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LONG-TERM CHANGES IN THE OCCURRENCE OF UNIONID BIVALVES IN A EUTROPHIC LAKE

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ABSTRACT: Earlier studies (1972–1987) on the occurrence of unionid bivalves in the eutrophicated Lake Mikołajskie (Masurian Lakeland, NE. Poland) were continued in 1992–2008. Of the five recorded species (*Unio tumidus*, *U. pictorum*, *Anodonta cygnea*, *A. anatina,* and *Pseudanodonta complanata*), *A. cygnea* and *P. complanata* disappeared by 1987, whereas *U. pictorum* was observed sporadically at that time, and the unionid occurrence zone was markedly reduced. Beginning in 1992, a pronounced increase in abundance of *U. tumidus* was observed, and since 2002–2003, a decline of the other two species. Since 2003 the maximal original vertical distribution of *U. tumidus* (down to ca. 5 m) was re-established. The size and age structure of its population changed markedly during the study. No individuals of shell length exceeding 55 mm and aged more than 5–6 years were recorded since 1987. Between 1972 and 1987 one-year-old individuals prevailed, whereas in the following years the age structure changed slowly, and in 2008 two- to four-year-old bivalves were most frequent. The potential effects of changes in trophy and the effects of other factors, e.g. decline of *Dreissena polymorpha*, on changes in the occurrence of Unionidae in Lake Mikołajskie are discussed.

KEY WORDS: Unionidae, *Unio tumidus*, long-term changes, eutrophication, Lake Mikołajskie

INTRODUCTION

Bivalves of the order Unionoida are widespread on all continents except Antarctica, and are represented by ca. 900 species (GRAF & CUMMINGS 2006, 2007). However, in Poland only six native species of three genera are known: five occur in standing waters, namely *Anodonta anatina* (Linnaeus, 1758), *A. cygnea* (Linnaeus, 1758), *Pseudanodonta complanata* (Rossmässler, 1835), *Unio pictorum* (Linnaeus, 1758), *U. tumidus* Philipsson, 1788 while one, *U. crassus* Philipsson, 1788, is associated only with running waters.

Unionid bivalves are among the largest freshwater invertebrates, commonly occurring in different types of water bodies in Poland. Although their densities are usually low, their contribution to the overall lake benthos biomass often exceeds 90% (ÖKLAND 1963), and their influence on the functioning of freshwater ecosystems may be very significant (STAŃCZYKOWSKA & LEWANDOWSKI 1997, VAUGHN & HAKENKAMP 2001, STRAYER 2008).

The decline of Unionoida is observed world-wide (e.g. BOGAN 1993, LYDEARD et al. 2004). Literature data point especially to the recent sudden extinction of unionids in North America, observed there since the beginning of the 20th century (WILLIAMS et al. 1992, BOGAN 1993, LYDEARD et al. 2004). Some of the endangered species are functionally extinct (species surviving but not reproducing; BOGAN 1993). In Europe, although many populations are locally endangered, no species is known to have become extinct (BOGAN 1993, and references therein). At a national scale, the picture is worse; for example, *Margaritifera margaritifera* (Linnaeus, 1758) (Unionoida: Margaritiferidae) most certainly went extinct within the present Polish boundaries by the first half of the 20th century (ZAJĄC & ZAJĄC 2014).

Studies on long-term changes in invertebrate macrofauna require data collected within the same habitats and with the use of the same methods over long periods of time. Such analyses, concerning mollusc fauna, have been conducted for a long time, especially in the Great American Lakes, and the unionid fauna of eastern United States has been intensively studied for over 150 years (BOGAN 1993). On the other hand, in Poland long-term studies of changes in the occurrence of molluscs are few and span relatively short periods of time. Most of them were carried out within the Masurian Lakeland, in the centrally-located Lake Mikołajskie (e.g. STAŃCZYKOWSKA 1975, LEWANDOWSKI 1991, STAŃCZYKOWSKA & LEWANDOWSKI 1993, STAŃCZYKOWSKA & STOCZKOWSKI 1997, PIECZYŃSKA et al. 1999), and sporadically in other lakes of this lakeland (PIECZYŃSKA et al. 1999, KOŁODZIEJCZYK et al. 2009). Such studies were also conducted in a few dam reservoirs (e.g. JURKIEWICZ-KARNKOWSKA 1998, JURKIEWICZ-KARNKOWSKA & ŻBIKOWSKI 2004, LEWIN & SMOLIŃSKI 2005, STRZELEC et al. 2005, JAKUBIK et al. 2007), which, however, are hydrologically different. The most-studied taxa are *Dreissena polymorpha* (Pallas, 1771), or sometimes Gastropoda or Mollusca in general, whereas detailed data on long-term changes of Unionidae are scarce (PIECHOCKI & DYDUCH-FALNIOWSKA 1993).

