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Daily migration cycles of fish populations in a tropical estuary (Sine-Saloum, Senegal) using a horizontal-directed split-beam transducer and multibeam sonar

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Abstract

The tropical Sine-Saloum estuary (Senegal) is an ecologically important area for fish population dynamics. Daily cycles of fish movements in a tidal channel were observed using both split-beam and multibeam sonar. A trap-net was set and lifted regularly and simultaneously with the acquisition of acoustic data. The relationship between the two sets of data was satisfactory when acoustic records for single targets were separated from those containing fish schools. The heterogeneity of fish spatial and temporal distributions is examined, as well as the rapidity of changes of fish population density in an environment subject to tides. The consequence of this on sampling strategies is discussed. © 1998 Elsevier Science B.V.

Keywords: Estuary; Split-beam; Multibeam; Senegal; Shallow waters

1. Introduction

This study carried out in the Sine-Saloum estuary (Senegal) was part of a research programme looking at the use of acoustic methods in shallow waters. The first part of the study was carried out in the coastal zone of Senegal (Guillard and Lebourges, 1996). The second part was carried out in an estuary, where the environmental conditions are better, for this kind of approach, than in the sea.

Many research programmes have been carried out in the Sine-Saloum estuary in order to understand estuarine and lagoon environments, and how they function ecologically and economically (Diouf, 1996). Estuaries are an interface between continental and marine environments and often have very high levels of production. They are important places for the development, growth and reproduction of many marine fish species (Odum and Heald, 1975). The rich and diverse Sine-Saloum estuary is inhabited by various categories of estuarine, marine and freshwater fish (Albaret and Diouf, 1994) and provides most of the animal protein for the local populations. In the estuary, fish catches have fluctuated between 48 582 t in 1978 (Bousso, 1991), to the present stable yield of 10 000 t/yr (Diouf et al., 1991). Over 111 species have been catalogued for this estuarine system (Diouf, 1996). The Bandiala estuarine branch is richest in fish species because of its proximity to the sea, its diversity of habitat, stable salinity (rarely > 40 mg. l^{-1}) and its relatively calm waters. Its fish fauna is dominated in number and weight by three clupeid

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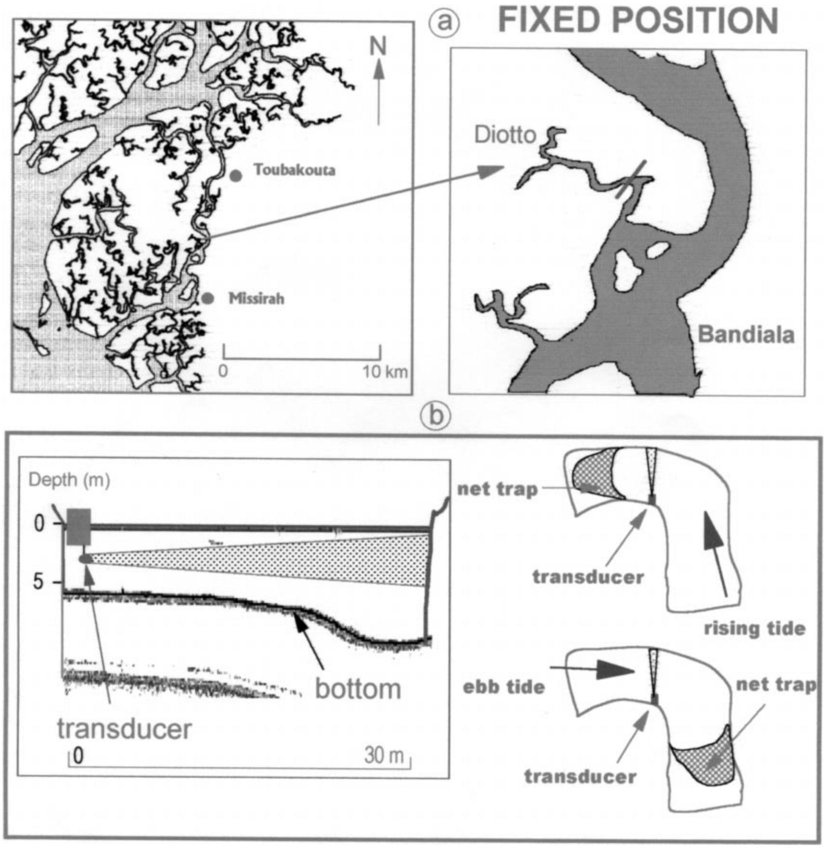

