, in turn, comprised of various numbers of single fibers. The diameter (thickness) of the twine depends on the number of fibrous elements that it is constructed of.

The similarity of the mechanical characteristics of braided twine relies on the total similarity of the core (the fibers or filaments that lie parallel to the long axis of the twine) and the partial similarity of the coat layer. This layer is comprised of fibers or filaments that cross the longitudinal axis of the twine symmetrically, and under loading (either stretching or compression) the resultant force is directed along the axis of the twine. Thus, the load of the twine is in some degree comparable to that of tensile wood or steel sample, for example.

The mechanical similarity of loaded twisted twine is different since its fibers are twisted several times – first into technical yarn and then into strands, three of which usually comprise the twine. Successive elements of the twisted twine are twisted opposite to each other, which mean that its fibers are parallel to the axis of the twine in certain strands, which prevents the twine from untwisting. In this case, the direction of the load exerted by the individual twine fibers is not known. True, they are located parallel to the axis of the twine, but the strands have a helix shape. The polyamide (PA – nylon) twisted twines used in the manufacture of netting are finished chemically; this provides them with greater stiffness and compactness. It is possible that this processing and the friction between the particular twine components also make it possible to apply the general laws of bending rod theory to this type of rope product to twisted twines.

Employing the same procedure for both types of twines, braided and twisted, is indicated even more by the fact that initial theoretical calculations of the mesh shape done a few years ago with the elasticity modulus obtained for PA were convergent with the actual shape of the real mesh of a given bar length and thickness (Moderhak 2005). The elasticity modulus was determined at the Sea Fisheries Institute in Gdynia based on tests in which polyamide twisted twine of a thickness of 1.1 mm and 1.8 mm was investigated (Moderhak 2000). The theoretical procedure developed was applied in the tests to estimate the selective properties of netting material. The mesh shapes were calculated and then compared with cross-sections of fish at its maximum point (Moderhak 2005). This shows how it is possible to obtain a preliminary selectivity evaluation of various netting materials used to manufacture codends and trawls. This approach permits quickly taking the appropriate steps towards protecting living marine resources without using time-consuming and expensive methods, so-called subsequent approximations (recurrent or trial and error) in order to achieve proper solutions.

## MATERIALS AND METHODS

### Determining twine elasticity modulus $E$

Determining the elasticity modulus  $E$  (then flexural rigidity  $EJ$ ) of PE and PA twines was possible due to tests conducted at the Institute for Fishing Technology and Fishery Economics (IFF) in Hamburg, which has a powerful tensile testing machine that simultaneously registers the tension process (dependence of tearing force on elongation of sample) on a paper ribbon. Since the device was not linked to a computer, processing the test results was more difficult and time-consuming than it would have been otherwise.

In order to determine the mechanical properties of twines used in the manufacture of netting, the tensile tests was conducted for eight types of PE and PA twines in four series of tests on each in the dry state, as follows:

polyethylene (PE):

- twisted twine – 4.43 mm thick;
- braided twine – 3.55 mm thick – standard;
- braided twine – 4.8 mm thick – Euroline;
- braided twine – 4.6 mm thick – Euroline Premium;

polyamide (PA):

- twisted twine – 2.6 mm thick;
- twisted twine - 3.2 mm thick – with a lesser twist and chemically finished;
- twisted twine - 3.4 mm thick;
- twisted twine – 3.5 mm thick.

The actual thickness (diameter) of the twines was determined with a micrometer adapted for taking measurements of netting twines. The length of all of the samples of various twines was uniform at 20 cm.

The most popular polyamide (PA) and polyethylene (PE) twines and netting that are used to manufacture the trawl codends used in Baltic cod fisheries were subjected to strengthening tests.

In order to determine the elasticity modulus of the tested materials, the proportionality range was selected from the tearing curves (the application range of Hook's law), with relative elongation from 0 to 0.125. This elongation range was characterized by the proportional dependence of force on relative elongation for polyethylene (PE) twine and the "approximate" proportionality for polyamide (PA) twine. The exception was PA twine of a thickness of 3.2 mm, which had a clearly lesser twist and is chemically finished differently than the other PA twines. Despite this peculiarity, it was decided to subject this twine to the same tests as the other twines. The stress that occurred during the tensile process was determined as the quotient of the acting force, in this case – tensile force, and the area of the sample transverse cross-section, which depends on the thickness (diameter) of the samples.

The dependence of tensile stress  $\sigma$  on relative elongation  $\varepsilon$  is described by the formula in which the coefficient of proportionality is elasticity modulus  $E$  (Young's modulus - e.g., Kurowski and Niezgodziński 1955):

$$\sigma = E \cdot \varepsilon$$

where:

$$\varepsilon = \frac{\Delta l}{l}$$

$\Delta l$  – increase of sample length;  
 $l$  – sample length.

The elasticity modulus can be calculated from the following dependence:

$$E = \frac{\sigma}{\varepsilon}$$

In order to simplify the problem, the shape of the twine cross-section was assumed to be circular, thus stress can be calculated from the dependence:

$$\sigma = \frac{F}{S}$$

$F$  – tensile force,  
 $S$  – total area of the twine elements transverse cross-section.

Where  $S$ , in this case, should be calculated as the sum of the transverse cross-section area of filaments which the twine consists of, according to dependence below:

$$S = \frac{\Pi \cdot d_f^2}{4} \cdot n$$

$d_f$  – filament diameter (thickness)  
 $n$  – number of individual filaments in the netting twine.

### Determining twine stiffness $EJ$

As was mentioned, in the science of material strength, stiffness is expressed as the product of the elasticity modulus ( $E$ ) and the moment of inertia ( $J$ ). The procedure for determining the elasticity modulus  $E$  in polyethylene (PE) or polyamide (PA) twines is given above. The moment of inertia of twine transverse cross-sections, given an assumed circular cross-section, can be calculated from the following formula (*e.g.*, Kurowski and Niezgodziński 1955):

$$J = \frac{\Pi \cdot d^4}{64}$$

where  $d$  is the twine diameter (thickness), for which this value is calculated.

The value of stiffness  $EJ$ , or the “resistance” of the twine to flexion can be calculated with the following dependence:

$$EJ = E \cdot \frac{\Pi \cdot d^4}{64}$$

This formula shows that twine made of the same material (constant elasticity modulus  $E$ ), but of a larger diameter (thickness –  $d$ ) is stiffer than twine with a smaller diameter. The impact of diameter on stiffness is very significant due to the  $d$  power which is 4. If it is assumed that:

$$\begin{aligned} d = 3 \text{ mm,} & \quad \text{then } d^4 = 81; \\ d = 4 \text{ mm,} & \quad \text{then } d^4 = 256; \\ d = 6 \text{ mm,} & \quad \text{then } d^4 = 1296; \\ d = 8 \text{ mm,} & \quad \text{then } d^4 = 4096. \end{aligned}$$

This simple example illustrates what a significant impact the diameter of the mesh bar has on its stiffness (resistance to mesh opening). Compared to the mesh bar that has a diameter of 3 mm, the mesh bar with a diameter of 4 mm is more than three times stiffer while that with a diameter of 8 mm is over fifty times stiffer. The assumed thicknesses were not unrealistic. Netting with such mesh bar thicknesses were applied in the past in the manufacture of trawl codends used in cod fisheries. Considering that it is possible to introduce materials of increasing elasticity moduli, it must be pointed out how ample the opportunities are for netting manufacturers and fishermen to protect resources, and if, consciously or not, they have no intension of doing so, they are leading to the destruction of both the fish and themselves.

### Impact of the value of stiffness $EJ$ on mesh bar deflection

The theoretical method developed to determine the shape of open mesh (Moderhak 2005) gives the dependence of mesh bar deflection in the function of parameters  $k$ ,  $l$ ,  $q$ ,  $P$  for coordinate  $x$  on the mesh bar:

$$\text{where: } k = \frac{1}{2 \cdot E \cdot J} \quad y = \int_0^x \frac{f(l, q, P, x)}{\sqrt{\frac{1}{k^2} - [f(l, q, P, x)]^2}} dx$$

$y$  – mesh bar deflection;

$l$  – mesh bar length;

$q$  – hydrodynamic pressure acting on the mesh bar;

$P$  – force exerted on the end of the mesh bar;

$x$  – current coordinate,

$f(l, q, P, x)$  – function resulting from bending moments (acting on the mesh bar) equation integration.

Assuming that parameters  $l$ ,  $q$ , and  $P$  are constant, it can be stated that the stiffness of the mesh bar twine of the netting (sea value  $k$  that is a function of  $EJ$ ), impacts to a great degree the deflection function  $y(x)$  (shape of the bent mesh bar). In this function,  $k$  ( $EJ$ ) impacts the value of the denominator. The greater the stiffness, the smaller the value of the integrand and thus the value of the deflection of mesh bar  $y$  is also smaller. Assuming that the elasticity modulus  $E$  of a given material is constant, it becomes clear just how significant an impact twine diameter (thickness) has on the deflection of the mesh bar. At the risk of oversimplification, mesh bar bending is inversely proportional to the square of its diameter. For example, while being towed through the water the openings of netting meshes with a bar diameter (thickness) of 6 mm can be twice as small as the same sized netting made of twine with a diameter (thickness) of 4 mm. Increasing the mesh bar diameter to 8 mm causes a four time decrease in mesh opening in comparison with a mesh bar diameter (thickness) of 4 mm. It follows that a mesh bar with diameter of 6 mm is two and of 8 mm four times “stiffer” than that of 4 mm.

The rest of the parameters also have an influence on the deflection value of the mesh bar. The degree of impact of particular twine and force parameters have on the opening of meshes is defined by the function  $y = y(E, J, l, q, P, x)$ .

### Tests on the breaking strength of 90° turned meshes compared to that of diamond (standard) meshes – in dry state

In recent years the Institute for Fishing Technology and Fishery Economics (IFF) in Hamburg has performed numerous tests on a variety of actual trawl codend netting material in order to determine the breaking strength of 90° turned and standard (diamond) meshes. Ten series were conducted on samples of both turned and standard meshes.

A detailed description of the breaking tests procedure was presented earlier (Modershak 2000). Generally, the procedure differs from the ISO standard. In this case, the meshes were tensile from the “outside” not from the “inside”. In reality (during towing through water), particular meshes of the netting are subjected to a load derived from the surrounding meshes. This reflects the real state of mesh tensile during fishing. It has been proven (although as yet unpublished) that both manners of tensile, from “inside” and “outside”, giving different breaking results for meshes extracted from the same piece of netting.

The detailed analysis of the tests that were made on the tensile force of the meshes was conducted identically to that of the twine. The breaking strength of turned and standard meshes was determined for the following variety of netting made of single twines:

polyethylene (PE):

- mesh opening – 95 mm, bar thickness 3.6 mm;
- mesh opening – 100 mm, bar thickness 2.7 mm;
- mesh opening – 105 mm, bar thickness 3.5 mm;
- mesh opening – 105 mm, bar thickness 4.0 mm;
- mesh opening – 130 mm, bar thickness 6.0 mm;

polyamide (PA):

- mesh opening – 100 mm, bar thickness 3.0 mm;
- mesh opening – 100 mm, bar thickness 4.2 mm;
- mesh opening – 120 mm, bar thickness 3.5 mm.



## TEST RESULTS

Figures 1 and 2 illustrate examples of twine stretching separately for PE and PA. They present the breaking process recreated from the original paper ribbon readouts – the mean value of stretching force for 20 attempts of breaking of every variety of twine were read-out for every 2.5 mm of ribbon movement, *i.e.*, for every 2.5 mm of sample elongation. In this respect, the course of breaking recreated from readouts differs slightly from that recorded on the paper ribbon in the range in which the stretching force is close to or greater than the breaking force. Naturally, the points read from the tape cannot fully represent the dynamic process of breaking itself, although it can give a proper picture of increasing tension in the sample. This systematic process of increasing force acting on the sample and the accompanying increase in its length are the area of interest in the search for the values of the elasticity modulus of various twines used in the manufacture of netting for trawl codends.

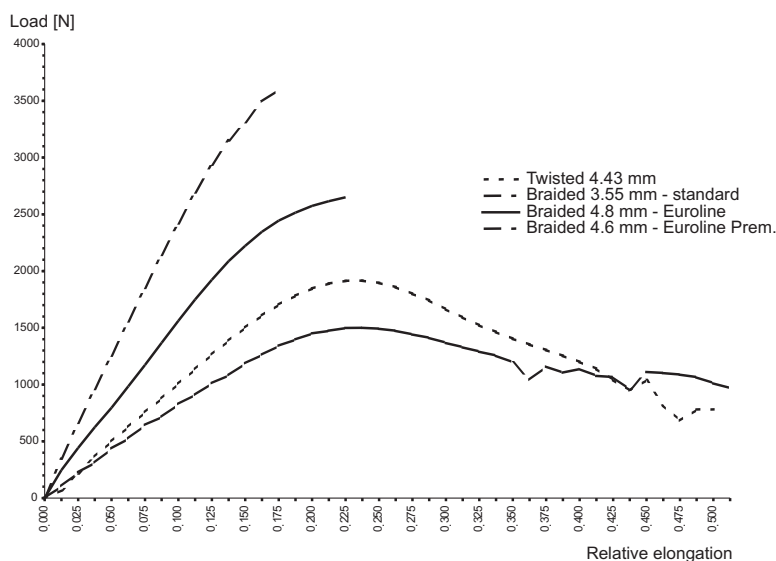


Fig. 1. Curves of polyethylene (PE) twine breaking strength.

The curves (Fig. 1 and 2) show the values of force as a function of the relative elongation. The comparison of the various curves reveals that there is good conformity in the shape of them for each type of material. As regards the PE curves, the stretching force in the initial period is proportional to relative elongation, while this is less evident with respect to PA, the shape of which is slightly concave (attention: the scale differs significantly on the two graphs).

The elasticity modulus for PE and PA twines was obtained from calculations done according to the given method and within the assumed range of proportionality (Figs. 3 and 4). These curves indicate that, in most cases within the analyzed range, elasticity modulus  $E$  can be considered as constant. Disregarding certain differences that occurred in the initial stretching period and certainly resulted mainly from decreasing twine thickness

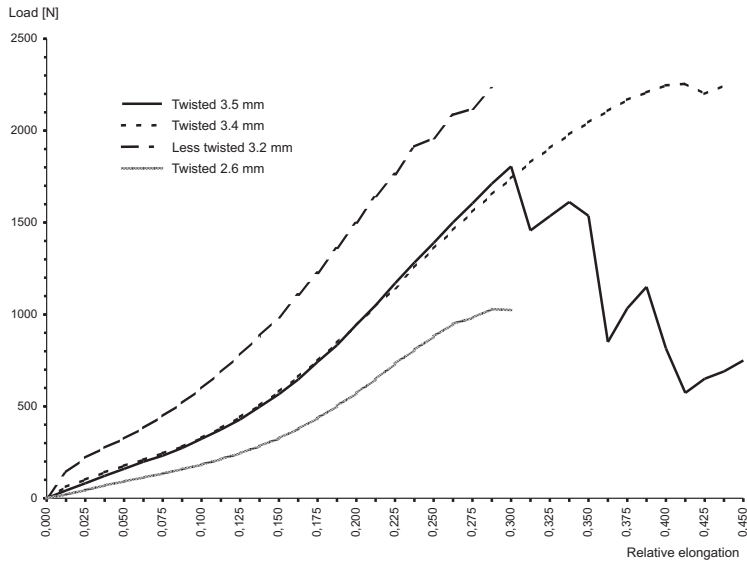


Fig. 2. Curves of polyamide (PA) twine breaking strength.

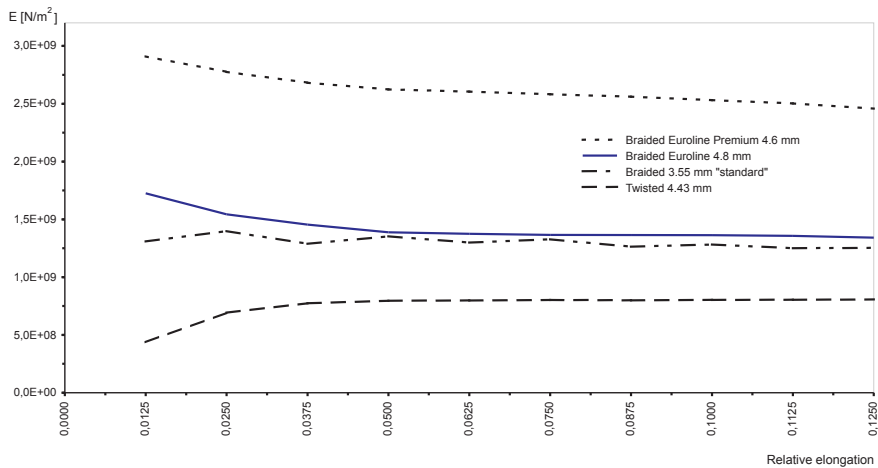


Fig. 3. Elasticity modulus (Young's) of polyethylene (PE) twine.

(taking up the slack between fibers or filaments), it can be stated that only the less twisted PA twine exhibited a fairly significant difference in the elongation range to about 0.050, after which the value of this parameter stabilized and became constant for the analyzed range of elongation.

The average elasticity modulus  $E$  (Young's modulus) of twines investigated in a dry state can be read from the curves presented. Within the polyethylene group, there were distinct differences for the modulus of the braided Euroline Premium twine and less for twisted twine. It is possible that in this case of modified PE monofilaments another type

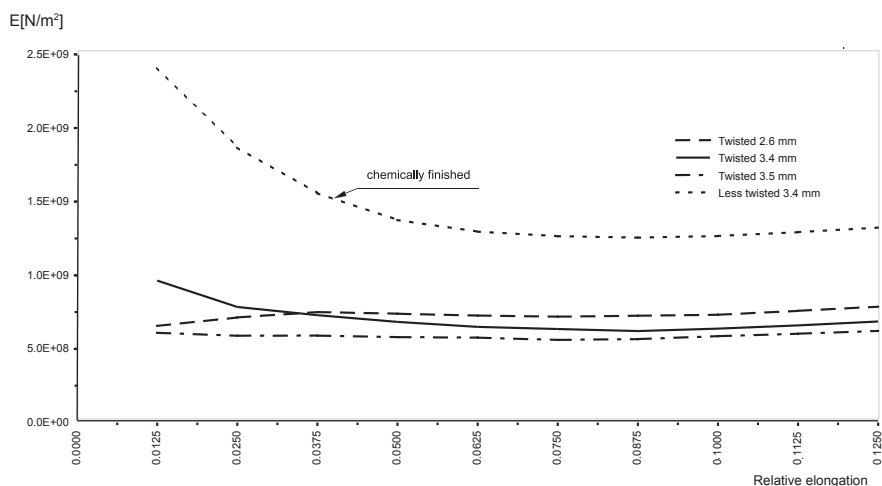


Fig. 4. Elasticity modulus (Young's) of polyamide (PA) twine.

of chemical fiber was used in the core. As regards the polyamide (PA) fibers, the highest elasticity modulus was obtained for the twine with the lesser amount of twist and chemically finished. The remaining twines, within the given relative elongation range, had an elasticity modulus that was nearly constant and similar in value.

The elasticity modulus  $E$  ( $\text{N} \cdot \text{m}^{-2}$ ) indicated below was calculated based on the tests:

polyethylene (PE):

- $8.0 \cdot 10^8$  twisted twine, thickness 4.43 mm;
- $1.28 \cdot 10^9$  braided twine, thickness 3.55 mm – standard;
- $1.36 \cdot 10^9$  braided twine, thickness 4.8 mm – Euroline;
- $2.53 \cdot 10^9$  braided twine, thickness 4.6 mm – Euroline Premium;

polyamide (PA):

- $7.52 \cdot 10^8$  twisted twine, thickness 2.6 mm;
- $1.31 \cdot 10^9$  twisted twine, thickness 3.2 mm – with a lesser twist and chemically finished;
- $6.61 \cdot 10^8$  twisted twine, thickness 3.4 mm;
- $5.94 \cdot 10^8$  twisted twine, thickness 3.5 mm.