Between 1972 and 1987, pronounced changes in the unionid occurrence were observed in Lake Mikołajskie: decline of some species and reduction in the vertical distribution range of the others, changes in age structure, and reduction in maximal length (LEWANDOWSKI & STAŃCZYKOWSKA 1975, LEWANDOWSKI 1991). The aim of this study is to present data on the changes in the occurrence of unionids in Lake Mikołajskie in 1972–2008 and to attempt an explanation of the situation. It is based on the published results of 1972 and 1987 (LEWANDOWSKI & STAŃCZYKOWSKA 1975, LEWANDOWSKI 1991) and the results of the studies on molluscs/macroinvertebrates of the Masurian Great Lakes conducted till 2008 within various projects.

STUDY AREA AND METHODS

The eutrophic Lake Mikołajskie (Table 1) is located in the central part of the Masurian Lakeland. It is characterised by a small flow of water entering from lakes Tałty and Bełdany, and exiting to the south-east into Lake Śniardwy (Fig. 1), and further to the rivers Pisa, Narew and Vistula. The town of Mikołajki (ca. 4,000 inhabitants) is located at the north-eastern shore, and is a popular summer sailing and water sports resort, and Lake Mikołajskie is heavily used for recreational tourism (CYDZIK et al. 2000).

Since the 1970s, Lake Mikołajskie has undergone significant eutrophication (GLIWICZ et al. 1980), and water transparency decreased sharply between 1954 and 1971 (Fig. 2). A slight recovery, probably due to opening of a mechanical-biological sewage treatment plant with chemical dephosphorisation in Mikołajki in 1997 (CYDZIK et al. 2000), was observed only in 2005.

Table 1. Characteristics of Lake Mikołajskie

Origin	post-glacial
Morphometry	tunnel-valley
Type of mixing	holomictic, dimictic
Surface area	460 ha
Depth	
max.	27.8 m
mean	11.0 m
Shoreline	
length	14 km
development	1.7
Littoral surface	87 ha (19% of surface area)

The research was conducted on Lake Mikołajskie in 1992, 1997, 2002, 2003, 2005, 2007, and 2008,