Fig. 1. (a) Map of the Sine-Saloum estuary (partial) and the Bandiala branch showing the geographical position of the sampling site. (b) The cross-section of the Diotto bolon shows the fixed position of the transducer with its horizontal sound beam and the position of the net-trap during a rising and ebbing tide.

species *Sardinella maderensis*, *Ethmalosa fimbriata*, and *Ilishia africana* (Diouf, 1996).

The Sine-Saloum estuary complex (Fig. 1a) is made up of three main and many subsidiary branches called «bolons». These tidal channels surround islands over a total surface area of more than 800 km^2. The downstream part of the estuarine complex is colonised by extensive mangrove that declines upstream. Unusually, the average duration of the rising tide (7 h) is longer than that of the ebb tide (5.5 h); this results from penetration of coastal waters due to shallow estuarine slopes and a combination of low freshwater flows and very high evaporation levels. There also exists a salinity gradient along the estuarine complex (Diouf, 1996).

Earlier studies had shown the need for sampling to be concentrated in a small spatial area for short time periods if the distribution in time and space of fish populations was to be understood (Guillard, 1994). The structure and size of the Diotto bolon within Bandiala (Fig. 1a) appeared to be suitable for this sampling strategy. According to Diouf (1996), the Diotto bolon was situated in an intermediate ecological zone with homogeneous spatial units which were also functional units (e.g., the zone directly influenced by the sea, one of the three main branches, the so-called central zone whose characteristics were the same as those of the closed waters in the upper part of the bolon). The tidal channel was rich in fish, was shallow but had deep holes. There was an abundant mangrove presence on both banks.

The main aim was to assess the feasibility of simultaneous acoustic and fish sampling at the same site in order to determine the spatial distribution of fish in a small branch of the sea, as well as the dynamics of fish movements over a tidal cycle of 24 h. Using a fixed point for acoustic sampling avoided the problem of fish escaping from a moving boat and might provide information about fish migration in rivers and estuaries (Bénech and Le Hong Chuong, 1993; Steig and Johnston, 1996; Thorne, 1998).

2. Methods and material

2.1. Site

The Diotto bolon was chosen and its position is set as shown in Fig. 1a. At each run, environmental parameters were recorded (hour, season, direction and strength of the tide, Secchi Disk).

2.2. Acoustic equipment

For a description of how acoustic sampling of fish works, the reader is referred to MacLennan and Simmonds (1992). Two kinds of acoustic sonar was applied in the present study.

The SIMRAD EY-500 split-beam echosounder was used at a fixed location with its sound beam emitting horizontally across the Diotto bolon (Fig. 1b) from the circular transducer, 2 m below the surface, 120 kHz frequency, with a total beam angle of 9.1° at −3 dB, emitted pulse lengths of 0.1 and 0.3 ms. The ping rate was set at 6 pings per second in order to gain maximal information about the targets. An IBM-PC compatible computer controlled the echosounder, and data were stored in an external hard disk. The amplification function (TVG) was set at (20 log R) and (40 log R).

Calibrations were carried out both in an experimental basin (IFREMER, Brest France), and during each series of acoustic runs, using a copper calibration sphere and the standard protocol as recommended by Foote et al. (1987). Acoustic data were analysed by means of the analysis programmes SIMRAD EP-500 and by visual counting on the echograms. Parameters for discrimination of single fish targets were set with a threshold fixed at −50 dB, using the tracking menu of the EP-500. For the acoustic biomass calculations (Area back-scattering coefficient, S_a) using 20 log R, the detection threshold was fixed at −55 dB. This was accompanied by a visual counting on the echogram of the number of individual targets, and shoals. The shoals were classified according to their size on the echogram: small, medium, or large, and allocated an arbitrary index on a scale between 1 and 10. During analysis, acoustic runs with or without shoals were treated separately. Noise level varied between −60 to −30 dB.