Thus, it can be assumed that the average elasticity modulus of the tested twines were, respectively:

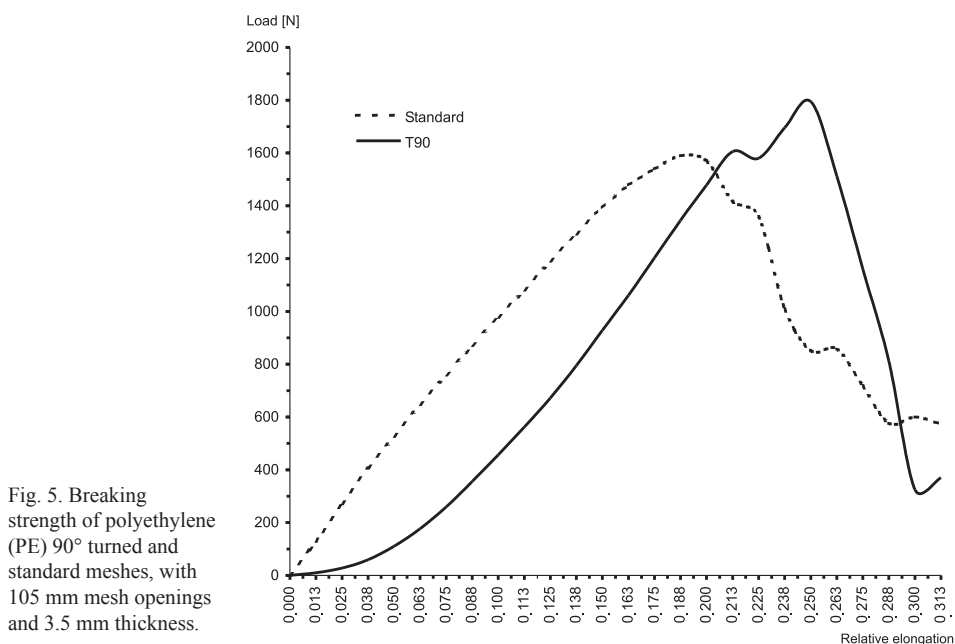
- polyethylene PE –  $8.0 \cdot 10^8$  to  $2.53 \cdot 10^9$   $\text{N} \cdot \text{m}^{-2}$ ;
- polyamide PA –  $5.94 \cdot 10^8$  to  $1.31 \cdot 10^9$   $\text{N} \cdot \text{m}^{-2}$ .

In order to evaluate elasticity modulus  $E$  obtained during tests of polyethylene (PE) and polyamide (PA) twines, the results obtained were compared with values of the elasticity modulus of various materials (e.g. from various types of mechanics handbooks). The following are the Young's modulus of several well-known metal and non-metal construction materials:

polyamide (PA)	$5.9 \cdot 10^8 \text{ N} \cdot \text{m}^{-2}$
leather	$6.9 \cdot 10^7 \dots 3.4 \cdot 10^8 \text{ N} \cdot \text{m}^{-2}$
epoxy resin	$\approx 3.32 \cdot 10^9 \text{ N} \cdot \text{m}^{-2}$
canvas reinforced with plastic	$5.9\text{-}8.8 \cdot 10^9 \text{ N} \cdot \text{m}^{-2}$
wood	$\approx 1.18 \cdot 10^{10} \text{ N} \cdot \text{m}^{-2}$
copper	$1.1 \cdot 10^{11} \text{ N} \cdot \text{m}^{-2}$
steel	$2 \cdot 10^{11} \text{ N} \cdot \text{m}^{-2}$

The elasticity modulus values of netting twine that were estimated based on tests relate well with the values for other materials. The comparison of the values of polyamide (PA) twine with values reported in the literature for this type of artificial material (the product type was not specified) indicated that the procedure applied in the current tests to determine the elasticity modulus of twine products was appropriate. This procedure allowed for determining correctly the value of these mechanical parameters, which have a significant impact on the selective properties of netting constructions used in fisheries.

Calculations conducted of stiffness  $EJ$ , based on  $E$  values obtained during the study and the assumed thickness of twines, are one to two orders higher than values reported in the literature. There are only a few related studies which considered the stiffness of netting (meshes), but not twine stiffness. O'Neill and Xu (1994) and Priour *et al.* all present stiffness determined from back calculations of the forces required to open netting meshes. The values for PE meshes obtained by these authors range from about 0.00005 to about 0.0017  $\text{N} \cdot \text{m}^2$  while the stiffness determined during the study for PE mesh bars ranged from about 0.01 to about 0.055  $\text{N} \cdot \text{m}^2$  and for PA twines from about 0.0017 to about 0.0044  $\text{N} \cdot \text{m}^2$ . The differences probably stemmed from differences in the behavior of both whole meshes and mesh bars (i.e., twine) during tensile processes.



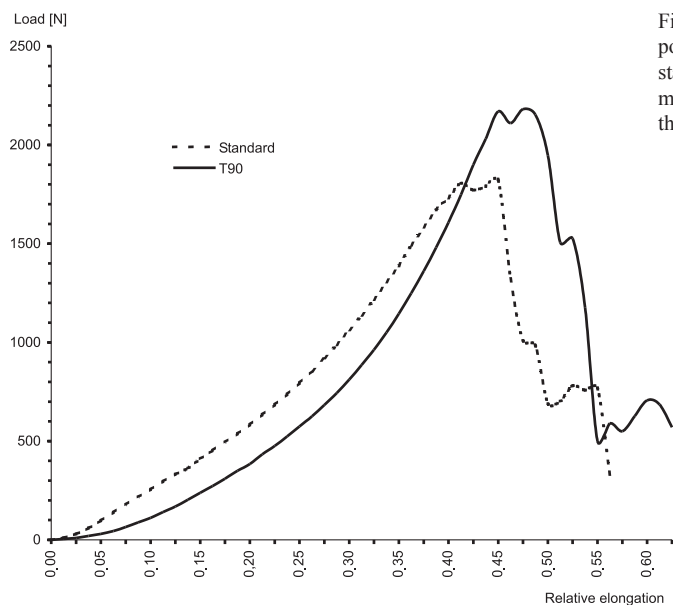


Fig. 6. Breaking strength of polyamide (PA) 90° turned and standard meshes, with 120 mm mesh openings and 3.5 mm thickness.

The breaking tests on netting meshes indicated that greater strength was exhibited by turned than standard meshes made from the same netting material in all the test series (both PA and PE materials). Sample elongation curves, the average from a series of tests on the same material, are presented in Fig. 5 for polyethylene mesh with an opening of 105 mm and a bar thickness of 3.5 mm, and in Fig. 6 for polyamide mesh with an opening of 120 mm and a bar thickness of 3.5 mm. The curves of tensile and the proportions of breaking strength of these two meshes that were stretched differently confirmed the results of previous tests (Moderhak 2000). The increased breaking strength of the turned meshes as compared with standard meshes in both material categories (PE and PA) is similar and ranges from approximately 10 to 25% depending on the construction of the netting material and twine diameter (Moderhak 2000).

The tensile curves indicate clearly that turning the meshes 90° increases the elasticity of the mesh as is depicted by the shift of the curve to the right of that of the standard meshes. The elasticizing of the turned meshes made of polyethylene (PE) was significant, while this occurred to a slightly lesser degree in the materials made of polyamide (PA).

## DISCUSSION

It is not necessary to be absolutely sure that the mesh opening process occurs precisely according to well-known theory in order to estimate the selectivity of a given netting material. It is sufficient to be sure that significant error is not made when adapting the existing theory for determining mesh openings. Conversely, certain assumptions inherent to

theoretical calculation methods mean that the results obtained more or less reflect reality. It is important to choose the appropriate method to solve the problem without neglecting economic considerations or the speed at which the method can be executed.

The comparison of results obtained during tests of total strength, *i.e.*, maximum breaking strength, indicates that the PA twine is more resistant than PE twine of identical thickness. Polyamide twine broke at a much higher relative elongation than did polyethylene twine. These tests confirm the widely held opinion that polyamide twine is stronger and more elastic than polyethylene twine. In addition to differences in the construction of the two twines (the PA twines are mostly twisted and are made of thin fibers, while PE twines are usually braided with a core and a cover made of considerably thicker filaments), the load and its distribution on particular components of the twine have great influence on the total strength of the twines. This means that not all of the filaments of the braided PE twine are equally loaded, as is probably the case with the twisted polyamide twine. As mentioned previously, the first component of braided PE to break is the core, which, as the less elastic, bears a greater share of the force acting on the stretched twine. The next element to break is the cover, as its construction is more elastic.

The quite wide ranges of the elasticity modulus  $E$  obtained in the tests occurred primarily due to the various properties of the artificial materials used in the manufacture of the fibers or filaments, and less due to construction differences. The exception might be chemical finishing and the twist in twisted PA products. The period of time elapsed following twine production as well as the way in which it was stored are also significant. It is known that "age" has a destructive impact on the properties of fibers and filaments manufactured of artificial materials as does, for example, solar radiation (Blady 1979, 1980). Neither the "age" of the tested samples used in the current tests nor the manner in which they were stored were known.

The results of calculations of the twine elasticity modulus coincide well with values from the literature. This could be verified by comparing the values of the elasticity modulus of the polyamide that were obtained with those of parameters published in the professional literature. The comparison verifies that this method can be applied to determine the shape of the meshes with theoretical calculations, especially the shape of T90 meshes.

Applying calculations to estimate the selective and protective properties of particular netting products used in the manufacture of fishing gear accelerates suitability analyses and the subsequent implementation of new constructions in commercial exploitation, thus ensuring that marine living resources can be properly protected in a timelier manner.

Turning the meshes by  $90^\circ$  in relation to the standard orientation permits increasing the breaking strength of the meshes in both the PE and PA material groups from about 10 to 25%. Turning the meshes also results in increased mesh elasticity, which is seen in the shift of the tensile strength curve to the right of the standard meshes curve. Considerable elasticizing of the turned meshes occurs in the polyethylene (PE) twine, while that in the polyamide (PA) twine is slightly lower.

Generally, the method presented in article can be used to determine the shape of mesh openings in particular netting material. However, the problem of how to determine the proper twine diameter remains. From calculations conducted for this project, it appears necessary to treat the diameter (thickness) dually. The proper way to calculate stress during tensile tests appears to be to sum the cross-sections of all the twine filaments.

However, to calculate the moment of inertia  $J$ , the diameter (thickness) obtained from measurements of total twine diameter taken with a special micrometer should be used. Therefore, further tests of netting twines are necessary in order to verify the values of the Young modulus that were obtained.

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## Variability of surface chlorophyll *a* and deep chlorophyll *a* maximum in the North Atlantic

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**Abstract.** The seasonal and spatial distribution of surface chlorophyll *a*, the deep chlorophyll *a* maximum (DCM), and integrated chlorophyll *a* were studied based on samples collected during ten oceanic cruises in the North Atlantic between 1980 and 1987. These data were related to the physical structure and nitracline. Seasonal variations were present and were more pronounced in surface chlorophyll *a* (with greater values in winter), while integrated chlorophyll *a* concentrations remained more constant, and the deep chlorophyll *a* maximum was always present. The current data suggest some geographical trends: surface chlorophyll *a* concentrations presented a more pronounced decrease to the south than the integrated chlorophyll *a* and deep chlorophyll *a* maximum concentrations and increased depth of the DCM and nitracline to the south.

**Key words:** Euphotic zone, nitracline, DCM, North Atlantic

### INTRODUCTION

The present work is based on oceanographic information collected from ten cruises carried out in the Atlantic Ocean during different months near the Gorringe, Ampère, Lion, Seine, and Unicorn banks and NE Arq. Madeira, (abbreviated to NE Madeira) located in the waters of the Portuguese EEZ. Sampling was conducted in the open ocean far from the continental Portuguese coast so no horizontal transports of nutrients and organic matter from river outflow and upwelling were present.

The main objectives of the cruises were studies of fishing technology and oceanographic conditions. It is widely known that banks are excellent fishing grounds. The fishing gear used was a long line, and the main species studied was *Aphanopus carbo* Lowe, 1839 (black scabbard fish) (Cavaco and Pissarra 1982, 1984a, b, c), which inhabit the slopes of the banks.

The zone around these banks (Fig. 1) can be characterized as oligotrophic with surface chlorophyll concentrations of less than  $0.15 \text{ mg} \cdot \text{m}^{-3}$  throughout the year, a well-developed deep chlorophyll maximum (DCM) normally close to the nitracline (the depth at which the nitrate concentration is about  $1 \mu\text{M}$ ), and a euphotic zone of 50-60 meters.

The data collected over seven years in these oligotrophic waters provide some knowledge of an oceanic area where only a few studies have been conducted. The majority of



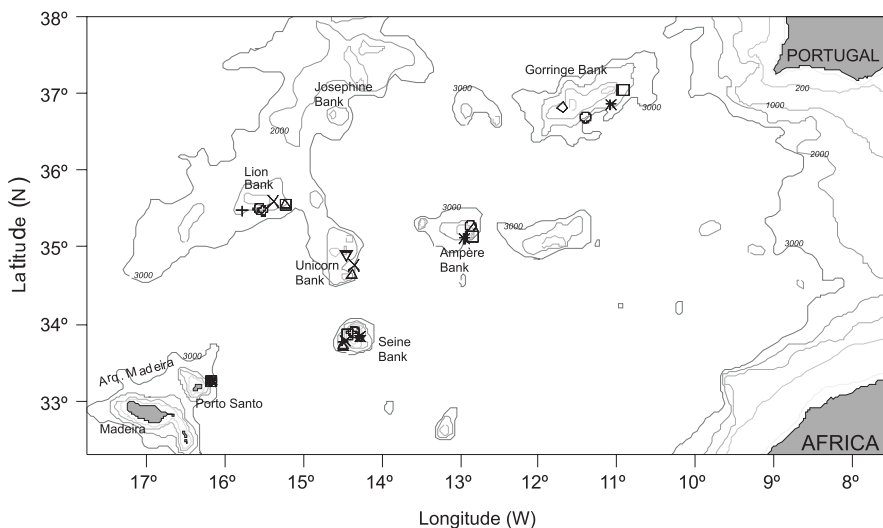


Fig. 1. Location of sampling stations during the different cruises.

previous research was carried out in the Tropical Atlantic Ocean (Herbland *et al.* 1979, Herbland 1983) and which assessed some aspects of the relationship between the vertical distribution of chlorophyll *a* (chl *a*) and hydrological structure. Other oligotrophic systems, such as the Mediterranean Sea, have been studied (Estrada *et al.* 1993, Raimbault *et al.* 1993, Yilmaz *et al.* 1994, Yacobi *et al.* 1995), and the DCM feature normally appears to be associated with the euphotic zone. The California area has also been studied for several years (Millan-Núñez *et al.* 1996), and some empirical relationships were found among these variables.

The purpose of this paper is to describe the spatial and temporal distribution of surface chlorophyll *a*, the DCM, and integrated chlorophyll *a* concentrations to verify their relationships and to attempt to relate them to physical and chemical parameters in the water column.

## MATERIALS AND METHODS

Ten cruises were conducted aboard the R/V Noruega between June 1980 and September 1987, and 101 oceanographic stations were monitored in the six studied areas (Fig. 1).

The cruises coincided with the four seasons – spring (April/May), summer (June), fall (September), and winter (November) (Table 1).

Water samples for salinity and nutrient analysis were collected with Nansen bottles equipped with reverse thermometers from the surface to 1800 meters (bottom depth normally exceeded 2000 meters). Samples for chlorophyll *a* determinations were collected with Niskin bottles at ten depths between the surface and 200 meters.

Water samples for nutrient analysis were stored at  $-20^{\circ}\text{C}$  and the determinations were made with a Technicon AAI three channel autoanalyzer according to the methods of Technicon Industrial Systems (1977a).

Table 1. Cruise codes, dates, and sites sampled

Cruise	Date	Sampling sites
020170680	19-20 June 80	Seine, NE Madeira
020330981	02-11 September 81	Gorringe, Ampère, Seine, NE Madeira
020390582	10-19 June 82	Lion, Seine, NE Madeira
020451182	24 Nov – 03 Dec 82	Gorringe, Ampère, Seine, Lion
020480583	11 - 27 May 83	Gorringe, Ampère, Seine, Lion, NE Madeira
02100984	04 -17 September 84	Ampère, Unicorn, Seine, Lion, NE Madeira
02010485	24 April – 03 May 85	Lion, Seine, NE Madeira
02100986	05-13 September 86	Seine, Lion, Unicorn
02121186	06 - 09 November 86	Gorringe
02110987	04 September 87	Unicorn

Salinity was calculated from conductivity measurements carried out with a Beckman RS9 salinometer. Sigma-t was determined from temperature and salinity using algorithms described in Fofonoff and Millard (1981). For chlorophyll *a* analysis, 250 ml of sample was filtered through Sartorius filters (0.45  $\mu$ , Ø 47 mm), extracted with 90% acetone (24 h), and measured with a Perkin-Elmer fluorometer (Yentsch and Menzel 1963). Calibration was done with pure chlorophyll *a* from SIGMA. Integrated total chlorophyll *a*, expressed as  $\text{mg} \cdot \text{m}^{-2}$ , was calculated from the surface down to 200 meters. Measurements with a Secchi disk 30 cm in diameter were done in order to determine the depth of the euphotic zone.

## RESULTS

The analysis of 100 chlorophyll profiles showed a deep maximum occurring at each station, and the concentration was always higher than at the surface, which is characteristic of oligotrophic waters.

### Seasonal variability

The mean surface chlorophyll *a* showed typical seasonal variations characteristic of temperate waters with higher values ( $0.11 \text{ mg} \cdot \text{m}^{-3}$ ) in winter that were 2.5 times those of summer. Chlorophyll *a* measured at DCM was three to four times the value of the surface waters except in winter (Table 2).

Table 2. Average values  $\pm$  SE of DCM (m), nitracline (m),  $\Delta\sigma_t$  ( $\text{Kg} \cdot \text{m}^{-3}$ ), surface chlorophyll *a* ( $\text{mg} \cdot \text{m}^{-3}$ ), and chlorophyll *a* concentration at the DCM ( $\text{mg} \cdot \text{m}^{-3}$ )

	N	DCM		Nitracline		$\Delta\sigma_t$		$\text{Cla}^{\text{sur}}$		$\text{Cla}^{\text{DCM}}$	
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Spring	20	84	$\pm 11$	90	$\pm 20$	0.16	$\pm 0.08$	0.08	$\pm 0.02$	<b>0.30</b>	$\pm 0.11$
Summer	10	<b>98</b>	$\pm 4$	<b>112</b>	$\pm 20$	0.65	$\pm 0.08$	0.04	$\pm 0.02$	0.18	$\pm 0.05$
Fall	30	89	$\pm 23$	95	$\pm 19$	<b>1.14</b>	$\pm 0.26$	0.04	$\pm 0.03$	0.13	$\pm 0.01$
Winter	15	74	$\pm 19$	68	$\pm 4$	0.22	$\pm 0.09$	<b>0.11</b>	$\pm 0.02$	0.17	$\pm 0.03$

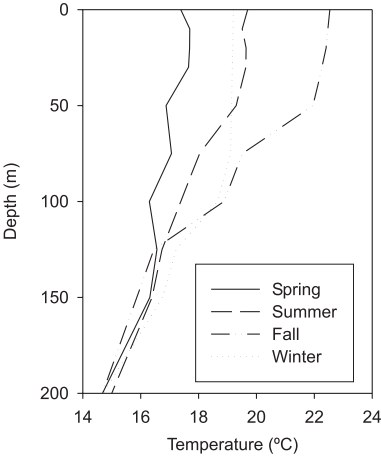


Fig. 2. Vertical distribution of temperatures throughout the year.