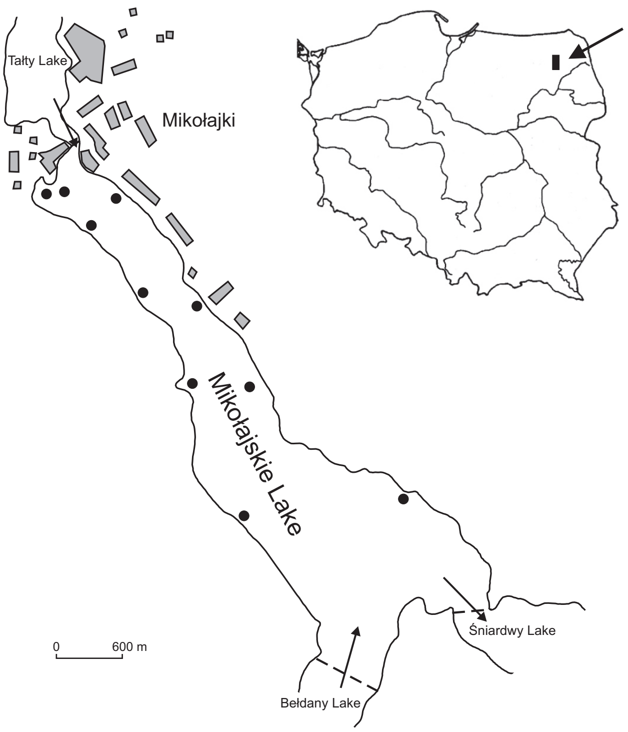

Fig. 1. Study area – sampling sites (black circles) in Lake Mikołajskie

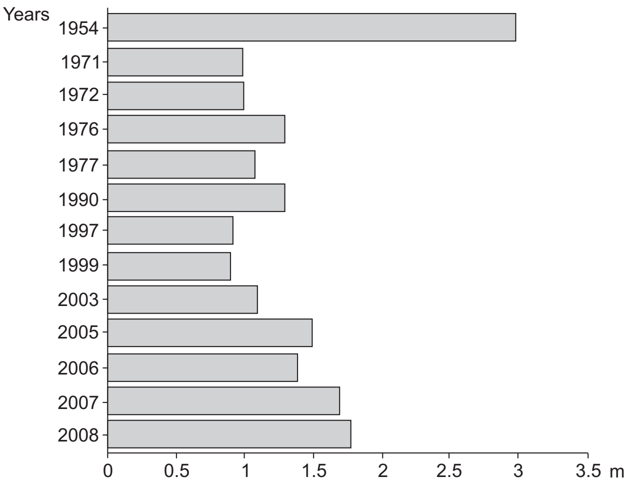

Fig. 2. Visibility of Secchi's disc in Lake Mikołajskie (summer). Data sources: 1954 – SZCZEPAŃSKI (1968); 1971, 1972 – PIECZYŃSKA (1976); 1976, 1977 – GLIWICZ et al. (1980); 1990 – CYDZIK et al. (1995); 1997 – CYDZIK et al. (2000)

once per summer, and the results were compared with the data from 1972, published by LEWANDOWSKI & STAŃCZYKOWSKA (1975), and from 1987 by LEWANDOWSKI (1991). In the 1990s, 10 sites along the lake shores were sampled (Fig. 1). They were identical to the sites from the previous studies and included the same depths (from 0.5 m, or where reed zone was present, from 1.0 m, every 1 m, down to the maximal depth of bivalve occurrence – usually to 5–6 m). In subsequent years the number and distribution of the sites were slightly corrected due to the development of the marina along the shores within the town.

At 0.5 m the bivalves were at first collected by hand from a square frame of 0.25 m² sampling area, thrown repeatedly at random to the bottom, or taken with (Fig. 3) a bottom scratch sampler (ZHADIN 1966), side length 20 cm, dragged along 0.5 m of the bottom. At deeper sites, initially, a dredge sampler of side length 0.4 m dragged along 3 m was used, later – Bernatowicz's grab (ZHADIN 1966) of a sampling area of 0.16 m² (1 to 3 samples from each depth), and (2005, 2007 and 2008) Günther's sampler of sampling area 0.276 m² (4 samples from each depth). The samples were washed on a sieve of 1 mm mesh, separated macroscopically, and the bivalves were isolated and identified using the key of PIECHOCKI & DYDUCH-FALNIOWSKA (1993). The vertical distribution of the bivalves, their frequency (% of sites with Unionidae), and density were determined, as was (except for 2003 and 2005) the maximal shell length of *Unio tumidus* Philipsson, 1788 (the only species commonly found throughout the study period). For 2007 and 2008 (years with sufficient number of collected specimens) the age of collected bivalves was estimated by counting winter rings, and the age structure of the population was compared to the data from 1972 and 1987.

