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Andrzej KOŁODZIEJCZYK[1], Krzysztof LEWANDOWSKI[2],
Anna STAŃCZYKOWSKA[2]

[1] Department of Hydrobiology, University of Warsaw, Banacha 2, 02-097 Warsaw, Poland
e-mail: a.kolodziejczyk@uw.edu.pl (*corresponding author*)
[2] Institute of Biology, University of Podlasie, B. Prusa 12, 08-110 Siedlce, Poland
e-mail: ekologia@ap.siedlce.pl

LONG-TERM CHANGES OF MOLLUSC ASSEMBLAGES IN BOTTOM SEDIMENTS OF SMALL SEMI-ISOLATED LAKES OF DIFFERENT TROPHIC STATE

ABSTRACT: It is a common view that increase of the trophic state of lakes has a negative effect on littoral invertebrate macrofauna, molluscs among them. However, the available data are often contradictory, and the decline of particular species is often observed only at a very pronounced raise in trophic state. The aim of this work was to present the changes of the composition and abundance of bottom malacofauna taking place during last 30 years in five small (area from 0.12 to 1.74 km^2), mainly shallow (mean depth from 3.7 to 11.8 m) lakes of different trophic state (eutrophic and mesotrophic), connected by a small river (Masurian Lakeland, Northeastern Poland). The research were conducted in years 1997 and 2006 and were compared with published data, collected in 1976. The trophic state of the lakes studied was still constant during the period of investigations. In the studied lakes the decrease of number of bottom mollusc species was observed in subsequent years. The previously recorded there alien, invasive species, *Potamopyrgus antipodarum* (J.E. Gray, 1843) and *Lithoglyphus naticoides* (C. Pfeiffer, 1828) also disappeared. *Dreissena polymorpha* (Pallas, 1771) remained the dominant species in most of the lakes. These changes were recorded in four eutrophic lakes as well as inone mesotrophic lake**.** The decline of the species in individual lakes didn't follow any regularity. Some mollusc species disappeared and value of similarity index between malacocenoses in these lakes decreased. It seems, that the trophic state was not the cause of disappearance of some mollusc species from the studied lakes. However, the effect of frequent anoxia in littoral zone related to eutrophication was raised up as the possible cause. The decline is of long-term character, probably resulting from small size and relative isolation of the lakes, which impede their recolonisation.

KEY WORDS: lakes, molluscs, long-term changes, trophic state, isolation, invasive alien species

1. INTRODUCTION

Eutrophication of freshwater environments usually affects the species composition and abundance of several groups of organisms. There exists a lot of data concerning phytoplankton, zooplankton, fishes and macrophytes; much less is known about macroinvertebrates. The increase in trophic state and pollution of aquatic systems are regarded as the main factors causing the decrease in number of the particular mollusc species, the narrowing of their vertical distribution in a lake, and even disappearance of some species from the aquatic habitats. This was observed for molluscs in general (Kansanen and Aho 1981, Jurkiewicz-Karnkowska 1998), *D. polymorpha* (Schloesser and

Nalepa 1993, Stańczykowska and Stoczkowski 1997), bivalves of the Unionidae family (Arter 1989, Lewandowski 1991), snails from Hydrobiidae family (Lillebo *et al.* 1999, Brzeziński and Kołodziejczyk 2001,) and snails associated with submerged macrophytes (Pieczyńska *et al.* 1999). However, the results of the research are not always conclusive. Timm *et al.* (2006), basing on an enormous material (107 lakes), showed differences between mollusc species in their reaction to the eutrophication. As a result, using individual species as trophic indicators might be difficult. According to Clark (1979), most of 91 studied species and sub-species of snails are eurytopic, and only seven are entirely, or almost entirely, restricted to lakes of particular trophic state. The same species sometimes are associated with trophic state differently, *e.g. Lymnaea stagnalis* in Clark (1979) and in Costil and Clement (1996).

