International Council for the
Exploration of the Sea

C.M. 1993/B:16

ON THE SHAPE, SIZE AND DENSITY OF NORTH SEA HERRING SCHOOLS AS MAPPED BY ECHO INTEGRATION AND ACCURATE SONAR PROJECTION

by

Ole Arve Misund and Asgeir Aglen

Institute of Marine Research,
P.O.Box 1870,
N-5024 Bergen, Norway

Abstract

The shape and horizontal extent of herring schools in the North Sea have been mapped by a naval sonar (SIMRAD SA 950) with narrow horizontal beam width. The density of schools that were passed over was measured by the SIMRAD EK 500 echo sounder.

In most cases the school shape fit a geometric category (circle, oval, square, rectangle, parabol), but a few schools had an undefined, amorph appearance. The fish density within the schools varied by a factor of about 100, but there were clear relationships between the geometric dimensions and biomass of the schools. The variation in the dimension-to-biomass relationships reduced substantially by classifying the schools according to density.

INTRODUCTION

During the last decade there has been a substantial development of fisheries sonars. The introduction of the multibeam technology has greatly extended the volume searched compared to that of using only a single beam (Bodholdt 1982). This enable complete mapping of the horizontal extent of schools in a single transmission. Application of modern computer technology has greatly improved the presentation of sonar recordings. The sonar picture can be viewed in true motion in which the movements of both the vessel and the schools are displayed (Bodholdt and Olsen 1977). Data on vessel navigation and fish swimming movements are calculated and presented on the screen. For fishermen, this information is vital in the tactical decision making on when and how to position a purse seine or a pelagic trawl most favourably to catch selected schools. This development has ended the Norwegian tradition that the master fisherman comands the shooting of a purse seine from a small skiff equipped with a sounder adjustable in tilt and train. Now he has either taken up a more comfortable position in front of the sonar display in the wheel house, or the skipper decides the shooting alone by watching the sonar display while he is also manoeuvring the vessel.

However, since most fisheries sonars are constructed to cover the volume in large sectors around the vessel, they are usually not very accurate when projecting the geometric area of recordings. Most conventional fisheries sonars are characterized by having horizontal beamwidths larger than 5^{o} between the - 3 dB points. Due to the beam geometry, this will cause a substantial, range dependent distortion in the projection of recorded schools. At a distance of about 200 m, the uncertainty in the horizontal extent across the sonarbeams will be up to about 35 m for a beam width of 5^{o}. In additon, the pulse length will contribute to make a school projection that differ from the real one. The effect of the pulse length is usually much less than that of the beam width. A pulse length of about 4 ms which is quite common for a sonar range up to about 400 m, enlarge the horizontal extent along the sonar beams by 3 m.

For accurate measurements of school dimensions it is therefore necessary having sonars instruments that can give better resolution. This demand is especially valid if the purpose of the measurements is to estimate the abundance of schooling fish. To obtain a proper coverage during surveys, schools up to 300 to 500 m away from the vessel has to be measured. Close to the vessel, the fish may perform strong avoidance reactions. If the fish is also swimming at such depth that a large tilt angle has to be applied, only fractions of the school may be covered. Measurements closer than 100 m from the vessel may therefore be rather unreliable.

As for the fisheries sonars, there has also been a substantial development in the echo sounder technology, especially for fisheries research. The calibration problem of echo integrators was more or less solved by the introduction of the standard spheres in the beginning of the eigthies (Foote, 1983; Foote et al., 1987). The receiving sensitivity for weak signals was greatly improved, and tendency to saturation for strong signals was overcome by the developement of the digitized SIMRAD EK 500 echo sounder and integration unit (Bodholdt et al., 1988). The dynamic range of this instrument was also greatly extended compared to that of previous sounders. Such a system may give more accurate measurements of fish density in schools because of the capability to quantify the strong signals that may be scattered from such dense concentrations.

With the intention of developing a system for automatic detection and sizing of schools (Totland and Misund, 1993), a naval sonar, SIMRAD SA 950 was installed onboard R/V 'G.O. Sars' in the summer 1993. The sonar operates on 95 kHz, and has a horizontal beamwidth (-3 dB points) of 1.7° of each of 32 beams that covers a sector of totally 45°. Since the vessel is also equipped with the SIMRAD EK 500 echo sounder, this enable sizing of schools fairly accurately. We report here measurments of herring schools in the North Sea during a cruise to test the new sonar.

MATERIALS AND METHODS

The cruise was conducted in the Eastern North Sea south eastward along the western slope of the Norwegian trench between 58° - 59° 30' North and 3° - 4° 30' East. To reduce the noise from bottom and surface reverberation, the SIMRAD SA 950 sonar was operated with frequency modulated transmission (FM Auto). In addition the automatic gain controlling filters (AGC and NORMALIZATION) were set to step one (WEAK), as was also the PING-TO-PING correlation filter. When searching for schools the sonar was operated at a range of 600 m, with the 45° beam sector directed forwards, and at a tilt angle of -5°. If a school was recorded in front of the vessel, the heading was adjusted so that the vessel was passing as directly as possible over the school. During this operation, the sonar range was reduced to 300 m and then to 150 m as the vessel approached the school. To record how accurately the vessel passed over the school, the sonar was tilted down stepwise to more than 70° in most cases so that the school projection was maintained as optimal as possible within the beam sector. The vessel speed during the school recordings varied from 3 - 5 m/s (6 - 10 knots). Often repeated trials were conducted on schools that were missed by the echo sounder due to avoidance or unprecise navigation.

