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STREAM HABITAT CONDITIONS AND FISH FAUNA WITHIN THE OCCURRENCE RANGE OF WAŁECKI BARBEL, *BARBUS CYCLOLEPIS WALECKII* ROLIK, 1970 (TELEOSTEI: CYPRINIDAE) IN POLISH PART OF THE CARPATHIAN MTS

ABSTRACT: Existing data on Wałecki barbel are very scarce and need a complement to the quantitative description of its habitat conditions. This fish is a subspecies of the Pontic species *B. cyclolepis* Heckel which occurs in some coastal rivers of the Black Sea or, as evidenced by some results of studies on mitochondrial DNA, it is a hybrid originating from natural crossing between the common barbel *Barbus barbus* (L.) and spotted barbel *B. carpathicus* Kotlík, Tsigenopoulos, Ráb et Berrebi. Until now the Wałecki barbel was reported from 26 sites in the river basins of the Upper Vistula and the Dniester in SE Poland (49°09'–49°49'N, 21°28'–22°50'E, altitude 200–590 m). Seventeen of these sites were studied in autumn 2002 and summer 2003 to collect data on habitat parameters of stream channels. The main characteristics of their morphology (i.e. length, width, depth, and gradient) were calculated on the basis of a set of field measurements. Current velocity was measured using float method. The composition of bottom substratum was estimated using a simple scale based on Wentworth scale. Additionally, two biotic characters were included, i.e. the occurrence of macroscopic aquatic vegetation and the species composition of fish community. According to the obtained results the habitat conditions appropriate for Wałecki barbel may be defined as follows: 1) The stream should be medium-sized, at least 10-m or better 20-m wide. 2) The mean channel depth should exceed 20 cm, while the maximum depth should be greater than 50 cm. The channel morphology with the zone of medium depth (i.e. that extending over the half of bottom) in range between at least 15 and 40 cm seems to be favorable. 3) The mean stream velocity of 0.30 m s^{-1} or more is desired. It seems that the zone of fast current (0.50–1.00 m s^{-1}) sharing a considerable portion of the channel is an important habitat feature. 4) Most of the bottom area should be covered by medium-sized particles (2–200 mm) with the mode within range of fine pebbles (20–50 mm). 5) In general, the stream should be rather oligotrophic than eutrophic with poorly developed macroscopic algae and the absence of vascular plants, and with flow fluctuations periodically disturbing structure of bottom substratum. 6) The abundant occurrence of spotted barbel, especially within lower part of its distribution area and in the zone of its co-occurrence with common barbel may be regarded as a good indicator of the stream habitat appropriate for Wałecki barbel. 7) Other frequent and abundant species accompanying Wałecki barbel are minnow *Phoxinus phoxinus* (L.), stone loach *Barbatula barbatula* (L.), chub *Leuciscus cephalus* (L.) and schneider *Alburnoides bipunctatus* (Bloch).

KEY WORDS: ecology, rheophilic fish, natural hybrids, *Barbus barbus*, *B. carpathicus*, *B. petenyi*.

1. INTRODUCTION

In Poland occur two well known species of the genus *Barbus* Cuvier et Cloquet, 1816 from about twenty living in European fresh waters. One of them lives in lowland rivers and attains relatively large size, while the distribution area of the second, small species is restricted to montane and submontane reaches of the right-side tributaries of the upper Vistula. They are the common barbel, *Barbus barbus* (Linnaeus, 1758) and spotted barbel, *B. petenyi* Heckel, 1847. Taxonomic position of spotted barbel was a matter of doubt and therefore it was classified also as *B. meridionalis petenyi* (Heckel, 1847) and *B. peloponnesius* Valenciennes, 1842. At present it should be properly determined as *B. carpathicus* Kotlík, Tsigenopoulos, Ráb et Berrebi, 2002 according to the description based on genetic data (Kotlík *et al.* 2002). Both barbel species occur together in the Carpathian rivers. Common barbel occurs in all Carpathian tributaries of the Vistula (for mentions published before the early 1970-ties see Rembiszewski and Rolik 1975; more recent are in Bieniarz and Epler 1972, Kołder 1973, Kołder *et al.* 1974, Skóra and Włodek 1988, 1991, Augustyn *et al.* 1996, Starmach J. 1998). In last decades it has become rare or even locally extinct as its distribution considerably decreased owing to anthropogenic alterations of rivers, mainly the fragmentation of water courses, and pollution (Witkowski *et al.* 1999, Kukuła 2001, 2003). Spotted barbel, on the contrary, is still common and abundant in Carpathian rivers (Starmach J. *et al.* 1988, Augustyn *et al.* 1998, Kukuła 1999, Włodek and Skóra 1999, Kukuła 2000; for earlier sources see Rembiszewski and Rolik 1975).

Since 1970 the list of Polish fishes has been completed with the third barbel, *B. cyclolepis waleckii* Rolik, 1970 which was discovered in south-eastern Poland, described as a new subspecies and named in honour of Antoni Wałecki, the 19th century Polish zoologist who as the first paid attention to enormously large specimens of spotted barbel collected in the middle Vistula near Warsaw (Wałecki 1864). Also Nowicki (1889) mentioned the reports on occurrence of such fishes in Carpathian river basins and supposed that these records may concern *B. plebeius* Valenciennes, 1842. One century later such "large" spotted barbels were reported again from several Carpathian rivers (Kux and Weisz 1958, Rolik 1967b) and considered as hybrids originated from natural crossing between the common and spotted barbel. Eventually, Rolik (1970) gathered all specimens available to her and described a new subspecies of the Pontic species *B. cyclolepis* Heckel, 1837 which occurs in some coastal rivers of Black Sea. Recently, however, the results of a study of mitochondrial DNA (Kotlík *et al.* 2002) support rather the supposition of hybrid nature of *B. cyclolepis waleckii*.

Regardless its validity as a subspecies of *B. cyclolepis* the Wałecki barbel remains interesting as a real member of Carpathian fish communities, which was recorded in the basin of the river San (SE Poland) with the frequency of about 35% and mean percent contribution to the fish abundance of about 2% (Rolik 1971a, b). According to the data taken from these two papers by Rolik, in 1964–1968 it was not numerous (mostly 1–5 ind. per 250–350 m stream reach, median 2 ind.) with percent contribution ranging from <1 to about 13% (median 2.1%, n = 17). In he qualitative samples taken by Weisz and Kux (1966) the Wałecki barbel comprised about 2–3% of total catch. Even if not valid subspecies, this fish is still worth of study as an example of natural hybridization between two species of considerably different ecology. However, it is still little known about its morphology (only Rolik 1967b, 1971b) and distribution and much less about its biology. As it was very briefly outlined by Rolik (1971b, pages: 307–308, 310–311, 315) this fish shows distinct tendency to avoid slowly flowing or stagnant water and prefers lotic habitats with large stones which offer appropriate hiding places, and as a result its occurrence is restricted to "montane-like" channel reaches with higher gradient, fast current, and stony bottom. However, it remains unclear why Wałecki barbel was reported only from a part of the zone of co-occurrence of its probable parent species. It is hard to explain why a search for it carried out in the 1980's in a 15-km long submontane reach of the river Poprad between towns of Piwniczna and Stary Sącz (basin of the Dunajec river, S Poland) in order to collect material for a planned electrophoretic study on sympatric populations of three barbels gave no result (Janusz Starmach, pers. comm.). Surprisingly, even within the documented distribution area of Wałecki barbel it was not found upon any later investigations (Pasternak and Wajdowicz 1983, Skóra and Włodek 1989, Włodek and Skóra 1999). As a result, three decades after its description Wałecki barbel is still somewhat mysterious fish.

This study is aimed to complete the possible synopis of ecological data on Wałecki barbel with a contribution to the quantitative outline of its habitat conditions. The obtained results may allow to define more precisely in what kind of riverine habitats it is probable to meet Wałecki barbel in Carpathian rivers.

2. STUDY AREA, MATERIAL AND METHODS

According to the more recent monographs of the ichthyofauna of Poland (Rembiszewski and Rolik 1975, Brylińska 1986, Rolik and Rembiszewski 1987, Brylińska 2000) the occurrence of Wałecki barbel within the Polish territory was mentioned only in the papers by Weisz and Kux (1966) and Rolik (1967a, 1967b, 1970, 1971a, 1971b). In total, this fish was recorded at 26 sites in south-eastern Poland (Table 1,

Table 1. Sites at which the occurrence of Wałecki barbel, *Barbus cyclolepis waleckii* Rolik, 1970 was recorded in Polish part of the Carpathian Mts according to the published papers (the map of the river network with all these sites is presented in Fig. 1). Sites omitted in this study are in italics (see text for explanation). The *locus typicus* of Wałecki barbel is marked with bold.