The second instrument was a multibeam Reson Seabat 6012 sonar system (Soria et al., 1996) which was used in combination with the above system during the preliminary series of runs. This had a frequency of 455 kHz, a pulse length of 0.06 ms and was made up of 60 transducers, each with a beam angle of 1.5° at −3 dB, thus covering a volume of 90° vertically and 15° horizontally (Fig. 2a). The TVG was set at 20 log R, the gain adjusted to 50 m, and the image generated was the resultant of smoothing 3 or 4 emissions–receptions. The sonar was connected to a video screen (Fig. 2b) and a recorder which stored signals as video images in two dimensions. The sonar head of transducers was placed at 2 m below the water surface in such a way as to record in the vertical plane of 90°. This sonar system, therefore, samples the water volume «extensively». No calibration procedure for this system was available at the time of the runs.

Analysis of signals from the multibeam sonar was carried out by playing the video tapes and by visual observation of echoes on the screen. Only echoes from shoals were analysed. The distance from the transducer and the depth and length of each shoal on the screen are measured. A density index was allocated by the operator, to each shoal determined, using a scale from 1 to 50 arbitrary units as a function of detected shoal size.

2.3. Combined acoustic and fish sampling

During a 24-h cycle, both the split-beam and multibeam sonar, fixed at each side of a boat, emitted continuously in a horizontal orientation for periods of 2.5–3 h. At the same time, a purse-seine (250 m long, 20 m height with a mesh size of 14 mm) was set as a net-trap to block the bolon (Fig. 1b) and was lifted after 3 h. Fish caught were identified, sorted, measured (as fork length) and counted, during which time sonar emissions were stopped to avoid record-

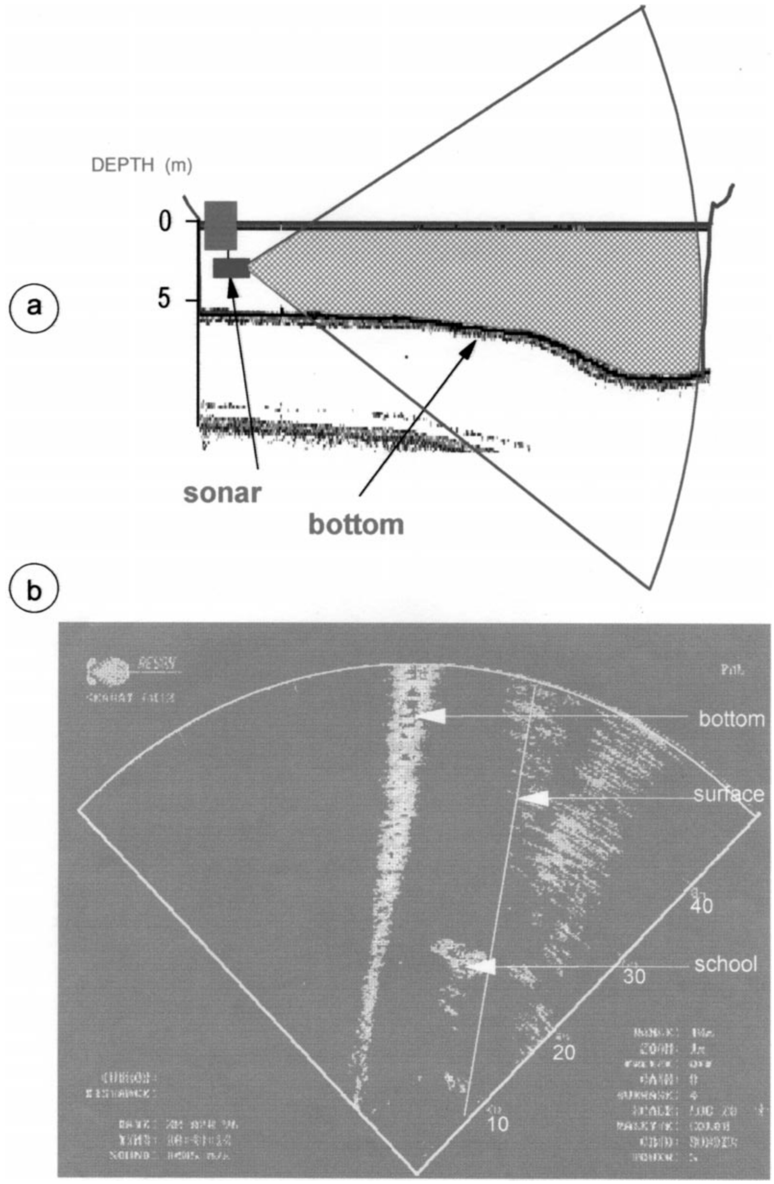

Fig. 2. Diagram of the zone sampled by the Reson multibeam sonar in vertical plane (a) and its image projected on the video screen (b).