During the measurement trials, the sonar picture was stored on video tape by a VHS recorder connected to the video output of the sonar. The echo sounder signals were stored by the BEI-system (Knudsen, 1990) for subsequent post processing. Each school approached was allocated a number that was noted on the echo sounder recording to ensure correct identification during the scrutinizing. The time and position were also noted for each trial, and used to identify the different school recordings on the video tape.

To identify the recordings and obtain biological samples, trawling by a Fotø pelagic trawl was carried out at 12 stations. During daytime, the trawling was aimed directly at school recordings. Large bouys were attached to the wings when fishing schools swimming close to surface. 12 hauls were made at night, and always with the bouys attached to keep the trawl close to surface. The fish length to the nearest 0.5 cm was measured on subsamples of about 100 herring from each catch. Sex and maturation stage were also noted.

The fish density (n/m^3) in the schools was estimated as described by Misund (1993). During the post processing of the echo signals by the BEI-system, the school window was drawn around each school so that the area backscattering coefficient (sA-value) of the single recording was measured. The BEI-system was operated with a threshold of -80 dB. The height and transect length of each recording were measured on the echo sounder outprint. The back scattering cross section (σ_{bs}) of the herring was calculated by using the target strenth equation 20 log L - 71.9 (Foote, 1987), where L is the average fish length. Possible extinction of the sound energy within dense schools was not compensated for.

The quality of the fish density measurements was controlled by checking if the vessel passed directly over the school. The echo sounder and sonar transducer is both mounted close to the center line on the vessel. Therefore a beam of 7.3° equal to that of the echo sounder was drawn in the center of the beam sector of the sonar on a transparent sheet. During playback of the video recordings from the sonar display when the vessel approached schools, this sheet was placed on the monitor screen to check if the school was hit by the 7.3° beam when the tilt angle of the sonar was more than -45°. If the school projection filled this beam completely or only partly, the echo sounder recording was catergorized as good or bad respectively.

The shape and horizontal extent of the schools were estimated by still picture analysis of the video recordings. The contours of the projections of each school recording were drawn accurately on a transparent sheet laid directly on the monitor screen. In most of the cases this was done at two sonar range categories; when the school was observed at a sonar range of 300 m, and then at a sonar range of 150 m. For the largest schools, this was done at a sonar range of 600 m and 300 m respectively. The extent of the school projection along (lengthwise) and across (crosswise) the sonar beams were measured by a ruler on the transparent sheets. The shape of the schools was categorized either as circle, oval, square, rod, parabol, and amorph if rather undefined. The horizontal school area was estimated by a planimeter ran exactly at the contour drawings of the schools on the transparent sheets. The planimeter measure was scaled to the real dimensions by multiplying with a factor between the dimensions on the playback monitor and the real one for each sonar range. When using the marker on the sonar screen or the tracking function, the real horizontal distance to the marker or the target symbol is calculated directly and presented on the sonar screen. As the sonar recordings is displayed in a slant presentation, the measurements of the scaling factor and the horizontal area was corrected by multiplying with the cosine of the tilt angle.

When the sonar is operated with a transmission in FM-3 mode, the pulse length is 1.6 ms. This will cause a distortion of the target of only 1.2 m in the direction along the beams. The accuracy of the contour drawings of the school projections on the playback monitor is about 0.2 cm which corresponds to about 1.0 m and 1.9 m at a sonar range of 150 m and 300 m respectively. Since the pulse length distortion is at the same level as this drawing accuracy, it is not corrected for in the area measurements.

Even if the SIMRAD SA 950 with its sector of narrow, 1.7° beams give rather detailed resolution of the recordings, there may still be substantial distortion due to the beamwidth. Traditionally it has been attempted to compensate for this distortion by subtracting a factor equal to tangens to half the beamwidth multiplied by the double range to the recording (Smith, 1970). This type of correction is applicable to the average of a number of repeated measurements of a target, but not to a single measurement.

The beam width dependent distortion of the school projection in a single measurement will be within the interval $[0, 2R(\tan(\varphi))]$ where R is the range to the target, and φ is the horizontal beam width (Misund, 1991). The area of a school at an outer (R_2) and inner (R_1) range will thereby decrease by a linear function that maximally has a slope (a_{max}) equal to $2(\tan(\varphi))$. Because schools may be dense and strong targets, the exact beamwidth at which schools are detected may be rather uncertain. Misund (1991) observed that the crosswise extent was about 1.5 the lengthwise extent of herring schools after a correction of a -3 dB beamwidth of the sonar. To obtain a one-to-one proportion, the crosswise recordings had to be corrected by a beamwidth extending 2-3^{o} beyond that of the -3 dB points.

Other factors than the beamwidth may also contribute to a reduction in the school area from the outer to the inner position. The school can pack denser or stack vertically so that there will be a real decrease in the school area. At the inner position the schools may also be only partly covered by the sonar beams.