The research on biotic structure of five small flow-through, but semi-isolated lakes of the Jorka River (Masurian Lakeland) began in the 70s of the 20th century. It included molluscs, and the most frequent species found in all lakes was *Dreissena polymorpha*, to which the attention of the researchers was directed (Stańczykowska *et al.* 1983). In 1993–94 the decline of *D. polymorpha* was observed in three from five of the studied lakes (Lewandowski *et al.* 1997).

The aim of our study was to evaluate the changes in diversity and abundance of molluscs in the bottom of these lakes during the last 30 years, and an attempt of explaining the causes of observed changes. We suppose, that the factors other than eutrophication are mostly responsible for mollusc species reduction.

2. STUDY AREA AND METHODS

The investigated lakes (Fig. 1) are located in the area of Masurian Lakeland (53°47'N to 53°50'N and 21°26'E to 21°32'E). These lakes are of different surface area (ranging from 0.12 to 1.74 km^2) and depth (Table 1). The lakes differ in littoral area as well. The Jorka River flowing through them is small (length 12 km) and shallow. They are distinctly isolated from the Great Masurian Lakes. Length of River Jorka between Lake Jorzec and Lake Tałty (Fig. 1) is 2 km, and average discharge at the outflow from Lake Jorzec is close to 1.5 m^{3}s^{-1} (Hillbricht-Ilkowska 2002a). Its mouth part to Lake Tałty, one of Great Masurian Lakes (area 11.7 km^2, maximal depth 44.7 m, average 15.3 m) is channel type overgrown with macrophytes. Visibilities of Secchi disc in individual lakes of summer 2006 were similar to values recorded in previous years (Table 2). Also average values of total P and total N concentration in successive lakes are similar for periods 1992–1993 (TP from 0.036 in Lake Majcz to 0.174 mg L^{-1} in Lake Jorzec and TN from 1.115 in Lake Majcz to 2.430 mg L^{-1} in Lake Jorzec) and 1996-1998 (TP from 0.096 in Lake Majcz to 0.181 mg L^{-1} in Lake Zełwążek and TN from 1.352 in Lake Majcz to 2.419 mg L^{-1} in Lake Jorzec (Hillbricht-Ilkowska 2002a). Only chlorophyll *a* concentration in Lake Głębokie decreased clearly in the second period of the investigations (Hillbricht-Ilkowska 2002a). Lake Majcz Wielki is mesotrophic, while the other lakes are eutrophic (Hillbricht-Ilkowska 1983, 2002a). Trophic state of these lakes has been for a long time at the same level, or increased slightly (Hillbricht-Ilkowska 2002a). In July 1997 the data were collected

Table 1. Characteristics of investigated lakes of the Jorka River watershed (acc. to Hillbricht-Ilkowska 2002b).

Lake	Area (km^2)	Depth (m)		Shoreline		Littoral (% of area)	Depth of hypol.[2] (m)
		max	mean	length (km)	development[1] (l)		
Majcz Wielki	1.74	16.4	6.0	7.85	1.8	42	<8
Inulec	1.61	10.1	4.6	10.60	2.3	31	<5
Głębokie	0.46	34.3	11.8	4.41	1.8	23	<8
Zełwążek	0.12	7.4	3.7	1.81	1.5	58	0
Jorzec	0.41	11.6	5.5	4.26	1.9	22	<5

1 Acc. to S. Sakowicz Inland Fisheries Institute (Olsztyn) data
2 Acc. to Planter *et al.* (1983)

Table 2. Visibility of Secchi disc in summer in the lakes of the Jorka River watershed.

