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How pulse lengths impact fish stock estimations during hydroacoustic measurements at 70 kHz

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Abstract – Water Framework Directive requires reliable and effective monitoring tools, and hydroacoustics has a potential to be one of them. The effect of pulse duration on *in situ* acoustical estimates of fish density and their size distribution was investigated. Measurements were performed in the oligo-mesotrophic Lake Hancza (Poland) using a SIMRAD EK60 split-beam echo-sounder at 70 kHz frequency. During the survey, two similar transducers pinged alternatively through the multiplexer using 4 different pulse lengths, from short to long ones. The results show that the volume backscattering coefficient (Sv) values, equivalent of the fish biomass, were not influenced by the pulse length. However, the number of the detected fish, the mean target strength (TS), and consequently the fish density, differed significantly for the long pulse duration data. This was especially noticeable in the layer above the thermocline with dense fish populations. In this upper layer, for the long pulse the Sawada index frequently exceeded value of 0.1 leading to overestimation of the mean TS and underestimation of the fish density.

Key words: Lake / Freshwater fish / Hydroacoustics / Pulse length / Fish stock / WFD

1 Introduction

A key issue facing fisheries management is the production of reliable stock estimates. A diverse range of sampling techniques has been developed for the assessment of fish populations in lakes and reservoirs around the world (Murphy and Willis 1996). However, none of the techniques is suitable for all types of fish in all types of habitats. Additionally, such methods as trawling or gill-netting involve high fish mortalities and so have a varying level of acceptance in different countries (Winfield et al. 2009). The use of remote observation techniques such as hydroacoustics is favoured as an option. Over the past few decades hydroacoustical methods have been increasingly used both at sea and in fresh water in order to acquire the detailed information about these aquatic ecosystems, and particularly about their living resources (Godlewska et al. 2004; Simmonds et al. 2009; Trenkel et al. 2009; Warner et al. 2009; Guillard et al. 2010). Hydroacoustic instrumentation has now matured to be used routinely in a number of applications, including fisheries and ecological studies of ecosystem quality (Knudsen et al. 2006; Mehner et al. 2007; Djemali et al. 2009; Kaartvedt et al. 2009). However, the internationally accepted standards need to be created and outlined to ensure comparability of results. It is especially important in inland waters, where Water Framework Directive requires reliable and effective monitoring tools, and hydroacoustics has a potential to be one of them. Important work towards the standardization of hydroacoustical measurements has been undertaken in the United States and Europe: the Study Group on Fisheries Acoustics in the Great Lakes has developed standard operating procedures (SOP) for collecting, processing, and analyzing acoustic data collected in the Great Lakes (Rudstam et al. 2009). European Committee for Standardization (CEN) "Water Quality – Guidance on the estimation of fish abundance with mobile hydroacoustic methods" is under development (CEN 2009). If acoustics is to be used as a monitoring tool for estimating fish abundance, it is of primary importance that all data collection parameters are checked for their effect on fish stock estimation, and their values are standardized if necessary.

As far as we know, up to now no systematic work on the effects of the acquisition parameters on total echo-energy and fish target strength has been performed *in situ*. Pulse duration is a collection setting and therefore cannot be modified after a survey. Our questions are: do all pulse lengths give the same values of basic acoustic data such as Sv and TS (MacLennan et al. 2002)? Do they equally describe the *in situ*