To study the slope (a_{obs}) of the function that describes the decrease of the area (A_2) of a school at the outer position to the area (A_1) of the same school at the inner position, an expression was formulated as;

$$a_{obs} = (\sqrt{A_2} - \sqrt{A_1})/(R_2 - R_1)$$

As the distance decrease, the beamwidth dependent decrease of the school projection may be expressed by the proportionality;

$$\Delta A_2/\Delta r_2 = \Delta A_1/\Delta r_1$$

This proportionality expresses the decrease in the school area from an outer to an inner position, and to an origo position where there is no distortion of the projected school area due to the beam width. The factors in the proportionality is expressed by;

$$\Delta A_2 = A_2 - A_1$$
$$\Delta A_1 = A_1 - A_0$$
$$\Delta r_2 = (R_1 + R_2)/2$$
$$\Delta r_1 = R_1/2$$

When in the origo position, the school area (A_0) can thereby be calculated by;

$$A_0 = A_1 - \Delta A_1$$

BEST ESTIMATE OF EXACT SCHOOL AREA

If $A_2 > A_1$ the area of the school when imagined to be centered in the origo of the beam sector (A_0) was used as a best estimate of the exact school area in most cases. But because other factors than just the beam width may cause a range dependency of the sonar projection of the school area, we had to choose other criterias for a best estimate of the exact school area in some other cases outlined below.

The range dependent slope (a_{obs}) of the function that describe the range dependent decrease of the school area was in average 0.0647 (range -0.11 to 0.95). Even if the majority of the observations (about 65 %) gave slopes below 0.0593 which corresponds to a -3 dB beam width of 1.7^{o} , there were observations which could indicate school detection by the first side lobes at a beamwidth of 9.5 ^{o} (a=0.34). However, there was no correlation between the fish density of the schools and the range dependent slope ($r=-0.06$, $p>0.05$, $n=58$). On the other hand there was a significant correlation between the range dependent slope and the horizontal extent of the schools in the outer position (Fig. 1, $r=0.49$, $p<0.05$, $n=98$). This indicate that the observations of a large decrease in the school area from the outer to the inner position could have been caused by other factors than the beam width. Probably the schools with the largest range dependent slope have been only partially covered by the sonar beam in the inner position. This is supported by a significant, negative correlation between the range dependent slope and the adjusted school area (Fig. 2, $r=-0.23$, $p<0.05$, $n=98$) which means that there has been a substantial reduction in the school area from the outer to the inner position. In some occations, mostly for schools with a large range dependent slope, this has even caused that the adjusted school area (A_0) becomes negative. This was the case for about 10 % of the schools (10 out of 98 cases). In the following analysis we choose to use the A_I-area as a best estimate for schools having a range dependant slope of more than 0.16, which is the maximal slope for the whole beamwidth (4^o) of the main lobe out to the first minimum.

After beamwidth correction according to the principles outlined, the possibility still exists that the A_0-area may be 0 or even negative. In such cases, the A_I-area was used as an best estimate of the horizontal extent of the school.

It is possible that the projected school area at the inner position is larger than in the outer position. This can be due to an increase in the number of beams that cover the school area in the inner position compared to that of the outer position. It may also be due to a weaker echo strength of the school in the outer position so that only the densest parts of it is projected. Another possiblity is that an unfavourable sonar tilt angle may have caused only partial insonification of the school in the outer position. If the school area observed at the inner position is largest, the outlined equations for beamwidth correction will not be valid. In that case the uncorrected A_I may be used as a best estimate of the school area.

To evaluate the validity of the best estimate of the school area as calculated by the method outlined above, the school area was estimated by use of the lengthwise and crosswise measurements of the school projection. By assuming a circular school shape, a school area estimate was calculated by using the lengthwise extent as diameter. Another estimate was calculated by assuming an elliptic school shape and using the lengthwise and crosswise extent as axes. According to Misund (1991), the crosswise extent should be corrected for a beamwidth that give a range independent crosswise-to-lengthwise ratio. For the actual measurements, the last criterion is fullfilled even without any correction (Table 1), but correction for a beamwidth of 1.7^o reduce the cw/lw-ratio from 1.38 to 1.10. This correction cause a significant, negative correlation between the cw/lw-ratio and range, but the significance is no longer present if 3 observation at a greater distance than 300 m is omitted. We therefore use this beamwidth correction when calculating an elliptic school area in the subsequent analysis.

RESULTS

The shape of most of the 166 herring schools recorded by the sonar fits a specific geometric category (Fig. 3). About 69 % of the schools were rather compact (shaped as a circle, an oval or a square), about 23 % were more stretched (shaped as a rod or a parabol), and about 8 % had a rather amorph appearance. The school maintained approximately the same shape when approached by the vessel. This is reflected in significant correlation ($r=0.63$, $p<0.001$, $n=99$) between the cw/lw-ratio in the outer and inner position.

The planimeter measurements of the school projection gave more accurate estimates of the school area than obtained by measuring the lengthwise and crosswise extents and assuming a circular or an elliptic shape. This is indicated by a substantial variation and an average ratio between the circle and planimeter estimate of about 1.5 (Table 2). Similarly, the average ratio between the elliptic and planimeter estimate (about 1.15) is also above unity. A lower average and reduced variation in the ellipse-to-planimeter ratio compared to the circle-to-planimeter ratio shows that the assumption of an elliptic shape gives a more accurate estimate of the school area than when just assuming a circular shape.

Totally, 99 schools were measured in two positions when approached by the vessel. In the outer position (R_2) at about 180 m in front of the vessel in average, the unadjusted school area (A_2) averaged 468 m^2 (Table 2). In the inner position (R_1) at a distance of about 100 m in average, the unadjusted school area (A_1) had decreased to 342 m^2 in average. The best estimate of the exact school area (A_0) averaged about 370 m^2, but there was a considerable variation in horizontal extent from 2.5 m^2 up to 3244 m^2 (Table 2).