Lake	Visibility (m)			
	1976[1]	1992–93[2]	1996-98[2]	2006
Majcz Wielki	3.0-4.5	3.9	3.7	4.4
Inulec	1.0-1.8	1.6	1.5	1.9
Głębokie	1.2-2.6	1.9	2.2	1.0
Zełwążek	1.6-2.7	1.7	1.7	—
Jorzec	1.0-1.7	1.2	1.4	1.5

1 Acc. to Spodniewska (1983)
2 Acc. to Hillbricht-Ilkowska (2002b)
— no data

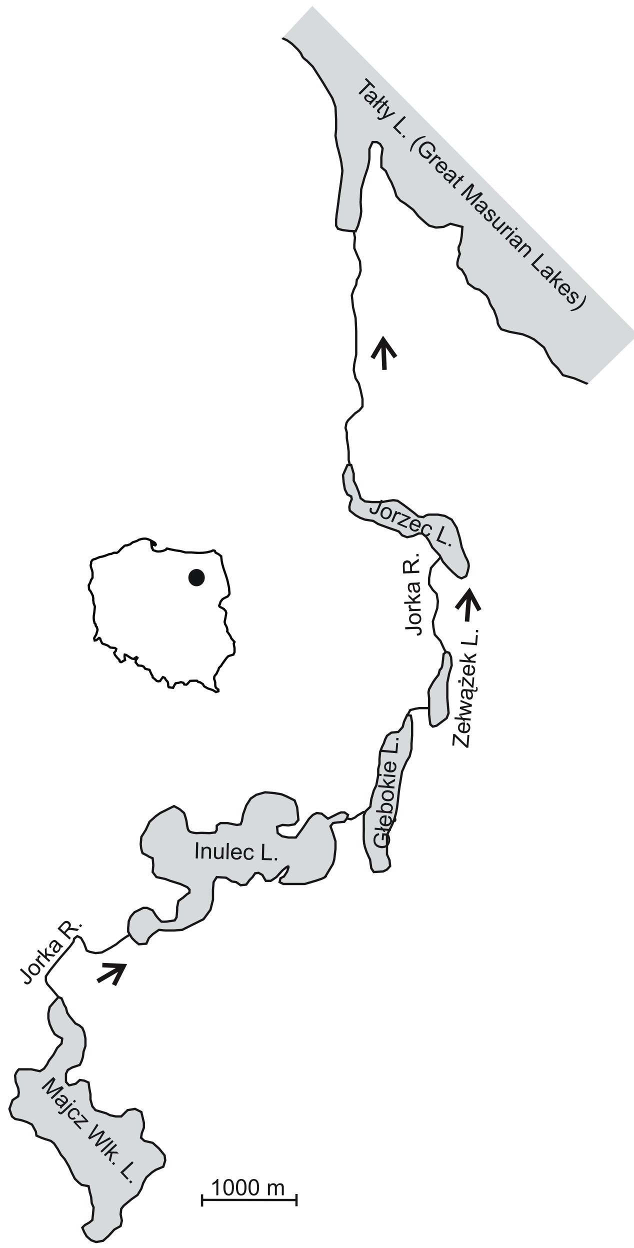

Fig. 1. Lakes of River Jorka (Masurian Lakeland).

at five sampling sites in lakes Majcz Wielki and Inulec, four sites in Lake Głębokie and three sites in Lake Zełwążek. Samplings were collected from the depth of 0.5 m from the area limited by a frame of 0.5 × 0.5 m, and beginning from the depth of 1 m every 1 m down to the maximum depth of molluscs distribution (5–6 m). A bottom drag of 0.4 m side was dragged behind the boat on the distance of 3 m parallel to the lake shore. Altogether 91 samples were collected. In August 2006 samples were collected in four lakes (Majcz Wielki, Inulec, Głębokie and Jorzec), from 10 sites in each lake. On every site one sample of the bottom sediments from the depth of 1–2 m was taken using a Günther's bottom sampler (sampling area of 276 cm^2). The samples collected in 1997 and 2006 were rinsed through a 1 mm mesh sieve. The molluscs were isolated and identified using keys by Piechocki (1979) and Piechocki and Dyduch-Falniowska (1993). Taxonomy of molluscs was actualized according to A. Piechocki (unpubl. data).

The published data from the July 1976 (Stańczykowska *et al.* 1983; molluscs were collected by diver and rinsed through a 1 mm mesh sieve) were compared with the data collected in 1997 and 2006.