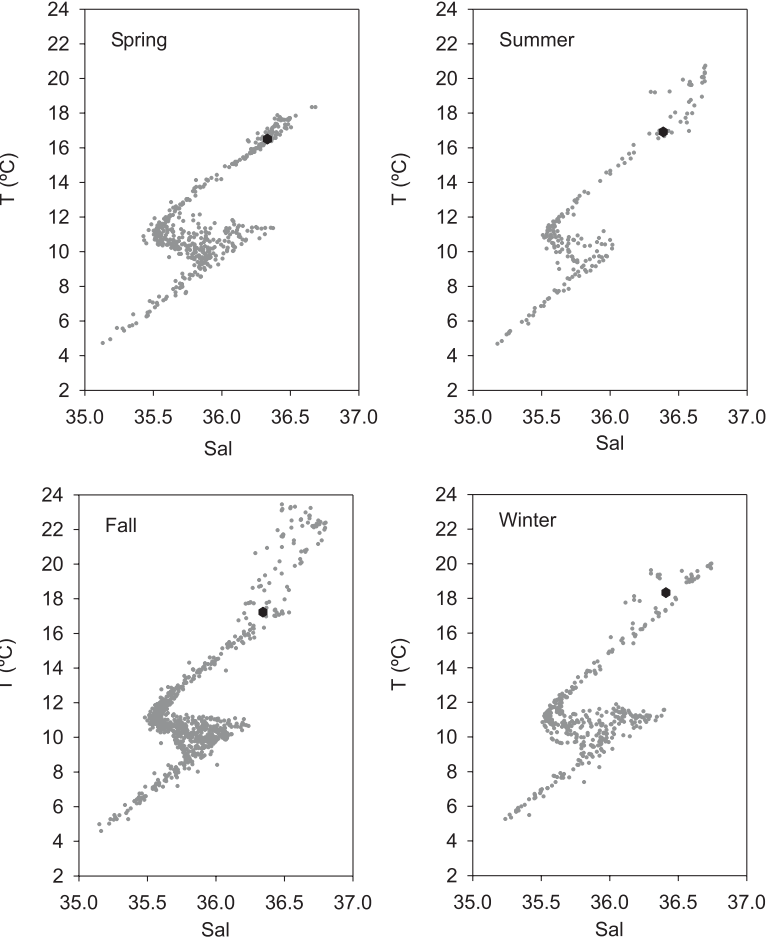


Fig. 3. T/S diagrams (• DCM localization).

Values of chl *a* at the surface and the DCM did not reach their maximums at the same times during the studied period.

Higher values of the density gradient  $\Delta\sigma_t$  ( $\sigma_t^{\text{DCM}} - \sigma_t^{\text{sur}}$ ) (Table 2) were obtained in summer and fall, when average surface chlorophyll *a* was at the minimum. This suggests the limited exchange of nutrients between the surface and deep layers. Seasonal thermoclines were observed in summer and fall ( $0.23^\circ\text{C}/10\text{ m}$  and  $0.34^\circ\text{C}/10\text{ m}$  – Fig. 2) and were associated with the deepening of the chlorophyll *a* maximum (Table 2).

Depth integrated chlorophyll *a* concentrations ranged from 12 to 23  $\text{mg} \cdot \text{m}^{-2}$  (fall and spring) and concurred with values noted in the North Atlantic Ocean (Bahamón *et al.* 2003).

The four T/S diagrams (Fig. 3) provide a glimpse of the different water mass distributions and the DCM in the North Atlantic Central Water location. The representation of the DCM on the diagrams can help to explain the major influence of physical parameters and the different surface layers that are observed in the four seasons. The dispersion points on the surface layers summarize seasonal and latitudinal effects.

## Spatial variability

The average profiles for each zone were calculated in order to analyze the latitudinal change in chlorophyll.

The results illustrated in Fig. 4 show that the change (north-south) in the concentration of chlorophyll *a* at the surface ( $0.09\text{--}0.04\text{ mg} \cdot \text{m}^{-3}$ ) decreased by more than 50% in comparison with the concentration of chlorophyll *a* at the DCM ( $0.23\text{--}0.15\text{ mg} \cdot \text{m}^{-3}$ ) or integrated chlorophyll *a* ( $19\text{--}13\text{ mg} \cdot \text{m}^{-2}$ ). This was very pronounced at Lion Bank.

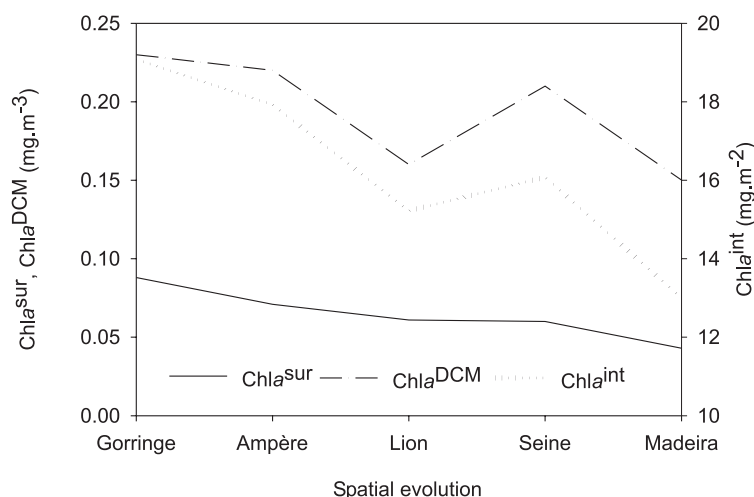


Fig. 4. The distribution of average values of chlorophyll *a* at the surface and the DCM and integrated chlorophyll *a* at the studied sites.

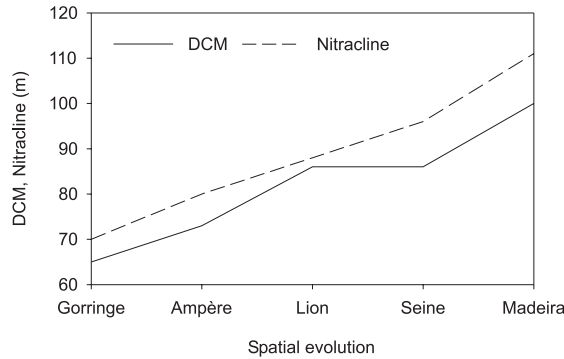


Fig. 5. The distribution of the average values of the DCM and the nitracline at the studied sites.

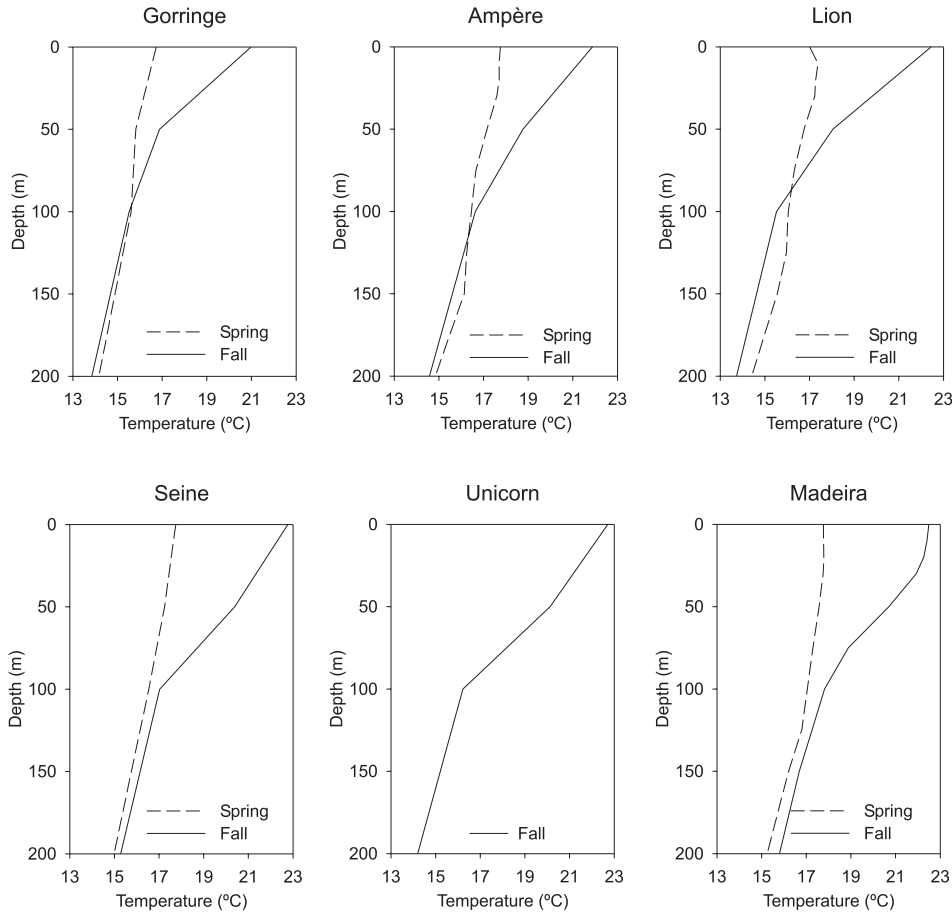


Fig. 6. Vertical distribution of temperatures at the studied sites.

The depth of the DCM was between 65 and 100 meters and was close to the nitracline (70-110 m); the distance between them increases to the south, except at Lion Bank (Fig. 5).

The depth of DCM did not correlate with the nitracline at any of the banks, except Gorringe ( $r^2$  0.85).

The influence of temperature on the position of the DCM is presented in figures 6 and 7. The vertical temperature distribution (Fig. 6) was intensely stratified in fall with the highest surface values (21-23°C), while in spring there was no stratification with surface values ranging from 16.7 to 17.7°C.

The vertical profiles illustrated in Fig. 7 show higher values of chl *a* in spring at the surface and a pronounced DCM, which must be related with the absence of thermal stratification, and a clear latitudinal effect can be distinguished.

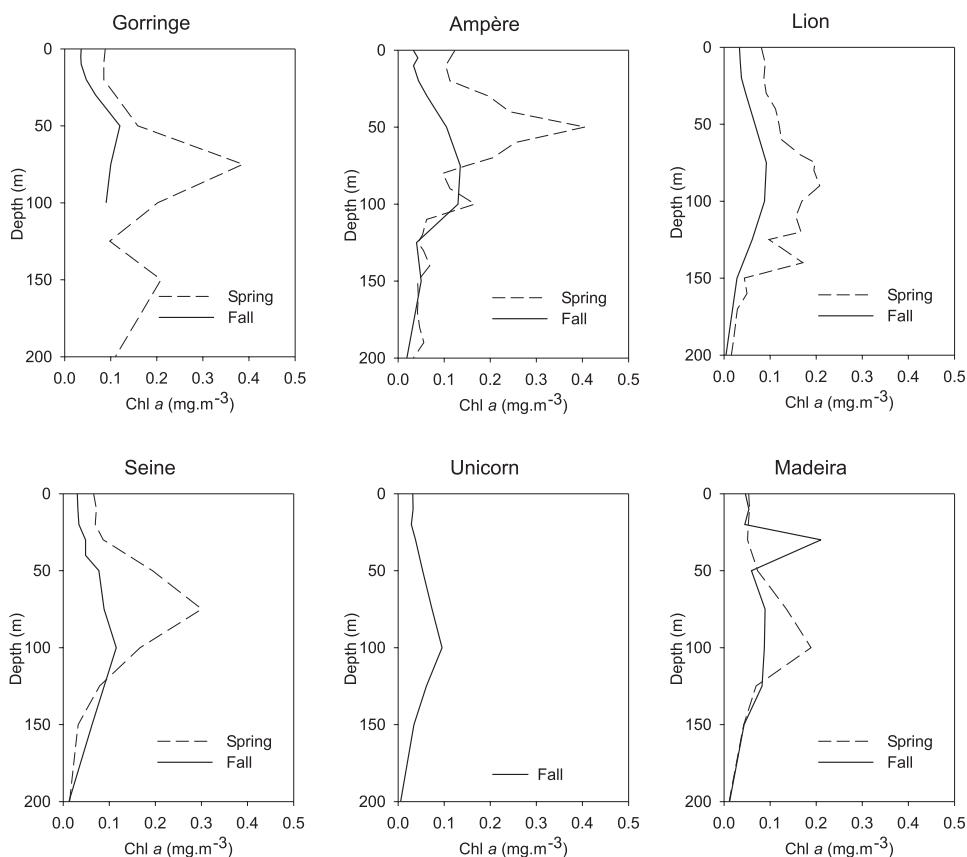


Fig. 7. Vertical distribution of chlorophyll *a* at the studied sites.

Table 3. Relationships between  $\text{Chl}a^{\text{DCM}}$ ,  $\text{Chl}a^{\text{int}}$ , and  $\text{Chl}a^{\text{sur}}$  at the studied sites

Area	<i>n</i>	Relationship	R Square	<i>p</i>
Gorringe	8	$\ln \text{Chl}a^{\text{DCM}} = 0.269 \ln \text{Chl}a^{\text{sur}} - 0.865$	0.088	No
	8	$\ln \text{Chl}a^{\text{int}} = 0.562 \ln \text{Chl}a^{\text{sur}} + 4.24$	0.255	No
Ampère	5	$\ln \text{Chl}a^{\text{DCM}} = 0.725 \ln \text{Chl}a^{\text{sur}} + 0.52$	0.432	No
	5	$\ln \text{Chl}a^{\text{int}} = 0.507 \ln \text{Chl}a^{\text{sur}} + 4.32$	0.610	No
Lion	19	$\ln \text{Chl}a^{\text{DCM}} = 0.515 \ln \text{Chl}a^{\text{sur}} - 0.38$	0.528	<0.02
	19	$\ln \text{Chl}a^{\text{int}} = 0.527 \ln \text{Chl}a^{\text{sur}} + 4.20$	0.726	<0.001
Seine	27	$\ln \text{Chl}a^{\text{DCM}} = 0.277 \ln \text{Chl}a^{\text{sur}} - 0.875$	0.114	No
	27	$\ln \text{Chl}a^{\text{int}} = 0.372 \ln \text{Chl}a^{\text{sur}} + 3.87$	0.402	<0.02
Madeira	6	$\ln \text{Chl}a^{\text{DCM}} = 1.692 \ln \text{Chl}a^{\text{sur}} + 3.12$	0.886	<0.01
	6	$\ln \text{Chl}a^{\text{int}} = 0.176 \ln \text{Chl}a^{\text{sur}} + 3.10$	0.082	No
Unicornio	7	$\ln \text{Chl}a^{\text{DCM}} = 0.14 \ln \text{Chl}a^{\text{sur}} - 1.91$	0.002	No
	7	$\ln \text{Chl}a^{\text{int}} = 0.38 \ln \text{Chl}a^{\text{sur}} + 3.58$	0.067	No
<b>Total</b>	71	$\ln \text{Chl}a^{\text{DCM}} = 0.105 \ln \text{Chl}a^{\text{sur}} - 0.594$	0.226	<0.1
	71	$\ln \text{Chl}a^{\text{int}} = 0.449 \ln \text{Chl}a^{\text{sur}} + 4$	0.467	<0.001

Some of the relationships between  $\text{Chl}a^{\text{DCM}}$ ,  $\text{Chl}a^{\text{int}}$ , and  $\text{Chl}a^{\text{sur}}$  for the different regions were calculated for the 1980-1987 period and for each area (Table 3).

The non-linear relationships among the selected variables were significant for all the data; nevertheless, the lack of correlations among the individual sites may be due to insufficient data.

## DISCUSSION

In the present work deep chlorophyll *a* was clearly observed at all the studied areas and its localization depended on the seasonal cycle.

The current results indicated that the DCM follows the depth of the nitracline as has been described by several authors for the South Tropical Atlantic (Herbland 1983) and the Pacific oceans (Cullen and Eppley 1981). The depth of the nitracline and DCM increased from spring to summer and then decreased until fall, as Estrada *et al.* (1993) reported for the Mediterranean. The seasonal variation of the DCM, with lower values in fall and winter, must be the consequence of reduced light penetration (Yilmaz *et al.* 1994, Radenac *et al.* 1996) and of seasonal stratification.

The latitudinal trend of DCM and nitracline (with deeper chlorophyll maximums and nitraclines) concur with the reports of Augusti *et al.* (1999) from across the Tropical Atlantic and Teira *et al.* (2005) for the Eastern North Atlantic oceans due to changes in surface layer temperatures.

The mean surface chlorophyll *a* values are representatives of oligotrophic waters.

The current results revealed a non-linear relationship between concentrations of integrated chlorophyll *a* and those at the DCM with those of surface chlorophyll *a*; this suggests greater variability in surface chlorophyll *a*. The examinations of these relationships revealed that throughout the study period  $\text{Chl}a^{\text{DCM}}$  and  $\text{Chl}a^{\text{int}}$  changed more slowly than surface concentrations as Augusti *et al.* (1999) suggested.

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## Some biological information on walleye pollock (*Theragra chalcogramma*) from the Sea of Okhotsk (1997-2000) based on Polish commercial catches

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**Abstract.** This work presents the results of biological observations of walleye pollock conducted in the 1997-2000 period in four areas of the Sea of Okhotsk: the TINRO Depression, Deriugin Depression, the area between the Deriugin Depression and western Kamchatka, and Lebed Seachannel. The analyses of the distributions of length, age, and the sexual maturity of walleye pollock indicate that there are certain differences in these parameters among the areas. The walleye pollock from the area of the TINRO Depression had decidedly the smallest length and age ranges as well as the slowest growth rate. During the 1997-2000 period, the number of dominant year-classes in the walleye pollock stock decreased, which was probably the result of intense fisheries exploitation of the pollock stock

**Key words:** walleye pollock, biology, Sea of Okhotsk

### INTRODUCTION

The Sea of Okhotsk is one of the main walleye pollock regions of occurrence in the northern Pacific Ocean. The walleye pollock biomass in the Sea of Okhotsk comprised approximately 80% of the total ichthyofauna biomass, which was estimated in 1988 to be 14 million tons (Shuntov *et al.* 1990). In the early 1990s, walleye pollock catches reached 2.0 million tons annually (Shuntov *et al.* 1993). In the 1991-1995 period, resources of walleye pollock were exploited intensely in the waters outside of the Russian Federation EEZ by fleets from China, South Korea, and Poland. In accordance with bilateral agreements, these fleets have fished the shelf waters of the Russian Federation within its annual catch quota since mid 1995.

Studies conducted by Russian scientists indicate that the population structure of the walleye pollock inhabiting the Sea of Okhotsk has not been fully described. The main reasons are, according to Temnykh (1991), a lack of isolation between spawning grounds and, according to Vdovin and Smirnov (1992), the mixing of fish during feeding. Thus, it is difficult to determine the number of populations in this area, and various authors estimate that there are from two to ten (Temnykh, 1989, 1990, 1991). Generally, it is agreed that in the waters of the northern part of the Sea of Okhotsk there are two basic walleye pollock populations: the western Kamchatka and the northwestern. Fish from both of

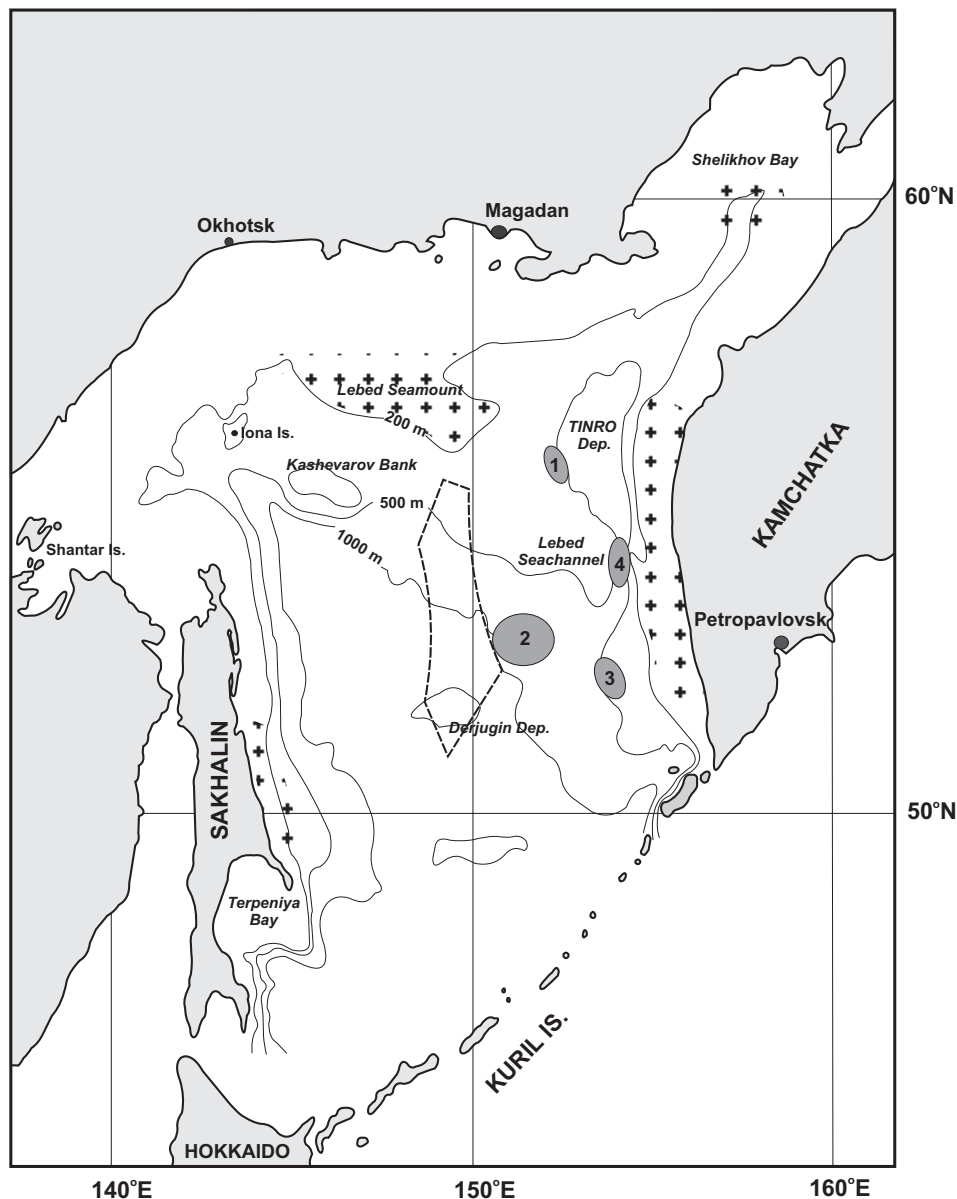


Fig. 1. Walleye pollock study areas in the Russian EEZ of the Sea of Okhotsk in subsequent years: 1 – October–November 1997; 2 – January–March 1999; 3 – February 2000; 4 – February–April 2000. Spawning grounds (according to Fadeev and Smirnov 1987) denoted with crosses and international waters with a broken line.

these stocks migrate throughout the sea and often mix. Only during spawning periods do they migrate to the spawning grounds whose main areas are located in the waters of western Kamchatka and the northwestern part of the Sea of Okhotsk (Fig. 1). The char-

acter of the concentrations noted here, their migration directions, and spawning grounds have also been described by, among others, Satoshi (1978), Vyshegorodtsev (1987), and Fadeev (1995).

