

**Title: MODELLING THE EFFECT OF FOOD DEPLETION ON SCALLOP GROWTH IN SUNGO BAY (CHINA)**

**Authors:** Cédric Bacher<sup>1</sup>, Jon Grant<sup>2</sup>, Anthony J. S. Hawkins<sup>3</sup>, Jianguang Fang<sup>4</sup>, Mingyuan Zhu<sup>5</sup>, Mélanie Besnard<sup>6</sup>

<sup>1</sup> CREMA, BP5, 17137, L'Houmeau, France, [cbacher@ifremer.fr](mailto:cbacher@ifremer.fr)

<sup>2</sup> Dalhousie University, Dept. Oceanography, 1355 Oxford Street, Halifax, NS B3H 4J1, Canada

<sup>3</sup> Plymouth Marine Laboratory, Prospect Place, Plymouth PL1 3DH, United Kingdom

<sup>4</sup> Chinese Academy of Fishery Sciences, 106 Nanjing Road, 266071 Qingdao, People's Republic of China

<sup>5</sup> SOA-FIO, Xianxialing Road, Hi-Tech Industrial Park, 266061 Qingdao, People's Republic of China

<sup>6</sup> CREMA, BP5, 17137, L'Houmeau, France

**Original Publication Reference:** Bacher, C., Grant, J., Hawkins, A.J.S., Fang, J., Zhu, M. & Besnard, M. 2003. Modelling the effect of food depletion on scallop growth in Sungo Bay (China). *Aquatic Living Resources*, 16(1): 10–24.

**Application Tool:** GIS, Mathematical models.

**Main Issues Addressed:** Siting, assessment of culture density.

**The general problem, or aim of the study, and the contribution of GIS, remote sensing and/or mapping to the solving the problem:** Sungo bay (China) has a mean depth of 10 m, a total area of 140 km<sup>2</sup> and is occupied by several types of aquaculture, whilst open to the ocean. Production of scallops (*Chlamys farreri*) cultured on long lines is estimated to exceed 50 000 tonnes (total weight) per year. Selection of sites for scallop growth and determination of suitable rearing densities have become important issues. We focused on the local scale (e.g. 1 000 m) where rearing density, food concentration and hydrodynamics interact. We have developed a depletion model coupling a detailed model of *C. farreri* feeding and growth and a one dimensional horizontal transport equation. The model was applied to assess the effect of some environmental parameters (e.g. food availability, temperature, hydrodynamism) and spatial variability on growth, and to assess the effect of density according to a wide range of hydrodynamical and environmental conditions. The model was integrated within a Geographical Information System to help decision-making about appropriate scallop densities suitable for aquaculture at different locations throughout the bay. Concepts (depletion), methods (coupling hydrodynamics and growth models), and the underlying framework (GIS) are all generic, and can be applied to different sites and ecosystems where local interactions must be taken into account.

**Main Environments:** Coastal environment.

**Culture Systems:** Shellfish culture using lantern nets.

**Organism Divisions:** Molluscs.

**Genera and Species:** *Chlamys farreri*.

**Target Country:** China.

**Target Audience:** Scientists, aquaculture planners.

**Duration of the Study and Year Begun:** 1998–2001.

**Personnel Involved:** Modeller, ecophysiological, and marine ecologist, about 30 person months in total, including field and experimental work, modelling and GIS with some of the results published elsewhere as complementary outputs such as ecosystem models.

# MODELLING THE EFFECT OF FOOD DEPLETION ON SCALLOP GROWTH IN SUNGO BAY (CHINA)

## Introduction

The development of shellfish aquaculture raises questions regarding its sustainability defined via the carrying capacity concept, i.e. the maximum production achievable in a given ecosystem given the biological constraints and characteristics of the aquaculture activity. Assessment of the maximum yield is relevant if one considers that until recently little was known on the capacity of ecosystems to support aquaculture activity apart from some empirical knowledge or successful/unsuccessful trials to adapt different species in coastal areas. Since shellfish production is an important component of the fisheries resources of coastal communities, carrying capacity assessment has become a major focus of scientific studies facilitating coastal zone management. These topics are of particular importance in China where traditional aquaculture has been ongoing for centuries, but undergoing especially rapid growth in the past ten years (Guo *et al.*, 1999). Coastal zone management in China has become a major concern because of a) the impact of human activities on environmental and water quality, and b) the need for optimization of aquaculture strategy (Fang *et al.*, 1996). Within this context, a project was funded by the European Union to build tools capable of characterizing the carrying capacity and impact of shellfish and kelp aquaculture in two Chinese bays situated in Shandong province. Cooperative studies were conducted on the feeding responses and growth of cultivated species, variation in key environmental parameters in the field, and modelling hydrodynamics, filter-feeder growth and ecosystem dynamics.

Sungo bay is a small bay with mean depth of 10 m, total area of 140 km<sup>2</sup>, open to the ocean and occupied by several types of aquaculture, e.g. kelp (*Laminaria laminaria*), oysters (*Crassostrea gigas*) and scallops in lantern nets (*Chlamys farreri*) (Figure 1).

