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The Gerrico project: modelling to support Integrated Coastal Zone Management

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The Gerrico Project is jointly managed by Ifremer and the University of Nantes, and focuses on the Bay of Bourgneuf. Located in the South of the Loire estuary on the French Atlantic coast, this bay is extensively utilised for oyster farming (13,000 tons annually) and is characterised by many interesting habitats such as seagrass beds and honeycomb worm reefs.

The Bay of Bourgneuf has been faced with a number of problems in recent years such as oyster growth and edible quality, survival rates, the maintenance of water quality and biodiversity, and the sustainability of oyster farming and related activities.

The originality of Gerrico lies in its objective to develop methods capable of taking the entire area into account, from the watersheds down to the marshes and the coastal zone, using a chain of coupled models to integrate the different activities by combining physical modelling (sedimentology, hydrodynamics), biological modelling (growth of the algal biomass, oyster growth), and economic modelling (management of oyster rearing parks at the scale of the production basin or the shellfish farming business as a whole).

The common issue driving this approach is water quality, on which any optimisation of coastal activities depends.

Several scenarios at different spatial and temporal scales: increasing nutrients; oyster growth variability between farming sites, impact of trophic competitors (slipper limpets, wild oysters), or water carrying capacity assessment, for example, have been implemented in order to simulate the biological and socio-economic consequences of different types of management.

The objective is to establish a dynamic tool that will provide a reliable platform for integrated management of the coastal area.

Key words: physical modelling, ecological modelling, economic modelling, watersheds, marshes, coastal area, oyster farming.

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Introduction

Coastal marine resources are one of the natural riches of the Pays de la Loire region in France. They are fragile nevertheless, and subject to high levels of demand by many different users. The inherent risks of exploiting natural resources are heavily influenced by the sum total of human activities that create increasing pressure on the coastal strip and can lead to problems, conflicts and wastage.
Ifremer and the Universities of Nantes and Brest decided to join forces in 2007 in response to a call for action on the part of the Pays de la Loire regional authorities to address these challenges.
The purpose of Gerrico is to create a centre of expertise on the sustainable management of marine resources and risk in coastal areas, and ultimately put forward new solutions for their management. For this reason, a major component of this project is the development of pertinent tools to help decision makers.

The project focuses on oyster culture, which is particularly sensitive to environmental changes, and the development of human activities such as tourism, agriculture, and industry.

It has become apparent as the project runs its course that the activity of rearing bivalve molluscs poses a number of problems that can only be solved by a multidisciplinary approach, and many research teams are now collaborating and combining their different competencies in marine biology, physiology, economy, geography, and marine technology to address the particular problems this industry faces.

1 - The Bay of Bourgneuf

The Bay of Bourgneuf was chosen as a pilot site for a variety of reasons: the fact that of the human activities there, some have existed for many years (oyster farming, salt production) and some are more recent (tourism, spat production), plus its physical and biological properties (salty underground waters used for oyster rearing and spat production).

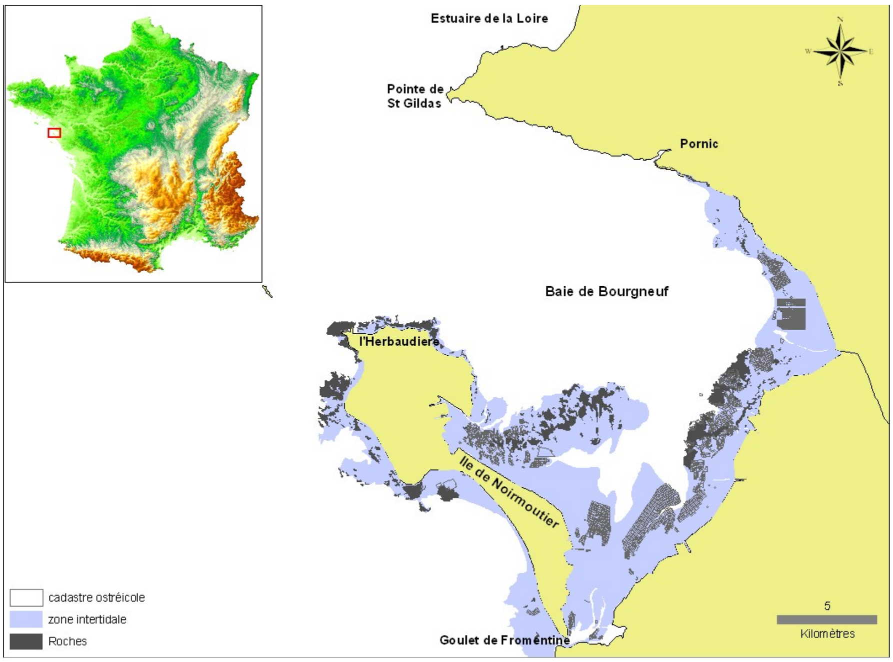

Figure 1 : location of the Bay of Bourgneuf

The Bay of Bourgneuf is located in the South of the Loire estuary on the French Atlantic coast. It is sheltered from the ocean by the island of Noirmoutier which is today linked to the continent by a bridge.