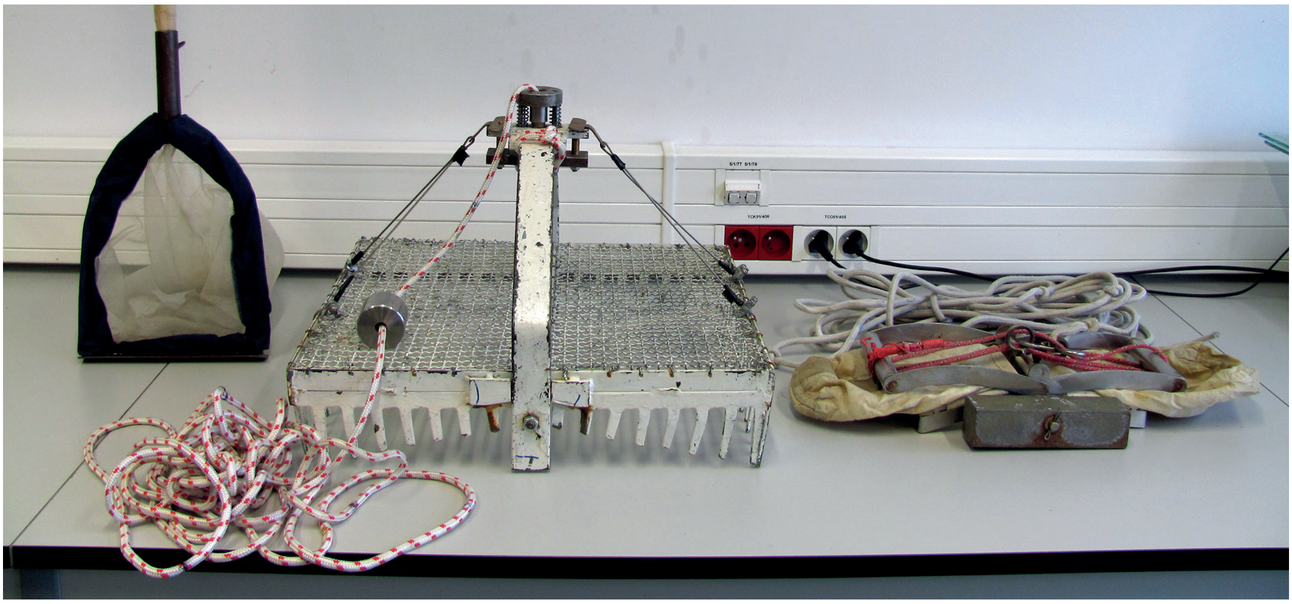

Fig. 3. From the left: bottom scratch sampler, Bernatowicz's grab and Günther's sampler

RESULTS

Both in 1972 and 1987 the frequency of Unionidae in Lake Mikołajskie was 100%. Since 1992 it decreased markedly, with the minimum in 2002 (Table 2), and its fairly low values persisted until 2005. No pronounced increase in the unionid frequency (F = 100%) was observed until 2007 and 2008.

Table 2. Some parameters of occurrence of unionid bivalves in Lake Mikołajskie

Year	Number of sites	Frequency (%)	Density (indiv. m^{-2})	
			mean	max.
1972*	10	100	0.4	7.2
1987**	10	100	0.4	4.0
1992	10	50	1.6	16.0
1997	8	60	2.4	10.4
2002	9	40	1.9	20.0
2003	10	70	5.6	64.0
2005	9	60	10.6	48.3
2007	8	100	16.2	145.0
2008	10	100	9.2	45.0

* after Lewandowski & Stańczykowska (1975)
** after Lewandowski (1991)

In 1972 the bivalves were recorded from the depths of 0.5 to 5.5 m, whereas by 1987 the occurrence zone was considerably reduced (Fig. 4). In the 1990s their vertical distribution did not reach below 3.5 m, and in 2002 not even 2.5 m. One year later the occurrence zone again, though sporadically, reached down to 5.5 m, and a similar distribution range was recorded throughout the rest of the study period.

The mean density of Unionidae in their occurrence zone at the beginning of the study period was ~0.4 ind. m^{-2} (Table 2). By 1992 a fourfold increase in the mean and two- to fourfold increase in the maximal density was observed. In subsequent years a further increase tendency was recorded. The highest mean, 16.2 ind. m^{-2}, and the highest maximal density (145 ind. m^{-2}) were observed in 2007, at the depth of 1 m at the western shore in the middle part of the lake.

In 1972 five species of Unionidae were found in Lake Mikołajskie (Fig. 5). By 1987, *A. cygnea* and