The fish density varied by a factor of about 100 among the schools. The density of 76 schools that were recorded by the echo sounder averaged 4.25 herring/m^3, but the density varied from 0.3 herring/m^3 to 22.2 herring/m^3. The large variation in fish density was the same wether the schools were recorded perfectly or just seem to be partly hit by the echo sounder beam (Fig. 4). There was also no significant difference (Wilcoxon test, $p>0.005$) in average fish density between the perfect (28 schools, average 4.35 herring/m^3) and partial recordings (46 schools, average 4.41 herring/m^3). There was no significant difference in average fish density among schools of different shape that were recorded both by the echo sounder and sonar, although the average density varied from about 3 herring/m^3 in the amorph schools up to 6.7 herring/m^3 in the rod-shaped schools (Table 3).

There were clear relationships between the area or volume and the biomass of the schools (Fig. 5). The elevation of the relationships differed according to the four fish density classes defined in Figure 5 so that the denser the schools, the greater the elevation for the dimension to biomass relationship. There was a variation by a factor of up to about 10 in the area-to-biomass relationships, but only by a factor of 2 in the volume-to-biomass relationships (Fig. 6).

The size of the schools averaged about 25 000 individuals, but varied from about 100 individuals up to about 420 000 individuals. There was a significant difference in the size of the schools of the different shapes (Table 3). The variation in average size ranged from just about 91000 individuals in the circle schools up to about 51000 individuals in the rod-shaped schools.

DISCUSSION

The capability of high resolution of the SIMRAD SA 950 sonar revealed that the shape of herring schools could vary from an undefined, amorph appearance to that of geometric structures as circle, oval, square, rod or parabol. To a certain extent, the intensity of the projections seem to reflect the fish density distibution within the schools. In cases with schools of rather low fish density, the intensity distribution of the sonar projection seem to reflect individuals or groups of individuals within the schools when observed at short range. In several cases, consistent empty areas within the schools were detected. Dense schools were displayed with a high intensity throughout the whole projection. In many cases single echoes could be observed in the vicinity of schools. This could be individuals on excursions from the main school or possibly following predators. The more accurate projection of the schools by this sonar is a considerable improvement to that of conventional, widebeamed, fisheries sonars which in most cases display schools as a weakly bended square with more or less constant intensity all over (Misund, 1991).

The shape of about 90 % of the schools fit a geometric category, and about 70 % were formed as compact units like circles, ovals or squares. This may reflect that herring organize schools with a certain geometric packing structure which also influence the external shape. Probably, the shape of the schools is also determined by functional aspects. Circlular or disc shaped schools may have been formed to reduce the visual image of the school and thereby the chance of beeing detected by predators (Cushing and Harden Jones, 1968; Pitcher and Partridge, 1979). Parabol shaped schools may indicate a combined feeding/migration behaviour (Partridge et al., 1983).

The planimeter method gave a more accurate estimate of the school projection than calculations based on measurements of the crosswise and lengthwise extent. Calculating the area by using the lengthwise extent as diameter gave an overestimate by a factor of about 1.6. Similarly, by analysis of airplane photos of images of anchoyv schools, Squire (1978) estimated that school size estimation by sonar based on the assumption of a circular shape would overestimate the school area by a factor of 1.7. By taking account of both the lengthwise and crosswise extent, correcting for the horizontal beamwidth, calculation of an elliptic area reduced the overestimate to a factor of about 1.15 only in average.

The described method to obtain an estimate of the school area that is adjusted for the distortion by the beam width is developed for the special case of two succeeding measurements of a school at an outer and inner position. In cases where there exists several area measurements of a school at different ranges from the vessel, an adjusted school area estimate (A_0) may be obtained by simple regression analysis. However, as illustrated by the analysis above, it may be nesessary to identify a range window in which the beamwidth is the only factor that influence the size of the school projection, and restrict the regression analysis to this window.

The fish density within the schools varied from about 0.3 herring/m^3 up to about 22 herring/m^3, and averaged about 4.3 herring/m^3. Similar variation, and about the same average density have been measured for schools of herring of about the same length in other areas in the North Sea (Misund 1993). In earlier investigations there has been a great uncertainty connected to fish density measurements of schools because it has been difficult to monitor how accurately the school is hit by the echo sounder beam when overpassed by the vessel. We could now record the position of the school relative to the echo sounder beam during this critical stage by tilting the SA 950 sonar so that the school was continously monitored as the vessel approached and passed over. However, there was no difference in the variation and average density between the schools that were perfectly recorded and those who were only partially hit by the echo sounder beam. The possibility to classify the accuracy of the echo sounder recording of the schools has two important implications. First, the large variation in fish density among the schools that were perfectly recorded is probably real. Secondly, the measured fish densities in the schools that were only partially hit by the echo sounder beam was an underestimate because it is averaged over the whole equivalent beam angle. With the method applied, it is not possible to correct the underestimation of fish density in the partial school recordings.

There were clear relationships between the geometric dimensions (area and volume) and the biomass of the schools as demonstrated for North Sea herring earlier (Misund et al., 1992). The fish density has a major influence on the relationships, and classifying the schools in four density categories gave four dimension to biomass relationships that differed in elevation. For the area-to-biomass relationships, there was a variation by a factor of up to about 10, while the variation in the volume-to-biomass relationsips followed a factor of about 2 only. This shows that if it is possible to classify the schools according to density, it is possible to enhance the accuracy of school dimension to school biomass conversion substantially.