The mean depth is about 10m and the tidal range is about 6m. Turbidity levels can reach 200 $g.L^{-1}$, due to the combined effects of flooding in the Loire estuary and the fine sediments lying in the bay (Gouleau, 1968).
The intertidal zone is an area of about 100 km², and has both environmental and economic importance. Many interesting habitats are found here, such as seagrass beds and honeycomb worm reefs. Furthermore, the area is used relatively intensively by oyster farmers: 13,000 tons of oysters (10% of all French oyster production) are produced annually by 300 farms.

For a number of years the Bay of Bourgneuf has been faced with several problems including oyster growth (closely dependent on turbidity levels and the concentration of oysters growing on the banks) survival rates and product quality; spat availability; food safety; maintenance of water quality and biodiversity.

But there are also gaps in our knowledge about, for example, hydrosedimentary exchanges between local watersheds, the Loire estuary and the Bay of Bourgneuf, and the impacts of turbidity, pollution or climate change on oyster growth. Moreover, these kinds of problems have always been studied separately. Gerrico, conversely, aims to take all the problems occurring in the bay into account, and to understand how the bay functions globally so as to be able to propose the best possible solutions.

2 - Administrative structure of the Gerrico project

Gerrico is run jointly by Ifremer and the University of Nantes, and is monitored by an Evaluation and Diffusion Committee (EDC) that assesses the results produced by Gerrico's teams and sets out guidelines to improve research initiatives. The EDC is made up of local partners (the oyster farming and salt culture syndicates, the Water Agency, associations for water management or environmental protection) and three independent scientific experts.

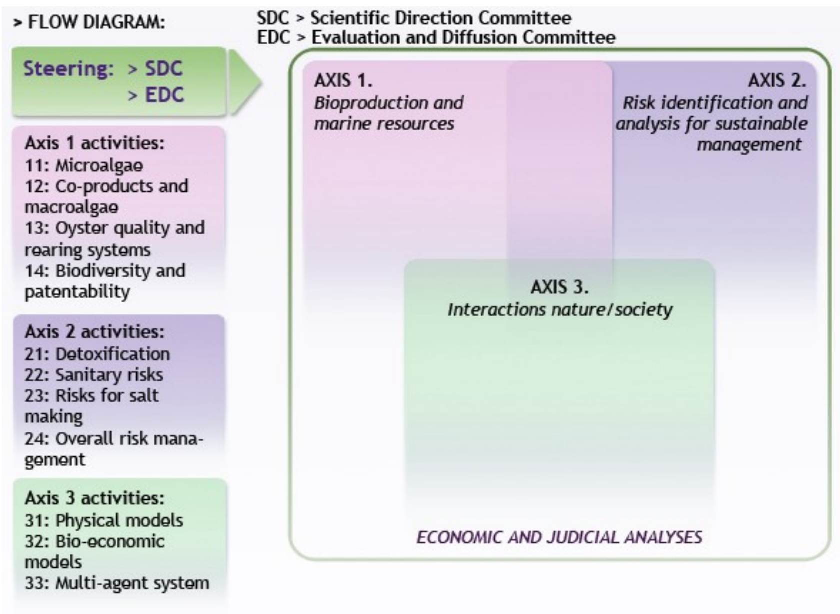

Figure 2 : Administering the Gerrico project

The Gerrico project has three main strands:

- **Bio production and marine resources :** this part of the project proposes to develop knowledge and production techniques along with their commercial applications in the areas of micro algae, shellfish farming, macro algae and fishery co-products, including new techniques and procedures potentially of interest for sustainable production ;
  As these questions are likely to inspire wide public debate, scientists specialising in maritime law will also be working in the area of marine biodiversity and the patentability of living matter and related legal aspects.