ing perturbations due to boat movement and trap lifting (Kubecka et al., 1992). The trap was set again for another 2.5–3 h and acoustic sampling re-started. In this way, two sets of samples were achieved for each tidal cycle. The periods of slack tide were not sampled. Datasets were reduced to 1 h duration in July due to technical problems.

When working in the tropics, problems arise resulting in loss or deliberate elimination of acoustic or fish capture data. High temperatures and high humidities can cause computer failure for as long as 20–30 min, thus preventing continuous acoustic data recording. As recorded earlier (Guillard, 1994), the speed of pelagic fish movement is such that the two techniques cannot be compared. There were times when the seine was not completely closed, so that fish escaped, and fish capture was underestimated. Such incomplete samples were not included in the comparative analysis for which only 78% or 22 out of 28 field sampling data was available.

3. Results

3.1. Species and number of fish captured

Only a few species dominated the catch in the Bandiala (Table 1, Fig. 3a), as also reported by Diouf (1996). The three main species caught were pelagic clupeids (*Ethmalosa fimbriata*, *Ilischia africana*, and *Sardinella maderensis*) together with a variety of fish species, shrimps, crabs, and various floating objects such as drift wood and leaves. The number of fish caught varied greatly on different dates and time in 24 h (Fig. 3b). For the main species captured, their size structures were generally monomodal and characteristic of juveniles. For example, the bonga shad (*E. fimbriata*) caught belong to the same size class at a given date, and were always juveniles (Table 2).

3.2. Acoustic results

Each time the fish trap was set and operated for 2.5–3 h, the split-beam sounder was emitting horizontally and perpendicularly across the bolon. Several kinds of echograms appeared which represented different situations (Fig. 4). In Fig. 4D, numerous

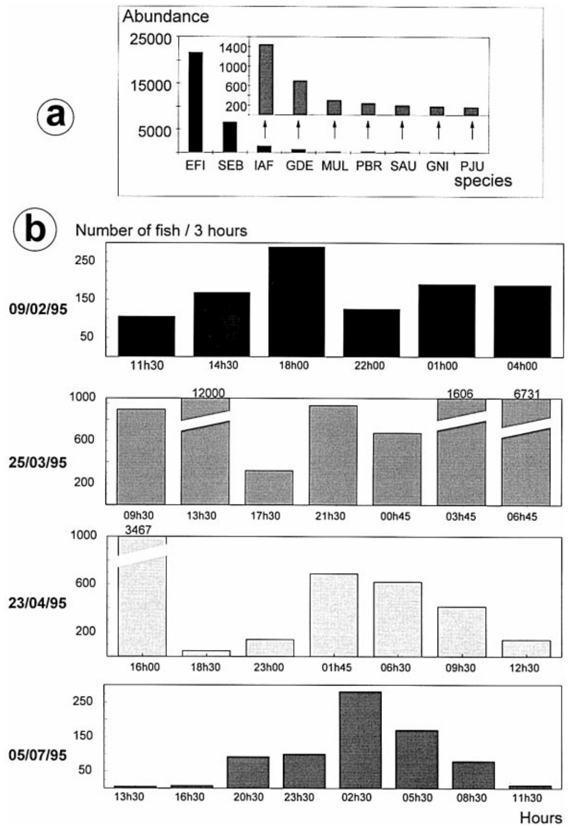

Fig. 3. (a) Relative numbers of the main fish species captured by the net-trap in the Diotto bolon (see Table 1 for key to species names). (b) Total number of fish per 3-h exposure captured throughout 24 h on four sampling dates.

targets were detected during the same cycle. The acoustic data for runs like this were eliminated from the dataset because the environmental noise level was more than −30 dB and masked fish passages. Such echograms may be caused by concentrations of