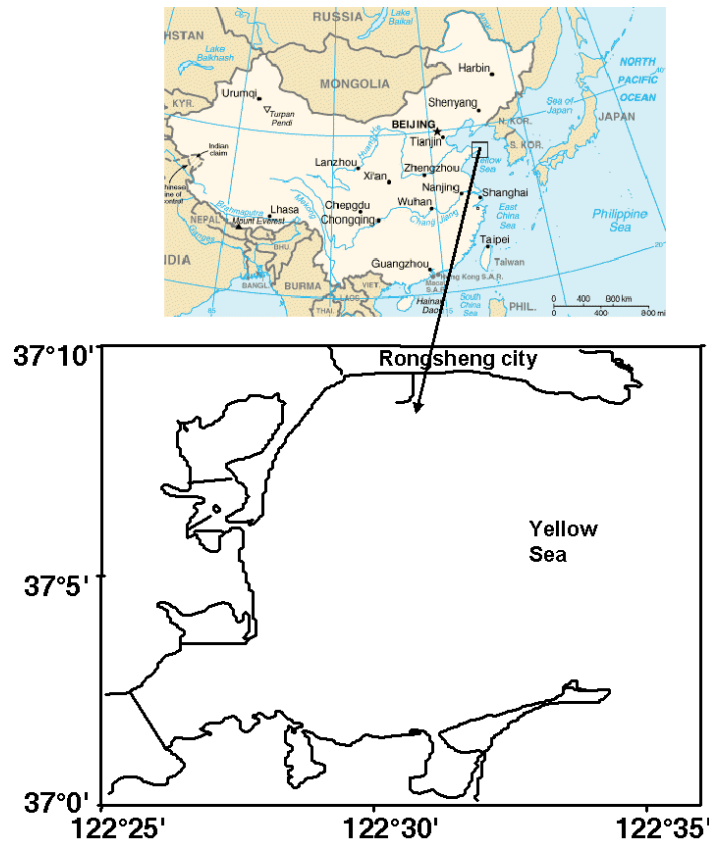


Figure 1 Location of Sungo Bay (China)

It is one of the most intensively cultured bays in China. Current velocity is driven by the tide and is usually less than  $20 \text{ cm s}^{-1}$ . Due to low nutrient inputs from rivers, primary production originates from import of organic matter and nutrients from the sea, including recycling of nitrogen within the bay. Total production and standing stocks have changed over the past 20 years, including a shift from kelp to shellfish production. However, overexploitation is apparent from reduced shellfish growth and the increased incidence of disease. Scallops are the dominant cultivated filter-feeders, and production is estimated as  $\sim 50\,000$  tonnes (total weight) per year. Selection of sites favourable for scallop growth and determination of suitable rearing densities have become important issues. Here we focus on the local scale where rearing density, food concentration and hydrodynamics interact. The first objective was to assess individual scallop growth by combining an hydrodynamic model to predict current velocity and food delivery (Grant and Bacher, 2001) with an ecophysiological model to predict responsive adjustments in scallop feeding and growth (Hawkins *et al.*, 2002), taking into account any food depletion. The combined “depletion model” was used to simulate individual growth at several sites where food concentration had been measured, determining the sensitivity of annual growth to scallop density. The second objective was to integrate the model within a Geographical Information System to assist in making decisions about the appropriate densities suitable for aquaculture at different sites throughout Sungo Bay.

## Materials and Methods

### *Depletion model*

The depletion model is coupling food transport, food consumption by the scallop population and scallop growth at the scale of a cultivated area, e.g. within a domain of a given length (typically 1 000 m). Since we restricted the computations to local scales, we considered the main direction of the current at a given site. The model is based on a 1D equation comparable to Pilditch *et al.* (2001) and Wildish and Kristmanson (1997) when vertical mixing prevents a vertical gradient of particle concentration:

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} = N \cdot f(C, w) \quad (1)$$

where  $C$  refers to either phytoplankton, organic or inorganic particulate matter,  $u$  is the current velocity,  $f(C, w)$  the individual food consumption,  $N$  is scallop density,  $w$  is scallop tissue dry weight (DW),  $x$  the distance along the main current direction. Compared with Pilditch *et al.* (2001), we neglected dispersion terms, since a) dispersion coefficients are difficult to determine, b) their major effect is smoothing the variation inside the domain, and c) the numerical integration scheme yields numerical dispersion.

The weight change of the scallop is described by:

$$\frac{dw(x, t)}{dt} = g(C, w, T) \quad (2)$$

where  $T$  is the water temperature and  $g(C, w, T)$  is net energy balance established using a model of feeding and growth that has been developed, calibrated and validated for *C. farreri* on the basis of field measurements in Sungo Bay (Hawkins *et al.*, 2002). In that model, rates of filtration, ingestion, assimilation and respiration are predicted from the abundances of total particulate matter, particulate organic matter and chlorophyll *a*, including seawater temperature. Net energy balance is determined as the difference between rates of assimilation and respiration, and the balance is allocated between somatic tissue, shell and reproduction. Equations 1 and 2 above use these functions from the model of Hawkins *et al.* (2002) to couple food concentration and

scallop growth, such that high scallop densities were expected to result in increased food depletion and diminished growth.

Current velocity was predicted by a hydrodynamic model described in Grant and Bacher (2001). This model computes water height and current velocity on an irregular grid of 227 nodes all over the bay, which yields more accurate calculations in area of strong gradients as in the vicinity of the coastline (Figure 2a). The amplitude of the water level variations was around 1 m and the relatively low current velocities were generated by the tidal amplitude (Figure 2b).