- **Risk identification and analysis for sustainable development :** part 2 of the project will enhance our understanding of the different risks oyster farmers have to face, including the public health risk (microbiological), the toxic risk (micro algae), the overloading of shellfish farming basins, multiple utilisations of the waters in and around the coastal zone, and interactions with other local users (agriculture and tourism). The outcome will be the identification of means of prevention, corrective action, and management that take into account the frequency with which these risks occur, their intensity and correlations between them.
- **Interactions between nature and society :** the objective of part 3 of the project is to study how inputs from local shellfish farming, and those from the sea and the estuary, affect water quality in the Bay of Bourgneuf, and to analyse the resulting constraints (natural, human) on oyster rearing. This is achieved by combining physical, biological and economic modelling techniques to build different development scenarios and simulate their impact. The results obtained by part 3 will be detailed below.

3 – Materials and methods

The originality of Part 3 of the Gerrico project lies in its objective to develop methods capable of taking the entire area into account, from the watersheds down to the marshes and the coastal zone. The common issue driving this approach is water quality, on which the optimisation of coastal activities depends. This part of our research will aim to establish a method that will provide a firm basis for integrated management of the whole coastal area.

The proposed methodology consists of building and combining models from the watersheds down to the coastal zone. This means that one or many models will be developed in any one project part or "compartment " (fig. 3) :

- an agro hydrological model in the watersheds compartment ;
- a hydraulic model in the freshwater and salt marshes compartment ;
- in the bay itself, physical models (hydrodynamics and sedimentology), biological models (growth of algal biomass, oyster growth) and economic models (at the scale of a group of individual farms or at the scale of the whole production basin).

The outputs each model provides become inputs for the following model : for example, nitrogen as an outcome of the hydraulic model will be used directly as an input for the hydrodynamic and sedimentary model. It goes without saying that at each step of the process field data are collected for the purpose of validating the different models.

An artificial intelligence model is envisaged for the purpose of suggesting different scenarios and simulating their impact. The model is based on a fine-scale spatio-temporal description of practices in the basin. The main idea consists of building a decisional tool (management tool) for coastal managers to help them identify priority areas where intervention is most needed to restore coastal water quality.

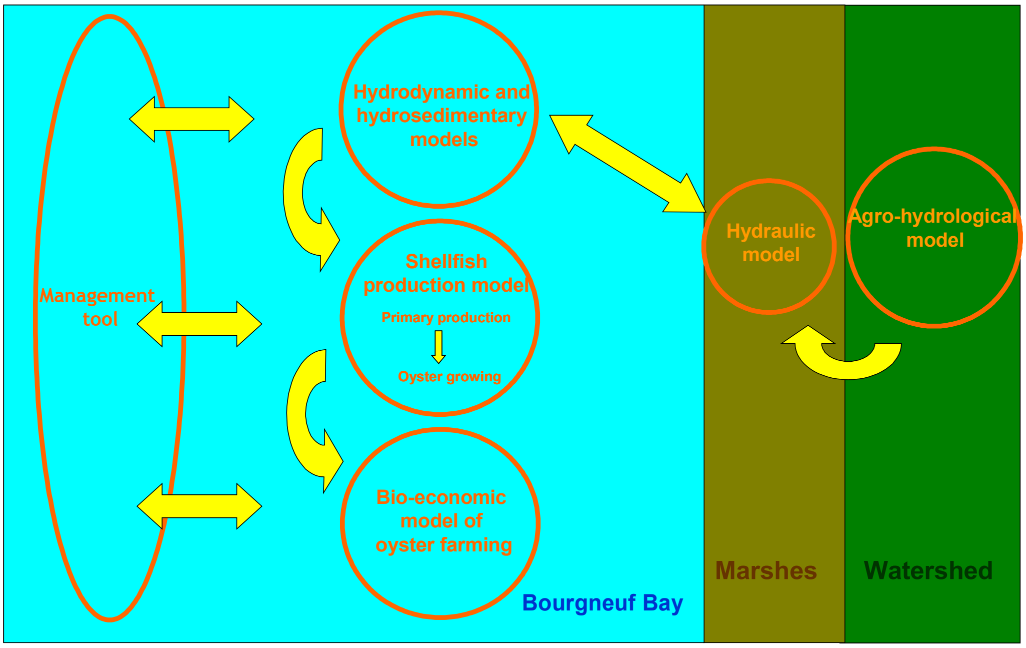

Figure 3 : the principle of coupling between models in the different project compartments

Several models were employed for the purpose of studying the "Bay of Bourgneuf and its watersheds" system, and adapted to suit the study zone in question ; in some instances, the models were interconnected.