Site No.	River system	Stream or river	Locality (Local name)	Geographic coordinates[*] N	E	Altitude zone[**] (m a.s.l.)
1	Wisłoka [V]	Wisłoka	Świątkowa Mała [e]	49°31'10"	21°28'10"	380–390
2		Jasiołka	Żarnowiec [a, c]	49°41'55"	21°39'45"	260–270
3	Wisłok [S]	Wisłok	Rudawka [d, e,]	49°31'50"	21°55'45"	330–340
4			Besko [d, e],	49°36'15"	21°58'15"	285–290
5			Haczów [a, c,]	49°40'35"	21°53'35"	270–280
6	San [V]	San	Smolnik [d, e]	49°11'55"	22°40'55"	540–550
7			Sękowiec [d, e]	49°14'20"	22°33'10"	490–500
8			*Rajskie* [d, e]	49°19'05"	22°30'05"	400–410
9			*Lesko/Łukawica* [d, e]	49°30'00"	22°19'15"	300–310
10			*Temeszów I* [d, e]	49°40'20"	22°15'10"	260–270
11			*Dubiecko II* [e]	49°48'55"	22°23'29"	220–230
12		Wołosaty	Pszczeliny [d, e]	49°09'35"	22°41'35"	580–590
13		Solinka	Buk [d, e]	49°14'55"	22°24'00"	480–490
14			*Wołkowyja* [d, e]	49°19'10"	22°25'10"	430–440
15			*Solina* [e]	49°22'00"	22°26'35"	370–380
16		Wetlinka	Jaworzec [d, e]	49°12'55"	22°26'20"	550–560
17		Hoczewka	*Nowosiółki* [d, e]	49°24'20"	22°17'55"	360–370
18			Hoczew [d, e]	49°24'55"	22°18'50"	350–360
19		Osława	*Duszatyn* [e]	49°18'30"	22°07'25"	480–490
20			Prełuki [c, e]	49°19'50"	22°06'20"	450–460
21			**Zagórz I** [d, e]	**49°29'40"**	**22°16'00"**	**320–330**
22			*Zagórz II* [e]	49°31'30"	22°15'55"	290–300
23		Baryczka	Nozdrzec [d]	49°46'20"	22°11'35"	250–260
24		Stupnica	Bachów [d]	49°46'15"	22°29'10"	220–230
25		Wiar	Krówniki [d, e]	49°45'55"	22°49'20"	200–210
26	Strwiąż [D]	Strwiąż	Krościenko [b, e]	49°28'40"	22°41'15"	430–440

[*] estimated to the nearest 5".
[**] altitudes of the nearest contour lines taken from the 1:50 000 maps.
Main rivers: *D* – Dniester (Black Sea basin), *S* – San, *V* – Vistula (Baltic basin).
Sources of sites: *a* – Weisz and Kux 1966, *b* – Rolik 1967a, *c* – Rolik 1967b, *d* – Rolik 1971a, *e* – Rolik 1971b.

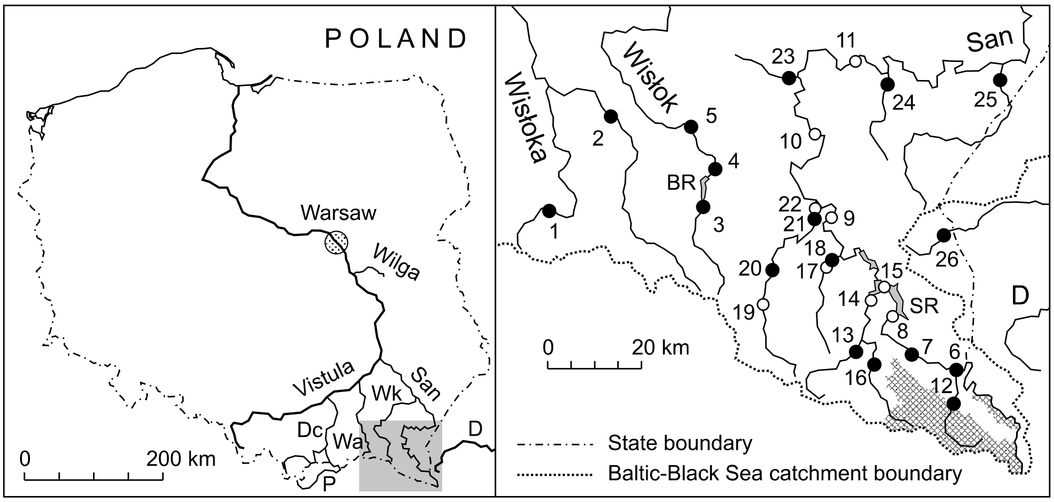

Fig. 1. Outline of the study area with location of sites where the occurrence of Wałecki barbel, *Barbus cyclolepis waleckii* Rolik, 1970 was reported (site numbers the same as in Table 1; open circles – sites omitted in this study). Rivers: D – Dniester, Dc – Dunajec, P – Poprad, Wa – Wisłoka, Wk – Wisłok. Dam reservoirs: BR – Besko, SR – Solina. Cross-hatched area indicates the Bieszczady National Park.

Fig. 1) and also "in the Dunajec river system (J.M. Rembiszewski *in litt.*) and in the Wilga river, a tributary of the middle course of the Vistula (J.M. Rembiszewski *in litt.*)" (cited after Rolik 1971b, page 259). It was collected in the Dunajec river also in later studies (Jan Kotusz, pers. comm.), however the locations of finding points within the basin of this river were not published. Three of the 26 precisely defined sites (labeled 8, 14 and 15 in Table 1) do not exist any longer because their areas have been inundated since construction of the Solina Reservoir on the upper course of the river San in late 1960-ties. Other three ones (9–11) were localized on the middle San which appeared too large to investigate in this study. Two sites (17 and 22) are so close to the other ones on the same stream that the possible differences between them seem to be negligible. And one of these sites (19) is very difficult of access at present because of change in local road network. At each of the remaining seventeen sites the selected abiotic and biotic features of habitats were studied in two field trips, in autumn 2002 and summer 2003.

The main characteristics of the morphology of a reach of stream channel (i.e. length, width, depth, and gradient) were calculated on the basis of a set of field measurements. The complete procedure of data collecting and processing was developed especially for this study. It utilizes some standard hydrometric techniques taken from several sources. The arrangement of the grid of measuring points within the channel and the formulae adopted to calculate the characteristics of its morphology are presented in Appendix I.

Water depth, current velocity and granulation of bottom substrate were regarded as the main habitat parameters. Depth was measured to the nearest 1 cm with a measuring rod. Measurements were spaced along transverse transects at 1–2 m intervals depending on the stream width. Surface current velocity was measured using float method. The measurements were regularly spaced along the transects (2–6 points according to the channel width; at 2–4 m intervals in most cases). The same equations as for the water depth were used in the calculations (Appendix 1). The average stream velocity was approximated by multiplying the surface velocity by 0.8. The composition of bottom substratum was estimated visually using a simple scale based roughly on Wentworth scale. Six particle size categories were distinguished: sand (<2 mm), gravel (2–20 mm), fine pebble (20–50 mm), medium pebble (50–100 mm), coarse pebble (100–200 mm), and boulders (>200 mm). For documentation and comparisons between sites a set of digital camera pictures of the bottom was collected. While taking a photo the brass scale frame (25×25 cm) was placed on stream bottom. In the estimation procedure one eighth of bottom surface in the picture was taken as a unit of the relative share of a given particle size category. Thus, the share of each category was ranked from 1 (distinctly <1/4 of the whole area) through 2 (for about 1/4 of the area), 3 (for 1/4–1/2) and so on up to 8 for a category covering approximately whole area. The sum of ranks of each particle category was divided by the number of examined pictures and 8, and the result was rounded to the nearest 10%.

Additionally, two biotic characters were included in this study, i.e. the occurrence of macroscopic aquatic vegetation and the species composition of fish community. Three categories of submerged plants were distinguished: macroscopic thalli of filamentous algae, clumps of aquatic mosses, and beds of vascular plants. While estimating the development of bottom algae the size of thalli was taken into consideration. Development of mosses and vascular plants was assessed on the basis of the portion of stream bottom covered by them. The species composition and number of fishes were recorded during single electrofishing conducted wading upstream. The IUP–1,2 (Radet, Poland; 350 V pulsed DC, 3.5 A, pulse frequency 20–100 Hz) backpack equipment was used during electrofishing. The individuals caught were currently determined and released immediately at the catching place. The result (i.e. percent contributions of all species to the total fish number recorded at the investigated site) was assumed as a random sample which approximates the composition of real community.