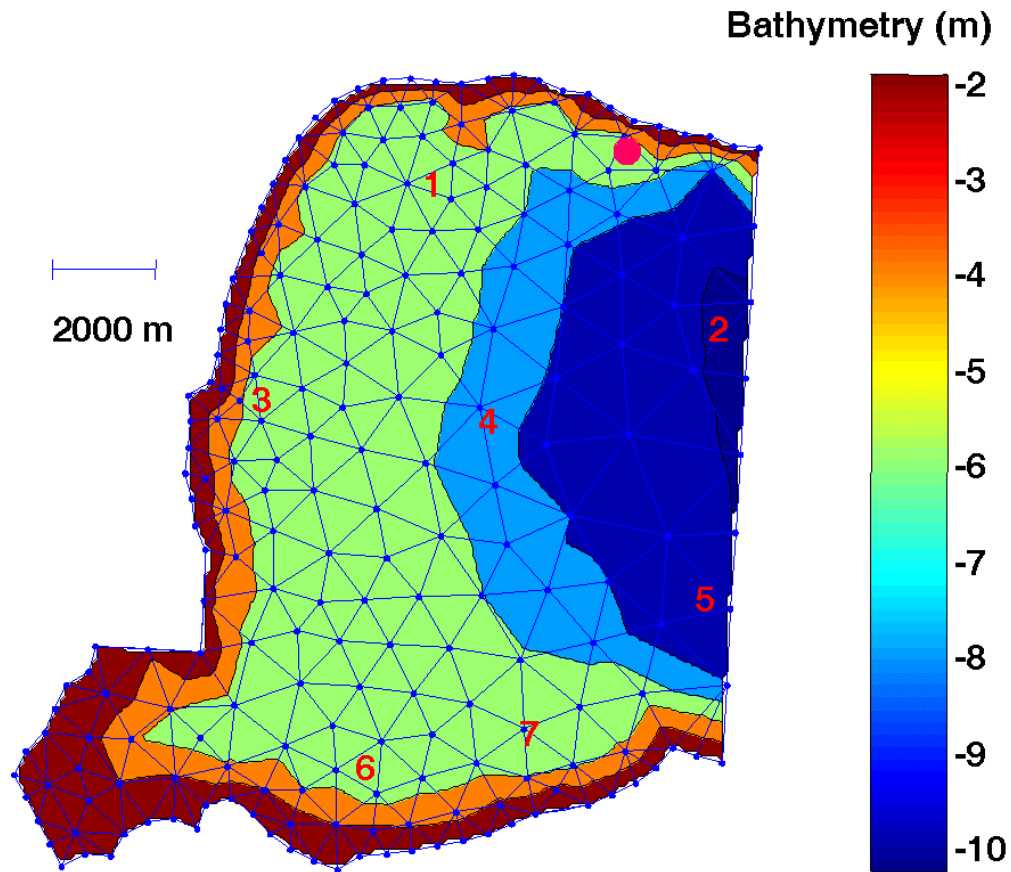


Figure 2a 2D hydrodynamical model: grid used for calculation of water height and current velocity (Grant and Bacher, 2001), location of sampling sites for the field survey (numbered from 1 to 7) and location of the continuous probe (red dot).

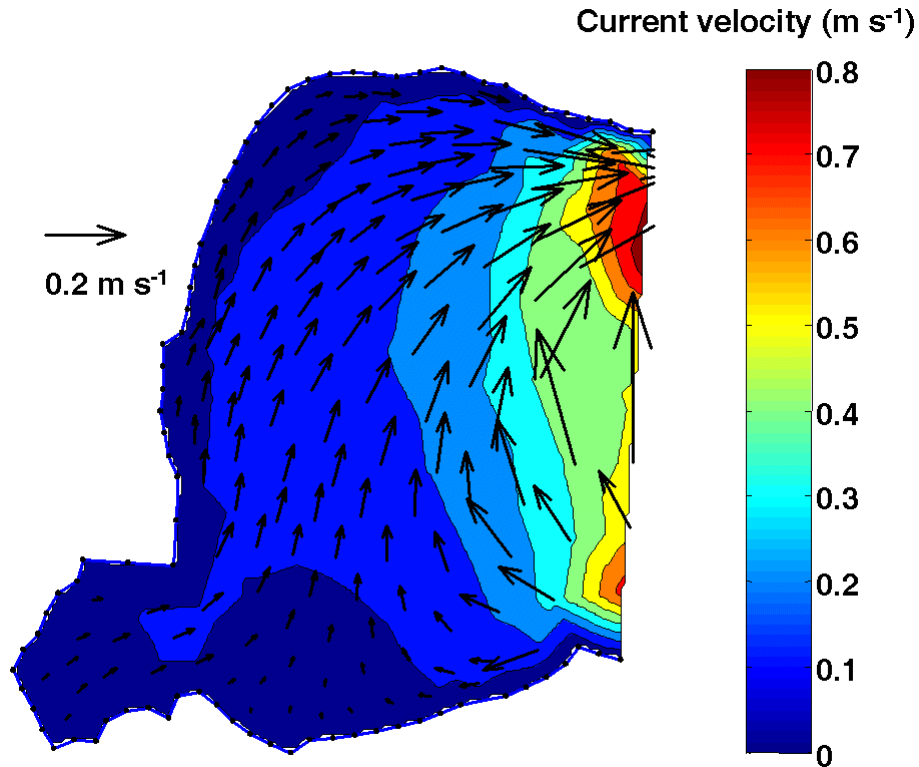


Figure 2b 2D hydrodynamical model: current velocity field at one time of the tidal cycle and map of the maximum current velocity.

Computations showed that maximum current velocity occurred at the open boundary with the ocean, as opposed to the inner parts of the bay where maximum current velocity is usually less than  $20 \text{ cm s}^{-1}$ . Water circulation is dominated by a gyre due to the tidal phase in the open ocean (Grant and Bacher, 2001). During the flow the water enters the bay at the north-eastern part of the ocean boundary and the tide reverses during the ebb. Residence time of the water is around 20 days but computed trajectories showed that the daily displacement of particles was less than 2 km in the inner part of the bay (Figure 3).

