The use of GIS for a quantitative description of essential fish habitats in the Bay of Biscay (France)

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Abstract: Coastal zone systems are highly productive areas that serve as nursery grounds for many marine species of commercial importance. However, habitat destruction is the most harmful means of slowing or preventing fish stock recoveries. In this context, the purpose of the present study is to identify and describe the coastal nursery grounds for the common sole, one of the most important species for the fisheries, in the Bay of Biscay. The relation between the physical properties of the coastal zone (bathymetry, sedimentology, river plume) and juvenile sole density was described with mathematical models for young-of-the-year sole. Hence, these model results were introduced in a Geographic Information System (GIS) to identify and describe quantitatively key sites for the early life stages of sole. The respective influence of the different habitats is studied and the important role played by coastal areas under freshwater influence is pointed out. This GIS will be an important tool for coastal management.

Key words: Coastal management, GIS, mathematical models, essential fish habitats

Utilisation des SIG pour la description quantitative des habitats préférentiels dans la baie de Biscay en France

Résumé *: De nombreuses espèces de poissons passent leurs premières années sur des nourriceries côtières et estuariennes. Ces écosystèmes sont essentiels pour la croissance des juvéniles et leur dégradation peut affecter la taille des populations. Dans ce contexte, ce projet s'intéresse à l'identification des nourriceries de sole du golfe de Gascogne. La relation entre la répartition spatiale des juvéniles de sole et des descripteurs physiques du milieu (bathymétrie, couverture sédimentaire, panaches fluviaux) a pu être modélisée. Disposant d'une connaissance exhaustive de ces paramètres physiques, il est possible d'introduire les résultats de modèle dans un SIG afin d'obtenir une cartographie quantitative de ces habitats. Ce travail a démontré que ces nourriceries sont localisées dans une frange très côtière du plateau continental, dans des zones influencées par les apports d'eau douce ; il sera un élément important d'aide à la décision pour les responsables de l'aménagement du littoral.*

Mots clés *: Aménagement côtier, SIG, modèles mathématiques, habitats marins essentiels*

Introduction

Coastal zone systems are highly productive areas that serve as nursery grounds for many marine species of commercial importance (Costanza et *al.*, 1997). However, habitat destruction is the most harmful means of slowing or preventing stock recoveries (Hall, 1998). Constant demands on the coastal zone from a wide range of human activities suggest that the continued function of natural communities may be threatened in some areas. Thus, the identification of these essential fish habitats is important for coastal management.

The inshore waters of the Bay of Biscay (ICES Division VIIIa/b; *Fig. 1*) support nursery areas for several commercially important species, especially the common sole (*Solea solea*, L.). The purpose of the present study was to identify and describe in quantitative terms the coastal nursery grounds for these species, using physical parameters known to influence the spatial distribution of juvenile sole (Gibson, 1997): bathymetry, sediment structure and estuarine influence.