Polish catches of walleye pollock in the Sea of Okhotsk were conducted in two periods: the first was from 1991 to mid 1995 when international waters were fished, and the second was from mid 1995 to 2001 in the Russian Federation EEZ. Biological and monitoring studies were conducted along with the catches. The results of the studies from the early 1990s (Janusz and Horbowy, 1997) and those from the later period permit tracking the changes that have occurred in the populations inhabiting this areas.

The aim of this work is to present the biological characteristics of walleye pollock caught by Polish commercial fishing vessels in the 1997-2000 period.

## MATERIALS AND METHODS

The study materials were collected during three cruises on Polish commercial fishing vessels in 1997, 1999, and 2000. The walleye pollock from four areas in the Russian Federation EEZ were studied (Fig. 1). The catch locations were limited due to the disposition of the fishing fleet as prescribed by the fishing license. In 1997, investigations were conducted in the area of the TINRO Depression (area 1). In 1999, they were done near the international waters to the northeast of the Deriugin Depression (area 2). In the second decade of February 2000, investigations were initiated between the international water zone and Kamchatka near the 52°N parallel (area 3), and then continued near Lebed Seachannel (area 4). The catch depth in areas 1 and 4 was from 400 to 480 m, while in the areas 2 and 3 it was from 450 to 600 m.

Length measurements were taken on a total of 32 000 fish, while more than 2100 specimens were subjected to detailed biological analyses (Table 1).

Each measuring event was comprised of approximately 800 individuals chosen at random from the catch. The fish were then sorted by sex, and measurements from the end of the snout to the fork in the caudal fin were rounded down to the nearest cm. Each biological analysis was comprised of 100 fish, of which 80 were chosen at random and 20 were chosen from the least abundant length classes in the catches. Each fish was measured, weighed to the nearest 10 g, sexed, and the state of the gonads was determined according to the eight-stage Maier scale (FAO, 1965). Otoliths were also collected for

Table 1. Characteristics of the study material

Area	Study period	Vessel	Males		Females		Total	
			measure- ment	analysis	measure- ment	analysis	measure- ment	analysis
1	X-XI. 1997	m/t Acamar	2910	152	2965	156	5875	308
2	I-III. 1999	m/t Alphard	2644	116	4633	168	7277	284
3	II. 2000	m/t Amarel	1040	89	1793	111	2833	200
4	II-IV. 2000	m/t Amarel	5898	567	10283	768	16181	1335
Total			12492	924	19674	1203	32166	2127

ageing the walleye pollock at a later date according to the procedure developed and described by a special working group (Anon., 1990).

The von Bertalanffy equation was used to determine growth rate:

$$l_{(t)} = L_{inf} (1 - \exp(-K(t - t_0)))$$

where:

$l_{(t)}$  – fish length at age  $t$  (in cm);

$t$  – age for which length is calculated  $l_{(t)}$ ;

$L_{inf}$ ,  $K$ ,  $t_0$  – parameters calculated based on empirical data,

( $L_{inf}$  – asymptotic length;  $K$  – shape of the growth curve;  $t_0$  – theoretical beginning of growth)

The dependence of weight on body length was described with the equation:

$$W = k \cdot L^n$$

where:

$W$  – fish weight (in g);

$L$  – fish length (in cm);

$k$  – constant;  $n$  – exponent.

## RESULTS

The length of the pollock in the commercial catches ranged from 20 to 81 cm. Only 31 length classes were observed in the catches in area 1 in 1997 and 59 length classes in area 2 in 1999. The mean lengths of males and females were similar in areas 1 and 4 and almost identical in areas 2 and 3. The length frequency for the four areas is presented in Fig. 2.

The age composition of the pollock is presented in Fig. 3, with the age of the fish caught ranging from 2 to 23 years. In area 1 in 1997, seven year classes (from 1993 to 1987) dominated. In 1999, following two years of exploitation in area 2 only, two year classes predominated (1994 and 1993) while the older ones were less notable. The age composition of pollock was similar in 2000 in areas 3 and 4. Two younger year classes dominated (1995 and 1994), and the share of older fish was very small. This age structure meant that the mean age of fish was higher in 1997 and 1999 in areas 1 and 2 and smaller in 2000 in areas 3 and 4. The similarities in structure between areas 3 and 4 stemmed from the fact that the catches were conducted in a similar period of the same year. However, their differentiation in relation to the other areas indicates that between the period of 1997 and 2000 a reduction occurred in the number of older generations of walleye pollock.

The comparison of the growth rates of male and female walleye pollock indicated that they were similar in areas 2, 3, and 4 but lower in area 1. The curve derived from the calculated parameters of the von Bertalanffy equation (Table 2) indicates that the female growth rate was higher than that of the males (Fig. 4).

The weight of the walleye pollock ranged from 70g to 3190g. The average weight of females in the length classes was higher in each area (Table 3). The curve derived from

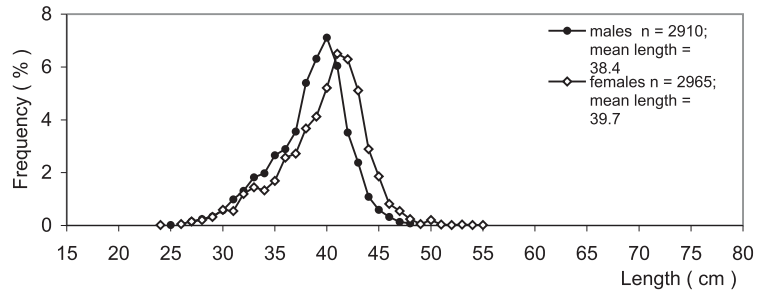
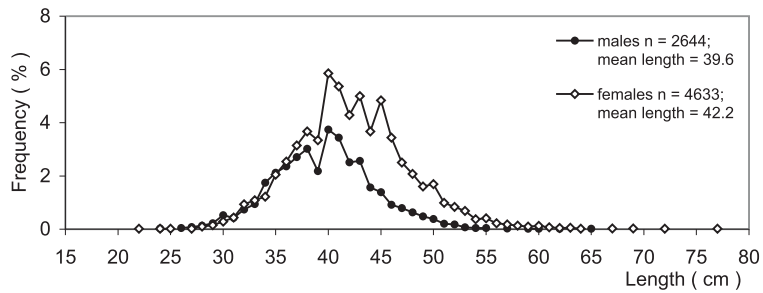
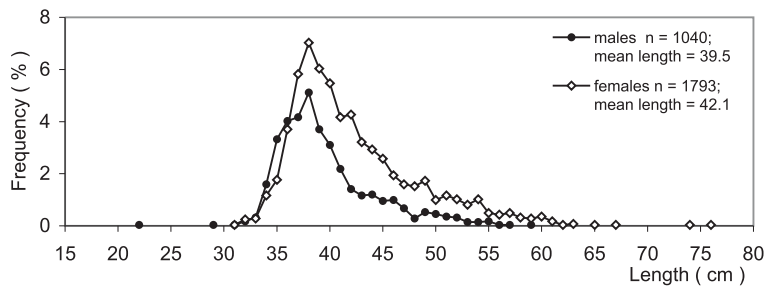
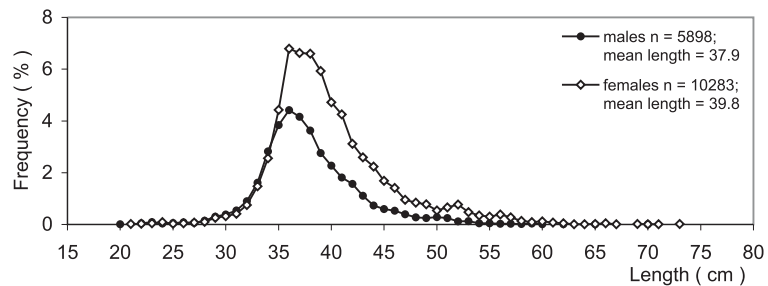
**Area 1****Area 2****Area 3****Area 4**

Fig. 2. Length frequency of male and female walleye pollock according to study area.

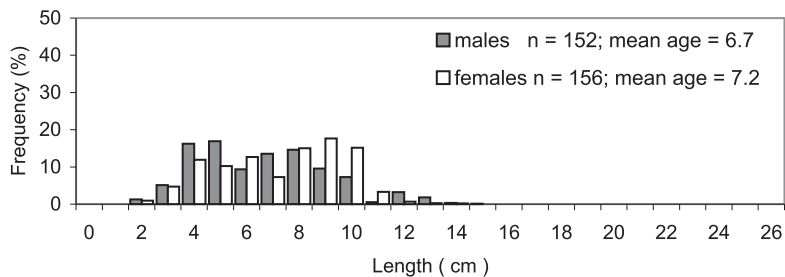
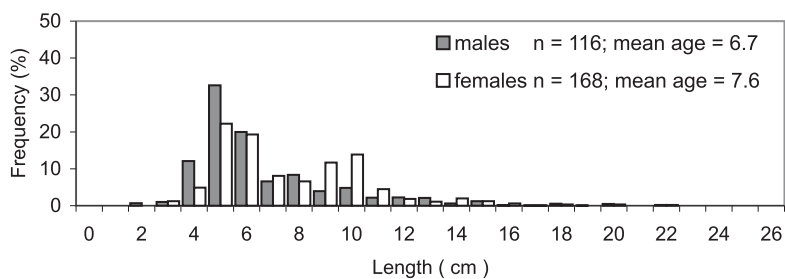
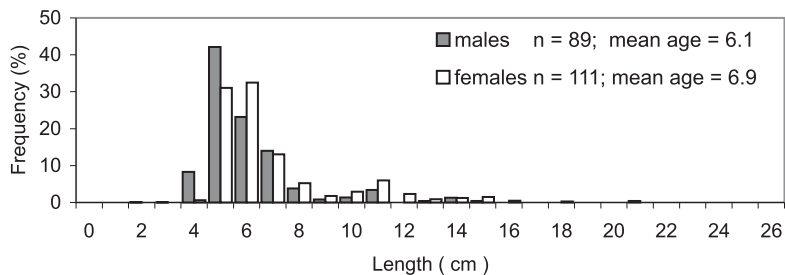
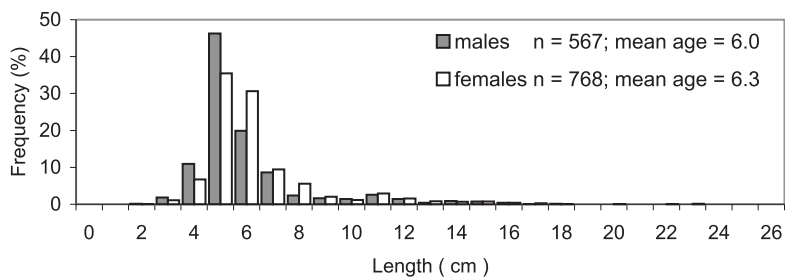
**Area 1****Area 2****Area 3****Area 4**

Fig. 3. Age structure of male and female walleye pollock according to study area.

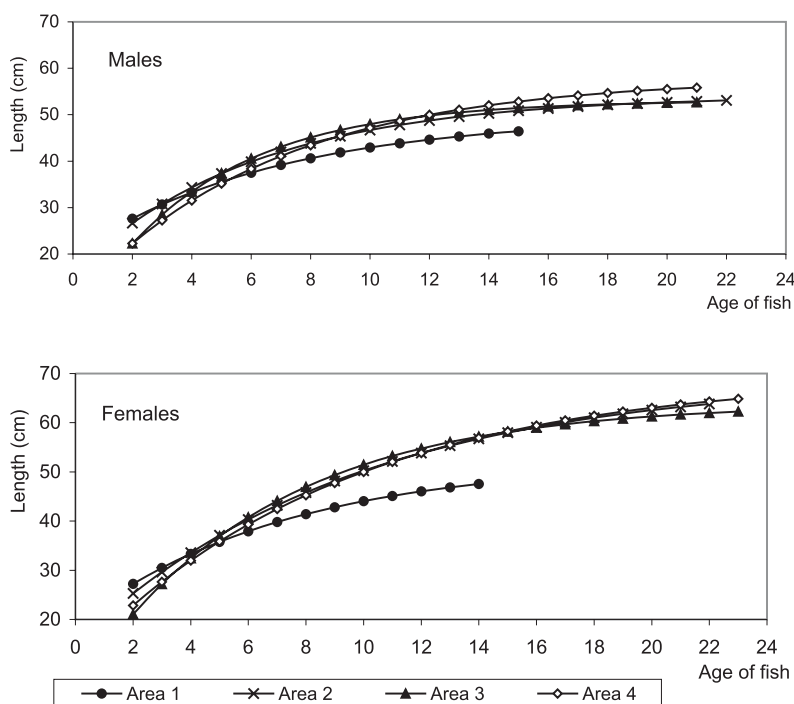


Fig. 4. Growth rate of male and female walleye pollock by study area according to the von Bertalanffy equation.

the individual length-weight dependence indicates that individual weight gain for both males and females was similar in areas 2, 3, and 4, while it was the lowest in area 1. This was particularly evident in the case of the females from this area (Fig. 5).

A similar tendency was also observed in the analysis of the average weight in subsequent years of life (Table 3). In this case, fish weight in areas 2, 3, and 4 was also higher than the analogous weight in area 1, while females were heavier than males. These differences stemmed not only from the varied growth rates of length increase, but also from weight gain caused by the increasing weight of the gonads. Studies in area 1 were conducted during the resting phase and the beginning of the gonad maturation phase (between October and December), while those in the other areas were conducted in the pre-spawning and spawning periods (February to April). The analysis of maturity degree indicated that 71.7% of the male and 94.2% of the female gonads were in the second and third stages of maturity in area 1. In the other areas, maturing or mature (III – VI) specimens dominated (Fig. 6). The number of fish in these maturity stages ranged from 53.3 to 88.8% of the total number of studied specimens. Moreover, only in area 4 were spawning (VI and VII – 17.9%) and spent (VIII – 2.5%) males noted. This leads to the conclusion that this area was located near the spawning grounds.



Table 2. Average length in subsequent years of life and the parameters of the von Bertalanffy equation

Age	Males				Females			
	area 1	area 2	area 3	area 4	area 1	area 2	area 3	area 4
2	27.9	28.5	22.0	22.0	27.3			22.4
3	29.8	29.5	29.0	26.1	30.0	31.5		26.9
4	33.6	33.1	33.3	31.6	33.6	33.5	32.5	32.0
5	36.2	37.1	36.7	36.0	35.9	36.8	37.0	36.4
6	36.9	39.8	40.4	39.7	37.8	39.9	39.4	40.0
7	39.5	43.5	43.4	42.3	39.2	42.8	44.4	43.3
8	40.4	43.3	46.8	44.9	42.1	45.3	47.0	46.4
9	41.7	46.0	47.0	45.9	42.1	44.7	51.5	48.0
10	42.8	45.6	46.3	45.8	43.5	47.2	50.8	50.0
11	45.0	47.8	49.6	46.6	44.8	53.8	53.3	51.5
12	43.6	45.7		50.3	48.3	54.4	54.5	53.6
13	44.3	49.5	50.0	49.3	46.0	58.2	57.0	54.9
14	47.5	50.3	51.0	50.4	47.0	56.4	53.3	56.5
15	46.0	52.8	50.0	50.3		56.3	56.0	58.1
16		56.5		54.5		56.9	63.3	58.8
17		57.0		54.0		69.0		61.0
18		49.5		60.0		67.0	60.0	55.5
19		52.0						
20		50.5				57.5		61.7
21			54.0	55.0				73.5
22		50.0				59.4		64.7
23								61.7
von Bertalanffy equation parameters								
$L_{\text{inf}}$	49.61	54.10	53.08	57.91	52.19	69.20	63.95	69.66
$K$	0.1490	0.1640	0.2250	0.1500	0.1400	0.1049	0.1540	0.1085
$t_0$	-3.457	-2.137	-0.416	-1.237	-3.266	-2.333	-0.593	-1.662

## DISCUSSION

The 1997-2000 walleye pollock studies were conducted in the Russian Exclusive Economic Zone in four areas of the eastern part of the Sea of Okhotsk. Since the fish studied came from commercial catches, the study areas are a reflection of the occurrence of dense concentrations of these fish.

The changes observed in the length distribution and age of the pollock in particular regions should be understood as changes occurring in the pollock stock in the 1997-2000 period rather than changes in the regions in which the samples were collected.

This difference could have resulted from changes in a variety of factors, the most significant of which include intense fisheries exploitation and probably environmental conditions. The impact of fisheries exploitation on the state of walleye pollock stocks in the Sea of Okhotsk has been the subject of several publications. Various estimates indicated

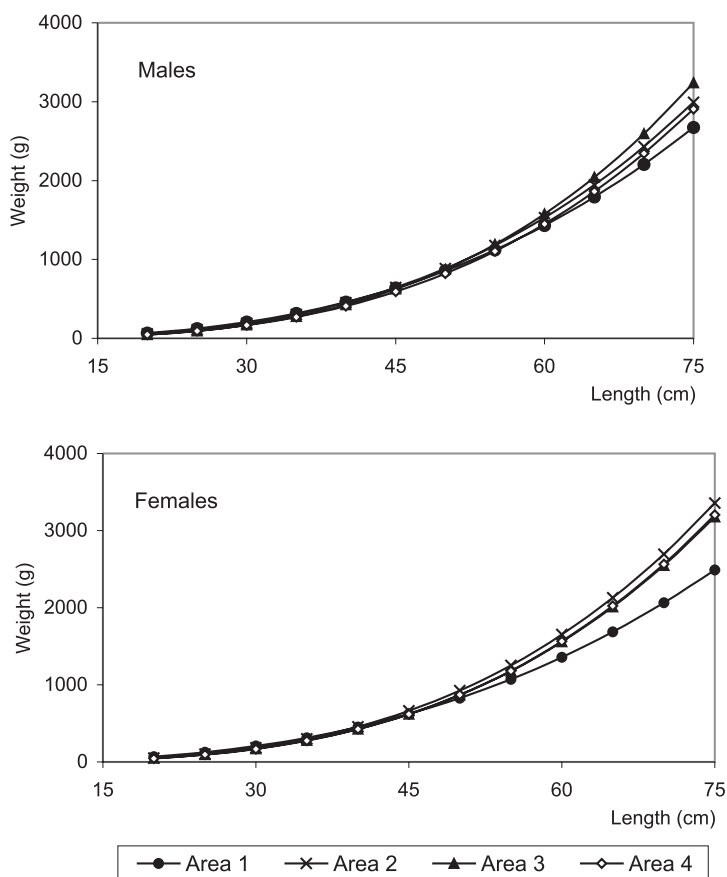


Fig. 5. Weight-length relationship of pollock (males and females) by study area.

that in the 1991-1994 period the total walleye pollock biomass in the Sea of Okhotsk was approximately 9 million tons (Janusz and Horbowy 1997) and that of the spawning stock was 7.5 million tons (Fadeev, 1995). Later estimations made with mathematical methods indicated the biomass of the spawning stock to be 7.4 million tons (Zwerkowa and Oktyabrsky 1996). Shuntov (1998) demonstrated that a distinct change occurred in the Sea of Okhotsk ecosystem as expressed by the increase of herring biomass at the cost of that of walleye pollock. The western Kamchatka stock analyzed in the current work decreased in size from 5.6 million tons in 1986 to 4.2 million tons in 1997. Therefore, it can also be concluded that the reduction of dominant generations in walleye pollock catches noted in the current study could also have been caused by fisheries and environmental changes. Confirmation of these changes was the increasing walleye pollock growth rate.