ACKNOWLEDGEMENTS

We thank J. Dalen for constructive critisism to the manuscript.

REFERENCES

Cushing, D. H. and Harden Jones, F. R. 1968. Why do fish school? Nature, London, 218, 918-920.

Bodholdt, H. 1982. A multi-beam sonar for fish school observation. ICES/FAO Symposium on Fisheries Acoustics, Bergen, Norway; 21-24 June 1982, Doc. no. 55.

Bodholdt, H. and Olsen, K. 1977. Computergenerated display of an underwater situation: Applications in fish behaviour studies. Rapp.P.-v.Reun.Cons.int.Explor.Mer, 170: 31-35.

Bodholdt, H., Nes, H. and Solli, H. 1988. A new echo sounder system for fish abundance estimation and fishery research. ICES C.M. 1988/B:11, pp. 1-6. [mimeo]

Foote, K. G. 1983. Linearities of fisheries acoustics, with addition theorems. J. Acoust.Soc. Am., 73, 1932-1940.

Foote, K. G. 1987. Fish target strengths for use in echo integrator surveys. J.Acoust.Soc.Am., 82(3), 981-987.

Foote, K. G., Knudsen, H. P., Vestnes, G., MacLennan, D. N. and Simmonds, E. J. 1987. Calibration of acoustic instruments for fish density estimation: a practical guide. ICES Coop. Res. Rep. No. 144.

Knudsen, H. P. 1990. The Bergen Echo Integrator: an introduction. J.Cons.int.Explor.Mer, 47, 167-174.

Misund, O. A. 1991. Swimming behaviour of schools related to fish capture and acoustic abundance estimation. Dr. Philos.-thesis, University of Bergen, 132 pp. (Unpublished)

Misund, O. A. 1993. Dynamics of moving masses: variability in packing density, shape, and size among herring, sprat, and saithe schools. ICES J.mar.Sci., 50: 00-00.

Misund, O. A., Aglen, A., Beltestad., A. K., and Dalen, J. 1992. Relationship between the geometric dimensions and biomass of schools. ICES J.mar.Sci., 49: 305-315.

Partridge, B. L., Pitcher, T. J., Cullen, J. M. and Wilson, I. 1980. The three-dimensional structure of fish schools. Behav.Ecol.Sociobiol., 6(4), 277-288.

Pitcher, T. J., and Partridge, B. L. 1979. Fish school density and volume. Mar.Biol., 54(4), 383-394.

Smith, P. E. 1970. The horizontal dimensions and abundance of fish schools in the upper mixed layer as measured by sonar. In: Proceedings of an International Symposium on Biological Sound Scattering in the Ocean, (Ed. by G.B. Farquhar), pp. 563-591. Washington D.C.: Department of the Navy.

Squire, J. L. 1978. Northern anchovy school shapes as related to problems in school size estimation. Fish.Bull.U.S., 76. 443-448.

Totland, B. and Misund, O. A. 1993. Computerbased detection of schools for counting and quantification of size and swimming behaviour by a high resolution, multibeam sonar. ICES C.M. 1993/B:

Table 1. Effect of beamwidth (φ) correction on CW/LW-ratio, and correction of CW/LW-ratio to range. Numbers in brackets refer to correlation of CW/LW when range is < 300 m.

φ	CW/LW	CW/LW correlated to R		N
		ρ	p	
-	1.38	-0.02	0.69	265
1.7°	1.10	-0.14 (-0.10)	0.02 (0.09)	265 (262)
4.0°	0.72	- 0.31	< 0.01	265

Table 2. School area by different methods of estimation at the outer (R_2) and inner (R_1) position.

	R_2 (m)	A_2 (m^2)	$Circle_2$ (m^2)	$Ellipse_2$ (m^2)	R_1 (m)	A_1 (m^2)	$Circle_1$ (m^2)	$Ellipse_1$ (m^2)	A_0 (m^2)
Mean	182	468	731	561	104	342	535	393	370
SD	54	531	1590	816	36	461	1115	562	570
MIN	87	36	12	14	31	11	9	11	2
MAX	429	3205	11467	4737	259	3244	8372	4075	3244
N	100	100	99	100	100	99	97	97	99

Table 3. Mean and standard deviation (SD) of estimated fish density and school size. n: number of fish, N: number of schools.

	Fish density (n/m^3)		School size (n)		N
	Mean	SD	Mean	SD	
Amorph	2.94	2.68	18100	26200	5
Circle	3.61	5.56	9100	21000	14
Oval	3.91	2.59	33200	111800	15
Parabol	4.06	3.27	32100	55900	11
Rod	6.68	5.36	51000	64300	7
Square	3.17	3.49	8500	10900	7
p (Kruskal-Wallis test)	> 0.05		< 0.05		