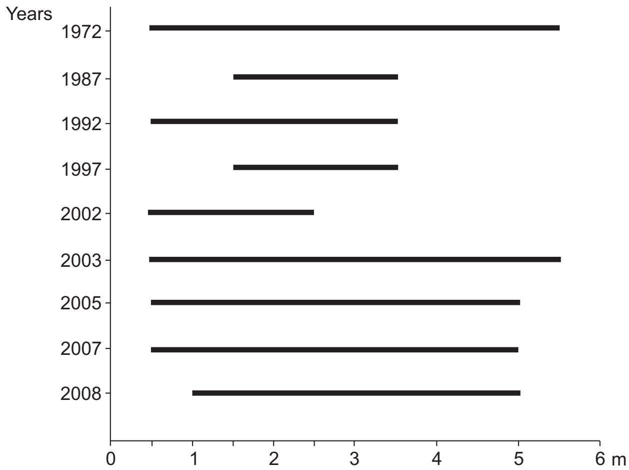

Fig. 4. Zone of occurrence of unionid bivalves in Lake Mikołajskie. Data for 1972 and 1987 – Lewandowski & Stańczykowska (1975) and Lewandowski (1991), respectively

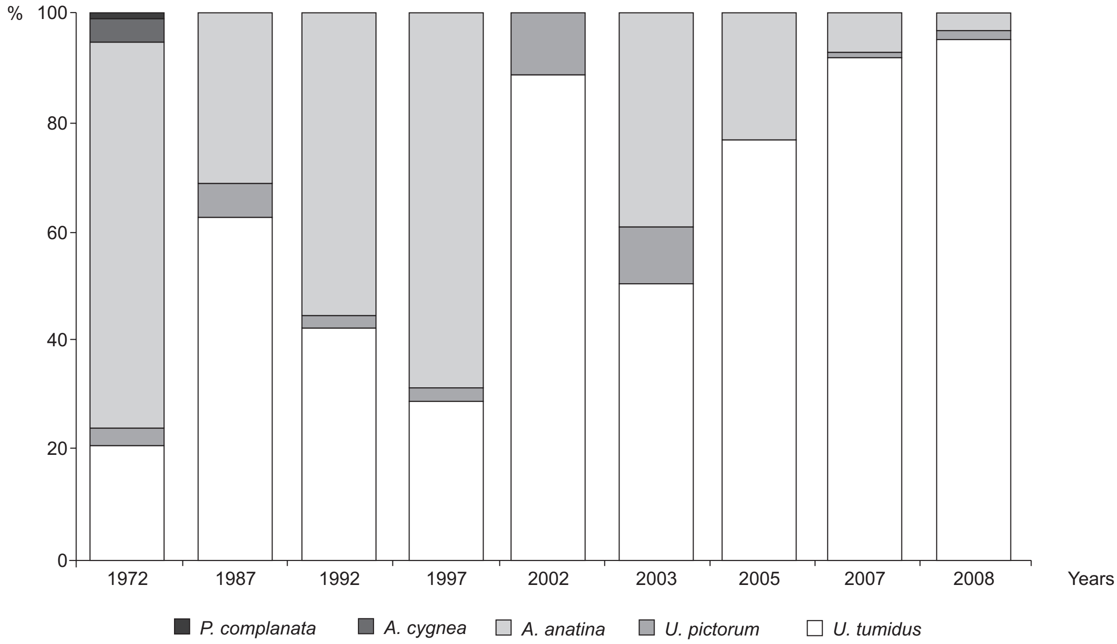

Fig. 5. Dominance structure of Unionidae in Lake Mikołajskie in consecutive years of studies. Data for 1972 and 1987 – Lewandowski & Stańczykowska (1975) and Lewandowski (1991), respectively

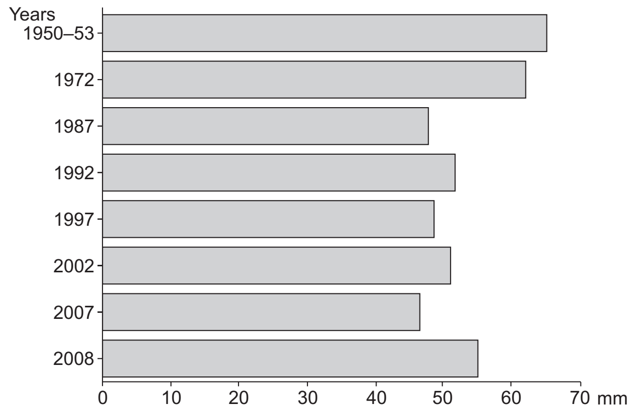

Fig. 6. Maximum length of *Unio tumidus* shells in Lake Mikołajskie. Data for 1950–53, 1972 and 1987 – BERGER (1960), LEWANDOWSKI & STAŃCZYKOWSKA (1975) and LEWANDOWSKI (1991), respectively