The differences in the numbers of dominant generations and the varied length class frequency in subsequent years of the study cannot be fully explained by fisheries exploitation and possible environmental changes. These were caused to a significant degree by

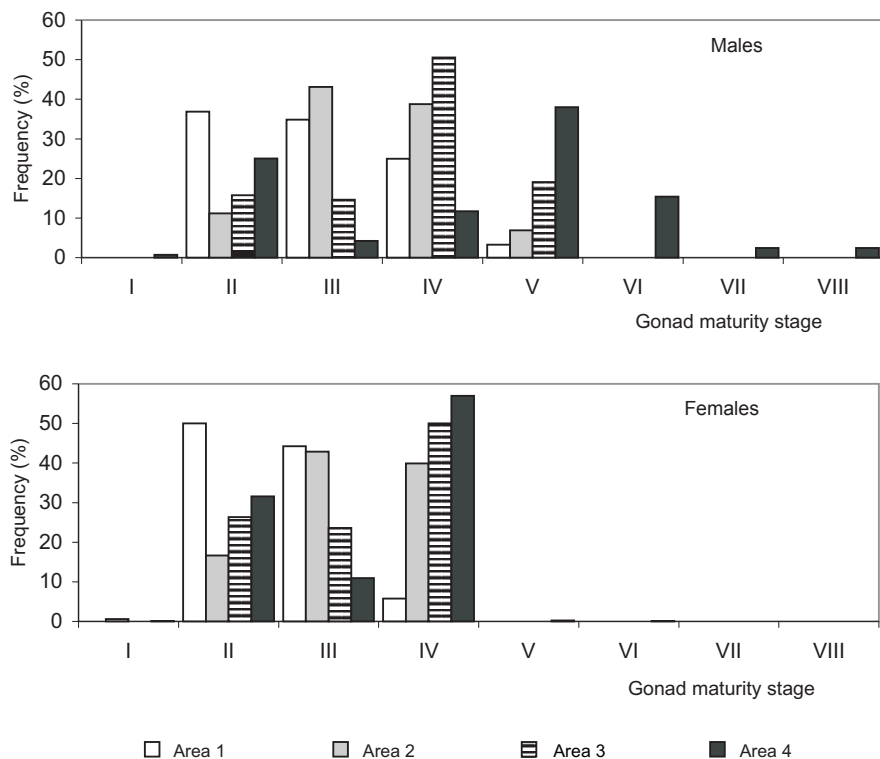


Fig. 6. Gonad maturity stage (according to the Maier scale) of male and female walleye pollock by study area.

the continuous migration of walleye pollock within the Sea of Okhotsk. This is indicated by, among other sources, the results of walleye pollock studies conducted in the international waters of the Sea of Okhotsk in the 1991-1994 period (Janusz and Horbowy, 1997). Throughout the four-year study, cyclic fluctuations were noted in the length structure and the age group frequency. According to these results for the 1992-1993 period, the bulk of the walleye pollock catch was comprised of fish from six generations, while only four in 1991 and 1994. Simultaneously, the calculated average length and age of the fish caught was similar to that presented in the current work.

Fadeev and Smirnov (1987) divided the annual lifecycle of walleye pollock into three periods: spawning, feeding, wintering. According to these authors, in winter walleye pollock form dense concentrations comprised of fish from various stocks at depths of 150 to 600 m. The sex ratio in them is close to 1:1. In the other periods, this varies due to the different migration rate of males and females, especially in the pre-spawning and spawning periods and after spawning when the walleye pollock begin feeding intensively (Fadeev and Suchkova 1987). This is confirmed by the results of the current study. In area 1 (TINRO Depression), where studies were conducted during the winter (November and December), the ratio of males to females was equal (49.5%:50.5%). However, females dominated in areas 2, 3, and 4 where studies were conducted during the pre-spawning

Table 3. Average weight in subsequent years of life of the male and female walleye pollock according to study area

Age	Males				Females			
	area 1	area 2	area 3	area 4	area 1	area 2	area 3	area 4
2	171.5	168.0	80.0	67.5	167.8			79.0
3	188.7	180.0	170.0	113.7	198.8	208.5		123.4
4	284.9	266.1	236.0	200.9	289.8	264.2	215.0	206.0
5	361.9	358.6	315.3	300.0	347.6	340.5	329.5	314.0
6	363.5	416.4	446.4	402.9	397.8	450.7	411.8	425.2
7	437.8	622.7	561.9	500.5	420.0	517.5	608.6	546.2
8	477.7	570.0	727.5	606.7	516.9	642.7	745.0	662.5
9	516.4	734.3	760.0	647.7	524.1	604.9	890.0	792.0
10	580.0	642.0	750.0	638.4	574.9	842.6	1035.0	877.5
11	592.0	811.6	912.5	668.4	633.6	1194.7	1118.0	975.1
12	590.9	693.3		885.2	757.5	1182.3	1188.3	1121.0
13	632.7	877.8	820.0	837.1	552.0	1484.7	1325.0	1223.2
14	668.0	943.3	972.5	876.4	706.0	1391.1	1086.7	1350.0
15	686.0	1195.6	910.0	865.4		1360.8	1267.1	1483.0
16		1150.0		1174.0		1473.9	1813.3	1534.4
17		1090.0		1100.0		2607.5		1831.3
18		926.0		1605.0		2445.8	1600.0	1385.0
19		1044.0						
20		891.0				1544.5		1628.3
21			1020.0	930.0				2700.0
22		926.0				1614.2		1976.7
23								1702.9
$W = k L^n$ equation parameters								
k	0.0149	0.0069	0.0029	0.0041	0.0202	0.0037	0.0032	0.0030
n	2.8021	3.0063	3.2255	3.1203	2.715	3.1773	3.1983	3.2151

and spawning seasons and comprised approximately 63% of the total number of fish measured in each of the areas. This differentiation probably resulted from the beginning of the spawning migration. The structure of gonad maturity differentiation in areas 2, 3, and 4 was fundamentally dissimilar from that observed in area 1. Specimens with gonads in the resting state (II and III) in area 1, while the other areas were dominated by maturing walleye pollock specimens (IV and V), and in area 4 there were also mature and spent males (VI, VII, VIII). The similarity in the distributions of length and age structure of the fish from areas 3 and 4 indicated that the specimens caught there belonged to the same stock migrating to spawning grounds in the northeast.

Walleye pollock from the southwest Kamchatka stock spawn from mid March to the end of May (Gorbunova 1954, Zverkova 1969, 1987). Pre-spawning concentrations reach their maximum in late February and early March (Zverkova 1969), when this species concentrates at depths of approximately 400-500 m (Fadeev 1987, Fadeev and Smirnov, 1987). As their gonads mature, the fish migrate to the spawning grounds located near the coast of Kamchatka at depths of 100-120 m (Gorbunova 1954, Zverkova 1969). These migrations

are not even interrupted by the variable ice cover on the Sea of Okhotsk in winter and most of spring (Satoshi, 1978).

As far as can be concluded from the results of the study, the walleye pollock caught in areas 3 and 4 belonged to the same stock spawning near southwest Kamchatka, which cannot be said of the fish of this species caught in area 2. However, the similarity of the frequency of gonad maturity stages to those described for the same months by Janusz and Horbowy (1997) could indicate that these fish were part of the stock migrating in the central Sea of Okhotsk. The degree of gonad maturity and the frequency of males and females indicated the pre-spawning character of the fish stocks in this area, but there was no way of determining the direction of their migration to a particular spawning ground. Earlier observations by other researchers (Temnykh 1989, Janusz 1994) indicate that the walleye pollock inhabiting the central part of the Bering Sea, in the Russian zone and international waters alike, can migrate to spawn to the east (as part of the southwestern Kamchatka stock) as well as to the west (east coast of Sakhalin).

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## Potentially pathogenic bacteria in water and siberian sturgeon (*Acipenser baeri* Br.) × Russian sturgeon (*Acipenser gueldenstaedti* Br.) hybrids in a closed water cycle

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**Abstract.** Throughout the experimental period, the lowest bacterial counts ( $0-10^1 \text{ cfu} \cdot \text{cm}^{-3}$ ) were reported for *Pseudomonas fluorescens* and *Staphylococcus sp.* in water samples, whereas the highest counts were noted for bacteria of the family *Enterobacteriaceae* in water discharged from the rearing tanks ( $0-8.1 \cdot 10^2 \text{ cfu} \cdot \text{cm}^{-3}$ ). In the skin surface mucus of the sturgeon hybrid, the number of bacteria from the family *Enterobacteriaceae* ranged from 0 to  $5.4 \cdot 10^2 \text{ cfu} \cdot \text{cm}^{-3}$ , whereas in their gastrointestinal digesta it ranged from 5 to  $1.6 \cdot 10^3 \text{ cfu} \cdot \text{g}^{-1}$ . The lowest counts in the samples collected from the fish were noted for *Pseudomonas fluorescens* and *Aeromonas hydrophila* bacteria which were detected in amounts of  $0-105 \text{ cfu} \cdot \text{cm}^{-2}$  and  $0-31 \text{ cfu} \cdot \text{cm}^{-2}$  in the skin surface mucus and  $0-55 \text{ cfu} \cdot \text{g}^{-1}$  and  $0-62 \text{ cfu} \cdot \text{g}^{-1}$  in the intestinal digesta, respectively. The Kruskal-Wallis test indicated statistically significant differences between population numbers of all potentially pathogenic bacteria determined in the water as well as between numbers of TVC  $22^\circ\text{C}$  and  $37^\circ\text{C}$  and those of potentially pathogenic bacteria in the sturgeon hybrid (both in the skin surface mucus and the intestinal digesta) and the feed.

**Key words:** potentially pathogenic bacteria, water, sturgeon hybrid

### INTRODUCTION

The pollution of the aquatic environment and the consequent presence of pathogenic gastrointestinal tract bacteria in that habitat is reflected in the composition of bacterial microflora isolated from fish that inhabit it (Zmysłowska *et al.* 2003a, Zmysłowska *et al.* 2003b). The occurrence of pathogenic bacteria in the microflora of mucus and intestinal digesta of fish is determined by their survivability in water and feedstuffs. Data from the literature (Del Rio-Rodriguez *et al.* 1997, Zmysłowska *et al.* 2001) suggest that the length of survivability time of bacteria in the gastrointestinal tract of fish is determined to a significant extent by environmental conditions.

Fish microflora are subject to change, and a number of factors influencing quantitative and qualitative changes have been identified including the development stage of fish, feed type, salinity, temperature, stress, and the administration of antibiotics (Sugita *et al.* 1990). The gastrointestinal tract microflora of freshwater fish are predominated by the genera *Aeromonas* and *Pseudomonas*, representatives of the family *Enterobacteriaceae*, and the anaerobes *Bacteroides*, *Fusobacterium*, and *Eubacterium*. Fish and other aquatic



organisms can be vectors, or carriers, of diseases that induce pathological states in humans, and thus are likely to become a source of infection. Microorganisms also occur in high numbers in the skin surface mucus, thus reflecting the microflora of the water. Psychrophilic gram-negative rods belonging to the genera *Pseudomonas*, *Vibrio*, *Aeromonas*, and *Flavobacterium* usually predominate on the skin of fish.

The breeding methods of fish are, and will continue to be, subject to far-reaching changes. This is linked to the general tendency observed in animal husbandry, namely a movement toward mass production and the maximal shortening of the breeding cycle through the use of the latest technical and technological means. In fish breeding, this is due to the creation of conditions that are distinctively different from natural ones. The homeostasis developed with the adaptation period of fish to different conditions and, consequently, their resistance to pathogenic factors, is stronger in fish living under natural conditions than in those kept under breeding conditions that have lost an appropriate, genetically-preserved adaptation capacity. This is also the reason for a higher incidence of diseases and the greater intensity of symptoms in farmed fish (Kolman 1999). Both the eradication of fish-borne diseases and the protection of waters against microbiological contamination are becoming increasingly difficult problems due to their increasing complexity.

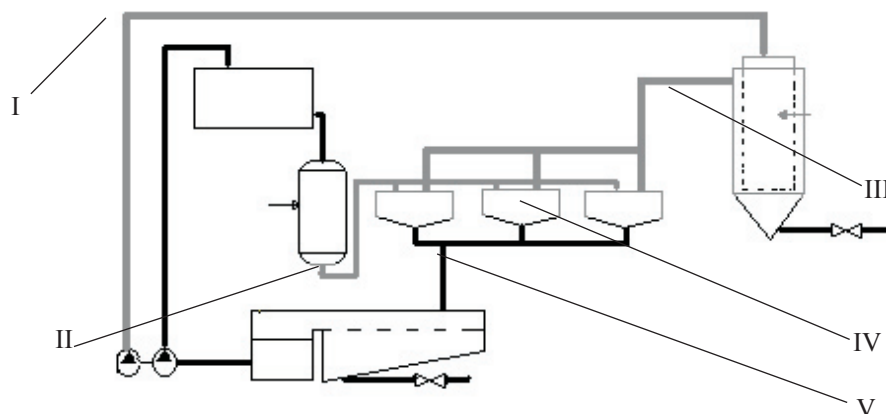
The current research aimed at determining the quantity of the indicator bacteria of contamination degree (TVC 22°C and TVC 37°C) and the pathogenic potential (of the family *Enterobacteriaceae*, *Pseudomonas fluorescens*, *Pseudomonas aeruginosa*, *Aeromonas hydrophila*, *Staphylococcus* sp.) as well as statistically significant differences in their occurrence in the water, feed, and Siberian sturgeon  $\times$  Russian sturgeon hybrid in a closed water cycle.

## MATERIALS AND METHODS

In 2001, a Siberian sturgeon (*Acipenser baeri* Br.)  $\times$  Russian sturgeon (*Acipenser gueldenstaedti* Br.) hybrid was bred at the Dgał Experimental Hatchery, Inland Fisheries Institute in Olsztyn. The hatchery has a closed water cycle equipped with 14 flow tanks (2.0 m  $\cdot$  1.0 m  $\cdot$  0.9 m in size), a fluid biofilter with a settling tank with a total water capacity of approximately 5 m<sup>3</sup>, a preliminary horizontal filter with a settling tank with a capacity of 8 m<sup>3</sup>, and two storage reservoirs (upper and lower) (Fig. 1). The average water flow is 15 dm<sup>3</sup>  $\cdot$  min<sup>-1</sup>.

The experimental material included water collected at five selected test sites within the cycle, a hybrid of Siberian sturgeon (*Acipenser baeri* Br.)  $\times$  Russian sturgeon (*Acipenser gueldenstaedti* Br.) that was stocked at a density ranging from 8.13 to 9.48 kg  $\cdot$  m<sup>-3</sup>, and pelleted high-protein feed Trauvit Classic by Nutreco administered to the studied fish. According to manufacturer data, the feed composition was as follows: protein 46%, fat 14%, carbohydrates 21.5%, ash 9.0%, and cellulose 1.5%. In addition, the feed contained vitamins (A, C, D<sub>3</sub> and E) and mineral salts. The fish were fed with a belt feeder that delivered feed to the fish 24 h per day throughout the experimental period.

Samples of water were collected at five test sites within the cycle: I – tap water; II – water after oxygenation; III – water after biofiltering; IV – water from a rearing tank;



I – tap water, II – water after oxygenation, III – water after biofiltration, IV – water from rearing tanks, V – water discharge from tanks

Fig. 1. Diagram of the closed water cycle and sites of water sample collection.

V – water discharged from the tanks and collected at a depth of 0.3 m (Fig. 1). The water samples were collected from the selected test sites directly into sterile glass-stoppered bottles (250 cm<sup>3</sup>).

The fish were transported to the laboratory in bags filled with tank water and oxygen. For microbiological analyses, samples of gastrointestinal digesta and skin surface mucus were collected under sterile conditions. The samples of intestinal digesta were weighed and ground in a mortar with sterile sea sand and a saline solution (0.85 % NaCl) at a ratio of 1 : 10. The samples of mucus occurring on the fish skin were collected at the top of the muscle above the lateral line after the fish had been rinsed with running water. The mucus was collected from the skin with a sterile swab from a surface area of 1 cm<sup>2</sup> and fixed in a sterile saline solution (9 ml).

Feed was sampled at the experimental site and placed in sterile measuring vessels. A 10 g sample of feed was homogenized with 90 cm<sup>3</sup> of sterile saline solution. Measurements were carried out according to Polish Standard PN-76/R-64791 for indicative microbiological analyses of feedstuffs.

Samples of water, fish (skin surface mucus and intestinal digesta) and feed were collected from March to October 2001 at approximately one-month intervals.

The quantitative microbiological analyses of water, fish, and feed were conducted with breeding methods and covered the following measurements:

- the number of bacteria from the family *Enterobacteriaceae*, grown on Endo medium after 48-h incubation at a temperature of 37°C;
- the number of *Pseudomonas fluorescens* bacteria cultured on King B medium after 72-h incubation at a temperature of 26°C;
- the number of *Aeromonas hydrophila* bacteria cultured on mA medium after 20-h incubation at a temperature of 37°C (Rippey and Cabelli 1979);
- the number of *Staphylococcus sp.* bacteria cultured on Chapman medium after 48-h incubation at a temperature of 37°C.

In addition, the samples collected from the fish (mucus and intestinal digesta) and feeds were measured for the total number of the indicator bacteria of contamination degree cultured on nutritive agar at temperatures of 22°C (TVC 22°C) and 37°C (TVC 37°C).

Inoculations were run in three parallel repetitions following general microbiological standards. The results of analyses carried out with the plate method were converted into colony forming units (cfu).

In measuring the counts of *Aeromonas hydrophila*, *Pseudomonas fluorescens*, *Pseudomonas aeruginosa*, and *Staphylococcus* sp. bacteria, consideration was given to colonies grown on selective culture media that were identified based on their morphological (cell shape, reaction to Gram staining, motility in microscope preparations), enzymatic (capability of producing catalase and cytochrome oxidase and for oxidation or fermentation of glucose on Hugh-Leifson medium), and physiological (temperature requirements and oxygen relationships) traits.

The number of *Aeromonas hydrophila* bacteria was determined by counting the yellow-colored colonies grown on mA medium. In the assay of *Pseudomonas fluorescens* bacteria, colonies cultured on selective medium King B were analyzed under a Wood's UV lamp, and the counts were recorded for colonies producing fluorescein. In the assay of *Staphylococcus* sp. bacteria on Chapman medium, yellow-colored colonies were counted that were confirmed with preparations stained according to the Gram method. These colonies were then re-inoculated on broth-agar culture medium with the addition of 2% glucose and 5% ram blood (Burbianka and Pliszka 1983) to examine the hemolytic properties of the bacteria.

The results of microbiological tests were subjected to statistical analysis. The Kruskal-Wallis non-parametric ANOVA test and the test of medians (Stanisz 1998) were used. The Kruskal-Wallis non-parametric ANOVA test was applied to verify the null hypothesis assuming the same number of bacteria in the water at the test sites examined in particular testing periods.

## RESULTS

Table 1 presents the population numbers of the potentially pathogenic bacteria examined in the water from particular experimental sites.

Over the entire experimental period, no bacteria of the family *Enterobacteriaceae* were detected at site I, whereas the highest number of these bacteria was reported at site V (03.08.01; 810 cfu · cm<sup>-3</sup>). Likewise, the *Pseudomonas fluorescens* bacteria was not identified at site I, and occurred in the highest number (16 cfu · cm<sup>-3</sup>) at site V (03.08.01). While *Aeromonas hydrophila* bacteria was not observed at site I (24.04.01, 30.05.01, 27.06.01, 03.08.01, 06.09.01) or at site V (30.05.01, 01.10.01), they occurred in the highest number (i.e., 267 cfu · cm<sup>-3</sup>) on 23.03.01 at site V. The *Staphylococcus* sp. bacteria was not detected at site I (23.03.01, 30.05.01, 27.06.01, 01.10.01) or at site IV (23.03.01), but at site V they occurred in the highest number (30.05.01; 92 cfu · cm<sup>-3</sup>) of all the water samples analyzed.