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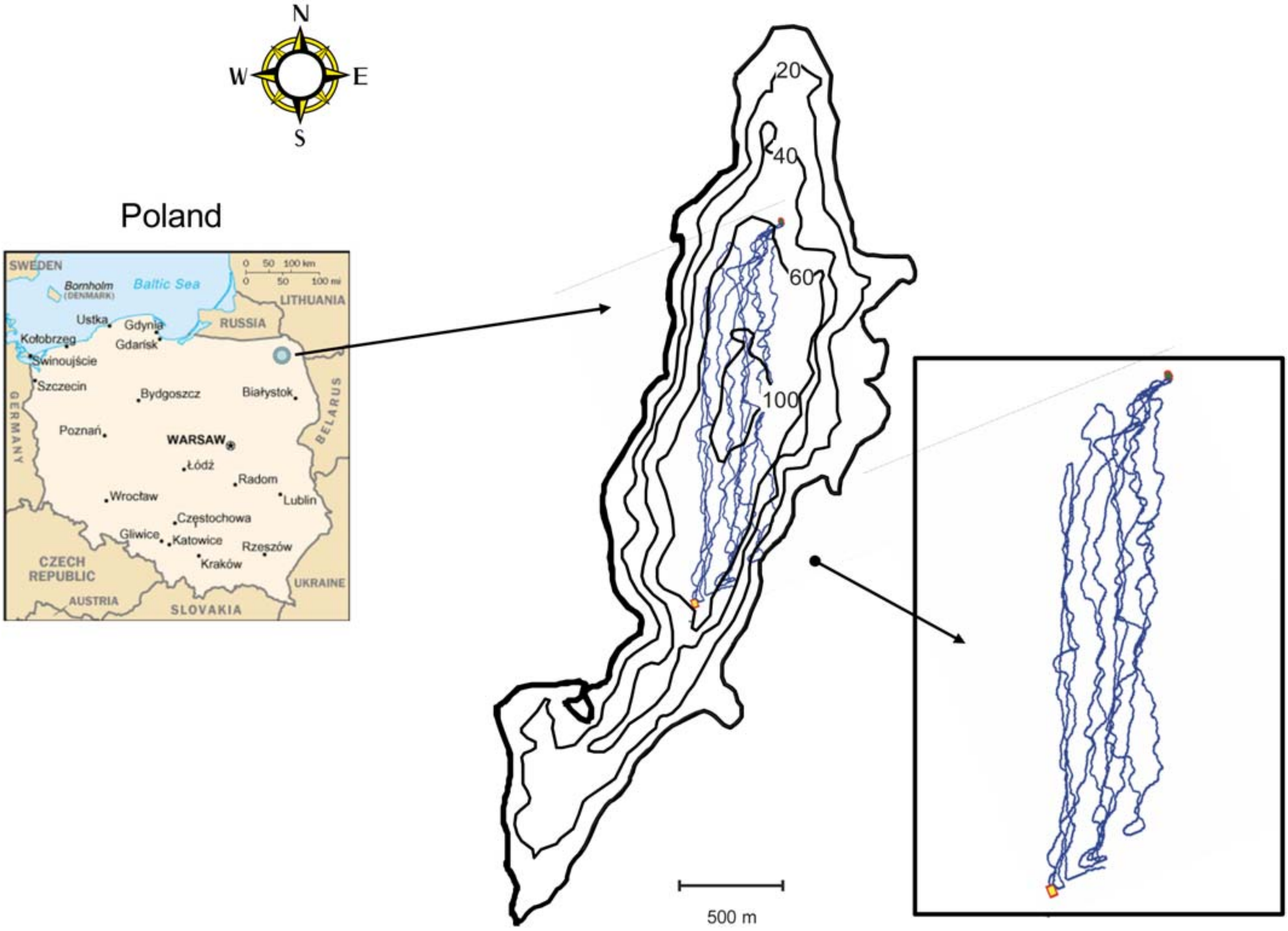

Fig. 1. The study area, localized in Poland, mapping the bathymetry and acoustic tracks, with a zoom on the tracks.

fish size distribution and density? The aim of this paper is to check these questions on real fish populations and to investigate which consequences, if any, pulse length has on the estimates of fish resources.

2 Materials and methods

The measurements were performed from 8 to 10 September 2008 in Lake Hancza in north-eastern Poland (Fig. 1). It is a deep (max depth 108 m, area 330 ha), oligo-mesotrophic lake which hosts a diversified fish population, approximately 24 fish species (Kozłowski et al. 2008). The most numerous are roach, *Rutilus rutilus* (Linnaeus 1758), perch, *Perca fluviatilis* (Linnaeus 1758), vendace, *Coregonus albula* (Linnaeus 1758) and white fish, *Coregonus lavaretus* (Linnaeus 1758). Temperature and oxygen profiles were taken at 1 m intervals, from the surface to 25 m at the deepest point of the lake before the survey and during calibrations.