Table 1
Main species of fish captured by the net-trap in the Diotto bolon

Family	Species	Codes
Clupeidae	*Ethmalosa fimbriata*	EFI
	Ilischia africana	IAF
	Sardinella aurita	SAU
	Sardinella maderensis	SEB
Polynemidae	*Galeiodus decadactylus*	GDE
Gerreidae	*Gerres nigri*	GNI
Mugilidae	*Mugil* spp. and *Liza* spp.	MUG
Haemulidae	*Pomadasys jubelini*	PJU
Sciaenidae	*Pseudotolithus brachygnathus*	PBR

Table 2
The average fork length size of the bonga shad (*E. fimbriata*) captured by the net-trap in the Diotto bolon

Date of capture	Average size (cm)	Standard deviation
09/02/95	13.20	1.50
25/03/95	9.41	0.89
23/04/95	11.54	1.13
07/07/95	8.22	0.92

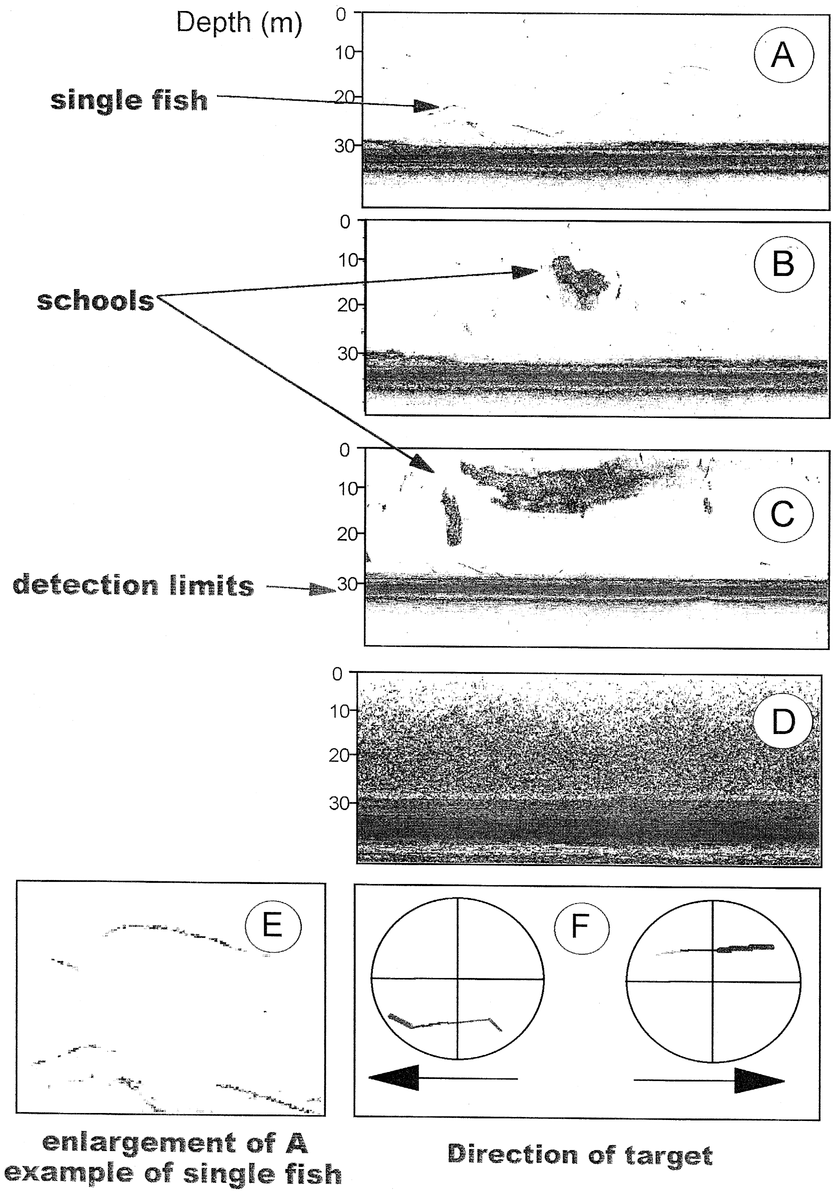

Fig. 4. Examples of echograms from the split-beam echosounder, showing (A) single fish; (B) small shoal of fish; C: larger shoals of fish; (D) environmental noise; (E) an enlargement of (A); (F) direction of fish movement by EP-500 tracking techniques.

zooplankton, fish larvae and suspended particles detected at 120 kHz frequency. Similar observations have already been recorded in the estuary (Levenez and Albaret, 1992).