All data were used to calculate the similarity index of species composition (S) for pairs of samples, after Marczewski and Steinhaus (1959):

$$S = w/(a + b - w) \tag{1}$$

where:
a – number of species in lake A,
b – number of species in lake B,
w – number of species common for lakes A and B.

S ranges from 0 to 1; values > 0.6 suggest high similarity of assemblages.

3. RESULTS

In 1976 in the five lakes 27 taxa of Mollusca were found altogether, from 20 (Lake Zełwążek) to 26 (Lake Jorzec) in each of them (Table 3)*. The most numerous were: *Dreissena polymorpha* (numerous in four lakes and frequent in one), *Bithynia tentaculata* (numerous in one and frequent in four lakes), bivalves from the Sphaeriidae family (frequent in five lakes) and *Valvata piscinalis* (frequent in four lakes and rare in one). In 1997 in the same lakes altogether 16 taxa were found, from 7 (Lake Zełwążek) to 12 (Lake Inulec) in each (Table 3).

The numerous species remained: *D. polymorpha* (but numerous only in two, frequent in one, rare in one and absent in one of the lakes) and *B. tentaculata*. Rather numerous were also *Unio tumidus* (but numerous in one and frequent in four lakes) and *Anodonta anatina* (frequent in four lakes and rare in one).

Of the species common in the previous years individuals of the Sphaeriidae species were recorded rarely in four lakes, and of *V. piscinalis*, also rarely, but only in Lake Inulec. Individuals of 12 species recorded before were not found in any of the lakes. These were: *Valvata cristata, V. macrostoma, Lithoglyphus naticoides* (invasive alien species), *Bithynia leachi, Physa fontinalis, Lymnaea corvus, Planorbis carinatus, Anisus vortex, Gyraulus crista, Planorbarius corneus, Ancylus fluviatilis* or *Pseudanodonta complanata*. An invasive alien species *Potamopyrgus antipodarum* was a new species recorded in 1997 and was frequent in lakes Inulec and Głębokie (Table 3).

In 2006 in four lakes altogether 8 species were found (Table 3), mainly *D. polymorpha* (93% of all collected individuals) and only single individuals of other species. Most mollusc species (6) were found in bottom sediments of Lake Inulec, least (2 species in each) in bottom sediments of lakes Majcz Wielki and Głębokie.

The number of Mollusca species found in subsequent research years in each of the studied lakes was visibly decreasing (Table 3). Relatively smallest changes were observed in Lake Inulec. The number of Gastropoda species decreased very pronouncedly in subsequent years, especially in Lake Majcz Wielki. In 2006 no individuals were found in bottom sediments of this lake. The smallest change in the species number was observed in Lake Jorzec between 1997 (4 species) and 2006

* In this year two species, *Lymnaea peregna* and *L. auricularia* were distingnished, at present they are considered as genus Radix (as *Radix sp.* in Table 3).

Table 3. Occurrence of molluscs in lakes of the Jorka River watershed in different years.