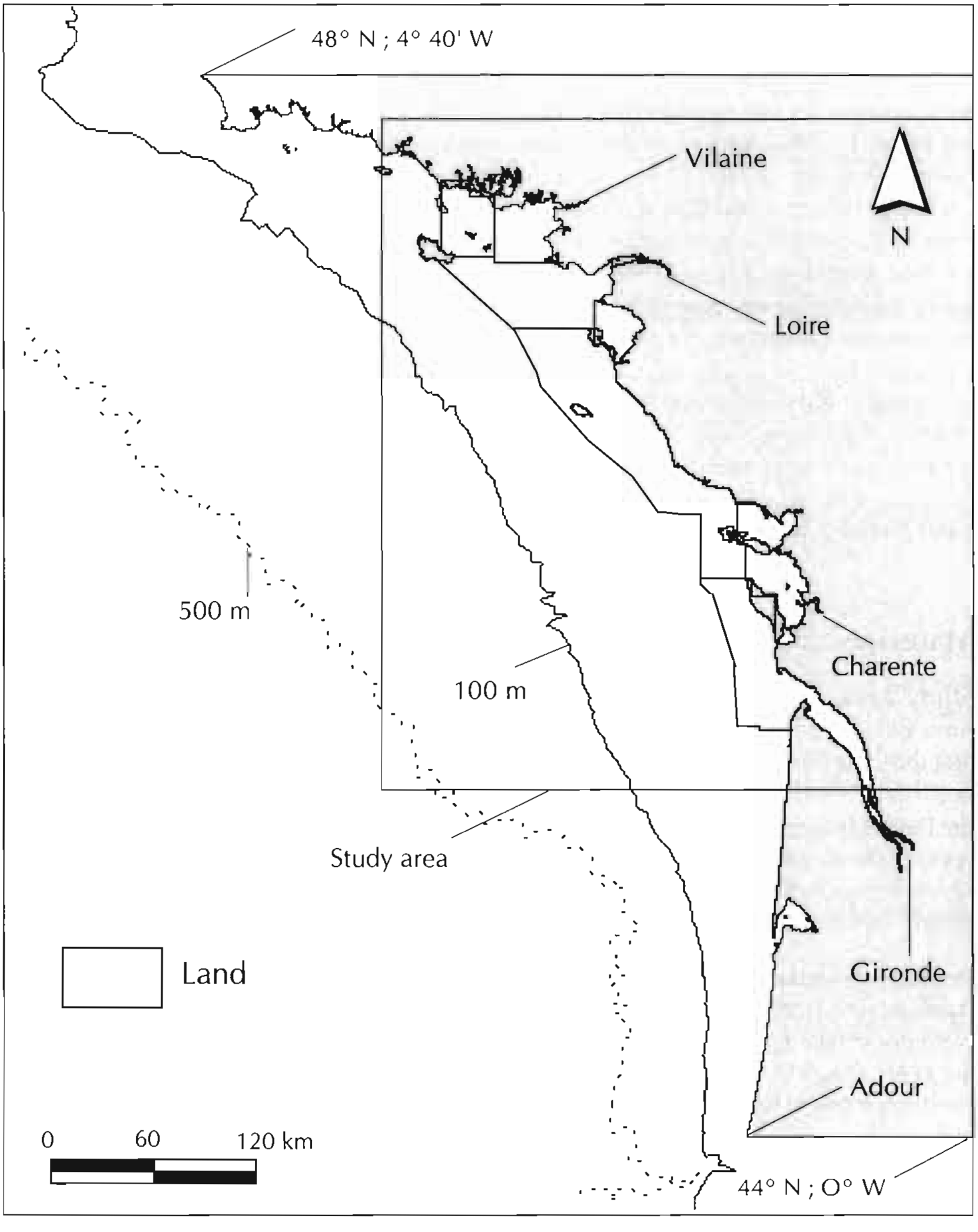
This analysis was based on a number of surveys of juvenile flatfish species undertaken throughout the Bay of Biscay during a 15-year period. The relation between the physical properties of the coastal zone and juvenile sole density was studied for young-of-the-year (y-o-y) sole. Generalized linear models and a Geographic Information System (GIS) were used to identify and describe key sites for the early life stages of sole. The respective influence of the different habitats was studied as well as the relation between interannual variations of nursery ground capacity (with respect to estuarine extend) and sole recruitment. The aim of this paper is to show how GIS has contributed as a main tool of scientific investigation in the field of this research.

Materials and Methods

Study area. Figure 1 shows the Bay of Biscay on the western coast of France (ICES Area VIIIa/b; fig. 1). In this region, the study area is an arm of the North Atlantic indenting the coast line. The continental shelf, which extends 160 km from the coast in the north and narrows to 65 km in the south toward the Spanish coast, underlies most of the Bay of Biscay. Sole is the most frequent, abundant and regularly exploited demersal species (Koutsikopoulos *& al.*, 1995). In the Bay of Biscay, sole born in well identified spawning grounds 80 to 100 km from the coast then migrate to offshore nurseries where they mature to adult age (Koutsikopoulos *& al.*, 1991).