Use of split-beam sonar enabled the direction of movement to be determined in fish hit by 3–4 pings (Fig. 4F). When working with relatively short ranges and with a narrow beam, the direction of movement could be detected in only about 30% of the targets. This was not possible for schools. Nevertheless, tracking showed that less than 10% of single targets moved against the current.

3.3. Comparison of acoustic and fish capture data per 3-h samplings

When fish capture data (by number and by weight per 3-h sample) were compared with the area backscattering coefficient per 3 h of all detected targets, there was no significant correlation. Therefore, captured fish were compared with data collected from counting in the 3-h-long echograms.

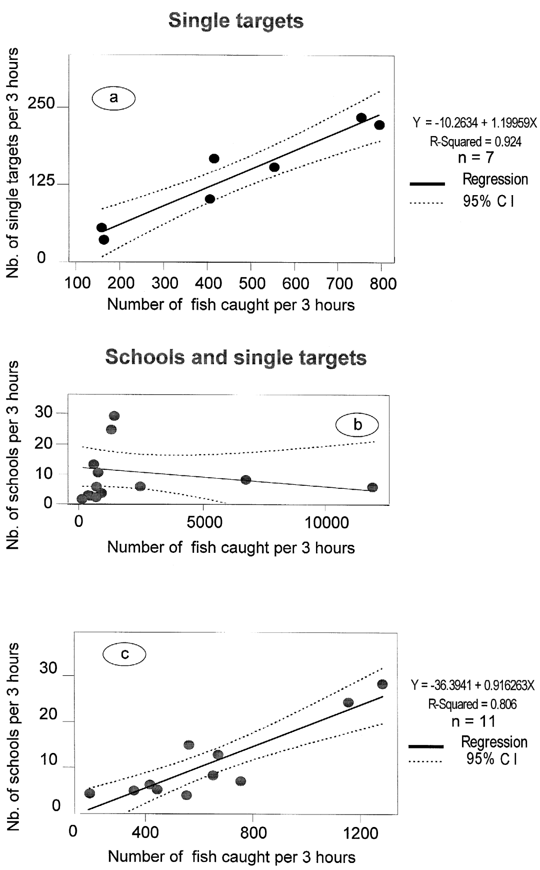

Fig. 5. Relationship between fish detected acoustically and fish captured in the Diotto bolon. (a) Significant regression of number of single fish targets on number of fish captured by net ($n=7$); (b) Relationship between number of fish schools and number of fish captured, using all the datasets ($n=12$); (c) Significant regression of number of schools and number of fish captured resulting from removal of 3 data points in (b).

A comparison between number of fish caught per 3 h and the number of single fish targets counted on the 3-h-long echogram was possible in 8 samples (36% of the total). As one of the eight points differed significantly from the rest, it was omitted from the analysis and a significant correlation was obtained with the remaining seven points (Fig. 5a). The rejected data point corresponded to a very large catch of bonga shad with 1250 fish.

A comparison between number of fish captured per 3 h and number of counted shoals on the 3-h-long echogram was based upon those echograms containing both shoals and single fish targets. When all the 12 samples were plotted (Fig. 5b), a non-significant negative relationship was obtained between fish caught per 3 h and the detected number of fish shoals per 3 h. In Fig. 5b, three points caused this negative relationship and, without these, the relationship became positive and significant (Fig. 5c). These three data points correspond to large catches of bonga shad (6440 and 12200 fish/3 h) and sardinella (*S. maderensis*) once (3440 fish/3 h).

3.4. Fish distribution in time and space

Counting per 3-h split-beam echogram permitted counts of single targets and shoals in time sequences of 7 min. Fig. 6 shows how fish and shoal number per 7 min varied through 24 h but reveals no clear pattern with time of day and tides.