The composition and overall similarity of fish communities at the investigated locations were examined using the SAHN clustering. The Euclidean distance in a *n*-dimensional space was applied as a measure of the distance between two samples, where *n* is the total number of species occurring at investigated sites, i.e. 20 in this study (the occurrence of Wałecki barbel was omitted in this analysis which concerns species accompanying this fish). The first and third quartile of all 136 pairwise distances between the 17 collected samples were assumed as the limits of the relatively negligible, average, and considerable differences. A phenogram for these 17 cases was constructed following the UPGMA procedure. While considering the obtained results the main attention was paid to the dominant species, i.e. those ones which relative abundance exceeded 10% of the total number of recorded individuals. All computations were done using the Microsoft Excel 2000 software.

3. RESULTS AND DISCUSSION

3.1. Stream size and velocity

The size of a stream is determined by its width and depth. The investigated streams differ considerably in their mean width ranging from about 6 to 40 m (Table 2). Including the 80–100 m wide sites on the San river (marked 9, 10, and 11 in Table 1) the range of this parameter extends over an order of magnitude. In seventeen studied streams the quartile values are as follows: *Q*1 – 11.9 m, *Q*3 – 22.2 m, median – 18.9 m in 2002, and *Q*1 – 11.6 m, *Q*3 – 24.0 m, median – 16.6 m in 2003. Considering the habitat preferences of Wałecki barbel the special attention should be paid to its *locus typicus*, i.e. the Osława at Zagórz (site 21; Fig. 2). The mean width of the reach selected there for this study was 37.9 m in 2002, and 39.8 m in 2003. It means that this fish may find the same appropriate habitat conditions in about 10-m wide streams as in 5–10 times wider rivers.

The differences in mean depth are less pronounced, ranging between 10 and 63 cm (Table 2). Especially the quartiles of mean depths in seventeen streams are relatively narrow: *Q*1 – 21 cm, *Q*3 – 32 cm, and median – 26 cm in 2002. A good approximation of the stream size may be also the area of channel cross-section, i.e. the product of stream width and mean depth. However, in investigated streams this parameter varies between 1.1 and 16.3 m^2, i.e. in a range even wider than the stream width. Therefore, it was regarded as useless in this study. Also the width-to-depth ratio is inaccurate to characterize habitats of Wałecki barbel, as the correlations between stream width and four depth characteristics were very weak (Fig. 3A).

According to the above, the channel depth is perhaps the best characteristic of

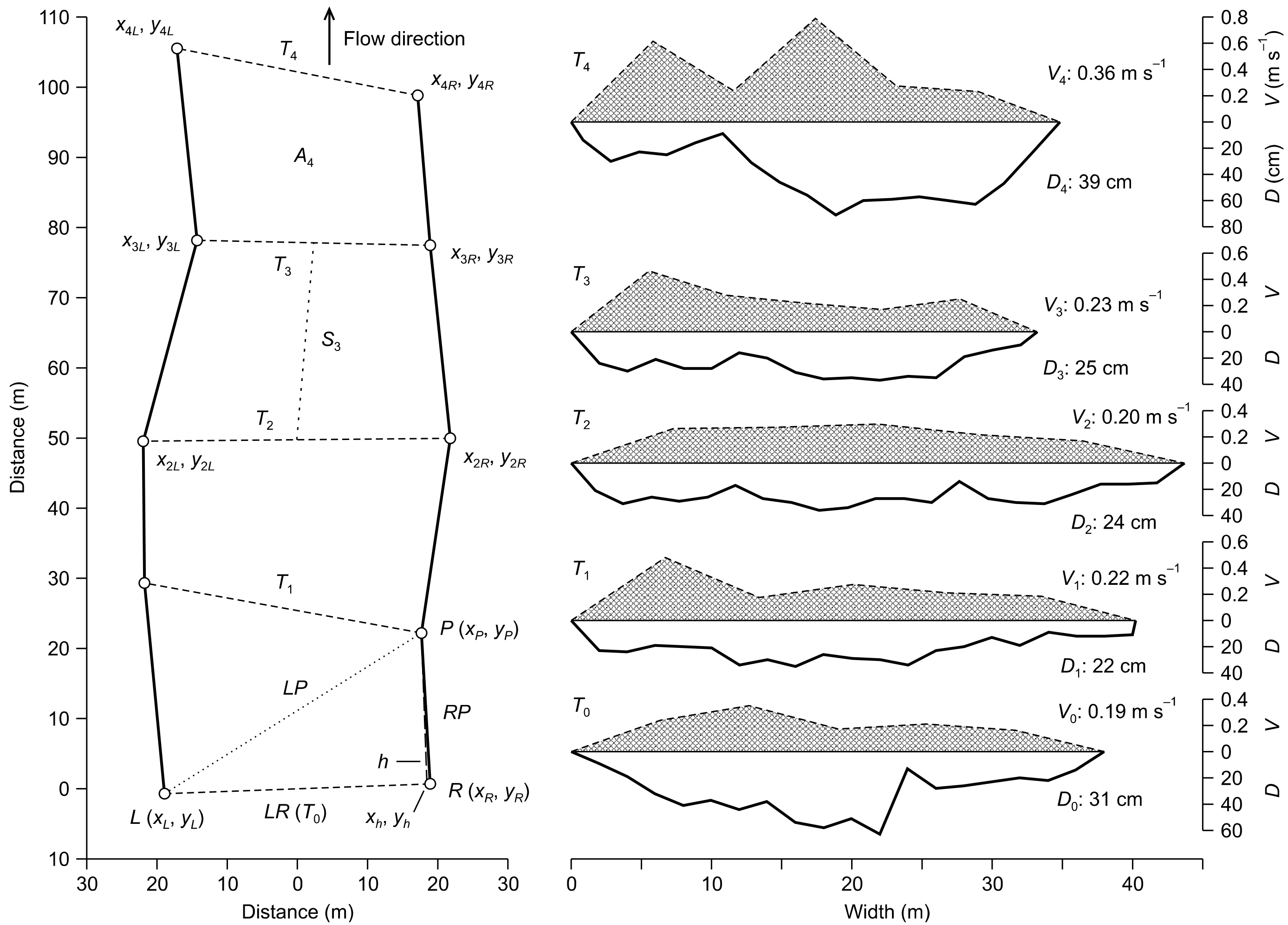

Fig. 2. Morphology of river channel of the Osława river at Zagórz, the *locus typicus* of Wałecki barbel, *Barbus cyclolepis waleckii* Rolik, 1970 (site 21; details in Table 1) within the reach investigated on 6 October 2002: shape of the channel (at left), and transverse profiles of depth (*D*; thick line, open area) and stream velocity (*V*; spaced line, cross-hatched area) (at right). All symbols used in this figure and the measurement and calculation procedures are explained in Appendix 1.

Table 2. Characteristics of stream channels at seventeen sites within the occurrence range of Wałecki barbel, *Barbus cyclolepis waleckii* Rolik, 1970 (details concerning sites in Table 1 and Fig. 1).

Site No.	Date (y-m-d)	Length (m)	Width (m)	Depth (cm)				Gradient (‰)	Current velocity (m s^{-1})			
				Mean	Q1	Q3	Max.		Mean	Q1	Q3	Max.
1	2002-09-21	172.9	11.1	10	8	13	54		0.26	0.23	0.32	0.88
	2003-07-17	146.1	11.5	15	6	25	60	2.4	0.20	0.13	0.34	0.54
2	2002-09-21	101.7	16.6	19	17	27	40		0.18	0.10	0.33	0.52
	2003-07-17	131.4	16.0	18	13	24	50	2.4	0.16	0.10	0.30	0.80
3	2002-09-23	58.9	19.5	25	16	35	89		0.32	0.27	0.50	0.66
	2003-07-18	78.0	15.1	11	7	15	57	12.3	0.20	0.10	0.41	0.88
4	2002-09-21	66.2	8.1	27	16	38	67		0.31	0.31	0.62	0.71
	2003-07-18	149.3	9.4	29	14	52	72	1.9	0.34	0.20	0.67	0.94
5	2002-09-23	68.0	12.8	26	21	38	50		0.34	0.28	0.53	0.60
	2003-07-24	71.5	13.3					1.8				
6	2002-09-22	51.0	23.0	25	13	33	68		0.30	0.11	0.46	1.01
	2003-07-19	46.5	26.1					10.1				
7	2002-09-22	49.6	31.5	40	15	57	100		0.24	0.21	0.40	0.70
	2003-07-19	78.5	36.3	45	22	60	101	5.4				
12	2002-09-22	47.5	18.9	20	9	32	63		0.29	0.20	0.50	0.62
	2003-07-19	66.2	21.9	28	14	40	88	14.1	0.38	0.25	0.62	0.82
13	2002-10-05	76.7	20.4	25	13	36	62		0.29	0.25	0.46	0.67
	2003-07-19	93.9	19.9					7.8				
16	2002-10-05	74.3	14.5	30	22	41	77		0.40	0.36	0.61	0.96
	2003-07-19	87.5	16.6					6.7				
18	2002-10-05	50.1	21.4	27	21	41	54		0.24	0.18	0.38	0.93
	2003-07-24	73.3	21.8					8.3				
20	2002-10-06	104.2	26.1	18	10	28	76		0.27	0.20	0.41	0.74
	2003-07-24	119.4	26.8					8.7				
21	2002-10-06	102.5	37.9	27	19	35	71		0.23	0.20	0.29	0.79
	2003-07-18	87.3	39.8	17	10	27	51	2.6	0.18	0.13	0.30	0.40
23	2002-10-06	48.0	7.3	23	11	46	90		0.16	0.05	0.35	0.76
	2003-07-24	41.6	5.9					9.1				
24	2002-10-27	105.4	10.0	34	16	52	83		0.49	0.47	0.79	0.98
	2003-07-23	113.7	11.7					6.2				
25	2002-10-26	49.8	18.6	63	56	82	98		0.54	0.55	0.82	0.87
	2003-07-23	96.8	17.9	37	24	45	60	1.4	0.37	0.34	0.58	0.71
26	2002-10-26	149.9	19.0	39	25	54	79		0.56	0.54	0.84	0.94
	2003-07-23	136.2	11.6	21	12	29	63	10.9	0.28	0.19	0.54	0.73