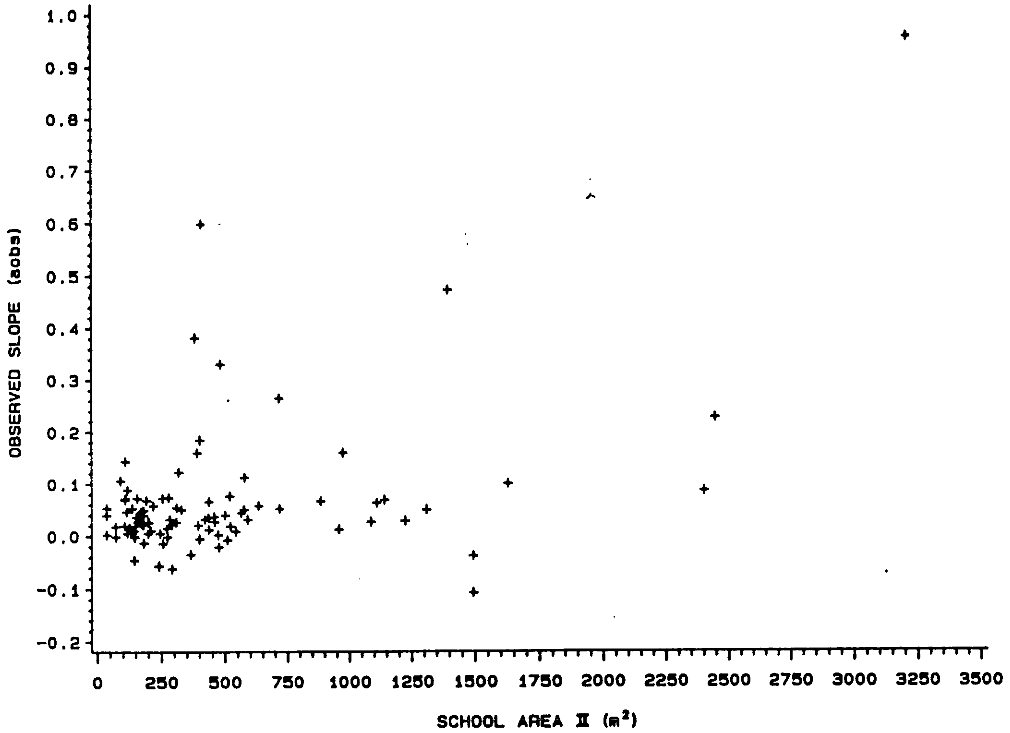

Figure 1. Scatter plot of observed slope (a_{obs}) related to area measurement (A_2) of the schools in the outer position.

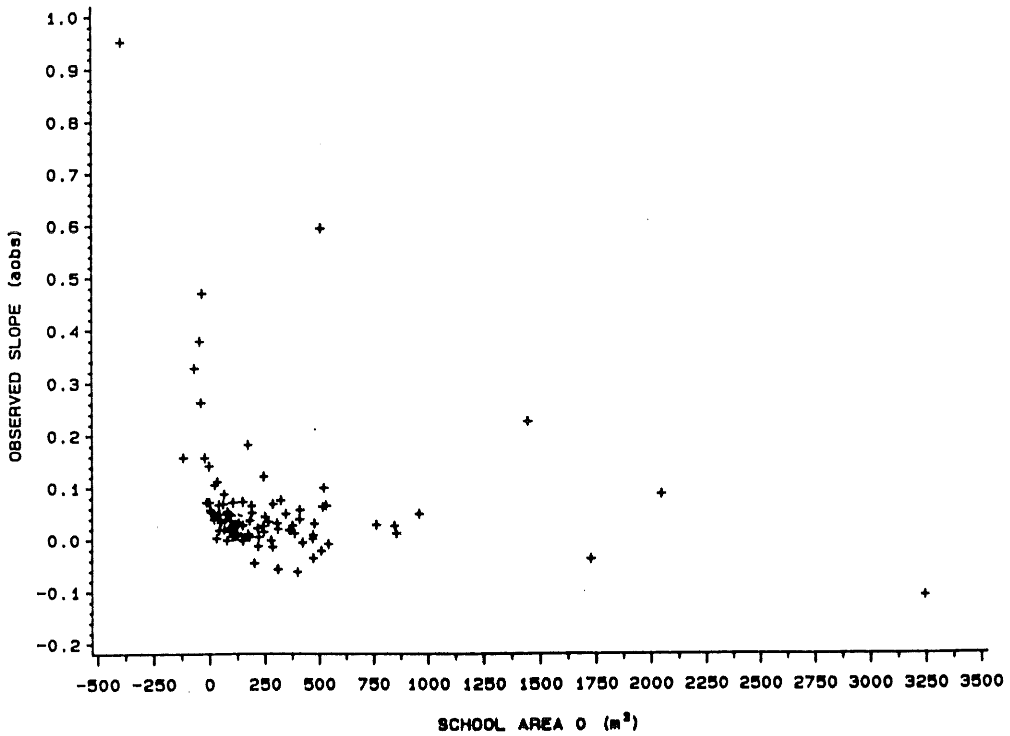

Figure 2. Scatter plot of observed slope (a_{obs}) related to the adjusted school area (A_0).