Table 1. Number of potentially pathogenic bacteria in the water from the studied closed water cycle (cfu · cm<sup>-3</sup>)

Microorganisms	Site	23.03.01	24.04.01	30.05.01	27.06.01	03.08.01	06.09.01	01.10.01
<i>Enterobacteriaceae</i>	I	0	0	0	0	0	0	0
	II	197	420	688	562	518	207	273
	III	269	576	325	652	349	265	229
	IV	224	390	396	476	540	310	418
	V	339	712	648	588	810	362	354
<i>Pseudomonas fluorescens</i>	I	0	0	0	0	0	0	0
	II	7	11	8	2	6	4	5
	III	6	8	7	6	10	1	3
	IV	2	1	4	2	2	2	6
	V	5	3	7	3	16	2	3
<i>Aeromonas hydrophila</i>	I	2	0	0	0	0	0	4
	II	42	139	15	73	26	23	10
	III	111	130	92	61	220	49	105
	IV	212	179	3	56	226	13	59
	V	267	169	0	53	122	57	0
<i>Staphylococcus</i> sp.	I	0	1	0	0	2	2	0
	II	17	1	35	13	38	11	11
	III	1	3	34	4	57	13	1
	IV	0	1	30	9	33	16	66

Table 2 Number of the bacteria groups examined (cfu) in skin surface mucus (1 cm<sup>-2</sup>) and gastrointestinal digesta of fish (1 g<sup>-1</sup>)

Group of bacteria	Sample	Date						
		23.03.01	24.04.01	30.05.01	27.06.01	03.08.01	06.09.01	01.10.01
<i>Enterobacteriaceae</i>	a	0	0	150	0	540	65	50
	b	365	5	1660	395	325	345	410
<i>Pseudomonas fluorescens</i>	a	105	15	55	0	80	41	0
	b	55	0	45	30	0	0	0
<i>Aeromonas hydrophila</i>	a	31	0	0	0	1	6	5
	b	62	0	45	30	0	0	0
<i>Staphylococcus</i> sp.	a	100	190	120	0	18	15	20
	b	0	5	665	275	90	215	34
TVC 22°C	a	2755	85	3805	385	2120	1535	155
	b	2345000	45000	780000	4740000	1760000	1750000	2040000
TVC 37°C	a	350	35	1420	10	170	130	110
	b	39000	5000	185000	4440000	73000	104250	344000

a – mucus from a 1cm<sup>2</sup> area of fish skin; b – gastrointestinal digesta of fish

The occurrence of the examined groups of bacteria in mucus from the area of 1 cm<sup>2</sup> of skin and in 1 g of gastrointestinal digesta of the fish analyzed is presented in Table 2.

In the mucus from 1 cm<sup>2</sup> of skin, the number of bacteria from the family *Enterobacteriaceae* ranged from 0 cfu · cm<sup>-2</sup> (23.03.01, 24.04.01, 27.06.01) to 540 cfu · cm<sup>-2</sup> (03.08.01). The

Table 3. Number of the bacteria groups examined in the feed (cfu g<sup>-1</sup>)

Group of bacteria	23.03.01	24.04.01	30.05.01	27.06.01	03.08.01	06.09.01	01.10.01
<i>Enterobacteriaceae</i>	24	4	17	51	10	0	0
<i>Pseudomonas fluorescens</i>	0	0	1	0	0	1	1
<i>Aeromonas hydrophila</i>	0	0	0	0	0	1	0
<i>Staphylococcus</i> sp.	75	133	104	39	7	30	67
TVC 22°C	6225	449	1890	12438	545	1344	5961
TVC 37°C	431	164	371	725	256	157	341

minimal and maximal counts of this bacterium in intestinal digesta were 5 cfu · g<sup>-1</sup> (24.04.01) and 1.6 · 10<sup>3</sup> cfu · g<sup>-1</sup> (30.05.01), respectively. *Pseudomonas fluorescens* bacteria occurred in numbers ranging from 0 cfu · cm<sup>-2</sup> (27.06.01, 01.10.01) to 105 cfu · cm<sup>-2</sup> (23.03.01) of mucus collected from the skin surface, and from 0 cfu · g<sup>-1</sup> (24.04.01, 03.08.01, 06.09.01, 01.10.01) to 55 cfu · g<sup>-1</sup> (23.03.01) of intestinal digesta. The number of *Aeromonas hydrophila* bacteria identified in the mucus ranged from 0 cfu · cm<sup>-2</sup> (24.04.01, 30.05.01, 27.06.01) to 31 cfu · cm<sup>-2</sup> (23.03.01) and that identified in the intestinal digesta of the fish ranged from 0 cfu · g<sup>-1</sup> (24.04.01, 03.08.01, 06.09.01, 01.10.01) to 62 cfu · g<sup>-1</sup> (23.03.01). In the case of the *Staphylococcus* sp. bacteria, the number in the mucus fluctuated from 0 cfu · cm<sup>-2</sup> (27.06.01) to 190 cfu · cm<sup>-2</sup> (24.04.01), whereas in the intestinal digesta the range was from 0 cfu · g<sup>-1</sup> (23.03.01) to 665 cfu · g<sup>-1</sup> (30.05.01). The population number of indicator bacteria (TVC 22°C) in the skin surface mucus of the sturgeon hybrid ranged from 85 cfu · cm<sup>-2</sup> (24.04.01) to 3.8 · 10<sup>3</sup> cfu · cm<sup>-2</sup> (30.05.01), whereas that of the indicator bacteria (TVC 37°C) ranged from 10 cfu · cm<sup>-2</sup> (27.06.01) to 1.4 · 10<sup>3</sup> cfu · cm<sup>-2</sup> (30.05.01). In the intestinal digesta, the number of the indicator bacteria (TVC 22°C and TVC 37°C) were substantially higher and ranged from 45 · 10<sup>3</sup> (24.04.01) to 4740 · 10<sup>3</sup> cfu · g<sup>-1</sup> (27.06.01) and from 5 · 10<sup>3</sup> (24.04.01) to 4440 · 10<sup>3</sup> cfu g<sup>-1</sup> of intestinal digesta, respectively (27.06.01).

Table 3 presents results of determinations of population numbers of the bacteria from the family *Enterobacteriaceae*, *Pseudomonas fluorescens*, *Aeromonas hydrophila*, *Staphylococcus* sp., and indicator bacteria (TVC 22°C and TVC 37°C) in 1 g of feed administered to the fish examined over the experimental period.

In 1 g of the feed, the number of bacteria from the family *Enterobacteriaceae* ranged from 0 cfu · g<sup>-1</sup> (06.09.01, 01.10.01) to 51 cfu · g<sup>-1</sup> (27.06.01). Bacteria of the species *Pseudomonas fluorescens* and *Aeromonas hydrophila* occurred sporadically, and their numbers fluctuated from 0 cfu · g<sup>-1</sup> to 1 cfu · g<sup>-1</sup> of feed, depending on the date of study. In contrast, the number of *Staphylococcus* sp. bacteria ranged from 7 cfu · g<sup>-1</sup> (03.08.01) to 133 cfu g<sup>-1</sup> (24.04.01). The minimal number of the indicator bacteria (TVC 22°C) was 449 cfu · g<sup>-1</sup> (24.04.01), while the maximal number was 12.4 · 10<sup>3</sup> cfu · g<sup>-1</sup> (27.06.01). The respective numbers of the indicator bacteria (TVC 37°C) reached 157 cfu · g<sup>-1</sup> (06.09.01) and 725 cfu · g<sup>-1</sup> (27.06.01).

The results of statistical analyses conducted with the Kruskal-Wallis test and a test of medians in the water, fish, and feed are presented in figures 2-4.

The mean numbers of the potentially pathogenic bacteria in the water at particular sampling sites within the cycle were statistically significantly different.

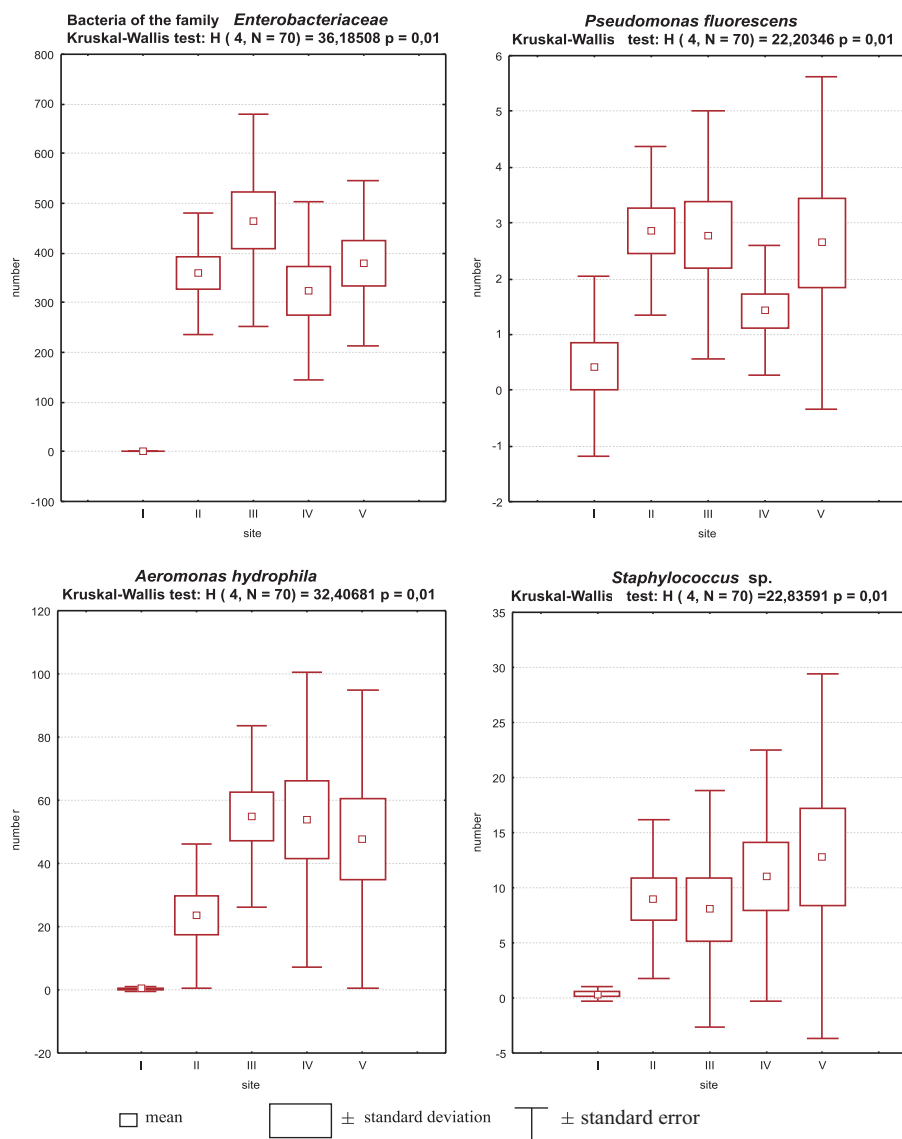
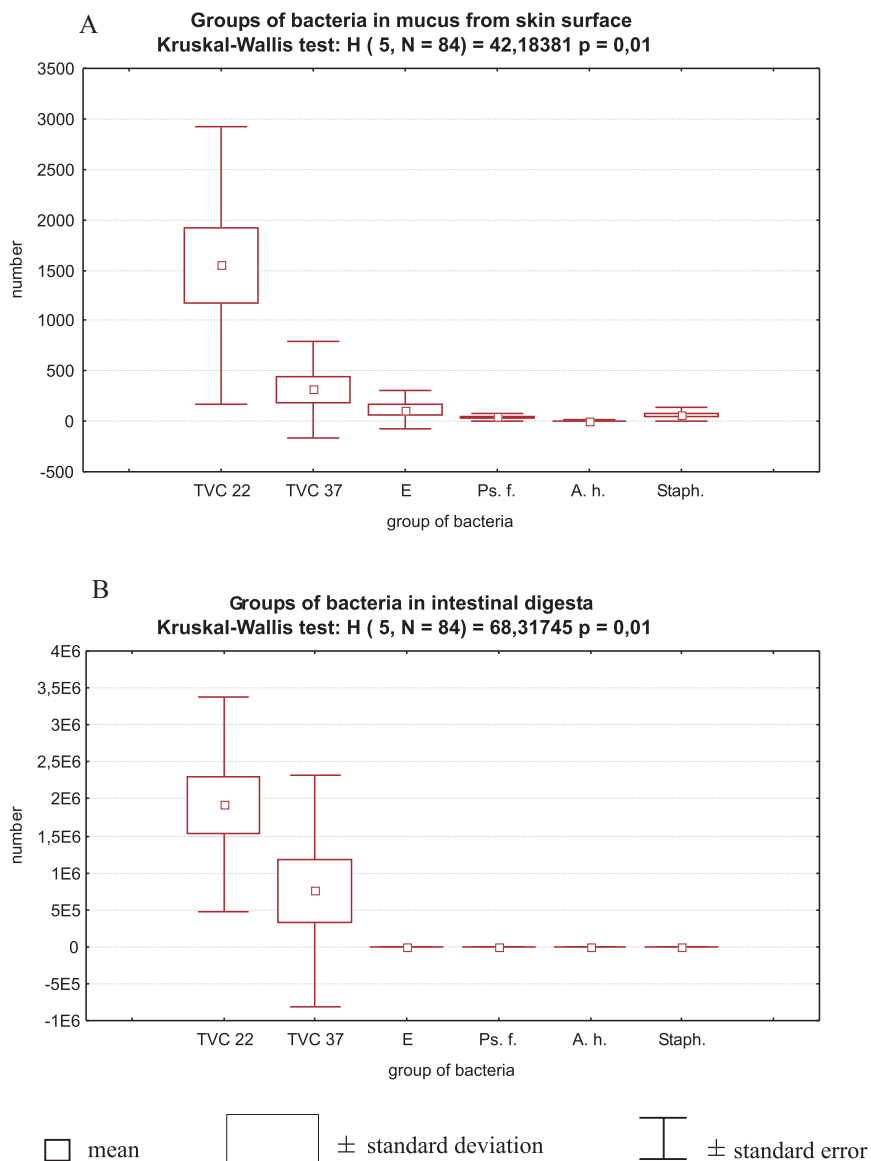


Fig. 2. Mean numbers ( $\pm$  standard deviation and  $\pm$  standard error) of potentially pathogenic bacteria from the family *Enterobacteriaceae* (A), *Pseudomonas fluorescens* (B), *Aeromonas hydrophila* (C), and *Staphylococcus* sp. (D) per 1 cm<sup>3</sup> of water in the closed water cycle.

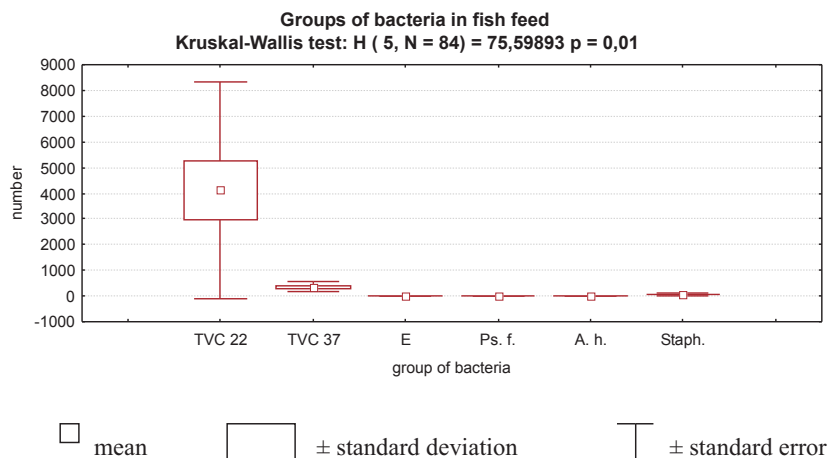
In the skin surface mucus of the fish, as well as in their intestinal digesta and feed, the statistical analysis made with the Kruskal-Wallis test demonstrated significant differences in the statistical means of the population numbers between the indicator bacteria of contamination degree (TVC 22°C and 37°C) and all of the potentially pathogenic bacteria analyzed.



TVC 22 – total number of bacteria indicative of contamination degree cultured on nutritive agar at a temperature of 22°C  
TVC 37 – total number of bacteria indicative of contamination degree cultured on nutritive agar at a temperature of 37°C

E – *Enterobacteriaceae*,  
Ps. f. – *Pseudomonas fluorescens*,  
A. h. – *Aeromonas hydrophila*,  
Staph. – *Staphylococcus* sp.

Fig. 3. Mean numbers ( $\pm$  standard deviation and  $\pm$  standard error) of the examined groups of bacteria in mucus from 1cm<sup>2</sup> of skin surface (A) and 1g of intestinal digesta of the fish analyzed (B).



TVC 22 – total number of bacteria indicative of contamination degree cultured on nutritive agar at a temperature of 22°C

TVC 37 – total number of bacteria indicative of contamination degree cultured on nutritive agar at a temperature of 37°C

E – *Enterobacteriaceae*,  
Ps. f. – *Pseudomonas fluorescens*,  
A. h. – *Aeromonas hydrophila*,  
Staph. – *Staphylococcus* sp.

Fig. 4. Mean numbers ( $\pm$  standard deviation and  $\pm$  standard error) of the examined group of potentially pathogenic bacteria in 1 g of feed.

## DISCUSSION

In the water samples examined, irrespective of the site or testing period, the highest population numbers were reported for the bacteria of the family *Enterobacteriaceae* ( $0-810 \text{ cfu} \cdot \text{cm}^{-3}$ ), whereas the lowest ones were reported for *Pseudomonas fluorescens* and *Staphylococcus* sp. bacteria ( $0-92 \text{ cfu} \cdot \text{cm}^{-3}$ ). In fish and feed, the minimal counts were noted in the case of *Pseudomonas fluorescens* and *Aeromonas hydrophila* bacteria ( $0-105 \text{ cfu}$ ), and the maximal counts were noted in indicator bacteria (TVC 22°C and/or TVC 37°C). Significant differences in the quantitative distribution of most of the microorganisms examined in particular habitats were demonstrated statistically. Bacteria of the family *Enterobacteriaceae* are an important indicator of the evaluation of the sanitary condition of waters. In this study, the highest numbers of these bacteria were observed in waters discharged from the tanks ( $10^3 \text{ cfu} \cdot \text{cm}^{-3}$ ). Bacteria belonging to this family colonize the gastrointestinal tract but are also capable of surviving outside that habitat, hence they were detected in the water. Sugita *et al.* (1990) demonstrated that the alimentary tract of carp, tilapia, and crucian carp was predominated by bacteria of the family *Enterobacteriaceae*, which was also confirmed in a study by Esteve and Garay (1991) carried out on European eel. The latest research (Harnisz *et al.* 2004) on the presence of Gram-negative rods conducted during intensive rearing of European wels (*Silurus glanis* L.) also confirmed



the occurrence of this group of bacteria in the aquatic habitat. These microorganisms are transferred to waters with fish feces.

The widespread occurrence of *Pseudomonas* bacteria is linked to their ability to adapt to specific environmental conditions. According to Niewolak (1990), these bacteria, which are similar to *Aeromonas*, demonstrate a higher resistance to the activity of bactericidal substances secreted by algae. Liao and McCallus (1998) investigated *Pseudomonas* and *Aeromonas* rods and demonstrated their proteolytic and ammonifying properties. In addition, they reported that the growth of these bacteria was enhanced by residues of feed not utilized by fish and present in the water of the closed water cycle. Moreover, the high population numbers of these bacteria in waters exploited for fishery purposes are likely to result from the fact that they constitute the dominant microflora of the gastrointestinal tract of fish, and high numbers of them are excreted into the water via fish feces (Gennari *et al.* 1988). This was reflected in the elevated numbers of these bacteria in the water at all the sites within the closed water cycle as compared to the water flowing into the rearing tanks (site I).