stream size. The distributions of average values at investigated localities seem to be normal-like (Fig. 3B). Therefore, an approximation of depth ranges in possible habitats of Wałecki barbel was obtained by rejecting the wings (i.e. all values smaller than the first, and greater than third quartile in a data set) which may be affected by epizodic droughts and spates. Such defined zone of medium depth which covers half of the channel bottom extends between 10–21 cm and 27–49 cm. However, the deep zone of a stream channel is probably of the same or even greater importance, as Wałecki barbel is a medium-sized fish attaining the body length of 30–40 cm (Rolik 1970). On average, places 55–85 cm deep were available with studied localities. Weisz and Kux (1966) collected Wałecki barbel in two streams at the depths of 20–30 and 50 cm, however in one of them pools to 2 m deep were found.

The maximum surface current velocity measured in this study was 1.26 m s^{-1}, which corresponds to the mean stream velocity of 1.01 m s^{-1}. The mean velocities at investigated stream reaches ranged from 0.16 to 0.56 m s^{-1} (Table 2), while their average values were: *Q*1 – 0.24 m s^{-1}, *Q*3 – 0.37 m s^{-1}, and median – 0.29 m s^{-1} in 2002. Assuming that in a stream all parameters except the slope of the energy gradient in Manning equation are constant the current velocity may be approximated by a power function of the channel gradient. The gradients measured at seventeen localities over the distances of 42–149 m ranged between 1.4 and 14.1‰ (Table 2).

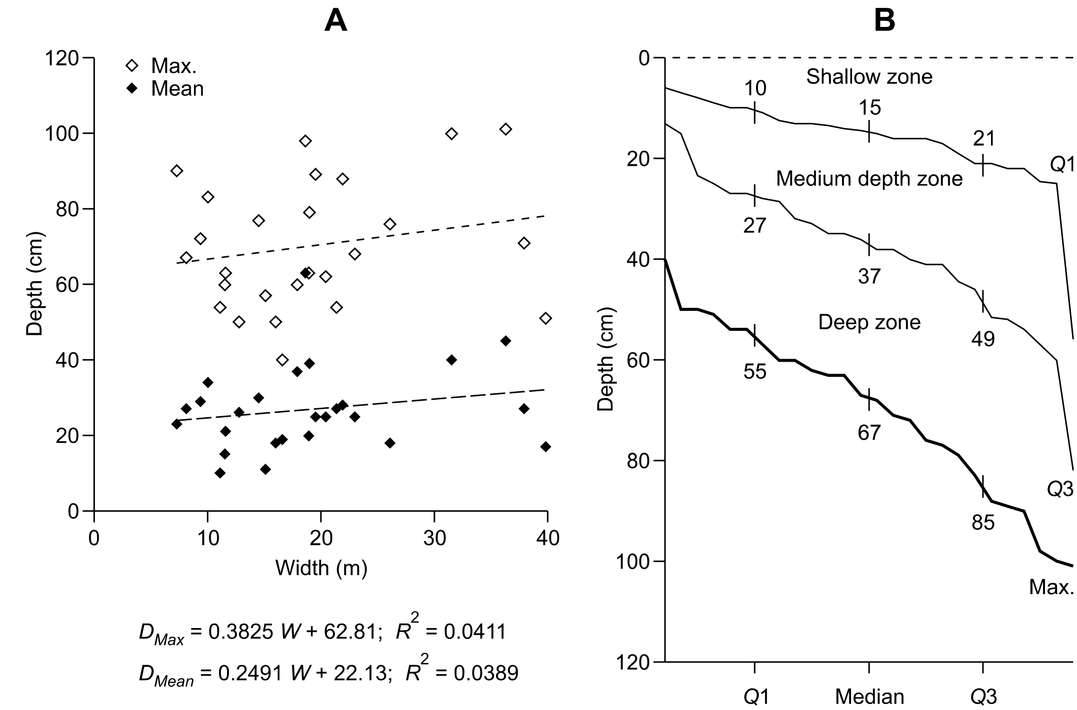

Fig. 3. Average characteristics of water depth within the occurrence range of Wałecki barbel, *Barbus cyclolepis waleckii* Rolik, 1970 according to the data collected at seventeen investigated sites in 2002–2003 (details concerning sites in Fig. 1 and Tables 1 and 2). A – width-depth relationships; B – distribution of depth characteristics.

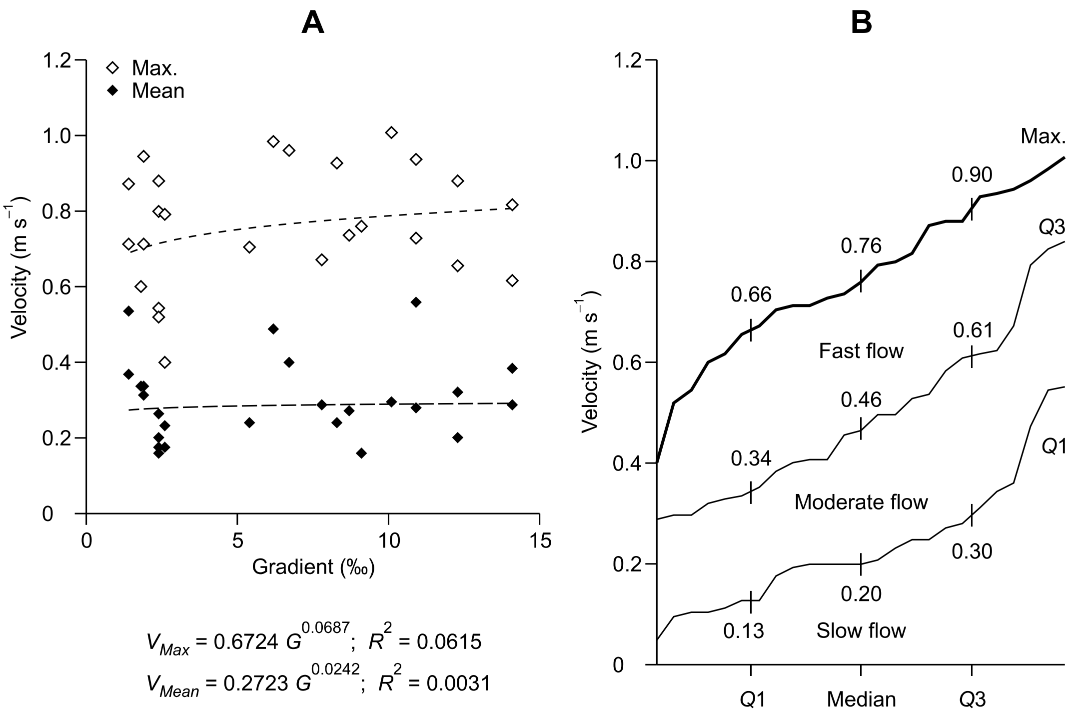

Fig. 4. Average characteristics of stream flow velocity within the occurrence range of Wałecki barbel, *Barbus cyclolepis waleckii* Rolik, 1970 according to the data collected at seventeen investigated sites in 2002–2003 (details concerning sites in Fig. 1 and Tables 1 and 2). A – gradient-velocity relationships; B – distributions of velocity characteristics.