3.5. Comparison of split-beam and multibeam acoustic data

A comparison of the split-beam data (shoals counted on echograms) and the multibeam data (shoals counted on video screen) was possible, despite the difference in sampled volumes and in sonar frequencies. A positive linear correlation was obtained:

$$X = 1.30 + 0.47Y$$

$$(R = 0.659, \text{ with a risk of 5\%},$$

$$n = 25, \text{ February 1995}),$$

where X is the number of shoals detected by the

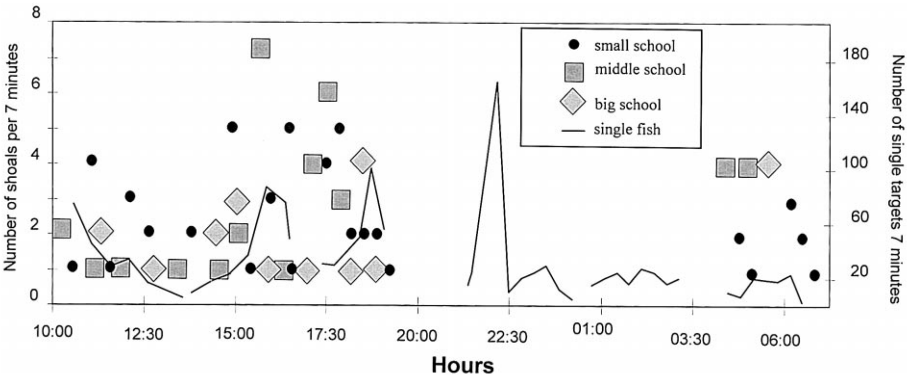

Fig. 6. Number of fish schools (left abscissa) and single fish targets (right abscissa) detected acoustically in the Diotto bolon at different times within 24 h on February 9, 1995.

split-beam system and Y the number of shoals detected by the multibeam sonar.

4. Discussion

Because of the very few number of data points, no significant relationship between fishing data and environmental data was obtained. Nevertheless, certain generalisations can be made: (1) there is a strong heterogeneity between fishing operations; (2) fewer fish were caught on the ebb tide, than on the rising tide; (3) fewer fish were caught during the hot season than during the cold one; (4) *Sardinella* were mostly captured at night and bonga shad were mainly caught on high tides and towards the end of the cold season; (5) the average size of fish caught was small and were juvenile fish, thus conserving the ecological functions of the estuary (Diouf, 1996).

As Diouf (1996) also found, captures of the main species are independent of the hour at which the net is set. However, when the quantity of fish caught by species or as a total is considered, our results do not confirm this suggestion but neither do they contradict it.

Although 20 log R data was recorded, echo integration analysis was not possible due to the high quantities of suspended particles in the bolon (with Secchi Disk depths of 0.5 and 1 m), the speed of fish movement across the sonar beam, and integration of high bottom/surface noise levels into the acoustic data. Targets counting on the echograms overcame some of these limitations.

Despite the special problems associated with acoustic work in the tropics, significant relationships were obtained between the number of single targets counted, the number of shoals detected and the number of fish captured. All the removed data points were associated with large catches of small pelagic fish species; that is when a large shoal was captured, but not recorded acoustically for various reason: (1) the shoal was captured while the echosounder was not operating; (2) the echosounder was inactivated (to avoid boat noise) during the 10–15 min period while the seine-net was being lifted and a shoal may have passed; (3) a shoal may have passed too near the transducer to be detected or too near the opposite bank. Two or more split-beam transducers might cover a greater volume of water or a properly calibrated multibeam sonar might solve some problems, since it can sample the whole water section. The weak correlation between the split-beam and multibeam data may also be associated with some of these sampling problems. The multibeam sonar seems well-adapted for acoustic work in shallow waters as shown by Gerlotto, Hernandez and Linares and by Gonzales and Gerlotto in this volume.

5. Conclusion

The use of acoustic techniques in this environment has produced some information about the quickly changing fish populations in time and space. Echosounders are capable of generating large datasets. These can be analysed in relation to variable environmental parameters. This is particularly valuable for environments as variable as estuaries and for studies on the movements of clupeid fish, which require a sampling regime with short time scales. In estuaries, the influence of the tidal cycle upon fish movement requires a well-planned sampling strategy, as well as knowledge of the physiology and behaviour of the fish species.

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