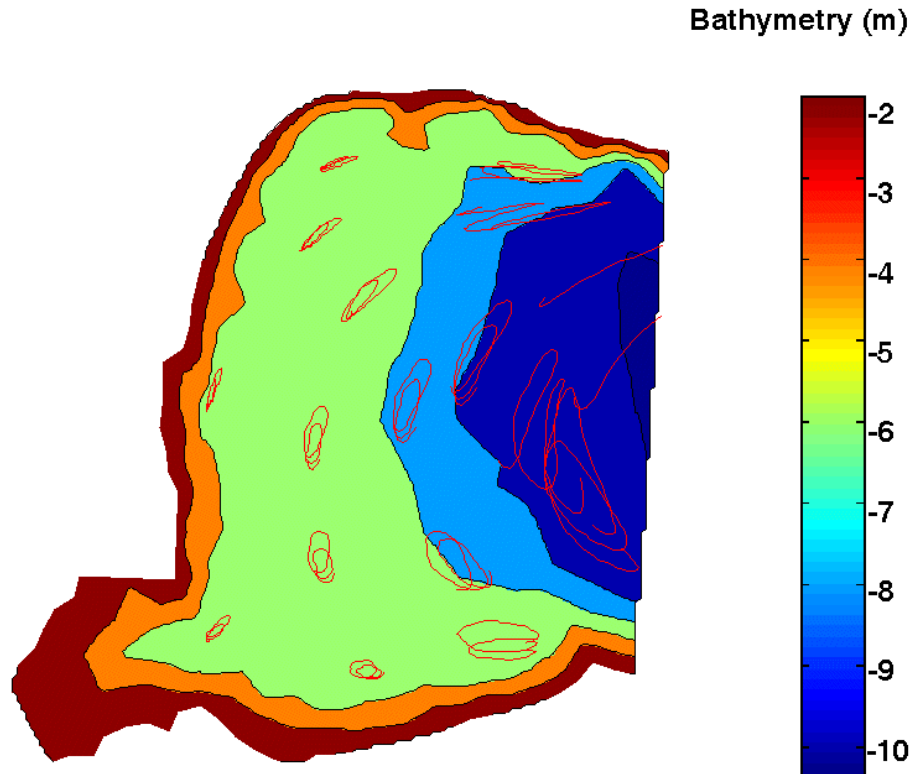


Figure 3 Trajectory of particles during several tidal cycles predicted by the hydrodynamical model.

Time series were also needed for the environmental parameters. A monthly field survey was conducted between May 1999 and April 2000 at seven sites to measure the following parameters: temperature T, suspended particulate matter SPM, particulate organic matter POM, particulate inorganic matter PIM, and chlorophyll a CHL (Hawkins *et al.* 2002). These time series were used to compute food transport within the domain. In order to apply the depletion model to different sites of the bay, we interpolated the environmental parameters in space using the seven sampling stations and a linear interpolation method based on inverse distance weights. Though there was not any obvious spatial gradient, we thought that environmental parameters mapping was the quickest and most relevant method to provide test values for the model at any location of the bay.

### *Simulations*

Numerical integration of equations 1–2 was based on discretization in space and time. The spatial domain was 1 000 m and was split into three equivalently sized horizontal boxes to account for potential spatial variability, and the time step was equal to 600 s. The model was successively applied to all the nodes used by the hydrodynamical model (149 nodes not counting the nodes at the terrestrial or oceanic boundaries). For each simulation, CHL, POM, PIM, individual scallop dry weight and total weight were computed for one year. Simulations started in October, which is the seeding time (Hawkins *et al.*, 2002). We therefore used our measured time series of SPM, POM, CHL, PIM, T to build annual forcing functions starting in October. Guo *et al.* (1999) describe the lantern net cultivation method in details but, for our model, it is more relevant to consider density of individuals (individuals per m<sup>3</sup>). We tested two different densities: 0 and 50 individuals per m<sup>3</sup>. The null density refers to a case where we simulated the growth of a single individual without depletion and therefore provides the maximum annual weight. Comparing the two series of simulations allows assessment of the density effect on the growth. After many sites with different hydrodynamic and food conditions were simulated, the results were mapped in order to assess the sensitivity of the density effect on the spatial variability of environmental

conditions, as well as produce baywide patterns of seston depletion and growth. Depletion factor was defined as the ratio between food concentration (e.g. CHL or POM) inside the spatial domain and at the boundary of the spatial domain.

## Results

### *Growth and depletion model*

Most findings related to food depletion were synthesized as maps of soft tissue weight at the end of annual simulations or of the seston depletion factor averaged over one year. The depletion model was run successively for all nodes used in the hydrodynamic model. It was first applied to compute annual scallop growth in the absence of any density or hydrodynamic effects, differences between sites being due to environmental conditions alone. The map of final tissue weights is shown in Figure 4a. Values varied between 1.5 and 2.3 g, the most favourable areas being located around sites 3 and 5 of the field survey. Sites 1, 2, 6 and 7 were the less favourable, while site 4 was intermediary. A second series of simulations assessed the effects of a density of 50 individuals  $m^{-3}$  (Figure 4b), and the difference between the 2 scenarios is illustrated in Figure 4c.

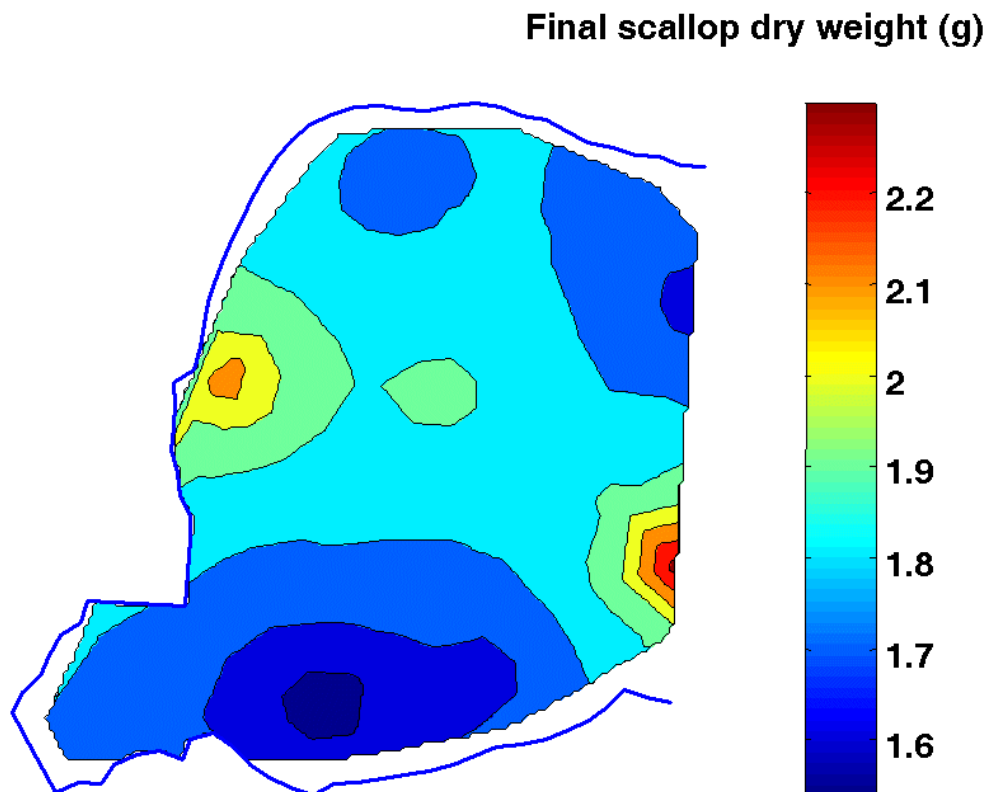


Figure 4a Map of the predicted effect of local density on scallop growth: annual scallop weight increase for a reference situation with no density effect.