Beam trawl survey data. From 1985 to 1997, a number of independent coastal beam trawl surveys (representing 855 trawl hauls) for juvenile flatfish species, especially sole, were undertaken (IFREMER, R.V. Gwen Drez) in autumn throughout an area located in the central part of the Bay of Biscay (Fig. 1). This season was chosen because it is the most appropriate for the study of nursery grounds (Dorel et *al.*, 1991). As demonstrated in Koutsikopoulos *& al.* (1989), only larvae completing metamorphosis within coastal nursery grounds are likely to develop. Hence, these coastal surveys are appropriate for studies of habitat suitability for juvenile sole. Operating conditions were checked and standardized from the first survey. All sole were counted, measured and age groups were determined from size groups. Young-of-the-year densities were calculated for each trawl haul (number of 0 group sole caught per hectare).

Figure 1 - The Bay of Biscay, showing the main rivers, the 100 and 500 m isobaths, the limits of the study area and the divisions between the coastal sectors used in the analysis



Physical descriptors and nursery grounds. Informations on the physical parameters known to influence habitat suitability for juvenile sole were taken from the following sources :

- A bathymetry map from *Service Hydrographique et Océanographique de la Marine, France,* at the scale of 1/500,000 indicating the coastline and isobaths of 5, 10, 20 and 50 m.
- A sediment structure map from *Bureau de Recherches Géologiques et Minières, France* at a scale of 1/500,000 showing five classes of sediment (mud, fine sand, rough sand, gravel and rock).

A three-dimensional hydrodynamic model of the Bay of Biscay with 5 km grid sides (Lazure and Jégou, 1998), which simulates hydrologic conditions relative to climatic factors and five main rivers flows (Fig. 1) and allows quantification of river plume extent. As described in Le Pape & al. (2003) for Vilaine Bay, the extent of the river plume before or at the beginning of the benthic life of y-o-y sole influences the size and biotic capacity of habitats in estuarine nursery grounds and determines the number of juveniles produced. In the Bay of Biscay, newly metamorphosed individuals settle into coastal and estuarine nursery grounds from April to June (Koutsikopoulos & al., 1989). Hence, the surface salinity given by the model for the beginning of April (Julian day 92) was used to describe the influence of the river plume. As it was necessary to dissociate estuarine areas from marine waters, two classes were determined for surface salinity data: < 31 PSS for estuarine waters and ≥ 31 PSS for marine waters. Thus, for each study year (from 1985 to 1997), the surface salinity map represents both classes at Julian day 92.

However, the different coastal areas of the Bay of Biscay do not receive the same quantity of sole larvae (Koutsikopoulos et *al.*, 1991). Rijnsdorp *& al.* (1992) showed that the sole recruitment pattern in the North Sea is only similar for coastal nursery areas with a similar coastline direction. Thus, it is important to take the different coastal sectors into account in modeling the distribution of juvenile sole in coastal nurseries. For this purpose, the study area was divided into 9 sectors according to coastal morphology (see Fig. 1).

Habitat suitability models for juvenile sole

Developing quantitative maps of juvenile sole distribution based on physical and geographic descriptors required three succesive operations:

Coupling data with a GIS

- Physical descriptors and coastal sectors were included in a GIS, which allowed different layers of data to be intersected to obtain a stratification of the study area year by year on the basis of four parameters (bathymetry × sediment structure × salinity in two classes at Julian day 92 × coastal sectors). Information on physical and geographic factors was then combined with survey data. The latter, identified from the mean position of the trawl haul and the year of the survey, were included in the GIS in order to associate, for each trawl haul, bathymetry, sediment structure, surface salinity class at Julian day 92 and geographic sector.