A SIMRAD EK60, split-beam, 70 kHz echo-sounder was used with two similar circular transducers (T1 and T2), each with a nominal beam angle of 11 degrees at –3 dB, pinging alternatively through a multiplexer. The ping interval was set to 0.1 s, so that each transducer sampled the water column 5 times per second. This high ping rate was chosen to minimize the differences in fish individuals sampled by the two transducers. Both transducers were aimed vertically downwards and mounted onto a custom frame, one behind the other and set as close as possible (distance between the transducers was around 0.20 m), so one can assume that both transducers have sampled the same fish population (although not exactly the same fish individuals). Particular attention was paid to the transducer calibration procedure, to be sure that the calibration parameters were not an additional source of variability. For each transducer, calibrations were firstly performed in a tank, according to procedure recommended by Foote et al. (1987), then repeated in field conditions to check for consistency. The calibration was performed separately for each pulse length. Surveys were conducted repeatedly along a track around 3 km long in the middle of the lake (Fig. 1, real positions were recorded by GPS), starting 1 h after sunset when all fish were scattered. Every 15 min a different pair of pulse length combinations was chosen. In total, 16 combinations were investigated (Table 1). The four pulse lengths that were used – 0.128, 0.256, 0.512 and 1.024 ms – were indicated in the text and tables respectively as short, medium1, medium2, and long.

Table 1. Pulse length combinations and key parameters calculated for the total transect length. "Upper " corresponds to a layer 1.8–11.8 m, "Deep" to 11.8 m–bottom depth. The data in bold correspond to records using the same pulse length.

Tran-sect	Pulse length	*N* of single echoes		% of single echoes		Sawada index Nv		Mean TS (dB)	
		Upper	Deep	Upper	Deep	Upper	Deep	Upper	Deep
T. 1	**short**	**3205**	**1219**	**61**	**68**	**0.020**	**0.008**	**–50.90**	**–45.87**
	short	**3222**	**1191**	**66**	**74**	**0.015**	**0.008**	**–50.91**	**–45.56**
T. 2	short	6225	2176	49	79	0.044	0.010	–49.92	–45.53
	medium1	4747	1970	42	75	0.078	0.013	–50.01	–44.58
T. 3	short	2291	1867	62	75	0.013	0.007	–50.53	–45.57
	medium2	1591	1595	49	72	0.050	0.020	–50.71	–43.27
T. 4	short	2947	1068	60	77	0.020	0.010	–50.23	–46.26
	long	1108	1009	38	67	0.130	0.052	–48.65	–42.95
T. 5	medium1	5399	5352	35	74	0.102	0.018	–49.29	–43.89
	long	1540	4040	22	31	0.262	0.073	–46.55	–43.52
T. 6	medium1	2532	995	61	75	0.035	0.013	–51.02	–42.87
	medium2	1831	992	51	71	0.065	0.020	–50.75	–43.44
T. 7	**medium1**	**2432**	**1236**	**55**	**81**	**0.032**	**0.013**	**–51.17**	**–43.14**
	medium1	**2464**	**1129**	**59**	**78**	**0.032**	**0.013**	**–51.37**	**–42.95**
T. 8	medium1	4905	4625	37	71	0.100	0.022	–49.19	–44.30
	short	7700	4833	49	76	0.055	0.013	–49.98	–44.81
T. 9	medium2	2131	1522	47	75	0.082	0.038	–50.03	–42.88
	short	4049	1272	67	76	0.020	0.017	–51.48	–43.80
T. 10	medium2	1933	1566	54	72	0.048	0.018	–50.75	–43.28
	medium1	2358	1474	58	68	0.023	0.010	–52.00	–43.36
T. 11	**medium2**	**2431**	**3947**	**39**	**62**	**0.135**	**0.053**	**–48.71**	**–43.94**
	medium2	**2430**	**3708**	**38**	**59**	**0.132**	**0.053**	**–49.20**	**–44.20**
T. 12	medium2	2289	3239	37	56	0.140	0.080	–48.62	–43.95
	long	1304	2522	31	36	0.230	0.040	–47.49	–43.63
T. 13	**long**	**913**	**845**	**46**	**62**	**0.065**	**0.030**	**–50.97**	**–43.26**
	long	**959**	**834**	**51**	**59**	**0.058**	**0.028**	**–51.19**	**–43.34**
T. 14	long	982	2046	32	54	0.140	0.050	–47.74	–42.89
	medium2	1859	2297	43	69	0.087	0.100	–48.87	–43.32
T. 15	long	970	3954	21	26	0.102	0.030	–46.20	–43.92
	medium1	3785	6606	37	66	0.255	0.110	–49.45	–44.38
T. 16	long	932	1815	46	57	0.082	0.018	–48.94	–42.83
	short	2394	2011	73	73	0.010	0.102	–50.56	–43.87