## Final scallop dry weight (g)

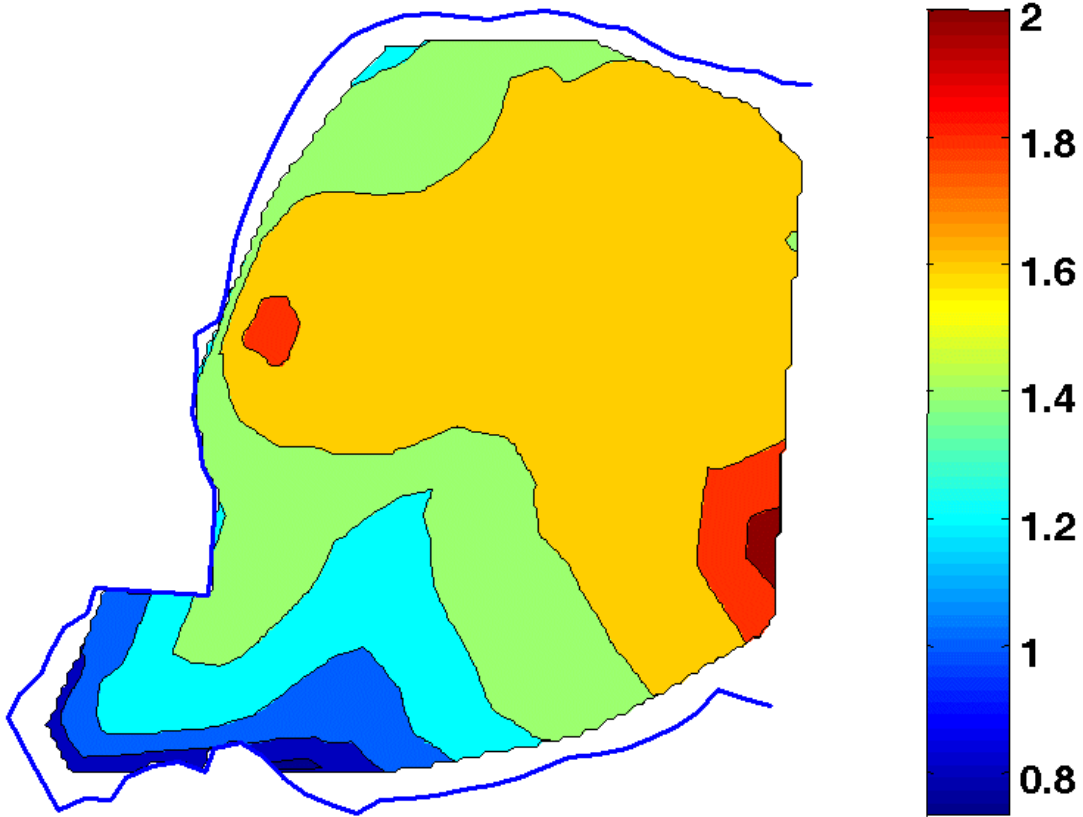


Figure 4b Map of the predicted effect of local density on scallop growth: annual scallop weight increase for a constant density of 50 individuals per  $\text{m}^3$ .

Maximum values of about 2 g did not change much, but minimum values of about 0.8 g were much lower at these higher densities. Faster growth again occurred along the south oceanic boundary and in the vicinity of station 3, whereas slower growth became more obvious in the south-western part of the bay. It is possible to compare the spatial variability of maximum current velocity (Figure 2b) with localized predictions of scallop growth (Figure 4c).