Lake	Majcz Wielki			Inulec			Głębokie			Zełwążek		Jorzec		
Taxon / Year	76[1]	97	06	76[1]	97	06	76[1]	97	06	76[1]	97	76[1]	97	06
Theodoxus fluviatilis (L.)	+	*	-	*	**+**	-	+	*	-	*	-	*	+	*
Viviparus viviparus (L.)	*	-	-	*	*	-	*	*	-	-	-	*	+	*
Valvata cristata O. F. Müller	*	-	-	*	-	-	*	-	-	*	-	*	-	-
Valvata macrostoma Mörch[2]	*	-	-	-	-	-	*	-	-	*	-	-	-	-
Valvata piscinalis (O. F. Müller)	+	-	-	+	*	-	+	-	-	+	-	*	-	-
Potamopyrgus antipodarum (J. E. Gray)[3]	-	-	-	-	+	-	-	+	-	-	-	-	-	-
Lithoglyphus naticoides C. Pfeiffer	*	-	-	-	-	-	-	-	-	-	-	*	-	-
Bithynia tentaculata (L.)	+	+	-	**+**	**+**	*	+	+	*	+	*	+	+	*
Bithynia leachi (Sheppard)	*	-	-	*	-	-	*	-	-	*	-	*	-	-
Physa fontinalis (L.)	*	-	-	*	-	-	*	-	-	*	-	*	-	-
Lymnaea stagnalis (L.)	*	-	-	*	-	-	*	*	-	*	+	*	*	-
Radix sp.[4]	+	+	-	*	+	-	*	-	-	*	-	*	-	-
Stagnicola corvus (Gmelin)[5]	-	-	-	*	-	-	-	-	-	-	-	*	-	-
Planorbis carinatus O. F. Müller	*	-	-	+	-	-	*	-	-	*	-	*	-	-
Anisus vortex (L.)	+	-	-	+	-	-	*	-	-	*	-	*	-	-
Gyraulus albus (O. F. Müller)	*	*	-	+	*	-	+	-	-	*	-	*	-	-
Gyraulus crista (L.)[6]	*	-	-	*	-	-	*	-	-	-	-	*	-	-
Planorbarius corneus (L.)	*	-	-	*	-	-	*	-	-	*	-	*	-	-
Ancylus fluviatilis (O. F. Müller)	*	-	-	*	-	-	*	-	-	-	-	*	-	-
Acroloxus lacustris (L.)	*	*	-	*	-	-	*	-	-	-	-	*	-	-
Unio tumidus Philipsson	*	+	-	*	+	*	+	+	-	-	+	*	+	-
Unio pictorum (L.)	*	-	-	-	-	*	*	-	-	*	+	+	+	*
Anodonta cygnea (L.)	-	-	-	-	+	-	-	-	-	*	-	*	-	-
Anodonta anatina (L.)[7]	+	+	*	*	+	*	*	*	-	*	+	+	+	-
Pseudanodonta complanata (Rossmässler)[8]	*	-	-	-	-	*	-	-	-	*	-	+	-	-
Dreissena polymorpha (Pallas)	**+**	**+**	+	**+**	**+**	**+**	**+**	+	**+**	+	*	**+**	-	-
Sphaeriidae[9]	+	*	-	+	*	-	+	-	-	+	*	+	*	-
Number of taxa	24	9	2	21	12	6	22	8	2	19	7	25	8	4

+ numerous – >100 ind. collected per sample

+ frequent – 10–100 ind.

* rare – <10 ind.

- absent

[1] Stańczykowska *et al.* 1983; [2] = *V. pulchella* Studer; [3] = *P. jenkinsi* (E. A. Smith); [4] in Stańczykowska *et al.* (1983), *Lymnaea peregra* (O. F. Müller) and *L. auricularia* (L.); [5]= *Lymnaea corvus* (Gmelin); [6]=*Armiger crista* (L.); [7]= *A. piscinalis* Nilsson; [8]= *A. complanata* Rossmässler; [9] in 1997, *Sphaerium corneum* (L.) and *Pisidium* sp.

(3 species). The difference in the number of species found was slightly more pronounced in the case of Pulmonata (Table 3) (in 2006 no individuals were found in bottom sediments of any of the four studied lakes) than in the case of Prosobranchia – in Lake Jorzec the same number of species of this group was found in 1997 and 2006.

The difference in the number of species of Bivalvia found in individual lakes is less pronounced than it is in the case of Gastropoda. In Lake Inulec 4 species were found in 1976 and 5 species in 1997 and in 2006, and in none of the other lakes their numbers fell to zero (Table 3). But in all lakes these species occurred in small numbers as the rare species. *Dreissena polymorpha* disappeared entirely only from Lake Jorzec in 2006. In other lakes the species was recorded during all research years, however its numbers in two of the lakes (Inulec and Zełwążek) decreased temporarily.

Table 4. Similarity (S) (formula 1) of the species composition of Mollusca in lakes of the Jorka River watershed.