Developing a model

A generalized linear model (GLM) based on survey data was then developed to describe the distribution of juvenile sole with regard to these factors. The model was built assuming a delta distribution for juvenile sole distribution. A binomial distribution for the presence of juvenile sole was coupled with a log-normal distribution for density when juvenile sole were present. The maximum likelihood estimation for this model amounted to fitting one GLM to 0/1 values and another to positive abundance values then to couple these two submodels (Stefansson, 1996).

1 - Developing a binomial model for the presence of y-o-y sole

$YS_{0/1} \approx$ *factor (Salinity) + factor (Sediment) + factor (Bathymetry) + factor (Sector)* $+ \varepsilon_{0/1}$

Where:

* $YS_{0/1}$ is the Boolean value for y-o-y sole density (0 if no y-o-y sole were caught, 1 otherwise), i.e. the response variable of the GLM fitted to a binomial distribution and a logit link;

* factor («physical factor») constitutes the four qualitative variables used as explanatory variables in the model;

* $\varepsilon_{0/1}$ constitutes the residuals assumed to be binomially distributed.

2 - Developing a model for positive y-o-y sole density values

$\ln(YS_{+}) \cong$ *factor (Salinity) + factor (Sediment) + factor (Bathymetry) + factor (Sector)* $+ \varepsilon_{+}$

Where:

* YS_{+} is the value for y-o-y sole density (number of fish per hectare) when juveniles are present. The logarithm of YS_{+} is the response variable of this GLM fitted to a Gaussian distribution and an identity link. Preliminary tests showed that these options were the best ones to describe log-normal distribution of positive values.

* ε_{+} constitutes the residuals assumed to be normally distributed.

This basic formulation, with no crossover effects between the different factors, was used because of certain spatial singularities in the sampling scheme. As all of the possible combinations among physical and geographical factors did not exist in survey data, these singularities would have led to numeric bias.

3 - Linking these models to estimate habitat suitability for y-o-y sole

$$\hat{YS} = \hat{YS}_{0/1} \times e^{\hat{\ln}(YS+)} \times e^{-\frac{\hat{\sigma}(\hat{\ln}(YS+))}{2}}$$

Where:

*$\hat{YS}$ is y-o-y sole density estimated with a delta model combining the two previous models;

* $\hat{YS}_{0/1}$ is the probability of the presence of y-o-y sole, as estimated with the binomial model;

* $\hat{ln}(YS+)$, is the logarithm for the density of y-o-y sole when present, as estimated with the log-normal model;

* $\hat{\sigma}\left[\hat{ln}(YS+)\right]$ is the standard error of the logarithm for the density of y-o-y sole when present, as estimated with the log-normal model.

This estimation takes account of the correction calculated by Laurent (1963) to obtain an unbiased estimate from a linear model based on log-transformation.

Including model results in the GIS

As the GIS takes into account an exhaustive description of the four model descriptors (bathymetry × sediment structure × salinity in two classes at Julian day 92 × coastal sectors), the model results (one fitted density for each combination of the descriptors) were included in the GIS to map the fitted densities of 0-group sole.

Moreover, results for the habitat suitability model and the GIS were also coupled to calculate an index of juvenile abundance based on the extent of geographic stratum areas:

- The surface area of each stratum (Bathymetric class × Sediment structure × River Plume class × Coastal Sector) was calculated using the GIS for the different hydrologic situations (one hydrologic situation per year between 1985 and 1997, i.e. one map per year of the surface salinity given by the model at Julian day 92).

- For each stratum, a number of 0 group sole was calculated as the product of this surface area multiplied by the corresponding density value, as determined with the model described in the previous section.

- It was then possible to use the number of fish calculated to determine the contribution of the different habitats to total stock as a percentage of the total number of fish in the overall area for the different hydrologic situations.