## Dry weight decrease (%)

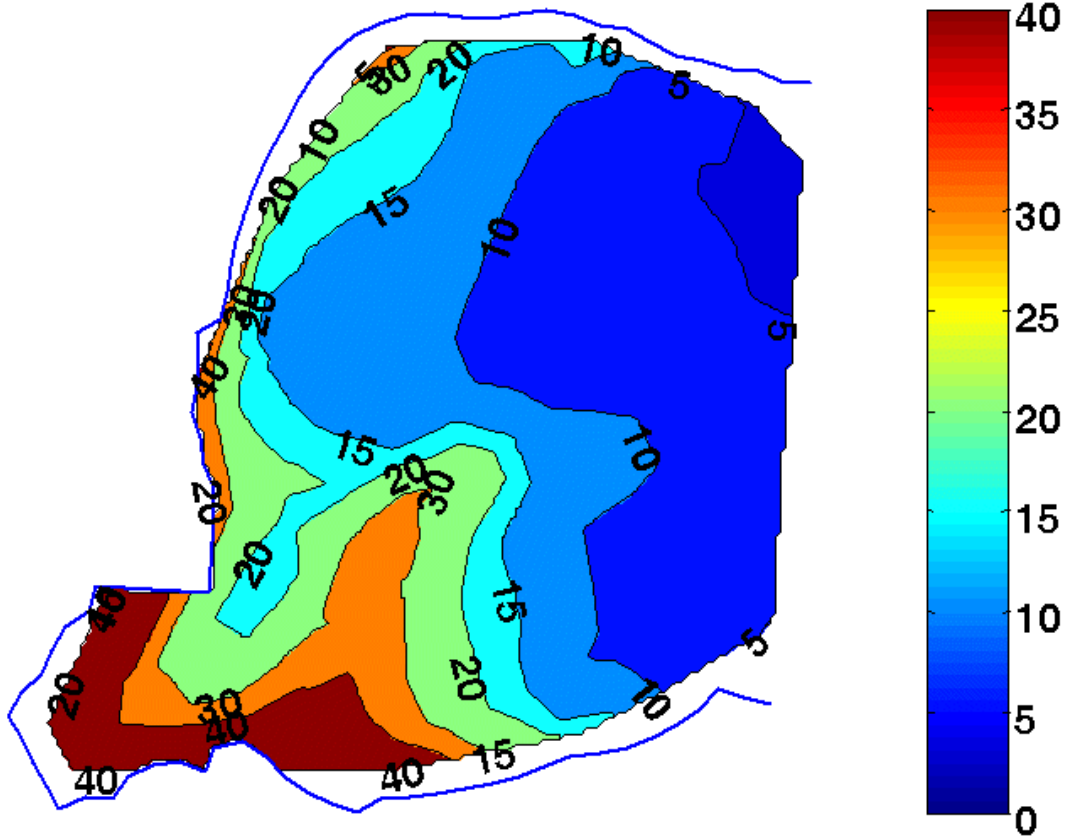


Figure 4c Map of the predicted effect of local density on scallop growth: sensitivity of scallop growth expressed as a percentage of annual growth variation between 2 simulations – null density, 50 individuals per  $m^3$ .

When expressed as a percentage of final growth, the effects of density varied between 5% in the eastern part of the bay where the current velocity was strongest, to more than 30% in the south-western part of the bay (Figure 4c). Density effects of 10% or more occurred in 56% of the bay area.

Since a) density would affect individual growth, b) final weight is an objective of the farmer, and c) final weight is maximum with 0-density, we used the model to estimate densities that resulted in a given decrease in final tissue weight. We assumed a linear relationship between density and decrease in final weight and interpolated that decrease from previous simulations. We considered depletion based upon ingestion rate or filtration rate as discussed above, but illustrate that based upon ingestion alone here (Figure 5).

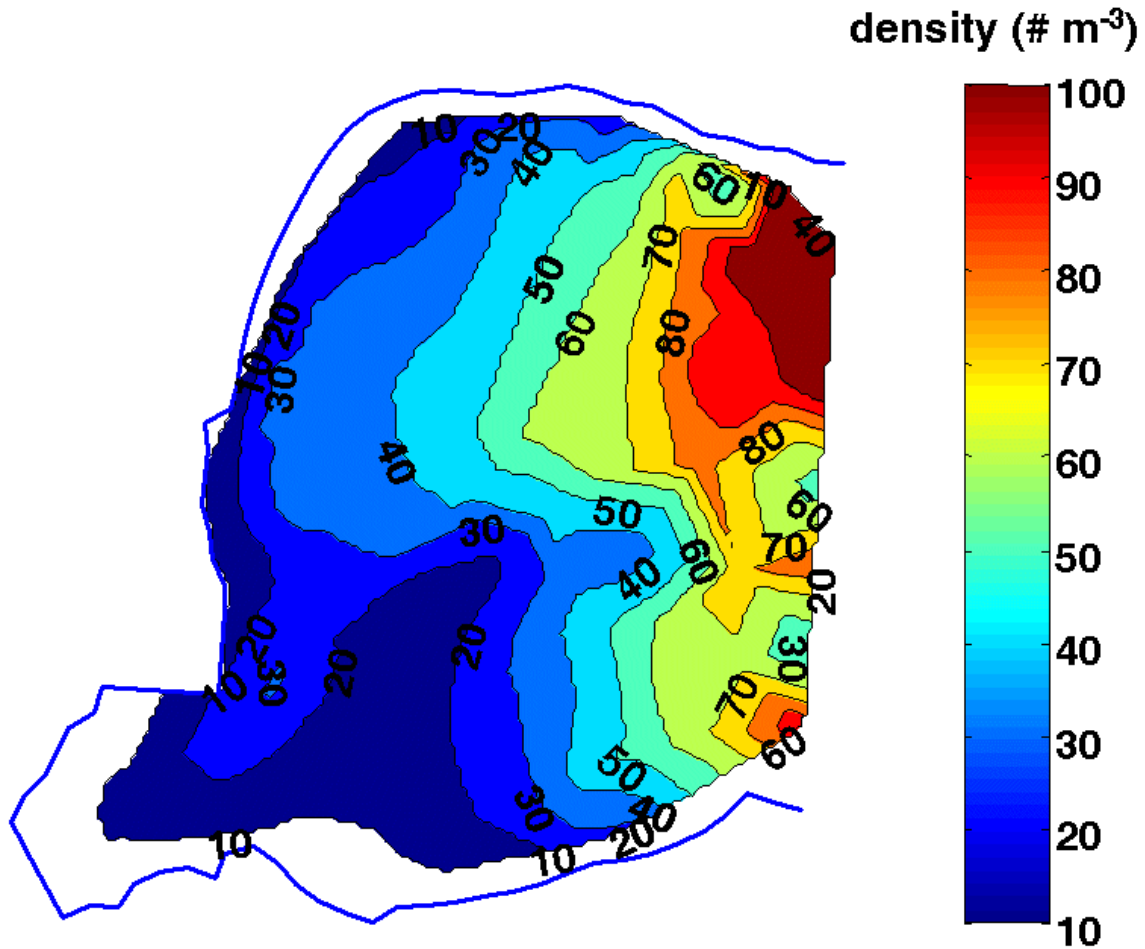


Figure 5 Map of scallop rearing density according to 10% decrease of the final total weight.

As an example we chose a 10% decrease as an objective. In both cases, densities were between 10 individuals m<sup>-3</sup> at sites where the density effect was the strongest and more than 100 in the eastern part of the bay. When calculated for ingestion, thereby accounting for pseudofaeces reutilization, a density less than 50 individuals m<sup>-3</sup> would be required over 67% of the bay to maintain a 10% weight decrease. This percentage would be 90% in case filtration was used in the calculation.