During the tank water analyses conducted for the current study, *Aeromonas hydrophila* bacteria were not detected or occurred in numbers reaching  $10^2 \text{ cfu} \cdot \text{cm}^{-3}$ , which corresponded with values reported in the literature (Zmysłowska *et al.* 2003a) from microbiological studies performed in other systems of intensive fish rearing. *Aeromonas hydrophila* is one of the more important species that is relatively pathogenic to fish (Zmysłowska *et al.* 2004), especially freshwater species. It is characterized by widespread occurrence which, according to Esteve and Garay (1991), is likely to evoke epizootics in eels. A number of species from the genera *Aeromonas* and *Pseudomonas*, commonly isolated from various aquatic systems, are potentially infectious to fish under specific environmental conditions and in the presence of factors that determine their pathogenicity (Rogulska *et al.* 1994). According to Siwicki *et al.* (2004), the conditionally pathogenic or even non-pathogenic bacteria occurring in the aquatic habitat are likely to induce pathologic changes in fish affected by stress factors or in the period of post-stress recovery. Simultaneously, the stress factors predispose the activation of the virulence of pathogens inhabiting fish. The observations Kolman (1999) conducted during controlled fattening have demonstrated that under those conditions, ganoid fish might be susceptible to infection with bacteria of the genus *Aeromonas* sp. As postulated by the present authors, in ganoid fish, these bacteria are also likely to induce hemorrhagic lesions of the gastrointestinal tract and hepatocrosis with symptoms similar to those that occur in the Cyprinidae and Salmonidae fish.

In the current experiment, either the lack or very low numbers ( $10^1 \text{ cfu} \cdot \text{cm}^{-3}$  water) of the *Staphylococcus* sp. bacteria was reported at particular test sites and slightly higher numbers of these bacteria ( $10^2 \text{ cfu} \cdot \text{g}^{-1}$  or  $\text{cfu} \cdot \text{cm}^{-2}$ ) were noted in samples collected from fish, which was probably due to temperature and their survivability. Studies by Lésel and Péringer (1993) have demonstrated similar correlations. Plumb (1999) reported that bacteria from the genera of *Staphylococcus* sp. were detected in diseased wels; however, they did not have any impact on the health status of this species. Campbell and Buswell (1983) claimed that the microflora of fish was affected by the type of feed consumed and the microflora it contained. The current study demonstrated that similar bacterial taxons dominated in water, fish, and feed, which suggests that a high concentration of protein en-

hanced the development of the same physiological groups of microorganisms, regardless of environment. The microbiological assays of the fish focused on the indicator bacteria (TVC 22°C) measured in the intestinal digesta and showed that they occurred in very high population numbers. According to Zaleski (1985), the microflora of the gastrointestinal tract of the prey fish is rich quantitatively but not diversified qualitatively. The qualitative diversity of the evolution in the intestinal and mucus microflora of the fish is commensurate to the microflora of water and fish feed (Zmysłowska and Krause 2003). The data available in the literature indicate that these bacteria occur in the highest numbers on the skin surface and in the gastrointestinal tract of the fish (Zmysłowska *et al.* 2000). This is an indication of the capacity of these bacteria to adapt rapidly to conditions of various environments (internal and external), and, consequently, they occur to be the dominant microflora of this environment.

The microbiological status of the feed applied was determined by the quality of its particular components, the course of the technological process, and conditions of storage - mainly temperature and humidity (Zmysłowska and Lewandowska 2000). By implementing appropriate fish feeding systems, as well as methods for feed production and storage, it is possible to reduce considerably the negative impact of the microbiological contamination of fish and the aquatic habitat (Mamcarz *et al.* 1992).

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## The relationship between the zooplankton structure of some coastal lakes and their trophic states

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**Abstract.** The qualitative and quantitative analysis of the zooplankton of coastal lakes was based on materials collected in the months of July and August from 1985 to 1988. It was found that the numbers of zooplankton species and their abundance and biomass were greatly variable and depended on abiotic factors and the trophic state of the lakes. An analysis of the structural characteristics of the zooplankton for potential bioindicators of eutrophication in these coastal lakes revealed the presence of some species of rotifers and crustaceans in the zooplankton community that could be considered good indicators of trophic state. The progressive eutrophication of the lakes was accompanied by a constant increase in the numbers and biomass of Rotifera and Crustacea. In the majority of the lakes zooplankton abundance was determined primarily by rotifers and biomass by crustaceans. The zooplankton-related trophic state indices enabled classifying most of the investigated lakes as eutrophic or mesoeutrophic.

**Key words:** coastal lakes, estuaries, zooplankton, zooplankton-related trophic state indices.

### INTRODUCTION

The lakes of the Polish Baltic coastal zone are estuarine water bodies (i.e., water bodies that are either permanently or periodically connected to the sea) that differ from inland lakes in terms of hydrology and ecology. The ecological characteristics of the lake biota are related closely to the hydrological characteristics, which include a low mean depth (1.5 m), a low lake volume to shoreline length ratio, no thermal-oxygen stratification, oxygen deficiency, surface elevation slightly above sea level, and a two-layer structure caused by varied water salinity (Mikulski 1972, Dethier 1992, Jasińska 1993). Despite similar origin, evolution, and geomorphological type, these various water bodies are characterized by different hydrological (Mikulski 1972) and hydrochemical (Trojanowski *et al.* 1991) conditions that are affected by the relative dominance of terrestrial or marine factors. The impact of terrestrial factors is related to the size of the catchment area and the water inputs from this source, while the significance of marine factors is dependent upon the contact between the lake and the sea, specifically the degree of water exchange between the two.

In coastal lakes zooplankton are strongly affected by abiotic environmental factors, such as temporal and spatial variations in salinity, water temperature, oxygen saturation, nutrient availability, water chemistry, wave-induced resuspension, and the inflow of nutrient substances from the sea or river catchment (Irvine *et al.* 1990, Hall *et al.* 2002). These factors influence the species composition, densities, and biomass of zooplankton

and, potentially, the occurrence of indicator species. According to Radwan (1976), Hillbricht-Ilkowska (1977), Karabin (1985a), and Matveeva (1991), zooplankton are good bioindicators of the physical and chemical conditions of aquatic environments.

Coastal lakes are prone to degradation caused by anthropogenic factors, such as drainage and the increased input of organic wastes and solids, most of which contribute to progressive eutrophication (Karabin and Ejsmont-Karabin 1993, 1996). On the other hand, the intrusion of marine waters into estuaries can inhibit eutrophication (Trojanowski 1990).

This paper presents the results of studies on the species structure, abundance, and biomass of zooplankton in the followings lakes: Sarbsko, Dołgie Wielkie, Dołgie Małe, Wicko, Kopań, Bukowo, Resko Przymorskie, Liwia Łuża, Koprowo, and Wicko Wielkie. It also examines their relationship with abiotic environmental factors. The aim of the study was to test the hypothesis that an understanding of the zooplankton communities of coastal lakes can provide a basis for determining their current trophic states and thus probable susceptibility to anthropogenic stress.

## RESEARCH AREA

There are between ten and twenty coastal lakes in the immediate vicinity of the Baltic Sea in Poland (Mikulski 1970); ten of these were the subject of ecological surveys conducted in the 1985-1988 period (Table 1, Fig. 1). A brief description of each one follows:

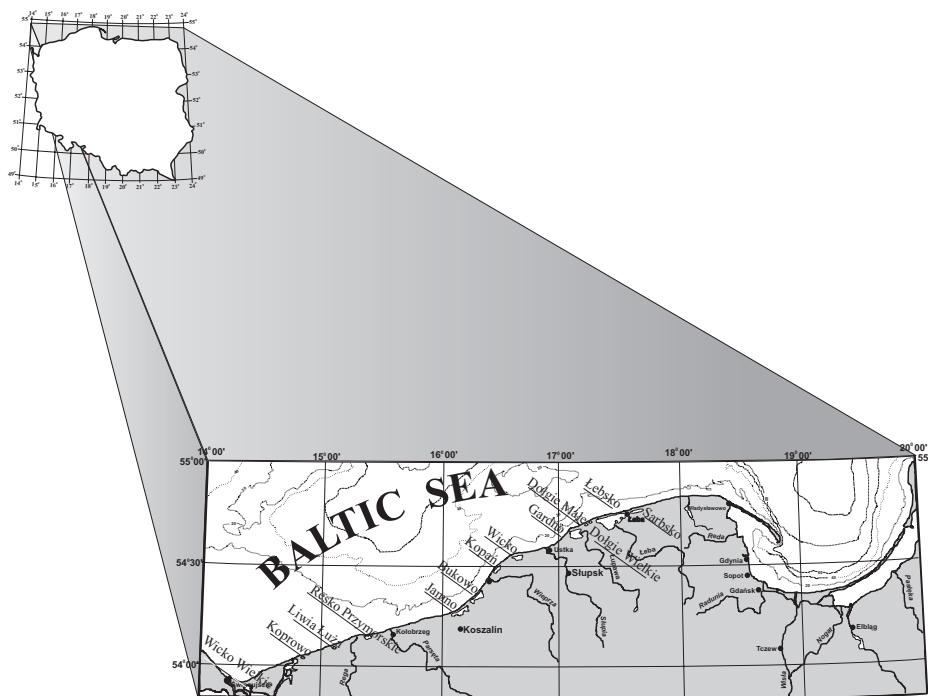


Fig. 1. Estuaries of Polish coastal area of the Baltic Sea.

Table 1. Morphometric characteristics of the studied coastal lakes (Jańczak 1997)

Parameters \ Lake	Sarbsko	Dolgie Wielkie	Dolgie* Male	Wicko	Kopań	Bukowo	Resko Przymorskie	Liwia Luża	Koprowo	Wicko Wielkie
Geographic latitude	54°46'	54°42'	54°41'	54°32'	54°29'	54°21'	54°08'	54°05'	54°58'	53°52'
Geographic longitude	17°38'	17°12'	17°10'	16°37'	16°27'	16°17'	15°22'	15°05'	14°39'	14°25'
Elevation m asl (m)	0.50	1.50	1.10	0.20	0.10	0.10	0.30	0.30	0.10	
Area:										
Surface area (ha)	651	156	6	1058	790	1747	577	211	487	1200
Catchment area (km <sup>2</sup> )	213.3	6.6	2.5	107.7	38.5	102.8	315.2	175.5	51.1	
Depth:										
maximum (m)	3.2	2.9	1.7	6.1	3.9	2.8	2.5	1.7	3.1	3.0
mean (m)	1.2	1.4	0.7	2.7	1.9	1.8	1.3	0.9	1.6	1.0
Volume (mln m <sup>3</sup> )	7.82	2.15	0.04	28.5	14.8	32.1	7.7	1.9	7.8	

\* Unpublished data, Inland Fisheries Institute in Olsztyn (from the 1958-1963 period)

**Lake Sarbsko** is in the catchment basin of the Łeba River. The Chelst River flows through the lake and into the Łeba River just 700 m before the latter flows into the Baltic Sea. The lake is supplied with water by over 25 channels and drainage ditches that dry out periodically. The direct catchment of the lake is made up of arable land (30%), forest (50%), and grassland and barren land (20%).

**Lake Dolgie Wielkie** and **Lake Dolgie Male** are mid-forest water bodies situated in Słowiński National Park. Their combined catchment area is comprised of forest (73%) and grassland (5%) with the remainder comprised of barren land and other open waters. In contrast to the other coastal lakes described here, these two lakes have no direct connection with the Baltic Sea. However, low concentrations of chloride ions have been recorded due to marine water percolation through dune sands.

**Lake Wicko** is located within the catchment basin of the Głównica River, which connects it to the Baltic Sea. The lake is divided into two by marshes and swamps on the southern side, while the western part is supplied with fresh water by the Klasztorna River.

**Lake Kopań** is a coastal lake whose basin is a cryptodepression with a water-surface elevation of 0.1 m above sea level. The lake is connected to the Baltic Sea by a channel about 400 m long. The underground spillway is no longer in use. The water system of Lake Kopań is connected to Lake Wicko by a drainage ditch. Water is supplied by intermittent streams in the south.

**Lake Bukowo** is located in the basin of the Szczuczy Channel next to Lake Jamno. Formerly, these two lakes formed a single large coastal lagoon. Today, lakes Bukowo and Jamno are only connected by a drainage ditch through which water from the former may overflow into the latter when water levels are high. The lakes are connected to the Baltic Sea by a channel about 500 m in length that is often filled with debris.

**Lake Resko Przymorskie** lies at the confluence of the Stara Rega, Łuzanka, and Błotnica rivers so the inflow of fluvial waters is considerable. The ratio between the annual fluvial inflow and lake volume is 10. The lake is connected to the Baltic Sea by a channel.



**Lake Liwia Łuża** is the smallest of all the coastal lakes studied here. It is connected to the Baltic Sea by a channel about 1 km in length. Freshwaters are brought by some small rivers that flow into the southwestern part of the lake. The ratio between the annual fluvial inflow and lake volume of 20 is the highest of the lakes described here.

**Lake Koprowo** is situated within the Dziwna Strait. The lake is supplied with about 10% of the water from the Oder River that flows through the Dziwna Strait from the Szczecin Lagoon. In turn, the waters of Lake Koprowo flow into the Kamieński Lagoon via the Lewińska Struga River. The immediate catchment area of the lake is bare of vegetation and non-urbanized.

**Lake Wicko Wielkie** is located south of Wolin Island in Wolin National Park within the zone of water exchange between the Szczecin Lagoon and the Bay of Pomerania. It constitutes a Szczecin Lagoon bay. This lake, which is situated within the reverse delta of the Świna River, is gradually becoming overgrown and shallower.

## MATERIALS AND METHODS

An analysis of the zooplankton of the coastal lakes studied here (Fig. 1) was based on materials collected in the months of July and August from 1985 to 1988 (Table 2). Zooplankton samples were collected with a 5-liter Ruttner sampler from the water column at intervals of one meter from the surface to the bottom or at intervals of 0.5 m at shallow sites. Between 25 to 50 liters of water were collected at each sampling site. The zooplankton samples were concentrated by pouring them through a plankton net with a mesh size of 60  $\mu\text{m}$ . They were preserved initially with Lugol's iodine solution and then with 2-4% formaldehyde. The samples were collected at sites representing three different habitats in each of the lakes investigated (i.e., those dominated by the inflow of freshwaters, which are typical of the central part of lakes, and those dominated by mixed fresh and salt waters). Water temperature and Secchi disc visibility were determined in each of the lakes

Table 2. The coastal lakes studied, the years in which they were studied, and the total number of samples collected at each lake

No.	Lake	Years of study	Number of samples
1.	Sarbsko	1985	5
		1987	5
2.	Dołgie Wielkie	1985	1
		1986	3
3.	Dołgie Małe	1986	2
4.	Wicko	1988	5
5.	Kopań	1985	4
		1987	4
6.	Bukowo	1987	5
7.	Resko Przym.	1988	5
8.	Liwia Łuża	1988	4
9.	Koprowo	1988	5
10.	Wicko Wielkie	1988	3

during each sampling event, and water samples were collected for subsequent chemical analysis using standard methods (Standard Methods 1976). A total of 51 zooplankton samples were collected throughout the study period.

The zooplankton abundance ( $\text{indiv.} \cdot \text{dm}^{-3}$ ) was estimated using the Hensen formula (Starmach 1955). The biomass of rotifers and crustaceans ( $\text{mg} \cdot \text{dm}^{-3}$ ) was estimated with the indirect method recommended by

Hillbricht-Ilkowska and Patalas (1967) and Bottrell *et al.* (1976). The Shannon indicators of species diversity and uniformity of species distribution concur with Odum (1982) and Krebs (1996). Zooplankton-related trophic state indices concur with Radwan (1976) and Karabin (1985a, b) and lake trophic state indices ( $TSI_{SD}$ ) with Carlson (1977).

The results of the study, in the form of the calculated indices, were analyzed statistically using Statistica PL 6.0 software and interpreted as recommended by Stanisław (1998). The relationship between the quantitative characteristics of the zooplankton populations and environmental variables was determined with principal component analysis (PCA). The aim of the analysis was to verify the statistical significance of correlations between zooplankton population characteristics and environmental variables. In order to determine significant sources of variation ( $p < 0.05$ ), the means were compared with the HSD-based Tukey test.

## RESULTS

The number of zooplankton species (either all Rotifers or Crustacea) of the coastal lakes examined varied widely from 9 to 20 (Table 3), and throughout the survey period 18 rotifer taxa and 8 crustacean species were recorded.

Several species of rotifers and crustaceans considered to be good indicators of the trophic state of lakes (Karabin 1985a, b, Radwan 1976) were found in the zooplankton communities (Table 3). Of the rotifers that comprised ecological group II (species whose proportion of the total biomass of a given community is very high; their domination and percentage of the plankton increase along with increasing trophic levels), there were five species indicators of a high trophic status (Karabin 1985a): *Brachionus angularis*, *Keratella cochlearis* f. *tecta*, and *Keratella quadrata* were recorded in all lakes, while *Filinia longiseta* and *Trichocerca pusilla* were not present in Lake Dołgie Małe or Lake Liwia Łuża. Among crustaceans, four species indicators of high trophic status (Karabin 1985a) were noted, which comprised ecological group II: *Bosmina coregoni*, *Bosmina longirostris*, *Chydorus sphaericus*, and *Diaphanosoma brachyurum*. The occurrence of these species was highly variable.

The zooplankton abundance in the coastal lakes studied was determined primarily by rotifers, while biomass was determined by crustaceans. The only exceptions were lakes Liwia Łuża and Dołgie Wielkie, where crustaceans dominated both zooplankton abundance and biomass (Table 4). Very high densities of rotifers in lakes Kopań and Resko Przymorskie (3417 and 1127 indiv · dm<sup>-3</sup>, respectively) indicated the high trophic levels of these water bodies, where all the species indicators of this trophic state were recorded. In the other lakes the numbers of Rotifera ranged between just 127 and 704 indiv · dm<sup>-3</sup>, thus they made an insignificant contribution to total zooplankton biomass. The high numbers and biomass of crustaceans (2812 indiv · dm<sup>-3</sup> and 24.697 mg · dm<sup>-3</sup>) in Lake Liwia Łuża were accompanied by low species diversity (Shannon index), which indicated progressive eutrophication. The zooplankton species diversity in other lakes was also low and thus typical of eutrophic waters.

The trophic state of coastal lakes was also assessed on the basis of zooplankton-related trophic state indices, both basic and supplementary (Table 5). One of the key indices that permits estimating the degree of lake eutrophication is the trophic state index

Table 3. List of Rotifer and Crustacean zooplankton species noted in the summer in the coastal lakes studied in the 1985-1988 period (total number of samples = 51)

Species	Lake									
	Sarbsko	Dolgie Wielkie	Dolgie Male	Wicko	Kopań	Bukowo	Resko Przym.	Liwia Łuza	Koprowo	Wicko Wielkie
<b>Rotifera:</b>										
<i>Asplanchna priodonta</i> Gosse										
<b><i>Brachionus angularis</i> Gosse*</b>	+	+	+	+	+	+	+	+	+	+
<i>Brachionus calyciflorus</i> Pallas	+	+	+	+	+	+	+	+	+	+
<i>Brachionus quadridentatus</i> Hermann	+									
<i>Brachionus urceolaris</i> Linnaeus	+	+								
<i>Euchlanis dilatata</i> Ehrenberg	+	+								
<b><i>Filinia longiseta</i> Ehrenberg*</b>	+	+		+	+	+	+		+	+
<i>Kellicottia longispina</i> Kellicott										
<i>Keratella cochlearis cochlearis</i> Gosse	+	+	+	+	+	+	+	+	+	+
<b><i>Keratella cochlearis f. tecta</i> Gosse*</b>	+	+	+	+	+	+	+	+	+	+
<b><i>Keratella quadrata</i> O.F.Müller*</b>	+	+	+	+	+	+	+	+	+	+
<i>Lecane luna</i> O.F.Müller	+	+	+	+	+					+
<i>Notholca acuminata</i> Ehrenberg	+	+		+	+	+			+	+
<i>Polyartha dolichoptera</i> Idelson	+	+		+					+	+
<i>Synchaeta baltica</i> Ehrenberg	+	+		+						
<i>Synchaeta litoralis</i> Rousselet										
<i>Trichocerca capucina</i> Wierzejski et Zacharias					+					
<i>Trichocerca cylindrica</i> Imhof		+		+						
<b><i>Trichocerca pusilla</i> Lauterborn*</b>	+		+	+	+	+	+		+	+
<b>Crustacea:</b>										
<i>Alona quadrangularis</i> O.F.Müller		+			+				+	+
<b><i>Bosmina coregoni</i> Baird*</b>	+	+		+	+	+		+	+	+
<b><i>Bosmina longirostris</i> O.F.Müller*</b>	+	+	+	+	+	+		+	+	+
<b><i>Chydorus sphaericus</i> O.F.Müller*</b>	+	+	+	+	+	+	+	+	+	+
<i>Daphnia cucullata</i> Sars										
<b><i>Diaphanosoma brachyurum</i> Liévin*</b>					+	+	+		+	+
<i>Leptodora kindtii</i> Focke					+					
<i>Cyclops vicinus</i> Uljanin	+	+	+	+	+	+	+	+	+	+
Copepoda juv. (not included in total)	+	+	+	+	+	+	+	+	+	+
<b>Total species</b>	18	19	11	15	21	15	11	10	17	17

\* - species indicators of trophy (Karabin 1985a)

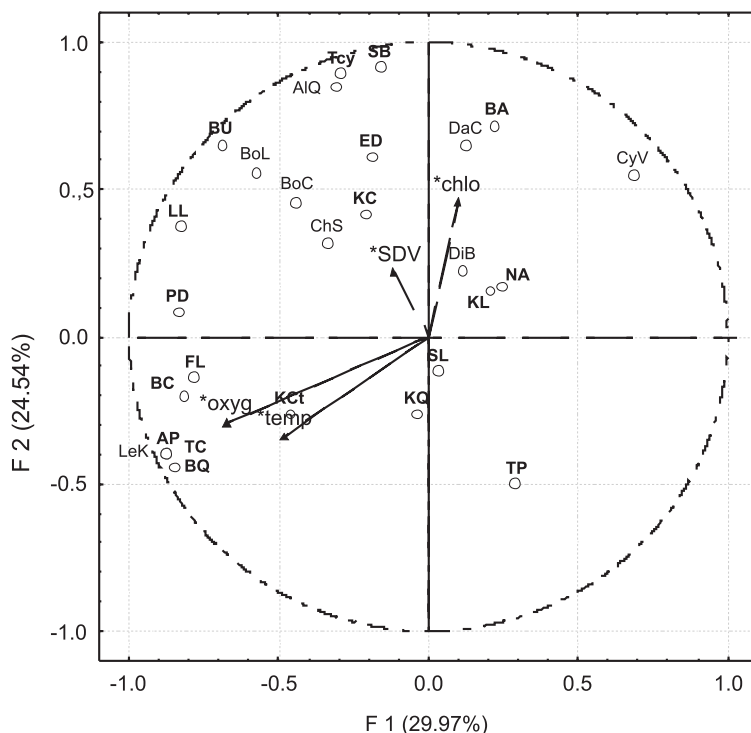


Fig. 2. Diagram of PCA results – zooplankton species occurrence in coastal lakes in the 1985-1988 period as dependent on environmental factors.