Results

Habitat suitability model

Y-o-y sole densities were characterized by a large number of zero values. In spite of targeted surveys on coastal areas where juveniles are located, y-o-y sole were caught in only 60% of trawl hauls. Thus, the delta model of habitat suitability, with zero values treated separately and positive values assumed to follow a log-normal distribution is quite suitable for description of these data (tab. 1). The effects of the four descriptors were significant for both the binomial and the positive models, and there was no trend in the residuals of the positive model.

Two geographic areas appear to shelter high densities of juvenile sole, one in the south, in the semi-enclosed bays located north of the Charente estuary, and the other off the Loire estuary (fig. 2).

Figure 2 - Fitted y-o-y sole abundance for mean hydrologic conditions in the study area

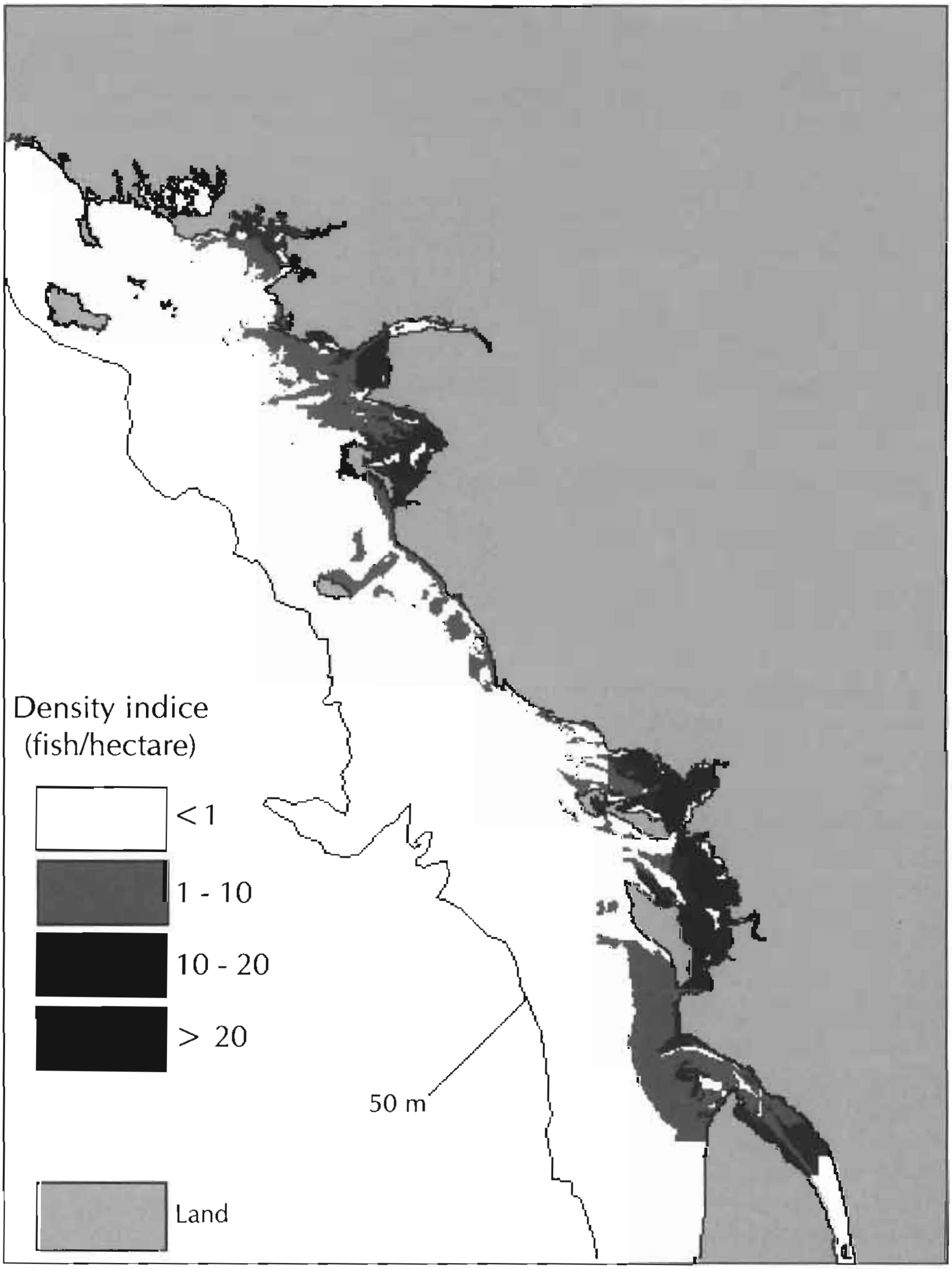


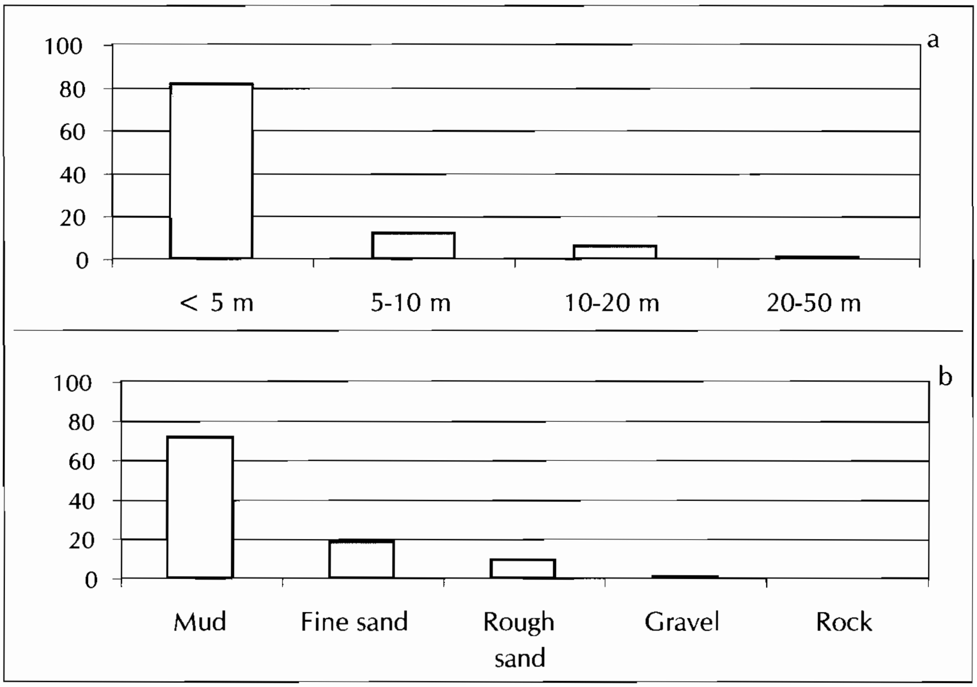
Table 1 - Analysis of deviances for the two parts of the delta log-normal Generalized Linear Model

	Binomial model			Positive value model		
	DoF	Deviance	Pr(Chi)	Dof	Deviance	Pr(Chi)
Null	853	1153		507	2043	
Estuarine plume	852	1128	4.89E-07	506	2015	1.15E-07
Sediment	849	1082	7.82E-10	503	1991	3.13E-05
Bathymetry	846	1021	3.00E-13	500	1878	0
Geographic sector	838	885	0	493	1450	0
Explained deviance (%)		23			29	

Columns indicate residual degrees of freedom (DoF), residual deviance and p-values when a χ^2-test was used for significance.

Thus, despite consequent residual deviance due at least in part to considerable small-scale variability, the factors of river plume extent, sediment structure and bathymetry contributed significantly to determine y-o-y sole distribution. Moreover, as juvenile sole distribution depended on the separate geographic sectors distinguished in the Bay of Biscay study area, it is not realistic to describe distribution without taking this geographic heterogeneity into account.