The comparative data of both transducers pinging with the same pulse length (short-short, medium1-medium1, medium2-medium2, long-long) were also used to check if there was no transducer effect. Data were stored in a computer and later processed by the Sonar 5 Pro analysis software (Balk and Lindem 2006).

When using *in situ* TS estimates it is important to analyze the data in depth regions with homogeneous fish groups (Foote 1987; Rose 1998). It is known from other deep temperate lakes, that thermocline structures the fish species distribution (Masson et al. 2001; Guillard et al. 2006; Mehner et al. 2010). To account for observed differences in fish populations, the cyprinids and percids above, and the salmonids below the thermocline, the analysis was performed separately in two layers: 1.8–11.8 m (from the area free of surface noise to the thermocline) and from 11.8 m to bottom depth. The TS threshold was set to –65 dB (based on *in situ* TS distributions), and the Sv threshold was set to –71 dB, thus ensuring that single fish, close to the threshold were detected at all ranges and off axis angles inside the accepted beam. The criteria used to distinguish individual targets, i.e. single echo detections (SED), were set alternatively to "strong" (the minimum and maximum returned pulse width relative to transmitted pulse duration =0.7 and 1.3 – default for Sonar 5) and "relaxed" (0.6 and 1.8 accordingly) to ensure that they did not influence the results. The maximum gain compensation was 3 dB (one way) and maximum phase deviation of 0.3 degrees. To ensure that conditions were suitable for *in situ* TS estimation, the Sawada index (Sawada et al. 1993) was calculated. To estimate fish abundance the Sv/TS scaling method was applied, which uses

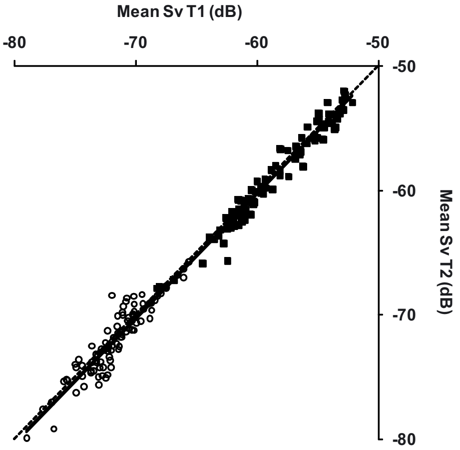

Fig. 2. Comparison of the volume back-scattering strength (S_v) as received by two transducers for all pulse lengths (short, medium1, medium2, long) from two layers 1.8–11.8 m (■ black square), and 11.8 m to bottom (○ white circle). The dotted line represents the equation $x = y$ and the black line is the regression between the two transducers outputs, when the two layers are pooled.

volume back-scattering strength, Sv, and the mean TS to calculate fish volume density according to the equation (Forbes and Nakken 1972)

$$\rho[\text{ind m}^{-3}] = 10^{0.1(\text{Sv}-\langle\text{TS}\rangle)} \qquad (1)$$

where Sv is the volume backscattering strength and ⟨TS⟩ is mean TS, both in dB.

Mean target strength can be estimated based either *i)* on single echo detections (SED); or *ii)* on tracked fish (Balk and Lindem 2006). For the purpose of comparisons between the pulse lengths we used only the first method since tracking involves additional criteria, which could affect the analysis results. Integration interval was set to circa 250 m, for which Sv and mean TS were determined.

Major axis regression was used to compare results received with two transducers (Warton et al. 2006) using Falster et al. (2006) software. Means TS between all possible pairs of the 4 different pulse lengths were compared using the Mann-Whitney test. A statistical test described in Warton et al. (2006) was performed to compare slopes of two regression lines, for the surface and deep layer, and against a slope on 1 (1:1 fit). A non-parametric test (Friedman ANOVA) was used to compare the TS distributions obtained by the four pulse lengths. For comparison of strong and relaxed criteria the Wilcoxon test was applied (Sprent 1992).