#### *Modelling tool*

A modelling tool was built to facilitate expertise on density dependent growth of scallops in Sungo Bay (Figure 6).

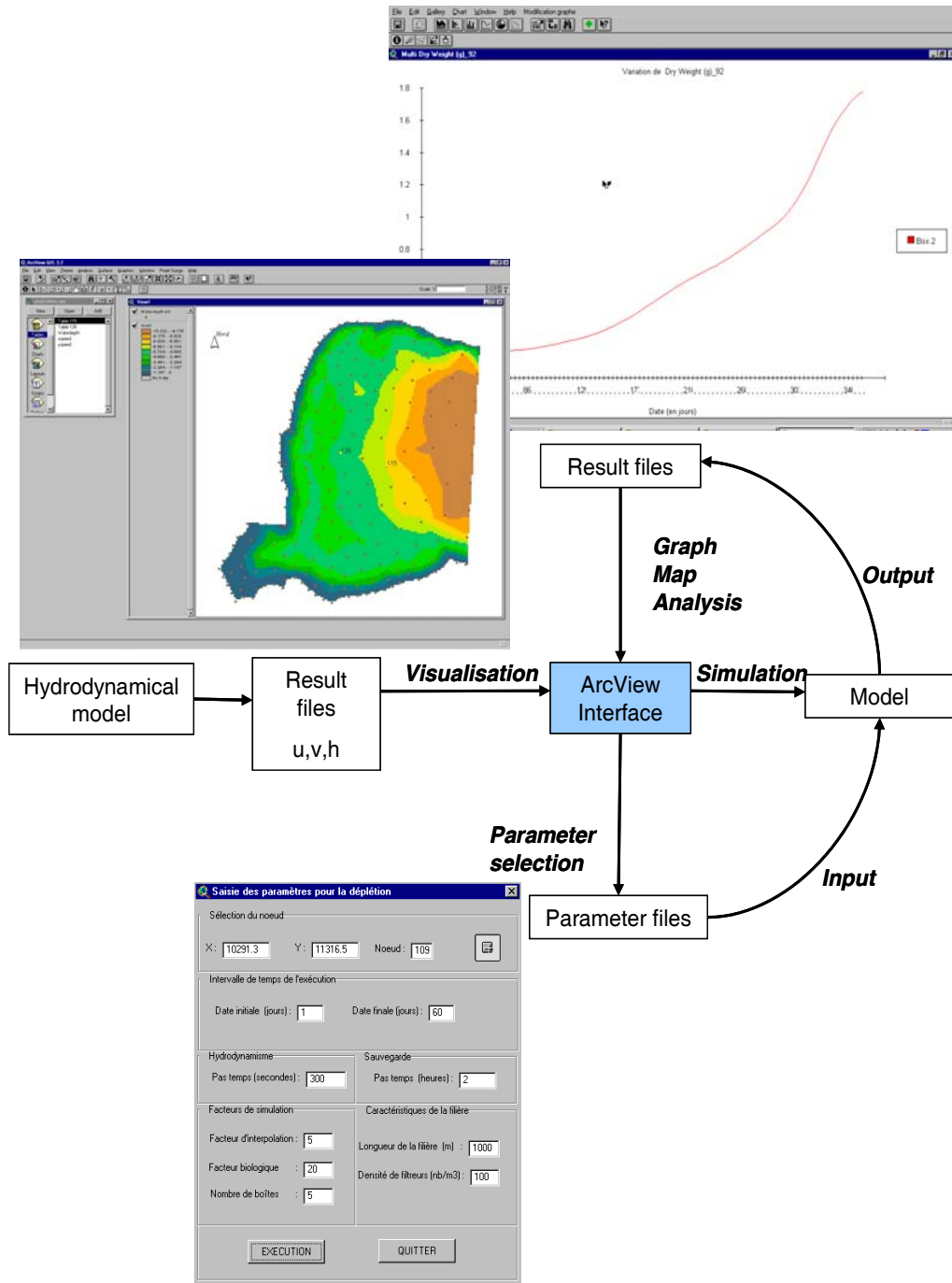


Figure 6 Integration of models and GIS.

This tool was based on the following components:

- hydrodynamics were computed by Aquadyn<sup>®</sup> software (Grant and Bacher, 2001), a Windows-based program that provides construction of the model finite element mesh as well as a hydrodynamic model (HydroSoft Energie, [www.hydrosoftenergie.com](http://www.hydrosoftenergie.com)). Outputs are saved in text files;

- Sungo Bay maps and database were implemented in a Geographic Information System with Arcview<sup>®</sup> software (ESRI, [www.esri.com](http://www.esri.com));
- field data were stored in Barcawin<sup>®</sup> software (GEM, <http://tejo.dcea.fct.unl.pt>); and
- the depletion model was developed in Fortran and Matlab computing language and compiled codes were interfaced with Arcview using Avenue<sup>®</sup> software.

The depletion model Graphical User Interface (GUI) helps the user to:

- plot current velocity and water height;
- compute and plot particle trajectories;
- select length scale, rearing density, site and simulate the annual scallop growth;
- map the final scallop growth or depletion factor;
- compare growth and depletion factors simulated with different densities on one site or over the bay;
- compute statistics of growth and depletion factors over the bay, such as the percentage of areas with a given depletion factor; and
- estimate by simple arithmetic the rearing density which guarantees a given depletion factor or a final scallop weight.

This tool provides information on suitable sites for scallop aquaculture, including appropriate local densities predicted on the basis of food depletion and limitation. All simulations and computations can be carried out within the GIS. When applied to one site, the time needed for a simulation of depletion and growth is in the order of few seconds. When simulations are iterated for all the nodes of the hydrodynamical model, the total simulation time is only of few minutes.