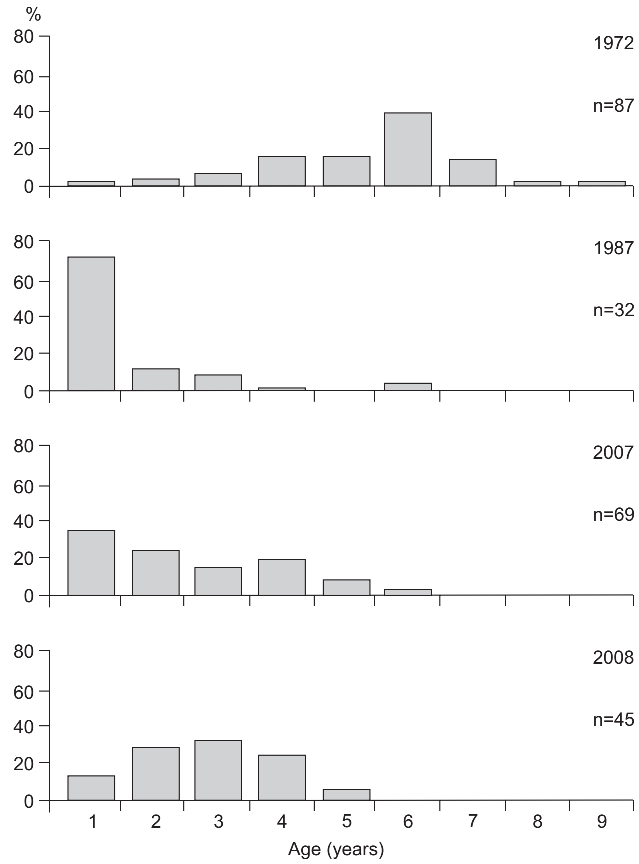

Fig. 7. Age structure of *Unio tumidus* in Lake Mikołajskie in consecutive years of studies. Data for 1972 and 1987 – LEWANDOWSKI & STAŃCZYKOWSKA (1975) and LEWANDOWSKI (1991), respectively

P. complanata disappeared from the list, and they were not observed again during the study. *Unio tumidus*, *U. pictorum* and *A. anatina* were recorded almost throughout the study period, although *U. pictorum* was always rare, and in 2005 it was not observed at all.

The percentage of *U. tumidus* and *A. anatina* fluctuated greatly in consecutive years (Fig. 5). In 1972, *A. anatina* was the dominant species (71.5%), and *U. tumidus* formed a significant proportion (20.5%). In 1987–2005 the proportion of these two species fluctuated further. In 2002, at a generally low frequency of Unionidae (Table 2), no *A. anatina* was found, since 2005 the proportion of *U. tumidus* increased markedly, and in 2007 and 2008 it exceeded 90% of all collected Unionidae.

The maximal shell length of *U. tumidus* collected in Lake Mikołajskie decreased considerably in the 1980s, from more than 60 mm in 1972 to 47–52 mm in 1987–2007. In 2008 the biggest *U. tumidus* found reached 55 mm, but still it was much below the values recorded at the beginning of the study period (Fig. 6).

Based on winter rings, the oldest individuals in 1972 were estimated to be 9 years old (Fig. 7). In subsequent years of the study the lifespan of the bivalves became noticeably shorter, and did not exceed 6 years in 1987 and 2007, or even 5 years in 1992 and 2008.

The age structure of *U. tumidus* also changed markedly. Whereas in 1972 individuals aged 4–7 years dominated, and 6-year-olds were most numerous (Fig. 7), in the following years the proportion of young individuals increased. In 1987 one-year-olds outnumbered the other age classes (ca. 70% of the population). In 2007 and 2008 the age structure of *U. tumidus* "flattened", and 1–4-year-olds constituted ca. 90% of the population.