3 Results

3.1 Comparison of transducers

Since results were received using two transducers, the first step was to ensure that there was no transducer effect. This was done by comparing results of two transducers (T1 and T2) pinging alternatively with the same pulse length. In both analyzed layers (above and below the thermocline) the slopes did not differ significantly neither for Sv ($p = 0.32$) nor for TS ($p = 0.40$), so we pooled the data from the two layers and calculated one regression for the Sv and one for the mean TS. Both regression lines had a slope not significantly different from 1 (for Sv data $p = 0.28$, for TS data $p = 0.69$). The mean TS from the two transducers operating at the same pulse length differed by less than 0.5 dB and the number of echoes detected was almost identical (Table 1, bold). These results confirm that there was no transducer effect and the data received by either transducer could be used for comparisons between the different pulse lengths.

3.2 Volume backscattering strength Sv

The Sv values recorded with each transducer, for all pulse length combinations were compared (Fig. 2). For layers 1.8–11.8 m, and 11.8 – bottom depth, the slopes were not significantly different ($p = 0.43$), therefore the data from both layers were pooled. The results indicate that the slope between the Sv values registered by two transducers was not statistically different from 1 ($p = 0.59$), which means that the influence of pulse length on the Sv measurements was not observed.

3.3 Target strength distributions (single echo detections)

TS distributions were compared by pooling data corresponding to the same pulse length from all the transects. The distributions show that the number of detections was highly dependent on the pulse length: in the surface layer, the short pulse detected the largest number of single echoes and the long pulse the smallest (Fig. 3a, left). The TS distributions presented as % of all detected single echoes in the surface layer (Fig. 3b, left) did not significantly differ between different pulse lengths ($p > 0.392$). Below the thermocline the differences in the number of fish detected by different pulse lengths were much smaller than in the upper layer. The largest number of single echoes was detected with 0.256 ms pulse. In this deep layer (Fig. 3b, right), all 4 pulse lengths expressed as % of total number of detected echoes gave similar distributions, i.e. the differences between them were not statistically significant ($p > 0.971$).

The mean TS values were calculated as a linear average of all single echo detections (SED) within an integration interval. The mean TS in the surface layer (Fig. 4) for the three shorter pulse lengths did not differ significantly from each other ($p > 0.44$), while values for the long pulse did deviate significantly (for the pair short-long pulse, $p = 0.004$; for medium1-long, $p = 0.004$ and for medium2-long, $p = 0.016$). There was no statistically significant difference ($p > 0.075$) between strong and relaxed criteria, which means that for our data set, influence of SED settings on the results was not detected.

3.4 Fish density

The calculation of fish density was performed for each integration interval and layer. Fish densities estimated in the surface layer were two orders of magnitude higher than below the