## Discussion

Scallop density had a clear net effect on growth at sites where maximum current velocities were below  $20 \text{ cm s}^{-1}$ . At greater current speeds, food renewal was always able to alleviate depletion. The percentage of variation in scallop growth that was due to density varied with the mean ratio between food available inside and outside the cultivated area (depletion factor). We also showed that scallop growth was correlated with maximum current velocity for a given density. Collective findings unequivocally establish that much of the variability in scallop growth resulted from food limitation. Our calculations clearly confirmed the importance of depletion in the case of a bay with a large range of hydrodynamical conditions, at a scale of 1 000 m and with a low density of animals. Our choice of 1 000 m length stemmed from the mixing length defined from trajectory simulations. This guaranteed mixing of particles when water mass exited the 1000 m area, so that boundary conditions were correctly prescribed. Depletion would certainly occur at shorter lengths, but would be weaker unless densities are much higher, such as in raft culture (Heasman *et al.*, 1998). For larger domains, we would have to consider other processes such as primary production, which would significantly compensate for the ingestion of particles by scallops. Here, we have demonstrated that managing rearing density at a 1 000 m scale according to food supply and depletion alone provides useful indications on how to optimise individual growth.

Our work was undertaken with the objective of helping to develop tools for the management of aquaculture. Campbell and Newell (1998) simulated local interactions between mussel beds and ecosystem processes, to provide recommendations on seeding density and timing. Pastres *et al.* (2001) also used a detailed ecosystem model to identify suitable sites for clam production in the lagoon of Venice. Other models have been developed to assess carrying capacity at the scale of the ecosystem (Raillard *et al.*, 1994; Dowd, 1997; Bacher *et al.*, 1998; Ferreira *et al.*, 1998). A different approach was proposed by Arnold *et al.* (2000) to select lease sites for clam aquaculture in Florida, using multiple criteria based on the limitation of culture impact, water quality and associated spatial requirements. The novelty of our approach has been in coupling bivalve growth and food depletion at a site of intensive aquaculture, where identifying sustainable rearing densities is a major challenge. Food depletion factors, suitable rearing densities and expected

individual growth rates can be superimposed with spatial information in a Geographical Information System (GIS), helping scallop aquaculture management. Concepts (depletion), methods (coupling hydrodynamics and ecophysiology), and the underlying framework (GIS) are all generic, and can be applied to different sites where local interactions are important. Whilst of undoubted application at the farm scale, more comprehensive models will be required to simulate processes at larger ecosystem scales.

### Acknowledgements

This work was supported by the INCO-DC project “Carrying capacity and impact of aquaculture on the environment in chinese bays”, contract number ERBIC18CT980291, EU.

### References

- Arnold, W.S., White, M.W., Norris, H.A & Berrigan, M.E. 2000. Hard clam (*Mercenaria* spp.) aquaculture in Florida, USA: geographic information system applications to lease site selection. *Aquac. Eng.*, 23: 203–231.
- Bacher, C., Duarte, P., Ferreira, J.G., Héral, M. & Raillard, O. 1998. Assessment and comparison of the Marennes-Oléron Bay (France) and Carlingford Lough (Ireland) carrying capacity with ecosystem models. *Aquat. Ecol.*, 31: 379–394.
- Campbell, D.E. & Newell, C.R. 1998. MUSMOD (c), a production model for bottom culture of the blue mussel, *Mytilus edulis* L. *J. Exp. Mar. Biol. Ecol.* 219: 171–203.
- Dowd, M. 1997. On predicting the growth of cultured bivalves. *Ecol. Model.*, 104: 113–131.
- Fang, J., Sun, H., Kuang, S., Sun, Y., Zhou, S., Song, Y., Cui, Y., Zhao, J., Yang, Q., Li, F., Grant, J., Emerson, C., Wang, X. & Tang, T. 1996. Study on the carrying capacity of Sanggou Bay for the culture of scallop *Chlamys farreri*. *Mar. Fish. Res.*, 17: 18–31 (In Chinese).
- Ferreira, J.G., Duarte, P. & Ball, B. 1998. Trophic capacity of Carlingford Lough for oyster culture: analysis by ecological modelling. *Aquat. Ecol.*, 31: 361–378.
- Grant, J. & Bacher, C. 2001. A numerical model of flow modification induced by suspended aquaculture in a Chinese bay. *Can. J. Fish. Aquat. Sci.* 58: 1003–1011.
- Guo, X., Ford, S. & Zhang, F. 1999. Molluscan aquaculture in China. *J. Shellfish Res.*, 18: 19–32.
- Hawkins, A.J.S., Duarte, P., Fang, J.G., Pascoe, P.L., Zhang, J.H., Zhang, X.L. & Zhu, M. 2002. A functional simulation of responsive filter-feeding and growth in bivalve shellfish, configured and validated for the scallop *Chlamys farreri* during culture in China. *J. Exp. Mar. Biol. Ecol.*, 28: 13–40.
- Heasman, K.G., Pitcher, G.C., McQuaid, C.D. & Hecht, T. 1998. Shellfish mariculture in the Benguela system: raft culture of *Mytilus galloprovincialis* and the effect of rope spacing on food extraction, growth rate, production, and condition of mussels. *J. Shellfish Res.*, 17: 33–39.
- Pastres, R., Solidoro, C., Cossarini, G., Melaku Canu, D. & Dejak, C. 2001. Managing the rearing of *Tapes philippinarum* in the lagoon of Venice: a decision support system. *Ecol. Model.*, 138: 231–245.
- Pilditch, C.A., Grant, J. & Bryan, K.R. 2001. Seston supply to sea scallops (*Placopecten magellanicus*) in suspended culture. *Can. J. Fish. Aquat. Sci.*, 58: 241–253.

Raillard, O. & Menesguen, A. 1994. An ecosystem box model for estimating the carrying capacity of a macrotidal shellfish system. *Mar. Ecol. Prog. Ser.*, 115: 117–130.

Wildish, D. & Kristmanson, D. 1997. *Benthic suspension feeders and flow*. New York, Cambridge University Press. 409 pp.