DISCUSSION

Despite numerous studies of German authors, which were conducted in the former East Prussia, now Masurian Lakeland in Poland, the first data on the occurrence of unionids come from the beginning of the 20th century. These data comprise a list of species of Lake Śniardwy (HILBERT 1912) and the nearby Krutynia River (HILBERT 1913). The first qualitative data on unionids of Lake Mikołajskie date from the 1950s (BERGER 1960). In 1953 four species were found in Lake Mikołajskie: *Unio tumidus*, *U. pictorum*, *Anodonta cygnea*, and *A. anatina*, and in 1972 LEWANDOWSKI & STAŃCZYKOWSKA (1975) found also *Pseudanodonta complanata*. In the mid-1980s *A. cygnea* and *P. complanata* completely disappeared, and *U. pictorum* was rare at that time (LEWANDOWSKI 1991), although, according to BERGER (1960), in the 1950s the species was relatively abundant. The rather abundant *A. anatina* (Fig. 5) became rare only in 2007.

Lake Mikołajskie underwent marked eutrophication (effect of intensification of agriculture and tourism) during the last 50 years, which is clearly illustrated by the decrease in water transparency (Fig. 2). Only in 2003 was a small increase in transparency observed, to 1.8 m in 2008. Biological indices, which have a more cumulative character, also point to eutrophication, and in more recent years – oligotrophication of this lake (Ozimek & Kowalczewski 1984, Kowalczewski & Ozimek 1993, Stułka 2004, J. Ejsmont-Karabin, unpublished data).

The effect of eutrophication and water pollution which is associated with, for example, periodic decreases in oxygen concentration in the water and disappearance of fishes which serve as hosts for glochidia, is often regarded as the main cause of unfavourable changes in the occurrence of Unionidae (e.g. Arter 1989, Nalepa et al. 1991, Bogan 1993, Piechocki & Falniowska 1993, Patzner & Müller 2001, Weber 2005, Pip 2006). In recent years there were no ichthyofaunistic studies in Lake Mikołajskie, but the drastic decrease in catches observed for at least a dozen years is a result of both eutrophication and overexploitation combined with the lack of stocking.

Among the five unionid species from the littoral of the eutrophicated Zegrzyński Reservoir (central Poland), *A. cygnea* and *P. complanata* disappeared entirely between 1980 and 1995, whereas *U. tumidus*, *U. pictorum*, and *A. anatina* remained (Jurkiewicz-Karnkowska 1998). Zettler & Jueg (2007) pointed to the disappearance of *U. crassus* from the rivers of north-eastern Germany as a result of eutrophication. In the Krutynia River, which retained high water quality, taxonomic composition of the unionids did not change for almost a hundred years (Hilbert 1913, Lewandowski 1996, Jakubik & Lewandowski 2008).

The decrease in the unionid shell size is also considered to be the effect of eutrophication (Arter 1989, Piechocki & Dyduch-Falniowska 1993). While according to Zhadin (1952) the adult shell length of *U. tumidus* ranges from 60 to 90 mm, and according to Urbański (1957) from 80 to 100 mm, in later years it was only 58±7 mm (Piechocki & Dyduch-Falniowska 1993). In Lake Mikołajskie the maximal length of *U. tumidus* decreased markedly in consecutive years; in 2008 a small increase was observed (Fig. 6), it did not reach, however, the values of earlier years. It should be stressed that the maximum shell length depends on the number of collected mussels, therefore some artifacts in our data are possible. Arter (1989) pointed out that the increase in trophy caused growth acceleration and shortening of lifespan of *U. tumidus*. Such phenomenon was clearly observed also in Lake Mikołajskie (Fig. 7).

Changes in trophy seem not to provide a sufficient explanation for the observed changes. According to Agrell (1949), the density of unionid populations in lakes of southern Sweden increased from oligotrophic to heavily eutrophic conditions, whereas the increase in abundance observed in Lake Mikołajskie occurred at a slight increase, followed by a decrease in trophy. The increase in abundance of Unionidae is mostly the result of the increase in abundance of *U. tumidus*. The species is regarded as the most resistant native unionid (Piechocki & Dyduch-Falniowska 1993). According to Agrell (1949), however, eutrophication resulted in a decrease in abundance of *U. tumidus* (and increase in abundance of *U. pictorum*). According to Arter (1989), the abundance of *A. cygnea* and *U. pictorum* was higher, and of *U. tumidus* lower, in lakes with increased trophy level. In the eutrophicated Zegrzyński Reservoir, besides *U. tumidus*, also *U. pictorum* and *A. anatina*, which are already rare in Lake Mikolajskie, remained (Jurkiewicz-Karnkowska 1998). In the eutrophicated Lake Miedwie (north-western Poland) *A. anatina* is abundant, whereas *U. tumidus* is less numerous and rarer than *U. pictorum* (Świerczyński 2002). In 107 Estonian lakes, an increase in trophy resulted in a decline in abundance of *Unio*, but not of *Anodonta* (Timm et al. 2006). Research conducted in 2005–2007 within the whole Masurian Lakeland (Kołodziejczyk & Lewandowski 2008) showed that in most of the lakes, both eutrophic and mesotrophic, only *U. tumidus* (dominant in most of them) and *A. anatina* were found, and low densities of these bivalves were also observed in lakes of both trophic types.