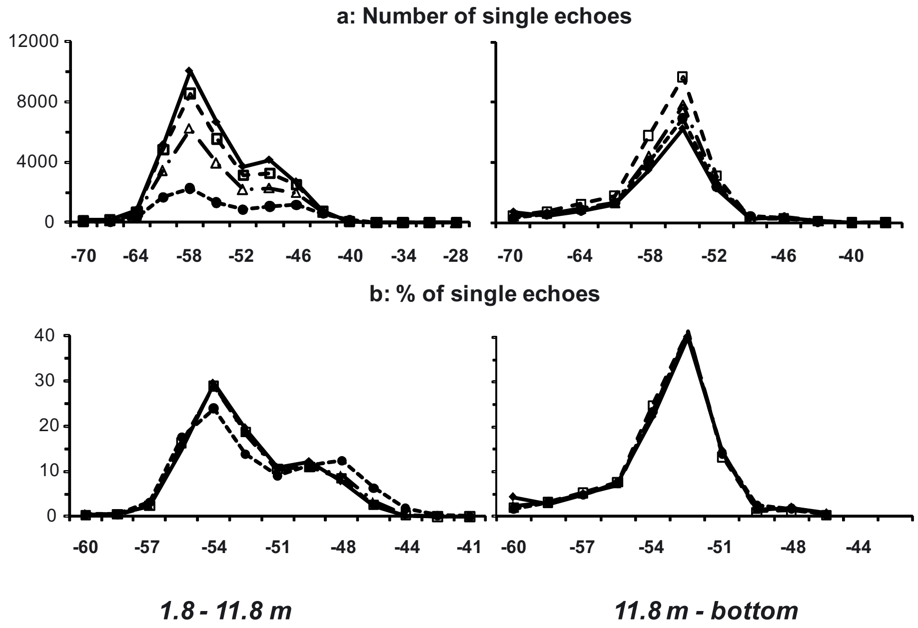

Fig. 3. Target strength (TS) distributions of single echo detections (SED) in two layers: 1.8–11.8 m (left), and 11.8 m to bottom (right). Based on data pooled for all transects and all pulse lengths (black lozenge ♦: pulse 0.128 ms; white square □: pulse 0.256 ms; white triangle △: pulse 0.512 ms; black circle •: pulse 1.024 ms; (a) total number of single echoes detected in 3 dB classes, (b) percentage of single echoes detected in 3 dB classes.

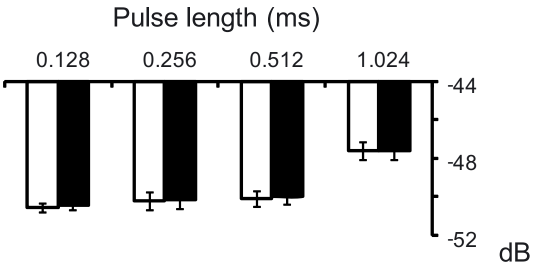

Fig. 4. Mean TS for different pulse lengths in the layer 1.8–11.8 m, white "relaxed SED criteria", black "strong SED criteria" (for definition see the text).

thermocline, therefore the two layers had to be treated separately. The inspection of Sawada index showed that it exceeded 0.1 (Sawada et al. 1993) both in surface and deep layers mainly for the long pulse. According to Soule et al. (1995, 1997) and Gauthier and Rose (2001) values of mean target strength calculated with Nv > 0.1 could lead to bias of TS due to acceptance of multiple echoes and thus to underestimation of fish density. Indeed, for the surface layer the trend of increasing mean TS with Nv above around 0.1 is clearly seen (Fig. 5). For the deep layer TS did not change within the observed Nv values (max Nv = 0.3, Fig. 5). The regression between the fish densities estimated with the two transducers in the surface layer (Fig. 6) had a slope significantly different from 1 ($p < 0.001$). The dependence between estimated fish densities, pulse lengths and values of Sawada index is clearly seen from Figure 7. For the registered densities in case of the short pulse the Sawada index exceeded value of 0.1 only on 2 occasions, while for the long pulse only on 3 occasions it was lower than 0.1.

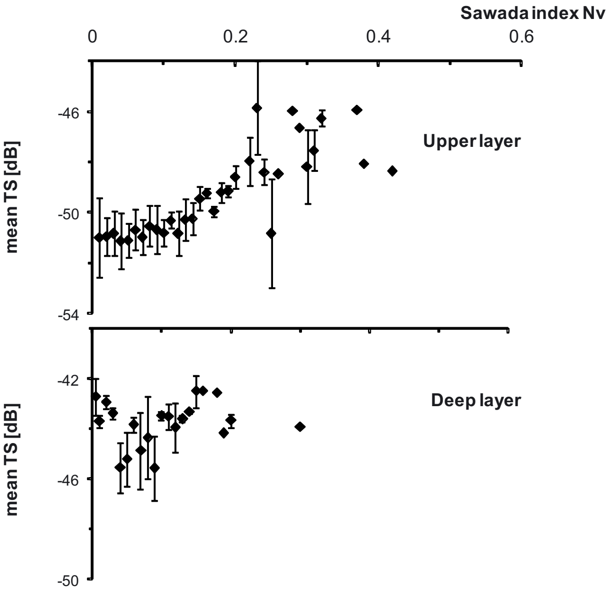

Fig. 5. Relationship between the mean TS and Sawada index for different pulse lengths and the two layers. The points represent the means and the standard errors for the number of cases with the same value of Sawada index.