However, despite such wide range of the channel gradient the correlations between it and both mean and maximum current velocity were very weak (Fig. 4A). It is worth of note that also the correlation between gradients of stream valleys (G_V) which were given by Rolik (1971b) and the mean stream reach gradients (G_M) measured in this study was even weaker ($G_M = 0.183\ G_V + 6.33$; $n = 9$, $R^2 = 0.0054$). The lack of stronger relations both in the stream reach and valley scales may evidence the leading effect of microhabitat scale (i.e. over a distance of few meters) channel morphology on the pattern of current velocities. The importance of local pattern of current velocities seems to rise along with the channel size. A characteristic feature of the middle course of the river San river is a sequence of "rapids", i.e. relatively short (approximately as long as channel width) reaches with large channel gradient and long (about ten times as channel width or more) flat "pools". Such reaches (sites 9, 10, 11) were excluded from this study. Rolik (1971a) found Wałecki barbel only in rapids at these sites (it was rather rare; few individuals per site, with average percent share in total catch of 1.3%).

The distribution of average values of stream velocities measured in seventeen streams where the occurrence of Wałecki barbel was reported in the past show a relatively narrow range of the stream current velocity (Fig. 4B). The average zone of moderate current extends from 0.13–0.30 m s^{-1} to 0.34–0.61 m s^{-1}, while that of fast current ranges from 0.66 to 0.90 m s^{-1}, regardless of the gradient of stream reach. The lack of a relation between stream valley gradient and percent contribution of Wałecki barbel to total fish number is evident also from the data provided by Rolik (1971a). In four ichthyocoenoses distinguished by her in four stream categories in the upper San river basin with gradient ranges 5.4–8.4, 6.3–8.6, 2.5–7.4, and 3.4–3.9‰ the mean percent share of this fish was very different (0.3, 1.2, 9.8, and 2.1%, respectively). Perhaps this evidences the strong relation between the microhabitat scale pattern of current velocity and Wałecki barbel occurrence which may depend on the portion of an area with the appropriate flow velocity range in the stream channel.

3.2. Bottom composition

The bottom in studied stream reaches was composed mainly of gravel, small pebble, and medium pebble (Table 3). At most sites

Table 3. Approximate composition of the bottom substratum at seventeen sites within the occurrence range of Wałecki barbel, *Barbus cyclolepis waleckii* Rolik, 1970 investigated in 2002–2003 (details concerning sites in Table 1). Relative shares of particle categories in % of total area, rounded (+ – approximate share <10%). Owing to rounding the sums in rows do not equal 100% in some cases.

Site No.	Bottom particles					
	Sand (<2 mm)	Gravel (2–20 mm)	Fine pebble (20–50 mm)	Medium pebble (50–100 mm)	Coarse pebble (100–200 mm)	Boulders (>200 mm)
1	+	30	40	20	10	
2		20	30	20	30	10
3	+	20	30	20	20	10
4	+	40	40	30	+	
5	10	40	30	20		
6	+	10	20	30	30	20
7	+	20	20	30	30	10
12		20	30	20	10	20
13		10	20	30	20	20
16	+	20	30	20	20	10
18	10	10	20	30	20	+
20		20	20	20	20	20
21	10	20	20	20	20	20
23	20	20	10	30	30	+
24		30	30	30	20	+
25	30	40	30	10		
26		20	20	20	30	10

the coarse pebble, as well as boulders were present in considerable amounts, while sand was found only at some of them and as a rule covered small portions of stream bottom. Distributions of the results of estimation of bottom particle size on the collected digital pictures show a pattern: fine pebble > gravel, medium pebble, coarse pebble > boulders > sand. Each of the four dominant size categries (gravel – coarse pebble; 2–200 mm) covers about 20% of the bottom on average (Fig. 5). Such composition of the bottom substratum should be regarded as an important factor of the habitat of Wałecki barbel because the structure of the river bed determines qualitative and quantitative composition of the communities of bottom macroinvertebrates, the exclusive food of this benthivorous fish (Brylińska 2000).

Other important factors determining composition and development of bottom biocoenoses are the productivity of the stream and the probability of disturbances caused by changing flow. Assuming that the development of bottom algae indicates to some extent the trophic status of a stream it may be supposed that the most appropriate for Wałecki barbel are oligotrophic and slightly eutrophic conditions where algae form only very small or small thalli (Table 4). As the development of aquatic mosses and especially vascular plants needs more stable hydrological conditions the abundant occurrence of these plants may reflect lower probability of possible changes in water flow which are enough to disturb the bottom structure. Wałecki barbel seems to prefer the streams where clumps of mosses or beds of vascular plants are not abundant or absent (Table 4). Therefore, as a riverine fish preferring habitats of lower trophic status and flow regime with considerable fluctuations it should be included into the category of fish species which at present are seriously endangered by pollution and eutrophication of rivers as well as by their regulation, both being currently the common kinds of anthropogenic impact on Carpathian rivers (Kukuła 2003). However, owing to the present state of existing data on Wałecki barbel it must still remain in the NE threat category (Not Evaluated species) of the World Conservation Union (Amirowicz 2001).

3.3. Distribution range

The results presented above allow to define a stream offering appropriate habitat conditions to Wałecki barbel. Taking the median stream width of seventeen investigated reaches (18.2 m), and median values of the characteristics of their depth (min. – 3 cm, *Q*1 – 15 cm, median – 26 cm, *Q*3 – 37 cm,

Table 4. Aquatic vegetation recorded at seventeen sites within the occurrence range of Wałecki barbel, *Barbus cyclolepis waleckii* Rolik, 1970 investigated in 2002–2003 (details concerning sites in Table 1). Algae: 1 – only very small thalli (<1 mm), 2 – small thalli (1–10 mm), 3 – large thalli (>10 mm). Mosses and vascular plants: 1 – clumps or beds present on <1/4 of the bottom area, 2 – on 1/4–1/2 of total area, 3 – on >1/2 of the bottom.

Site No.	Macroscopic algae	Aquatic mosses	Vascular plants
1	2		
2	3	1	1
3	1	1	
4	2	1	
5	2	1	1
6	1	1	1
7	2		
12	1	1	
13	1	1	
16	1		
18	3	1	
20	1		
21	3	2	1
23	1		
24	1		
25	1		
26	2	1	

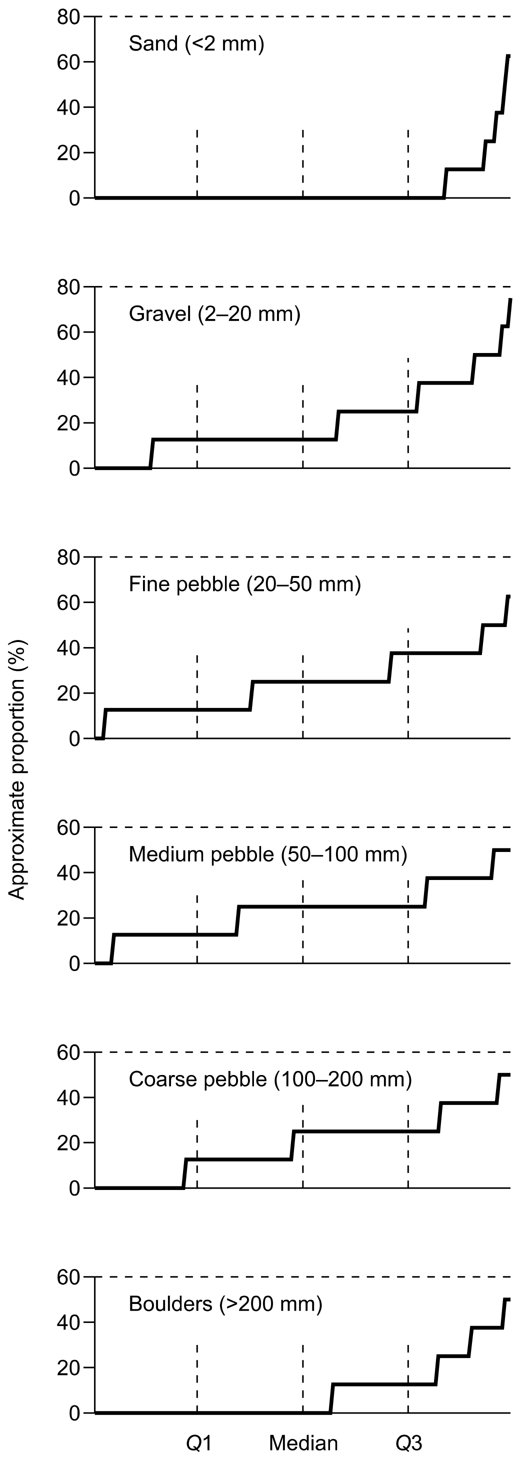

Fig. 5. Distribution of relative shares of bottom particle categories within the occurrence range of Wałecki barbel, *Barbus cyclolepis waleckii* Rolik, 1970 recorded at seventeen investigated sites in 2002–2003 (details concerning sites in Fig. 1 and Tables 1 and 2).

and max. – 67 cm; Fig. 3) and current velocity (0.07, 0.20, 0.36, 0.46, and 0.76 m s^{-1}, respectively; Fig. 4) the approximate average distributions of them were obtained and the mean values (the weighted means in this case) for such profiles calculated (Fig. 6). The picture is completed with the mean composition of bottom substrate. The characteristics of this idealized stream are very similar to those found in reaches measured at sites 4, 21, and 25 where the specimens with the combination of features concordant with the description of Wałecki barbel (Rolik 1970) were recorded in this study (Table 5). Therefore, these stream reaches may be regarded as good examples of habitats required by this fish. Thus, the description reduced to the depth, current velocity, and bottom substrate composition seems to be enough to characterize properly the possible habitats of Wałecki barbel. Unfortunately, the weak relation between stream depth and cross-sectional area, and between current velocity and valley gradient precludes delimitation of a potential distribution area of this fish in a river system carried out on the basis of the analysis of maps.