Figure 3 - Contribution (% of total juveniles in the study area) of the different habitats according to bathymetry (a) and sediment structure (b)

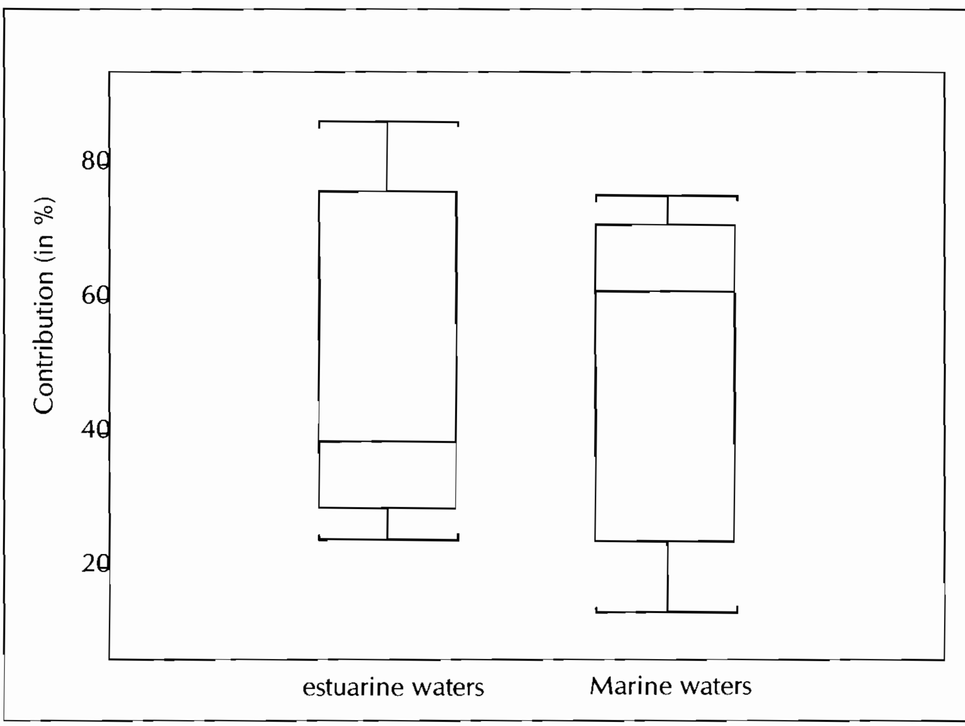


Location of nursery grounds and contribution to population size

Juveniles were concentrated in a few limited coastal sectors (fig. 2) close to the shore near the main river mouths (fig. 1) and in protected bays. Habitat variability was related to hydroclimatic conditions and did not significantly affect the contribution of the different bathymetric or sediment classes to sole stock.

Figure 3a shows the quite important role of very shallow areas (< 5 m depth) in providing nursery grounds for sole. These areas represented only 24% of the overall study area within the 50 m depth limit, but contributed 81% of the total number of juveniles during the productive period. The contribution to stock decreased as depth increased, and areas deeper than 20 meters were unsuitable for nursery grounds. Muddy areas represented only 29% of the study area, but contributed 71% of the total number of juveniles (Fig. 3b). The contribution to stock decreased with increasing granule size. Very shallow muddy areas (< 5 m) represented only 10% of the study area, but contributed 60% of the total number of juvenile sole.

Figure 4 - Contribution (% of total juveniles in the study area) of estuarine and non-estuarine waters (bar: upper and lower quartiles; whiskers: extreme values; bold line: median value)



The contribution of estuarine waters, defined as areas where surface salinity was lower than 31 PSS on Julian day 92, was very variable from one year to another (Fig.

4), accounting for less than 25% of total juveniles in dry years and more than 85% in years when the river plume was extensive at the beginning of the settling period. Nevertheless, the contribution of these plume sectors was considerable (a mean 48% of the total number of juveniles for 24% of total surface area).