According to Piechocki & Dyduch-Falniowska (1993), eutrophication and water pollution result in narrowing of the vertical distribution range of Unionidae and its shift toward the shore line. Instead, in Lake Mikołajskie the limitation of the distribution range of these molluscs occurred both at greater and lesser depths (Fig. 4). This tendency, persisting for at least 15 years, became subsequently largely reversed, although it happened before the slight decrease in trophy was observed.

The decrease in the density and reduction of the vertical distribution range were repeatedly observed also in *Dreissena polymorpha*, among others in Lake Mikołajskie. In 1960 its abundance dropped sharply, from over 2,000 ind. m^{-2} to almost 0, then the population was restored, reduced again in 1977, slightly restored in the 1980s, and finally disappeared in the 1990s (Stańczykowska 1961, 1978, Stańczykowska & Lewandowski 1993). Since 1997 *D. polymorpha* re-appeared, although in very low densities. These changes were mainly associated with the eutrophication of the lake (Stańczykowska & Stoczkowski 1997), long-term observations, however, suggest that periodic overcrowding may also be important (Lewandowski 1982, Stańczykowska & Lewandowski 1993, Lewandowski & Stańczykowska 2008).

The mass appearance of *D. polymorpha* is regarded as the main cause of the decline of Unionidae in the Great American Lakes (e.g. HAAG et al. 1993, GILLIS & MACKIE 1994, NALEPA et al. 1996, 2001, BURLAKOVA et al. 2000, STRAYER & MALCOM 2007). According to RICCIARDI et al. (1998), the effect of the introduction of *D. polymorpha* was, alongside habitat degradation, the second major cause of extinction of native unionids in North American freshwaters. Characteristically, after the replacement of Unionidae by *D. polymorpha* in Lake St. Clair, the total biomass of the bivalves remained unchanged, whereas the filtration rate of the population of *D. polymorpha* appeared to be 12 times higher than that of the former population of Unionidae (NALEPA et al. 1996). This may suggest that *D. polymorpha*, while overgrowing a unionid mussel, may limit its food accessibility. In Lake Mikołajskie no negative effect of *D. polymorpha* on overgrown unionid individuals was observed. However, the values recorded there in the 1970s: 85% of individuals colonised by *D. polymorpha*, and the mean of 20 individuals of zebra mussel per one unionid (LEWANDOWSKI 1976), approximate those presented by PIECHOCKI (2008), who observed increased mortality of colonised unionids in flowing waters.

According to RICCIARDI et al. (1995), unionid mortality increases at the zebra mussel density of more than 1,000 ind. m^{-2}. In the 1950s the density of *D. polymorpha* in Lake Mikołajskie was twice greater than this value. The initially low density of Unionidae may have been the result of the presence of *D. polymorpha*, and the drastic reduction in their abundance caused, after a few years, increase in the number of *U. tumidus*. The decrease of unionid density, compared to the time before the zebra mussel invasion, was suggested by STRAYER & MALCOM (2007), who referred to examples of European waters.

The disappearance of several unionid species, the decrease in size of *U. tumidus*, and even the temporary reduction of the vertical distribution range of unionids may result from the eutrophication, whereas the increase in density of *U. tumidus* is probably the result of the release from the competitive pressure of *D. polymorpha*. The relationships between different littoral invertebrate species are very complex and it seems that attributing all recent transformations exclusively to changes in trophy is by far too much of a simplification.

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