The possible occurrence range of Wałecki barbel may be more precisely predicted on the basis of known ranges of common barbel and spotted barbel as it occurs within the overlapping zone of areas of these species (Rolik 1971b) and its abundance seems to be correlated with high abundance of spotted barbel (Rolik 1967b). Habitat conditions in occurrence areas of common barbel and spotted barbel in the basins of the San and Wisłoka rivers may be characterized according to papers by Kukuła (1999, 2002, 2003) based on recent data collected by him at 119 sites and materials provided by the Regional Directorate of Polish Angling Association (ZO PZW) in Rzeszów (SE Poland), and completed with the results presented by Włodek and Skóra (1999). In general, common barbel occurs mostly in wide (about 30 m and more, max. 110 m) and relatively deep rivers (i.e. with maximum depth >1 m) with mainly gravelly bottom (also with considerable amount of pebbles and sand). Such conditions are typical of lower and middle courses of Carpathian tributaries of the Vistula in the altitude zone ranging up to 250–300 m. Formerly, before the construction of the Solina Reservoir in the upper course of the San river common barbel occurred in this river up to the altitude of about 550 m (Rolik 1971b). Spotted barbel inhabits streams about 10–30 m in width, medium deep (max. depth 0.5–1 m) with predominance of pebbles (rarely boulders or gravel) in bottom substrate. Such habitat conditions are characteristic of the upper courses of Carpathian rivers and of lower reaches of their major tributary streams between altitudes (150) 200–600 (700) m. Within these condition range the spotted barbel is most common and abundant in streams 10–20 m in width (max. to 40 m) located within 200–400 m altitude zone. According to all the data compiled in this study Wałecki barbel was found within the altitude zone 200–600 m (Table 1), i.e. the same as the vertical range of co-occurrence of both barbel species. Also

Table 5. Species composition and their percent contribution to the total number in fish communities recorded at seventeen sites within the occurrence range of Wałecki barbel, *Barbus cyclolepis waleckii* Rolik, 1970 investigated in 2002 (for details concerning sites see Fig. 1 and Table 1). Groups (1–3) and subgroups (A–E) of communities were distinguished according to similarities illustrated in Fig. 7. The boldface numbers indicate dominant species (>10%) while the + signs the rare ones (<1%). Black circles indicate the records of Wałecki barbel in 2003. Species introduced into studied river systems are marked with asterisks (their present populations may depend partially or fully on stocking).

Species	Sampling sites																
Group	1															2	3
Subgroup	*A*				*B*					*C*		*D*			*E*		
Site number	1	21	6	18	23	26	7	20	16	12	13	4	24	5	2	3	25
Sampling date (day/month)	21/9	6/10	22/9	5/10	6/10	26/10	22/9	6/10	5/10	22/9	5/10	21/9	27/10	23/9	21/9	23/9	26/10
Cyprinidae																	
Barbus carpathicus Kotlík *et al.*, 2002	8	6	**19**	**34**		2	3	2	8	3	+	3			**16**	8	1
B. barbus (L., 1758)												1					
B. cyclolepis waleckii Rolik, 1970		●										+					●
Gobio gobio (L., 1758)	**14**	**17**			1	5						**12**	**13**	**22**	**51**	9	2
G. albipinnatus Lukasch, 1933																	+
Rutilus rutilus (L., 1758)		1	1									6		8			+
Chondrostoma nasus (L., 1758)							9						+	2			8
Phoxinus phoxinus (L., 1758)	**50**	**38**	**28**	**45**	**74**	**83**	**63**	**70**	**49**	**30**	**47**	**24**	**20**		7		+
Leuciscus leuciscus (L., 1758)		+				3			3			+	6	**10**	1		+
L. cephalus (L., 1758)	8	3	**12**		**10**	1	5	1		1	+	**27**	**24**	**18**	**16**	**14**	8
Alburnus alburnus (L., 1758)			1				2					6					**77**
Alburnoides bipunctatus (Bloch, 1782)	+	**18**	**15**	4		1	5	**17**		1		**14**	**24**	**16**	7	1	2
Balitoridae																	
Barbatula barbatula (L., 1758)	**18**	**16**	8	7	7	6	5	5	3	1	1	+	+	4	3	2	
Thymallidae																	
**Thymallus thymallus* (L., 1758)			1				+	+	8	1	2	+	6				
Salmonidae																	
**Hucho hucho* (L., 1758)													+				
Salmo trutta m. *fario* L., 1758	1		1	4	7	+	3	3	**15**	**14**	3	3	5				
**Oncorhynchus mykiss* (Walb., 1792)											+						
Cottidae																	
Cottus gobio L., 1758				5			3	2			+	1		**20**			
C. poecilopus Heckel, 1836	1		8				3		**16**	**49**	**43**						
Percidae																	
Perca fluviatilis L., 1758			4							1	3	+			+	**65**	
Gymnocephalus cernuus (L., 1758)												+					
Total number of species	8	8	11	6	5	8	11	8	7	9	10	16	10	8	8	6	10

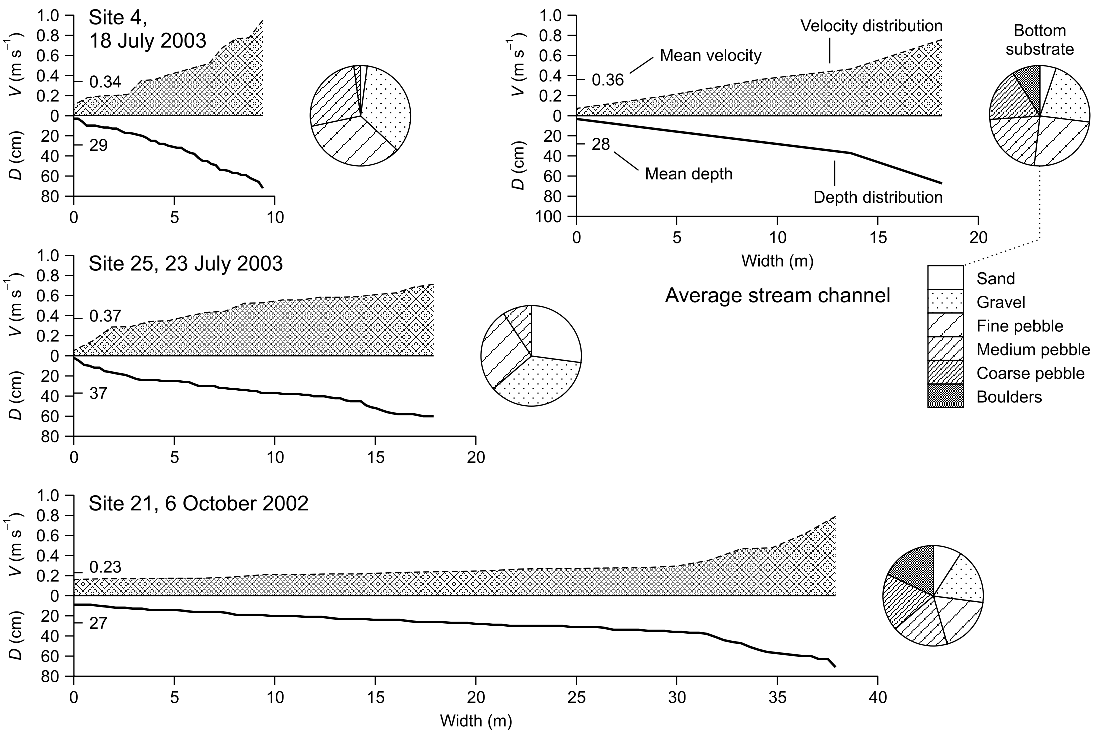

Fig. 6. Generalized description of stream habitat within the occurrence range of Wałecki barbel, *Barbus cyclolepis waleckii* Rolik, 1970 (top right) compared with three stream reaches where its occurrence was confirmed in 2002–2003 (details concerning sites in Fig. 1 and in Tables 1 and 2).