4 Discussion

The choice of pulse duration (τ) is dependent on the objectives and conditions of the survey. A shorter pulse duration is preferable for higher resolution of individual targets, whereas a longer pulse duration is desirable for a higher signal-to-noise ratio (SNR). Organisms to be identified as individual

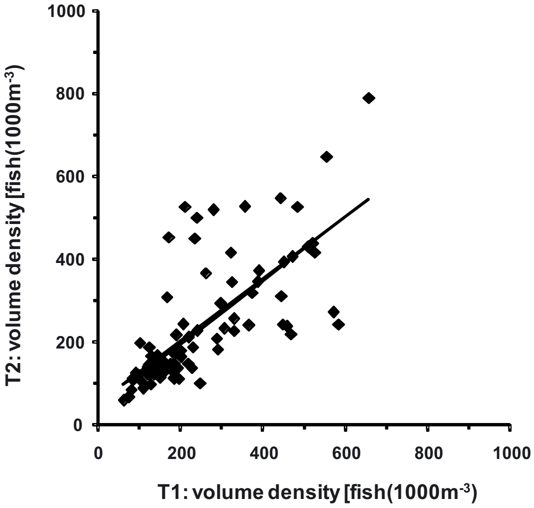

Fig. 6. Fish densities in the surface layer as estimated by both transducers operating at different pulse lengths.

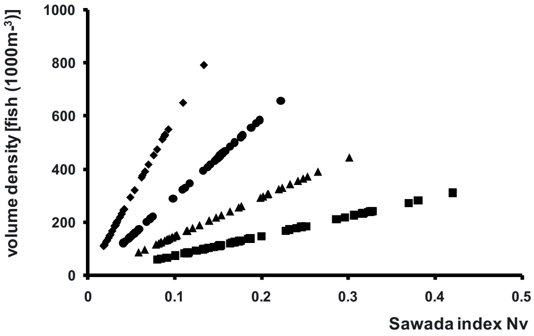

Fig. 7. The dependence between estimated fish densities, pulse lengths and values of Sawada index for the surface layer of Lake Hancza (lozenge ♦: short, circle •: medium1, ▲ triangle: medium2, ■ square: long).

targets must be sufficiently separated. Pulse duration (τ in s) and sound speed (c in m s^{-1}) affect the separation of echoes through the relationship:

$$\Delta R > \frac{c\tau}{2} \qquad (2)$$

where ΔR is the range between two targets at distances R_1 and R_2 (in m) from the transducer. Targets that are closer together than ΔR cannot be separated (Simmonds and MacLennan 2005). In our *in situ* studies using 70 kHz, differences up to 5 fold in the number of detected echoes were observed for different pulse lengths. However, for the pulse lengths from 0.128 to 0.512 ms, the number of echoes did not affect the TS distributions, represented as percentage of echoes in a given size class. Only for the long pulse (1.024 ms) in the upper layer, there was a slight difference, but not statistically significant. A high significant correlation of Sv values, with the regression line intercepting zero and the slope close to unity indicated that the total energy reflected by fish from a given volume and received by both transducers was independent of the pulse length. Thus, at a scale of the whole investigated area, hydroacoustical characteristics such as TS distribution and Sv were not affected by the pulse duration when using 70 kHz transducers. However, when translating acoustic data to biologically and ecologically meaningful metrics, such as fish density, the conclusion about independence of results on the pulse duration was not valid any more. This was probably due to a problem with receiving unbiased *in situ* estimates of TS. Practically, with present single frequency systems complete rejection of overlapping echoes is impossible to achieve (Soule et al. 1995). The probability to accept multiple targets as single ones, increases with increasing fish density and the pulse duration. In our investigations at small average fish densities (as observed mainly in a deep layer) the differences due to different pulse lengths were not manifested. However, in the areas which contained high density of fish (mainly surface layer), particularly of small sizes, fish abundance and mean TS differed considerably with the pulse length used. The mean TS for the long pulse increased as compared to the other pulse lengths, leading to an underestimate of fish density. The change of SED criteria (strong or relaxed) did not affect the results, which might suggest ineffectiveness of the duration limit algorithms for deleting multiple targets (as indicated already by Soule et al. 1997). It is thus imperative that TS estimates are confined to situations of low density to reduce the proportion of accepted multiples to minimum. Commonly the Sawada index Nv (Sawada et al. 1993) is used to set a threshold density to reduce bias attributable to multiple targets. However an order of magnitude differences in the maximum Nv values utilized in previous studies have been reported. O'Driscoll and Rose (2001) for small (5–10 cm) capelin, *Mallotus villosus* (Müller 1776) at short integration intervals found 0.4 threshold to be sufficient to limit bias caused by multiple targets, while Sawada et al. (1993) for the Atlantic redfish, *Sebastes* spp., and Barange et al. (1996) for walleye pollock, *Theragra chalcogramma* (Pallas 1814) used the threshold as small as 0.04. Gauthier and Rose (2001) have tested the effect of horizontal measurements scale on fish densities and determination of an appropriate Nv threshold, and found that TS could be estimated at higher densities without bias using smaller measurements scales. In our studies the Nv did exceed the value of 0.4 only on one occasion, and since both fish and integration scales were small, one could assume that such threshold was sufficient. The comparison of estimated TS values relative Nv have shown, that for densities observed in the deep layer it was sufficient, but for the surface layer it was not. Positive bias in TS estimates was observed for Nv values above around 0.1. It should be noted that the present study was performed at 70 kHz in a mesotrophic lake, where fish densities are usually not high. In eutrophic lakes one may expect much higher fish densities, and so, much higher differences related to the pulse length. Therefore, for the sake of comparability between results we suggest that shorter pulse lengths, from 0.128 to 0.512 ms, should be used, unless the density is low enough to avoid multiple echoes. Since in fresh water depths rarely exceed 100 m, using short pulses should not be a problem and they are preferable for *in situ* TS estimates. The conditions for unbiased TS estimates should always be checked, and have to be included in standardization procedures such as the SOP and CEN. Unfortunately at present, not many authors calculate Nv when estimating fish biomass, which can obscure the results and unable their comparability.