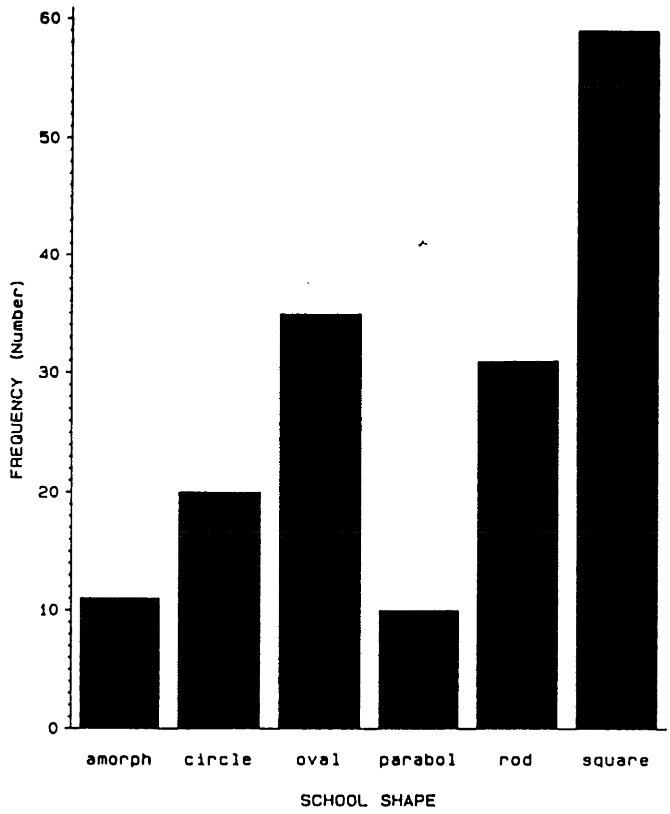

Figure 3. Distribution of observed school shapes.

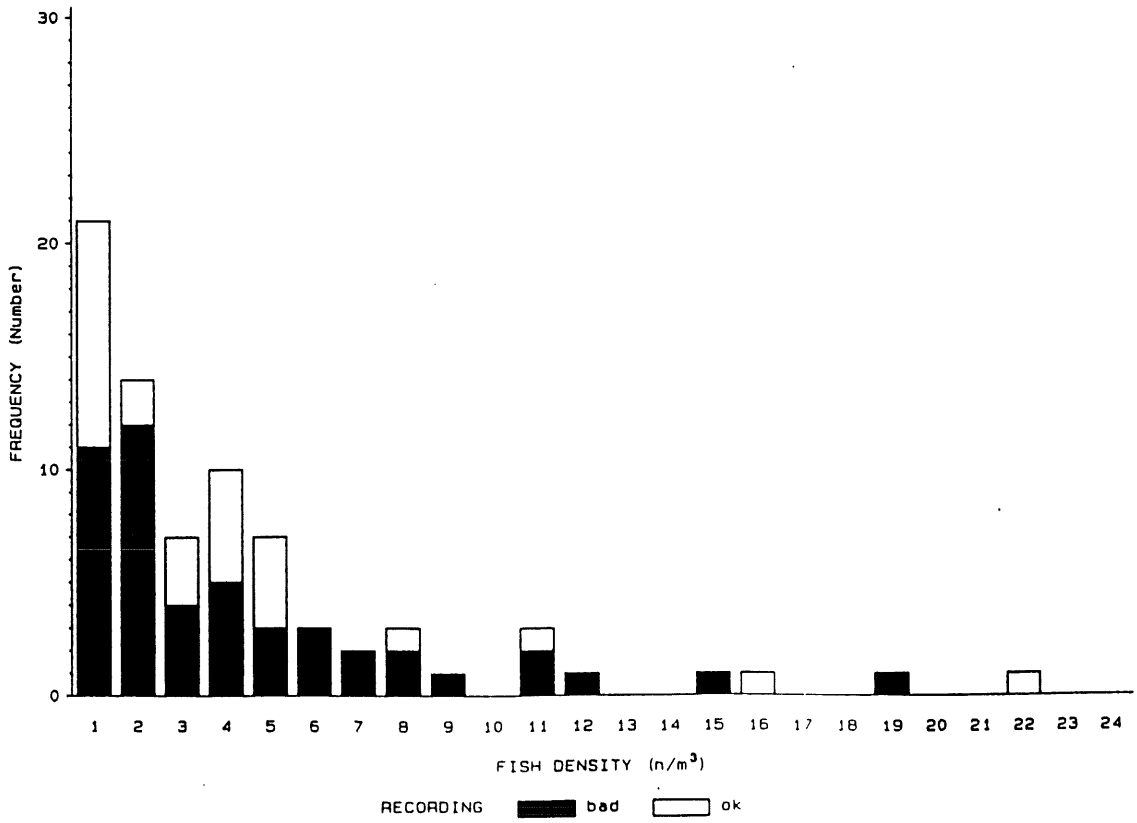

Figure 4. Distribution of fish density in schools recorded by the echo sounder.