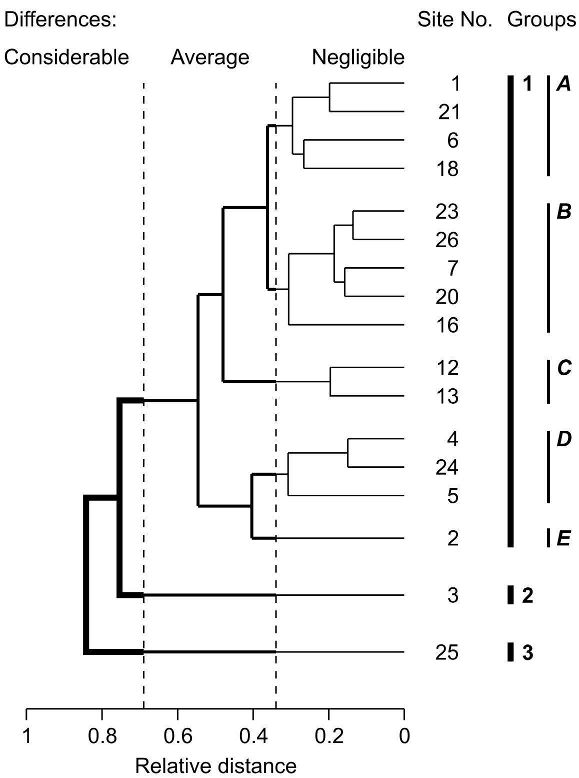

Fig. 7. Similarities between fish communities within the occurrence range of Wałecki barbel, *Barbus cyclolepis waleckii* Rolik, 1970 according to samples collected in seventeen investigated streams in 2002 (for details see Fig. 1 and Table 1): 1, 2, 3 – groups of fish fauna, A–E – subgroups. Linkage distances in this phenogram were standardized assuming the maximum distance in the data set (113.25) as a unit. Communities were divided into groups and subgroups on the basis of the first and third quartile of all pairwise distances between sites.

our data concerning width, depth, and bottom substrate at the investigated sites are in concordance with their preferences presented above. However, the ecology of Wałecki barbel seems to be more similar to that of spotted barbel than of common barbel, and therefore its possible occurrence area should be defined as the medium/lower zone of the range of spotted barbel and/or the upper zone of the range of common barbel.

3.4. Fish community – composition, abundance and long-term changes

Some conclusions concerning the ecology and distribution of Wałecki barbel may be drawn also from the analysis of fish communities recorded at investigated localities (Table 5). Their species composition does not differ significantly from the natural ichthyofauna characteristic of Polish Carpathian rivers (Starmach K. 1956, Żarnecki and Kołder 1956, Kołder 1964, 1973, Solewski 1965, Rembiszewski 1971, Bieniarz and Epler 1972, Skóra 1972, Kołder *et al.* 1974; Włodek 1975, Wajdowicz 1979, Starmach J. 1984; Skóra and Włodek 1988, 1989, 1991, Starmach J. *et al.* 1988, 1991, Augustyn *et al.* 1996, Kukuła 1999). However, if comparing the present state of Carpathian ichthyofauna to that recorded in 1960-ties (Rolik 1971a), 1970-ties (Pasternak and Wajdowicz 1983), and 1990-ties (Kukuła 1999) the anthropogenic changes are visible. The main factors causing these changes are deterioration of habitat quality by pollution and hydrotechnical alterations of stream channels, fragmentation of water courses by the dams, excessive exploitation of local populations, and introduction of alien species (Skóra and Włodek 1988, Witkowski 1992, 1996, Kukuła 1997, Starmach J. 1998). In 20th century all anadromous species, i.e. European sturgeon *Acipenser sturio* L., Atlantic salmon *Salmo salar* L. and sea trout *S. trutta* m. *trutta* L. become extinct there. In few last decades also the local populations of large rheophilic fishes, common barbel and nase *Chondrostoma nasus* (L.) decreased substantially and considerably reduced their occurrence ranges (Skóra and Włodek 1988, 1991; Włodek and Skóra 1999, Kukuła 1999, 2001). Both species are threatened mainly by the construction of dams, water pollution, and devastation of spawning grounds (Lusk 1995, 1996, Keckeis *et al.* 1996, Augustyn *et al.* 1998, Penczak *et al.* 1998, Kukuła 2001). Worth of note is also the considerable decrease of abundance of schneider *Alburnoides bipunctatus* (Bloch) which, formerly occurring in the most of streams now is included into the list of endangered species (Witkowski *et al.* 1999). In contrary to those, chub *Leuciscus cephalus* (L.) becomes more abundant in Carpathian rivers (Włodek and Skóra 1999). Three alien species were introduced into the basins of the Wisłoka and San rivers until now. They are Danube salmon *Hucho hucho* (L.), grayling *Thymallus thymallus* (L.), and rainbow trout *Oncorhynchus mykiss* Walb. The last one cannot establish self-sustaining populations there and fully depends on stocking, while the stocks of Danube salmon and grayling are supplemented by stocking to maintain them at a level desired by anglers. The same concerns populations of native brown trout *S. trutta* m. *fario* L. and at present nase and common barbel.

The set of collected samples of fish communities was organized into three main groups (Fig. 7). The first group contains almost all of samples. Ten species may be regarded as dominants in this group (Table 5). Their total contribution ranges within 86–100% of all recorded individuals. More frequent and abundant were five of them: minnow *Phoxinus phoxinus* (L.), chub, schneider, stone loach *Barbatula barbatula* (L.), and spotted barbel. In this group four subgroups were distinguished. The 1*A* subgroup contains samples collected at four sampling stations, including the *locus typicus* of Wałecki barbel (site 21: the Osława river at Zagórz; Table 1). This subgroup is characterized by relatively high position of minnow, spotted barbel, stone loach, and schneider. These species compose 70–94% of the total number of individuals recorded there. Similar dominant species complex, i.e. minnow, brown trout, stone loach, and schneider (66–95% of the whole) occur at five localities of 1*B* subgroup. In the 1*C* subgroup dominate even more "montane" complex, i.e. Siberian sculpin *Cottus poecilopus* Heckel, minnow, and brown trout (92–93%). In contrast to that a bit more "lowland" patterns of the dominant species characterize the subgroups 1*D* (chub, schneider, gudgeon *Gobio gobio* (L.), minnow, dace *Leuciscus leuciscus* (L.), bullhead *Cottus gobio* L.; 66–88%) and 1*E* (gudgeon, spotted barbel, chub; 82%). In general, the locations on small and medium-sized streams at which Wałecki barbel was recorded in the previous studies are now inhabited by the fish communities composed of 8–10 species, mostly rheophilic cyprinids (mainly minnow, spotted barbel, schneider, chub and gudgeon) accompanied with stone loach, two sculpin species, and brown trout. Such composition of fish communities is typical of submontane reaches of Carpathian streams and rivers in Poland and is also concordant with the set of species accompanying Wałecki barbel given by Rolik (1971b).

Only one sample (site 3: the Wisłok river at Rudawka; Table 1) belongs to the second group. It is more distant from those of the first group mainly because of the surprisingly high number of perch *Perca fluviatilis* L. at this sampling point. Small, probably mostly young-of-the-year perch make up about two thirds of the fish community. This untypical feature may be explained as the effect of the Besko Reservoir on the Wisłok river (surface area 1.3 km^2, volume 16 hm^3) as the sampling point is situated few hundred meters upstream from its backwaters (Fig. 1). Perch is abundant in this reservoir (Kukuła unpubl.). A reservoir may affect the composition of upstream fish communities over long distance, e.g. the effect of the Solina Reservoir extends in the basin of the upper San river even to the montane streams of the Bieszczady National Park (Kukuła 1995). At present perch and roach *Rutilus rutilus* (L.), which were not recorded there before, occur in these streams. They are abundant in the Solina Reservoir on the San river since its origin (Wajdowicz 1966, 1979, Bieniarz and Epler 1993). Similar changes of the occurrence ranges of these species were reported from other Carpathian rivers after construction of dam reservoirs (Skóra and Włodek 1988, 1989, Koščo and Košuth 1995, Starmach J. 1998). Probably the occurrence of ruffe *Gymnocephalus cernuus* (L.) in the channel of the Wisłok river downstream the dam (site 4; Table 1) is another effect of the Besko Reservoir. Proportions of other species at the site 3 (Table 1) also may be altered to some extent. Perhaps the abundance of chub is elevated there owing to the reservoir proximity. As a rule, this riverine species remains permanently in "lacustrine" fish communities of the Carpathian reservoirs. Besides the increased abundance of perch and chub the abundance of some species decreased considerably if comparing to the results of earlier studies (Rolik 1971a; Pasternak and Wajdowicz 1983, Skóra and Włodek 1989). The reason of remarkable absence of minnow at site 3 (Table 1) is hard to explain.