There are few published data sources with which our results can be compared. The effect of pulse duration on fish target strength was investigated by Kubecka (1995) under laboratory conditions. He studied the relationship between pulse length in the range of 0.1–0.8 ms and frequency bandwidth (1.25–10 kHz, at frequencies 200 and 420 kHz) and their impact on the measured, horizontal aspect target strength of fish. According to him, none of these parameters had any significant impact on the variability of the target strength. However, they affected the measured duration of the received pulses, through the change of pulse shape. Thus, the parameters used to fulfill single echo criteria were changed. Since the results were received with a Biosonics dual-beam echosounder and not a split-beam as in our case, and the two systems use different algorithms for data analysis, these results can not be directly compared with ours. Soule et al. (1997) tested phase algorithm at multiple pulse durations for sphere detection at 38 kHz. From his experiment TS data received with the short pulse length (0.3 ms) were critically dependent on the number of samples available for computation of phase deviation. Therefore, in his opinion the use of the short pulse duration should be discouraged. However, this conclusion is valid for low frequencies only, while for the higher frequencies this problem should not appear. Wanzenböck et al. (2003) have compared two systems, EY500 and Biosonics, which differed in many parameters including the pulse length. Their findings are concurrent with ours: the echosounder with a longer pulse length registered lower fish densities than the short pulse length, especially in regions of high density. Additionally, the proportion of targets registered by the long pulse length in the lower TS classes was smaller, while that of larger TS classes was higher than in the case of the shorter pulse length. However, because of the many other parameters in addition to pulse length that differed in the two systems, direct investigation of the pulse length effect was not possible. Guillard et al. (2004) compared 3 different frequencies whilst using different pulse lengths and reported variability in the TS values observed, once again however, the trend was not investigated in relation to the pulse length. Thus, the available literature data are inconclusive about the pulse length influence on fish density estimates in natural lake conditions.

5 Conclusion

To ensure comparability of results in assessing fish densities in lakes (as required by the Water Framework Directive) short or medium pulse lengths should be used whenever possible, at least when using high frequencies, 70 kHz or more. Pulse durations recommended for the Great Lakes (Rudstam et al. 2009) range from 0.2 to 0.6 ms, and we recommend to use a similar range of pulse lengths for standard operating procedures as the European standard of hydroacoustics (CEN 2009). A particular care must be taken that environmental conditions (fish density) are suitable for unbiased *in situ* TS estimates.

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