Taxa abbreviations of active variables: *\*Asplanchna priodonta* (AP); *Brachionus angularis* (BA); *Brachionus calyciflorus* (BC); *Brachionus quadridentatus* (BQ); *Brachionus urceolaris* (BU); *Euchlanis dilatata* (ED); *Filinia longiseta* (FL); *Kellicotia longispina* (KL); *Keratella cochlearis* (KC); *Keratella cochlearis* f. *tecta* (KCt); *Keratella quadrata* (KQ); *Lecane luna* (LL); *Notholca acuminata* (NA); *Polyartha dolichoptera* (PD); *Synchaeta baltica* (SB); *Synchaeta littoralis* (SL); *Trichocerca capucina* (TC); *Trichocerca cylindrica* (TCy); *Trichocerca pusilla* (TP); *Alona quadrangularis* (AIQ); *Bosmina coregoni* (BoC); *Bosmina longirostris* (BoL); *Chydorus sphaericus* (ChS); *Daphnia cucullata* (DaC); *Diaphanosoma brachyurum* (DiB); *Leptodora kindtii* (LeK); *Cyclops vicinus* (CyV).

Environmental variables: temperature (temp); oxygen (oxyg); chlorides (chlo); Secchi Disk Visibility (SDV)

\* Rotifera are in bold.

based on Secchi disk transparency ( $TSI_{SD}$ ). The values of this index indicated the polytrophic character of the lakes studied. The contribution of ecological group II of Rotifera to the biomass of the indicator community indicated the mesoeutrophic character of the lakes. The only exception was Lake Resko Przymorskie, in which polytrophication was confirmed by the *Keratella cochlearis* population being comprised nearly exclusively of the *tecta* form. With the exception of Dołgie Wielkie and Dołgie Małe, the contribution of the *tecta* form indicated polytrophication in all of the lakes. The numbers of rotifers increased along with an increase in the trophic status of the lake. The high abundance of these (exceeding 2000 indiv. · dm<sup>-3</sup>) was recorded in the polytrophic Lake Kopań, where the trophic state was also confirmed by the proportion of ecological group II of Crustacea. The number of rotifers was typical of the eutrophic status in other coastal lakes.

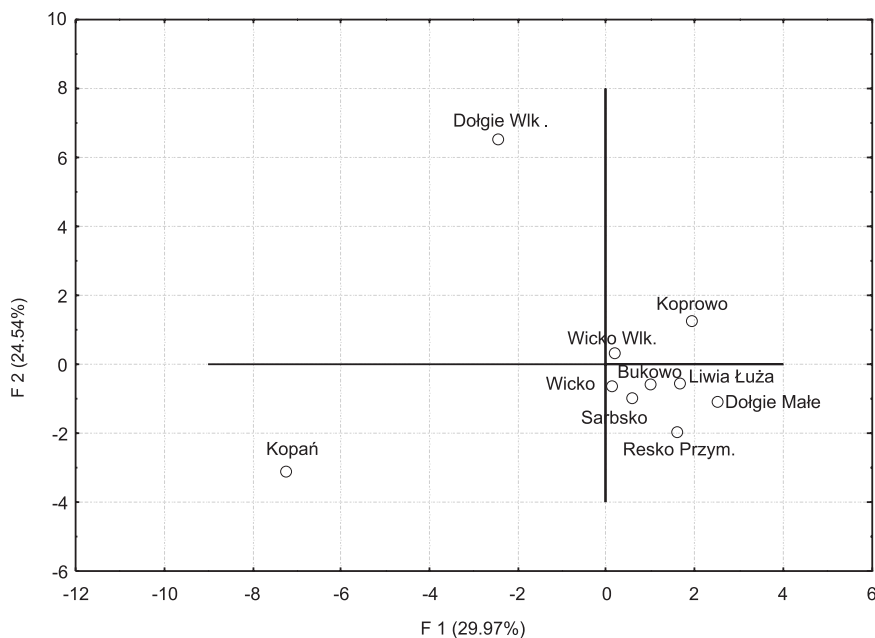


Fig. 3. Diagram of PCA components and the order of zooplankton samples collected from coastal lakes in the 1985-1988 period.

Although the other basic indices, which are based upon the structural characteristics of the crustacean population (Table 5), can be applied primarily to stratified lakes, they can also be useful tools to confirm the trophic state of non-stratified lakes. Their role as bioindicators is indeed less important in such lakes. The contribution of ecological group II of Crustacea to the biomass of the indicator community in the coastal lakes indicated

Table 4. Mean abundance ( $\text{indv.} \cdot \text{dm}^{-3} - N$ ), biomass ( $\text{mg} \cdot \text{dm}^{-3} - B$ ), and species diversity in the numbers ( $H_N$ ) and biomass ( $H_B$ ) of Rotifera and Crustacea in coastal lakes in the 1985-1988 period

Lake	Rotifera				Crustacea				$H_N$	$H_B$
	N	sd*	B	sd*	N	sd*	B	sd*		
Sarbsko	692	443.7	0.151	0.140	595	244.6	4.193	2.185	1.65	0.74
Dolgie Wielkie	872	226.7	0.554	0.203	954	192.4	26.704	10.165	2.02	1.24
Dolgie Małe	127	111.7	0.019	0.011	106	57.4	1.264	0.552	1.7	1.13
Wicko	298	221.5	0.112	0.074	128	45.3	1.120	0.341	2.15	1.57
Kopań	3417	1830.6	1.937	0.917	293	43.8	1.294	0.568	1.93	1.97
Bukowo	450	185.3	0.078	0.039	239	62.0	1.976	0.675	2.02	1.24
Resko Przymorskie	1127	174.1	0.682	0.318	102	24.6	1.208	0.317	0.61	0.95
Liwia Łuża	542	202.4	0.103	0.035	2812	1276.6	24.697	11.953	0.98	0.93
Koprowo	440	145.3	0.066	0.024	418	152.4	9.138	4.995	1.99	1.11
Wicko Wielkie	704	419.8	0.223	0.169	303	88.7	4.157	1.784	2.17	1.42

\*standard deviation

eutrophic states in lakes Sarbsko and Bukowo, mesoeutrophic states in lakes Dołgie Wielkie, Resko Przymorskie, Liwia Łuża, and Koprowo, and finally mesotrophic states in lakes Dołgie Małe and Wicko Wielkie. Taking into account the other crustacean-related indices, such as the contribution of Cyclopidae to the biomass of Crustacea and the ratio between the Cyclopiid biomass and the Cladoceran biomass, permitted dividing the lakes into two groups, namely eutrophic (Dołgie Wielkie, Wicko and Resko Przymorskie) and mesotrophic (all the remaining lakes).

The other elements of zooplankton population structure, referred to as supplementary indices, can only be used to determine water eutrophication stages to a limited degree. Total zooplankton abundance indicated the polytrophic character of Lake Kopań and the eutrophic character of the other lakes. The remaining structural characteristics of the zooplankton populations, specifically those of the crustaceans, suggested the eutrophic state of coastal lakes.

Among the factors analyzed with PCA (Fig. 2), factors 1 and 2 (the correlation between the occurrence and abundance of zooplankton species and environmental parameters, respectively) together explain 54.5% of the variation in the data. The analysis of environmental variables with PCA show that the occurrence of zooplankton species in particular years of the study is correlated negatively with water transparency, water oxygen content, and temperature and positively with salinity. The diagram of PCA results (Fig. 2) shows that among the zooplankton groups examined in the study, the occurrence of rotifers in coastal lakes depended on water temperature and oxygen content ( $p = 0.000$ ), whereas the occurrence of crustaceans depended on water transparency and the concentration of chloride ions ( $p = 0.000$ ). A strong negative correlation (values approaching  $-1.0$ ) was observed for the rotifer and crustacean indicator species of high trophic levels, namely *Filinia longiseta*, *Keratella quadrata*, *Keratella cochlearis* f. *tecta*, *Bosmina longirostris*, *Bosmina coregoni*, and *Chydorus sphaericus*, while a positive correlation (values approaching  $1.0$ ) was recorded for two rotifer species – *Brachionus angularis* and *Trichocerca pusilla* – and one crustacean species – *Diaphanosoma brachyurum*.

The results of the PCA analysis of the occurrence and abundance of zooplankton species in particular lakes (Fig. 3) indicated that in lakes Dołgie Wielkie and Kopań they were negatively correlated with variation-explaining factors, while they were positively correlated in the other lakes. These relationships were strong in Lake Kopań but weak in the other lakes.

Thus, the analysis of the structural characteristics of the zooplankton populations as bioindicators of lake eutrophication provided the basis for classifying the coastal lakes as follows:

- Lake Kopań – polytrophic with symptoms of eutrophication;
- lakes Resko Przymorskie and Liwia Łuża – eutrophic with symptoms of polytrophication;
- lakes Sarbsko, Dołgie Wielkie, Dołgie Małe, Wicko, Bukowo, Koprowo, Wicko Wielkie – eutrophic and mesoeutrophic, but the high contribution of the *tecta* form to the *Keratella cochlearis* population indicated polytrophication (except for Dołgie Wielkie and Dołgie Małe).

Table 5. Zooplankton-based indices of the trophic state in coastal lakes:  $TSI_{SD}$  (Carlson 1977); proportion of ecological group II in the biomass of the indicator rotifer community (%; group II – Rotifera); proportion of *Keratella cochlearis* (%; TECTA); abundance of rotifers (indiv. · dm<sup>-3</sup>; Rotifera N); proportion of ecological group II in the biomass of the indicator crustacean community (%; group II – Crustacea); proportion of Cyclopidae in the biomass of Crustacea (%; Cyclopidae in B Crust.); ratio between Cyclopidae biomass and Cladocera biomass (mg · dm<sup>-3</sup>;  $B_{CY} : B_{CL}$ ); total zooplankton abundance (indiv. · dm<sup>-3</sup>; Zoopl. N); ratio between rotifer biomass and rotifer numbers (mg, B : N Rotifera); abundance of Crustacea (indiv. · dm<sup>-3</sup>; Crust. N); ratio between crustacean biomass and crustacean numbers (mg, B : N Crustacea); biomass of Cyclopidae (mg · dm<sup>-3</sup>; Cyclop. B); Crustacea – indicator of the species diversity of biomass  $H_b$ ; uniformity of species distribution e; ranges of values for trophic types of lakes (Karabin 1985a)

Lake	TSI <sub>SD</sub>	II group Rotifera	TECTA	Rotifera N	Basic indices			Supplementary indices						
					II group Crustacea	Cyclopidae in B Crust.	B <sub>CY</sub> : B <sub>CL</sub>	Zoopl. N	B : N Rotifera	Crust. N	B : N Crustacea	Cyclop. B	Crustacea - H <sub>p</sub> ; e	
Sarbsko	73	33.8	100	692	89.2	10.3	0.114	1287	0.000218	595	0.000705	0.383	0.58	0.36
Dolgie Wielkie	77	10.7	45	872	30.4	5.0	0.053	1826	0.000635	954	0.027992	1.257	1.16	0.59
Dolgie Male	70	78.9	50	127	2.5	65.5	1.899	233	0.000150	106	0.011925	0.655	1.05	0.95
Wicko	70	41.1	80	298	31.1	54.0	1.172	426	0.000376	128	0.008750	0.443	1.21	0.87
Kopań	77	8.5	98.9	3417	69.9	5.1	0.054	3710	0.000567	293	0.004416	0.064	0.78	0.38
Bukowo	70	85.9	53.8	450	84.8	15.2	0.179	689	0.000173	239	0.008268	0.289	1.06	0.66
Resko Przym.	77	99.4	97.7	1127	50.9	49.1	0.964	1229	0.000605	102	0.011843	0.555	0.71	0.65
Liwia Luża	83	85.4	100	542	58.1	2.1	0.022	3354	0.000190	2812	0.008783	0.506	0.90	0.65
Koprowo	83	81.8	90.9	440	25.3	4.5	0.047	858	0.000150	418	0.021861	0.404	1.06	0.59
Wicko Wielkie	77	53.4	100	704	11.4	15.5	0.182	1007	0.000317	303	0.013719	0.547	1.18	0.66
Range of values														
Trophic type	<45	<10	0-5	<400	<25	<15	<0.2	–	–	<180-200	>0.05-0.06	<0.4-0.5	2.2-2.3	
	45-55	10-90	5-20		25-60	15-30	0.2-0.8	–	–	–	–	–	–	
	55-65	>90	20-60	400-2000	>60	>30	>0.8	–	<0.00015	–	–	–	–	
	>65		>60	>2000	–	–	–	>2000	–	–	–	–	–	

## DISCUSSION

In order to explain the functioning of lake ecosystems, it is essential to understand the significance of eutrophication factors. Eutrophication is related primarily to the load of nutritive substances supplied to a given water body within a specified period of time, as well as to the ecosystem's resistance to external impacts, most of which are anthropogenic. The resistance of coastal lakes to such impacts depends primarily on hydrological conditions (the relative dominance of terrestrial or marine impacts) and morphological conditions (surface area, depth) (Kudelska *et al.* 1994, Trojanowski *et al.* 1991).

Zooplankton is a crucial component of the trophic and functional structures of the biocenosis of coastal lakes. The species structure and abundance of the zooplankton have a significant effect on organic matter transformation and the energy flow in these ecosystems. Key ecological factors affecting the biocenosis of estuarine waters, including changes in the quantitative and qualitative composition of zooplankton, are salinity (Remane 1934, Guttowa 1956, Róžańska 1964, 1972, Hall *et al.* 2002), water temperature (Adamkiewicz-Chojnacka *et al.* 1985, Róžańska *et al.* 1985, Żmudziński *et al.* 1990, Paturej *et al.* 2000), and lake trophic status (Gliwicz 1969, 1974, 1977, Hillbricht-Ilkowska 1977, Matveeva 1991, Rogozin 2000). Irregular intrusions of marine waters cause considerable fluctuations in salinity levels and thermal conditions and permit the invasion and establishment of estuarine organisms (Hall *et al.* 2002, Telesh 2004). In the current studies on coastal lakes, species abundance was negatively correlated with water temperature and positively with temporally variable salinity (Fig. 2).

Reductions in the number of species accompanied by the dominance of a very limited number of them are typical features of the progressive eutrophication of brackish-water lakes (Remane 1934 and Karabin 1985a, b). Only a small number of species was recorded in the coastal lakes in the current study, but some of them (primarily those that are recognized indicators of the trophic state of waters) comprised large populations that dominated both total abundance and biomass. This was also demonstrated by Rogozin (2000) who analyzed lakes differing in trophic status.

Some researchers have determined the trophic state of lakes based on faunal analysis alone (i.e., through the absence or presence of specific indicator species). Such studies include those by Bowkiewicz (1938) of lakes situated in the Suwałki Lakeland and in the Wilno region and by Widuto (1987, 1989) in lakes Mutek and Bęskie. Other authors (Patalas 1954, Radwan 1973) demonstrated that in order to rely on bioindicators, faunal analysis must first be combined with an understanding of the relationships between the trophic states of lakes and the numerical population characteristics of zooplankton. Geographical differences in species occurrence should also be taken into account.

In the current study, the structural characteristics of zooplankton, when employed in the trophic state indices proposed by Radwan (1976) and Karabin (1985a, b), were found to be good tools for lake classification. One of the key indices applied to lakes representing various limnological types is the trophic state index based on Secchi disk transparency (Carlson 1977). Further, according to Hillbricht-Ilkowska (1977) and Karabin (1985a), one of the most reliable indices that permits determining the precise trophic state of lakes is the proportion of the *tecta* form in the *Keratella cochlearis* population, which increases along with an increasing trophic state. Calculating these two indices for



the coastal lakes examined in the present study indicated that they could be classified as polytrophic (except for lakes Dołgie Wielkie and Dołgie Małe).

The zooplankton densities in the coastal lakes of the current study varied widely (233-3710 indiv · dm<sup>-3</sup>). The relative abundance and biomass of zooplankton can serve as criteria for assessing the trophic state of lakes (Karabin 1985a, Radwan 1976); this conclusion was also confirmed by Parpala *et al.* (2003) in their study of Lake Balaton and by Lovik and Kjellberg (2003), who examined the Norwegian Lake Mjøsa. Zooplankton-related trophic state indices calculated in the present study revealed various correlations between the numbers and biomass of rotifers and crustaceans and the trophic status of the lakes. According to Karabin (1985a), the abundance of rotifers increases along with the increasing trophic status of a lake, whereas the abundance of crustaceans increases only between the mesotrophic and mesoeutrophic states. These observations were also confirmed in the present study (in lakes Kopań and Resko Przymorskie). In nine of the lakes analyzed, zooplankton abundance was determined primarily by rotifers while zooplankton biomass was determined by crustaceans. Only in lakes Liwia Łuża and Dołgie Wielkie were zooplankton abundance and biomass determined by crustaceans. Straile and Geller (1998) studied crustacean zooplankton in Lake Constance where trophic status changed from oligotrophic to mesoeutrophic, and these authors found that the biomass of crustaceans increased several times over this period. A similar situation was observed in the present study with regard to Lake Liwia Łuża, which was classified as eutrophic with certain symptoms of polytrophication. In addition, the species diversity of zooplankton in Lake Liwia Łuża was low, which was indicated by the dominance of a single species accompanied by low proportions of other taxa.

It should be stressed that the group of crustacean indicators of high trophic status did not include copepods in these coastal lakes. According to Kajak (2001), the contribution of Copepoda to the zooplankton community increases in oligotrophic waters.

According to Karabin and Ejsmont-Karabin (1993, 1996), advanced eutrophication may occur readily in shallow, polymictic lakes (e.g., estuaries), while deep, stratified lakes (like those located in the Suwałki Lakeland) are much more resistant to eutrophication. It is very important that coastal lakes, like those investigated in the present study, and their catchments are protected from degradation through reclamation, drainage, and increased organic inputs. With their variety of physical and biological assimilation mechanisms, coastal lakes comprise an effective biological buffer zone that prevents the transport of excess organic and associated toxic substances into the Baltic Sea.

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