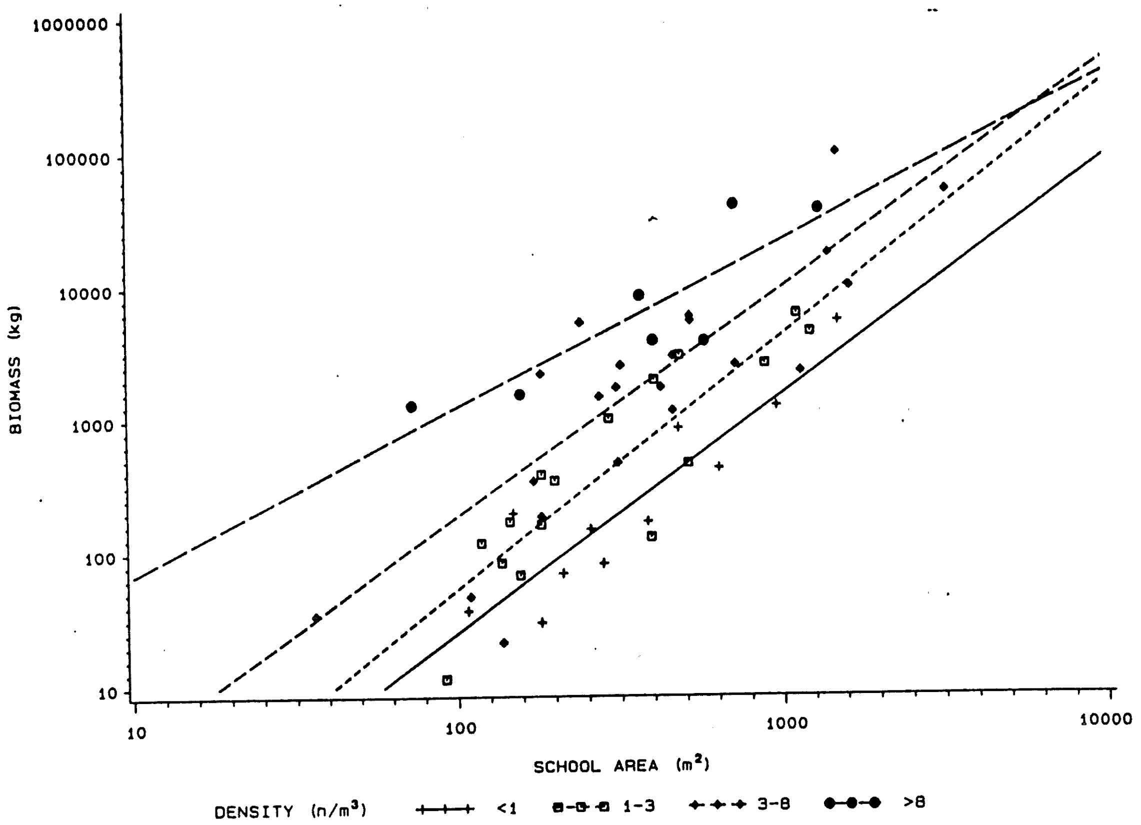

Figure 5. Relationships between school area and school biomass.

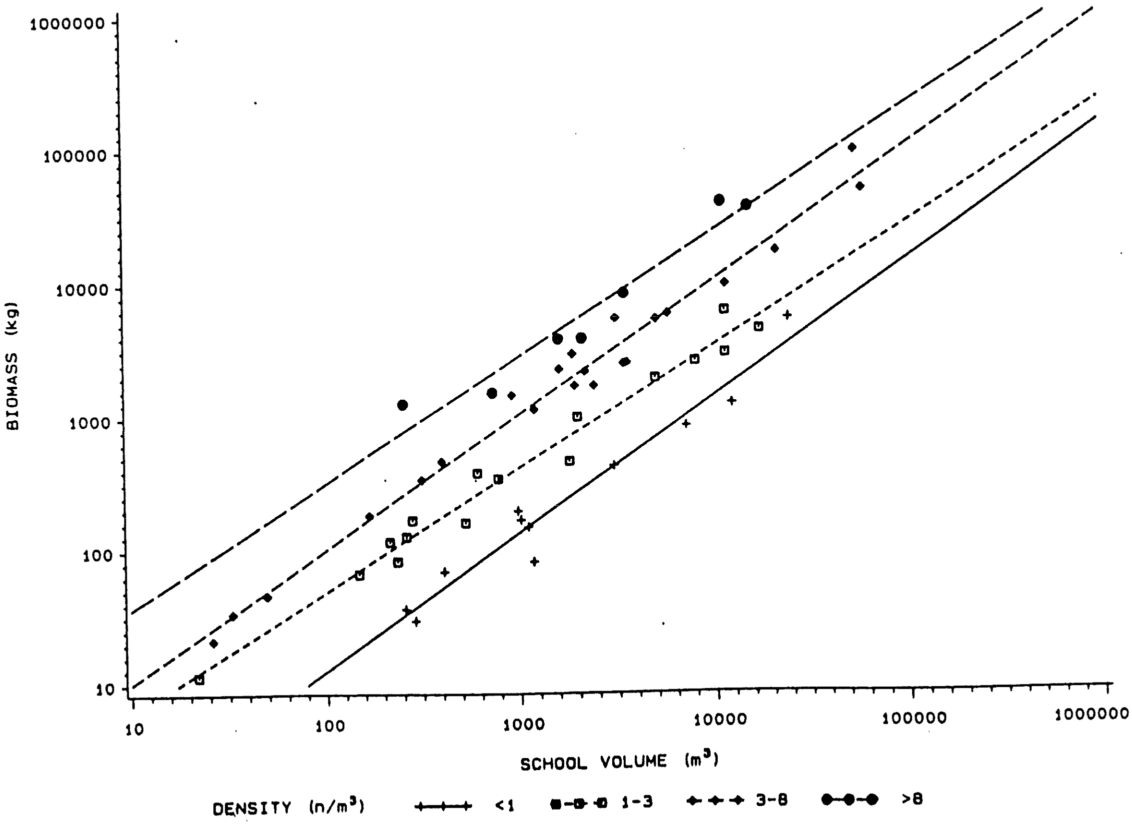

Figure 6. Relationships between school volume and school biomass.