Discussion – Conclusion

Habitat suitability for juvenile sole

As the study area covered a large part of the Bay of Biscay, our analysis provides a typology of nursery habitats on a Bay of Biscay sole stock scale. Previous studies showed that recruitment level is related to nursery ground area (Rijnsdorp et al., 1992; Le Pape et *al.*, 2003) and juvenile densities, depending on habitat quality (Gibson, 1997). In this respect, the present study can be used to assess the relative contribution of the different nursery habitats to Bay of Biscay sole stock.

Juvenile sole appear to be concentrated in limited shallow and muddy habitats. This descriptive typology is well known, and the preference of juvenile sole for shallow areas covered with fine sediment has been demonstrated (Gibson, 1997). Our quantitative approach concerning the respective contributions of different habitats clearly indicates that juvenile sole are concentrated in limited and essential habitats, i.e. very shallow muddy areas representing 10% of the total study area contribute 60% of the total number of juveniles.

This study also confirmed expectations about the important role played by estuarine areas (Koutsikopoulos *et al.*, 1989; Le Pape et *al.*, 2003). Our study, by focusing on the interannual variability of the estuarine influence relative to hydrologic conditions and interannual variations of habitat capacity, develops the concept of fluctuating habitat size, which adds a dynamic variable to condition the fixed relationship between nursery area and recruitment (Rijndorp *et al.*, 1992).

GIS as a tool for identifying the essential fish habitat

Multivariate models are commonly used to define habitat suitability (Norcross *et al.*, 1999) and can be combined with geographic information systems to create potential distribution maps (Guisan and Zimmermann, 2000; Eastwood *et al.*, 2001; Riou *et al.*, 2001; Stoner *et al.*, 2001).

The delta distribution method tends to limit the problems encountered in other models with zero values, which are generally frequent in fish survey data (Stefansson, 1996). Moreover, as stock abundance is represented by two sources of information with different meanings, i.e. the level of non-zero catch rates and the probability of catching the species, it is important to use a comprehensive abundance index that integrates both kinds of information (Ye *et al.*, 2001).

A method of this type, based on descriptors known throughout the study area, provides a relative index for mean juvenile distribution based on the extent of the respective geographic areas and thus an assessment of the contribution of different habitats to the common stock. In this way, the essential fish habitat can be determined, which is in fact a limited area contributing largely to fish stock renewal. The identification of essential fish habitats can prevent anthropogenic disturbance, especially when these areas are spatially limited. The method developed in this study, based on model on GIS coupling, can be applied to other species in order to provide a general description of essential fish habitats for the marine community (Rubec *et al.*, 2001).

This study well illustrates the interest of GIS to study marine resources habitats and to develop tools for coastal management. Actually, GIS is the single tool allowing to tranfer results of model based on localized *in situ* data to exhaustive quantitative maps (Eastwood *et al.*, 2001; Stoner *et al.*, 2001) and to quantify the respective influence of different habitats (Riou *et al.*, 2001 and the present study). These methods of model + GIS coupling are of course not specific to coastal marine management and can be used for other topics in ecology (Guisan and Zimmermann, 2000).

Acknowledgments

This project was suported by the French National Programme for Coastal Ecology. The authors are grateful to Pierre Beillois (IFREMER) for assistance in running "Arcview GIS" software.

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Le Pape O., Chauvet F., Fotsing Jean-Marie (2005)

The use of GIS for a quantitative description of essential fish habitats in the Bay of Biscay (France)

In : Fotsing Jean-Marie (dir.). *Apport des SIG à la recherche : actes du colloque international géomatique et applications n° 1*

Orléans : Presses Universitaires d'Orléans, p. 93-104. (Collection du CEDETE)

Colloque International Géomatique et Applications n° 1 : Apport des Systèmes d'Information Géographique au Monde de la Recherche, Orléans (FRA), 2003/03/13-14

ISBN 2-913454-25-9