Year	Number of pairs of lakes	Value S (mean and range of variation)	Proportion of the pair combination (%) of S>0.60
1976	10	0.78 (0.61-0.89)	100
1997	10	0.61 (0.31-0.67)	10
2006	6	0.22 (0.00-0.33)	0

The similarity (S) of the species composition in the studied lakes was very high in 1976 and decreased evidently in the subsequent years. Percentage of high values (S> 0.60) clearly decreased in successive years (Table 4).

4. DISCUSSION

The results obtained show that in all studied lakes there was a pronounced impoverishment of bottom mollusc taxonomic richness. However, Stańczykowska *et al.* (1983) included in their research molluscs inhabiting submerged macrophytes, which might decided of the greater number of species found in this period. Nevertheless, in subsequent years the exclusively bottom deposit species recorded before, such as *L. naticoides* or bivalves from Unionidae family, were not found in individual lakes (Table 3). Neither were found the species distinctly associated with the bottom deposits, such as *T. fluviatilis*, *V. viviparus*, *V. piscinalis*, *P. antipodarum*, *A. fluviatilis* or members of Sphaeriidae family. In the subsequent years of the research not only no members of generally rare species or small-sized species (that is potentially capable of being overlooked, such as *B. leachi*, *V. cristata*, *V. macrostoma* or *G. crista*) were found, but also none of common and those of greater size, such as *e.g. V. viviparus*, *P. fontinalis*, *L. stagnalis*, *Radix* sp., or *P. corneus*. Among the bivalves big, usually rare *A. cygnea* and small, usually common species from Sphaeriidae family disappeared (Table 3). Moreover, the decline in the number of species was observed not only between 1976 and 1997, but also between 1997 and 2006 (Table 3), as in 1997 and 2006 only the bottom molluscs were collected.

The unfavorable changes in the occurrences of molluscs are most often associated with eutrophication or water pollution (Kansanen and Aho 1981, Arter 1989, Lewandowski 1991, Stańczykowska and Lewandowski 1993, Stańczykowska and Stoczkowski 1997, Jurkiewicz-Karnkowska 1998, Pieczyńska *et al.* 1999, and others). The increase in trophic state might be one of the causes of the decline of particular mollusc species, from the three lakes of lower reaches of the Jorka River. In the 70s of the 20th century, as a result of rainbow trout, *Oncorhynchus mykiss* (Walbaum 1792) feedlot farming done in Lake Głębokie from 1974 (Hillbricht-Ilkowska 1983) to 1988 (Lewandowski *et al.* 1997), the increase in trophic state and organic pollution was observed in this lake and in the situated down the river, lakes Zełwążek and Jorzec (Hillbricht-Ilkowska 1983, Hillbricht-Ilkowska and Ławacz 1983, Węgleńska *et al.* 1983).

However, differences in trophic state observed in a few investigated lakes during long time are very small. Their present state (visibility of Secchi disc – Table 2) is probably the result of the return do the initial state, however water transparency in Lake Głębokie has not yet reached the values from 1976 (Table 2). Explanation of the trophic state stability of this lakes can be found in the paper of Hillbricht-Ilkowska (2002a). Besides, the decline of molluscs was observed both in the eutrophic lakes and in the mesotrophic Lake Majcz Wielki. Moreover, relatively smallest changes were observed in the eutrophic Lake Inulec (Table 3). In 2006 the highest number of mollusc species (6) was found in this lake, whereas in Lake Majcz Wielki only two species were found in bottom sediments – the same number as in the most eutrophicated Lake Głębokie. Thus, in the case of the studied lakes, the trophic state seems not to be the only cause of the impoverishment of malacofauna.

It is characteristic, that in subsequent years of research the similarity of Mollusca species composition between the studied lakes decreased (Table 4). This suggests that in particular investigated lakes different mollusc species extinct. This random extinction of the species may be not an effect of eutrophication, but rather result of other ecological factors, affecting individual species in each of the lakes differently. Perhaps an a sort of sudden physical change of habitat may be a reason of molluscs extinction.