The third group also contains single sample (site 25: the Wiar river at Krówniki; Table 1). The composition of this sample is characterized by distinct dominance of bleak *Alburnus alburnus* (L.), chub and nase (93% of the whole community) but with the presence of schneider and spotted barbel. Therefore, it seems transitional from Carpathian fish fauna to that of the lowland Central European rivers. Probably it is similar to fish communities at these locations on the San river which are not investigated in this study. In the classic river zonation (Huet 1954) such community composition corresponds to that characteristic of the barbel zone, i.e. of medium-sized to large rivers with moderate gradient (<1.5‰ in 60-m wide rivers) and pebble/gravelly bottom (Starmach K. 1956).

In general, the structures found in the set of samples of fish communities collected in this study allow to define the position of Wałecki barbel within a continuous range of coenotic complexes between the lower trout zone (characterised by communities composed of "montane" rheophilic cyprinids and stone loach with still abundant brown trout and Siberian sculpin) through the grayling zone ("montane" rheophilic cyprinids, stone loach and bullhead) to the middle barbel zone ("montane" and "lowland" rheophilic cyprinids). It is worth of note that the most of investigated localities belongs to the grayling zone in terms of the fish community composition.

3.5. Conclusions

The results collected during this study compiled with data from papers concerning Wałecki barbel allow to outline the habitat conditions appropriate for this fish. They may be defined as follows:

1. The stream channel should be medium-sized, at least 10-m or better 20-m wide. In wider rivers the habitat conditions other than the channel width become more important.

2. The mean channel depth should exceed 20 cm, while the maximum depth should be greater than 50 cm. The channel morphology with the zone of medium depth (i.e. that extending over the half of bottom) in range between at least 15 and 40 cm seems to be favorable.

3. The mean stream velocity of 0.30 m s^{-1} or more is desired. The important habitat feature seems to be the zone of fast current (0.50–1.00 m s^{-1}) sharing a considerable portion of the channel.

4. Most of the bottom area should be covered by medium-sized particles (2–200 mm) with the mode within range of fine pebbles (20–50 mm).

5. In general, the stream should be rather oligotrophic than eutrophic, with flow fluctuations periodically disturbing structure of bottom substratum. Such conditions are roughly indicated by poorly developed macroscopic algae and the absence of vascular plants.

6. As a good indicator of the stream habitat appropriate for Wałecki barbel may be regarded the abundant occurrence of spotted barbel, especially within lower part of its distribution area and in the zone of its co-occurrence with common barbel.

7. The possible most frequent and abundant species accompanying Wałecki barbel are minnow, spotted barbel, stone loach, chub and schneider. In most cases the species composition of fish community approximates that characteristic of grayling zone.

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APPENDIX 1

Computation of characteristics of the morphology of stream channel

Measurements

The shape of investigated stream reach is approximated by a polygon created by n pairs of points selected on the opposite banks (Fig. 2). This polygon is decomposed into $2n–2$ triangles and all $4n–3$ edge lengths of these triangles are measured to the nearest 0.1 m with measuring tape. Each pair of points makes a transect approximately transverse to stream channel. Along each transect the stream depths are measured with measuring rod. At each transect also the elevation of water level is measured in relation to those at adjacent transects using a laser level.

Mapping

Every point of the polygon is located on Euclidean plane. The coordinates are found following this procedure:

1. The coordinates of the most upstream pair of points $L(x_L, y_L)$ and $R(x_R, y_R)$ are fixed as

$$x_L = -LR / 2 \quad \text{and} \quad x_R = LR / 2$$
$$y_L = 0 \qquad\qquad y_R = 0$$

where LR is the distance between two points on left (L) and right bank (R).

2. The height of the first triangle LRP is

$$h = (LP^2 - ((LP^2 - RP^2 + LR^2) / (2\,LR))^2\,)^{1/2}$$

and the coordinates of the point of intersection between the straights of the triangle height and the edge LR are

$$x_h = (LR\,x_L + ((LP^2 - RP^2 + LR^2) / (2\,LR))\,(x_R - x_L)) / LR$$
$$y_h = (LR\,y_L + ((LP^2 - RP^2 + LR^2) / (2\,LR))\,(y_R - y_L)) / LR$$

where: LP – distance between points L and P, RP – distance between points R and P.

3. The coordinates of point $P(x_P, y_P)$ are calculated as

$$x_P = x_h - h\,(y_R - y_L) / LR$$
$$y_P = y_h + h\,(x_R - x_L) / LR$$

4. The next triangle is considered substituting appropriately coordinates of its base point on the left (L) or right bank (R) with x_P and y_P. Then the procedure is repeated from step 2 until the coordinates of all points of the polygon are obtained.

5. Orientation of the polygon is adjusted so that its long axis determined by the midpoints of the marginal transects become equation $x = 0$. It is achieved by rotation of the rectangular coordinate system by an angle α which tangent is calculated on the basis of coordinates of the most downstream pair of points $L(x_L, y_L)$ and $R(x_R, y_R)$ as

$$\mathrm{tg}\,\alpha = -\,(x_L + x_R) / (y_L + y_R)$$

According to the above the final coordinates of each point of the polygon are

$$x_F = (x + y\,\mathrm{tg}\,\alpha) / (1 + \mathrm{tg}\,\alpha^2)^{1/2}$$
$$y_F = (y - x\,\mathrm{tg}\,\alpha) / (1 + \mathrm{tg}\,\alpha^2)^{1/2}$$

The steps 2 and 3 were taken from a method of finding the coordinates of intersection points between two circles on a plane (Paul Bourke, a Website dated April 1997: http://astronomy.swin.edu.au/~pbourke/geometry/2circle/).

Calculations

Length of the polygon is the sum of lengths of its sectors between transects. The sector length is the distance between midpoints of two transects

$$S_1 = ((x_{1L} - x_{0L} + x_{1R} - x_{0R})^2 + (y_{1L} - y_{0L} + y_{1R} - y_{0R})^2\,)^{1/2} / 2$$

The indexes in the above equation concern first sector between transects T_0 ($L_0(x_{0L}, y_{0L})$, $R_0(x_{0R}, y_{0R})$) and T_1 ($L_1(x_{1L}, y_{1L})$, $R_1(x_{1R}, y_{1R})$). Transects are numbered downstream.

Area of the polygon is calculated as the sum of areas of all sectors. The area of a sector is

$$A_1 = ((x_{0L}-x_{0R})\ (y_{0L}+y_{0R}) + (x_{0R}-x_{1R})\ (y_{0R}+y_{1R}) + (x_{1R}-x_{1L})\ (y_{1R}+y_{1L}) + (x_{1L}-x_{0L})\ (y_{1L}+y_{0L}))\ /\ 2$$

Mean width of the polygon is obtained dividing its total area by the total length

$$W_M = (A_1 + ... + A_n)\ /\ (S_1 + ... + S_n)$$

Mean channel gradient is calculated dividing the difference in water level at marginal transects by the length of polygon as

$$G_M = E\ /\ (S_1 + ... + S_n)$$

where E is the relative elevation of the most upstream transect above the most downstream one, calculated simply as the sum of elevations between adjacent transects

$$E = (E_0 - E_1) + ... + (E_{n-1} - E_n)$$

The mean depth is calculated as weighted mean. For a transect with n depths (d) measured at fixed interval (I) it is

$$D = I\ (2\ (d_1 + ... + d_{n-1}) + d_n\ (1 - n + T\ /\ I))\ /\ 2\ T$$

where T is transect length.

The mean value for the whole stream reach is also calculated as the weighted mean using lengths of n consecutive sectors

$$D_M = (S_1\ (D_0 + D_1) + ... + S_n\ (D_{n-1} + D_n))\ /\ 2\ (S_1 + ... + S_n)$$

Distribution patterns of all depths measured in the stream reach are characterized by quartiles. To compute a quartile: 1) the data set is ranked from the smallest to the largest; 2) the position of the quartile is calculated as $Q\ (n + 1)$ where Q is the quartile value (i.e. 1/4 and 3/4) and n is the sample size (Helsel and Hirsch 1992); and 3) if the obtained position is not an integer the average of the adjacent data is calculated.