Anoxia might be such a disaster. This phenomenon is observed mainly in small and heavily eutrophicated water bodies. But in all investigated lakes hypolimnion is present below 5 m deep (Table 1), and layer with oxygen concentration below 1 mg L^{-1} in summer occurred in 1978 below 4 m (Planter *et al*. 1983), and in 1998 below 5 m (Hillbricht-Ilkowska 2002a). It is far below zone of occurrence of molluscs. Therefore it was probably the anoxic conditions which occur in the littoral zone. The oxygen concentrations were not measured in littoral zone of the studied lakes but the event of anoxia was noted (own observation) in mesotrophic Lake Majcz Wielki *i.e*. hydrogen sulfide was observed in the shallow (1 m) littoral zone over the Characeae belt in February 1985, during exceptionally long and strong winter. It was the presence of hydrogen sulfide in the littoral zone of another eutrophic lake, that was, according to Żmudziński and Grigelis (2002), the cause of the extinction of all five bottom snail species and one of the two species of bivalves. The changes resulting from the effect of anoxia on macrozoobenthic communities might be long-term, as was observed by *e.g.* Lardicci *et al*. (2001).

It might be then that the winter lack of oxygen and the presence of H_2S over the bottom sediments of the littoral zone of the studied lakes were the cause of the absence of snails, mainly Pulmonata (Table 3). Similar case of drastic decline of many Pulmonata species, more pronounced than that of Prosobranchia and Bivalvia, was observed in Zegrzyński Lake by Jurkiewicz-Karnkowska (1998). Pulmonata species can respire the dissolved oxygen, but only if its concentration in the water is high. In the case of Prosobranchia, the anoxia might have been the cause of the disappearance of the species most strongly associated with the bottom, that is the species most exposed to its influence. This applies particularly to *Lithoglyphus naticoides* inhabiting (and penetrating) bottom sediments exclusively (Krause 1949). The second invasive alien species, *Potamopyrgus antipodarum* is also, although not exclusively, associated with bottom sediments, and it occurs mainly at shallow sites. As a result, these species may be particularly exposed to winter oxygen deficit occurring in littoral zone. *P. antipodarum*, exceptionally common in one of great but shallow, eutrophic lakes (in other part of Northern Poland) in the 60s and 70s of 20^{th} century (*e.g.* Wolnomiejski and Furyk 1969), has not been found there already in 1994–95, similarly to *L. naticoides*, *T. fluviatilis*, *B. tentaculata* and *V. piscinalis*, precisely as a result of the oxygen shortfall and presence of hydrogen sulfide (Żmudziński and Grigelis 2002). The low values of the similarity index of species composition of the molluscs studied in 1997 and 2006 (Table, 4) point to considerable isolation (lack of species exchange) between lakes and, as a result, lack of recolonisation. The rivers present rather a barrier to limnetic molluscs and their species composition in subsequent flow-through lakes located on the same river may differ markedly (Kołodziejczyk 1989, Lewandowski 1990, 1996). What is more, sometimes these lakes are disconnected as a result of level down of ground waters (Hillbricht-Ilkowska 2002b). If the studied lakes are treated as small and isolated environmental islands, then according to the assumptions of the theory of island biogeography (MacArthur and Wilson 1967) their colonization and re-colonization might be a very slow process. Jurkiewicz-Karnkowska (2006) observed, that malacofauna of riverine lakes was richer in those younger and more exposed to temporal flooding, as compared to those older and isolated from the river. This might point to the crucial role of floods in reconstruction and enrichment of lake mollusc communities. In the case of alien species, *L. naticoides* and *P. antipodarum*, the process of recolonisation might be even more difficult, as in the nearest areas of occurrence (Great Masurian Lakes), which might be potential source of invasion they are dispersed and present in low densities (Kołodziejczyk 2001, 2005a, 2005b).

Mollusc species poverty in the studied lakes might be the effect of increase in trophic state in some of the past years, but more the result of environmental catastrophes, probably the anoxia. In the case of complete disappearance of a species, recolonisation of the habitat meets difficulties. These are most probably caused by small size of the water bodies and their isolation, and in the case of some species also by rarity of occurrence in areas which might potentially serve as sources for re-colonization.

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