- ✓ the **agro-hydrological SWAT®** model interfaced with ArcGIS (Di Luzio *et al*., 2002) models what happens to diverse substances utilised or produced in watersheds (nitrates, phosphates, bacteria, phytosanitary products…) as a function of land use (Conan *et al.,* 2003, Lomakine, 2005) ;
- ✓ **Mascaret®** is a mono-dimensional **hydraulic** model (CETMEF, 2008) that tracks what happens to diverse substances traversing the marshland area ;
- ✓ The **hydrodynamic Mars 2D** model (Salomon *et al*., 1991) has been used for many years to predict the behaviour of contaminants and the movements of larvae in the coastal zone (Riou *et al*., 2007) ;
- ✓ The **hydrosedimentary model, MIKE 21** (DHI, 2007), reproduces the behaviour of materials in suspension (Sanchez, 2008), this being a vital component in the overall functioning of the Bay of Bourgneuf (silting, and phytoplankton growth) ;
- ✓ The **biogeochemical ECO-MARS3D** model (Ménesguen *et al*., 2006; Lazure and Dumas, 2008) spatialises variations in primary production in the bay (simulation of temperature, chlorophyll *a*, and utilisation of the solids in suspension output from Mike 21) ;
- ✓ A purpose-built **biological oyster growth model** based on a Scope For Growth type model (Barillé *et al*., 1997) was specially developed in the Bay of Bourgneuf (Haure *et al*., 2008), and uses the data provided by ECO-MARS 3D as input ;
- ✓ the coupling of the **economic and oyster growth models** was initiated using the STELLA application to simulate the changing numbers of oysters being cultivated by the different kinds of oyster farming enterprises ;
- ✓ finally, a **multi-agent model** utilises output data from hydrosedimentary, biological and economic models to simulate how these activities operate at the scale of the individual marine concession (Tillier *et al*., 2010).

4 – Results and discussion

- ✓ the **agro-hydrological SWAT®** model is based on an exhaustive database structured around ArcGIS®. Now the model has been calibrated, we can simulate watershed flows using land use and land occupation as a starting point, and complementing this with meteorological and pedological data. The contribution each drainage basin makes to the flows entering the bay can be quantified and visualised (fig. 4). These drainage basins are for the most part agricultural, and the main substances tracked are suspended matter and nutrients. Phytosanitary products were not simulated by the model, because of the problems associated with obtaining reliable information on some of the agricultural practices in the area. Simulated data ouput from SWAT® is used as input data for Mascaret®.

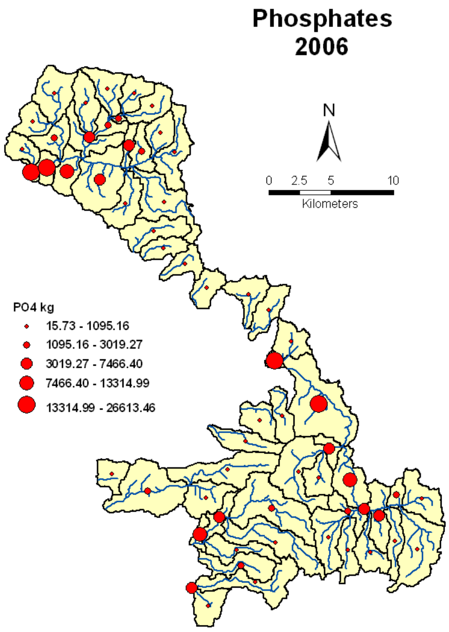

Figure 4 : identification of drainage basins yielding the highest levels of phosphate

- ✓ modelling the marshland area using **Mascaret®** in Part 3 of the Gerrico project represents an original advance because the hydraulic complexity of this type of zone situated between watershed and coastal water is rarely taken into account. Because of the relative complexity of this task, it was decided to model just the Falleron, this being the river responsible for the principal inputs in the bay. This modellisation enabled us to assess for the first time how long it takes water to traverse the marshland, and under different hydrometeorological conditions, and when subject to different types of hydraulic management. Difficulties encountered were mainly related to the lack of sufficiently detailed information for managing the hydraulic installations ; in addition, the flow data obtained are still insufficient for validation of the model. It is hoped that by 2011 we will be able to take the degradation of some substances (pesticides, bacteria) into account, once certain specific improvements have been made to the software.

- ✓ the **Mars 2D** model has allowed us to construct a number of simulations of dissolved substances (phytosanitary products, bacteria, nutrients). An attempt to couple the SWAT®, Mascaret® and Mars2D models was made for the purpose of tracking the movement of nitrates from the Falleron drainage basin through to the oyster parks (fig. 5). These results demonstrate that it is possible to set up a modelling chain that allows us to simulate transfers of water and solids in a continuum formed from different types of environment (drainage basins, coastal wet zones, coastal waters), that, once perfected, could be deployed in a coastal management setting (Gille *et al.*, 2009).

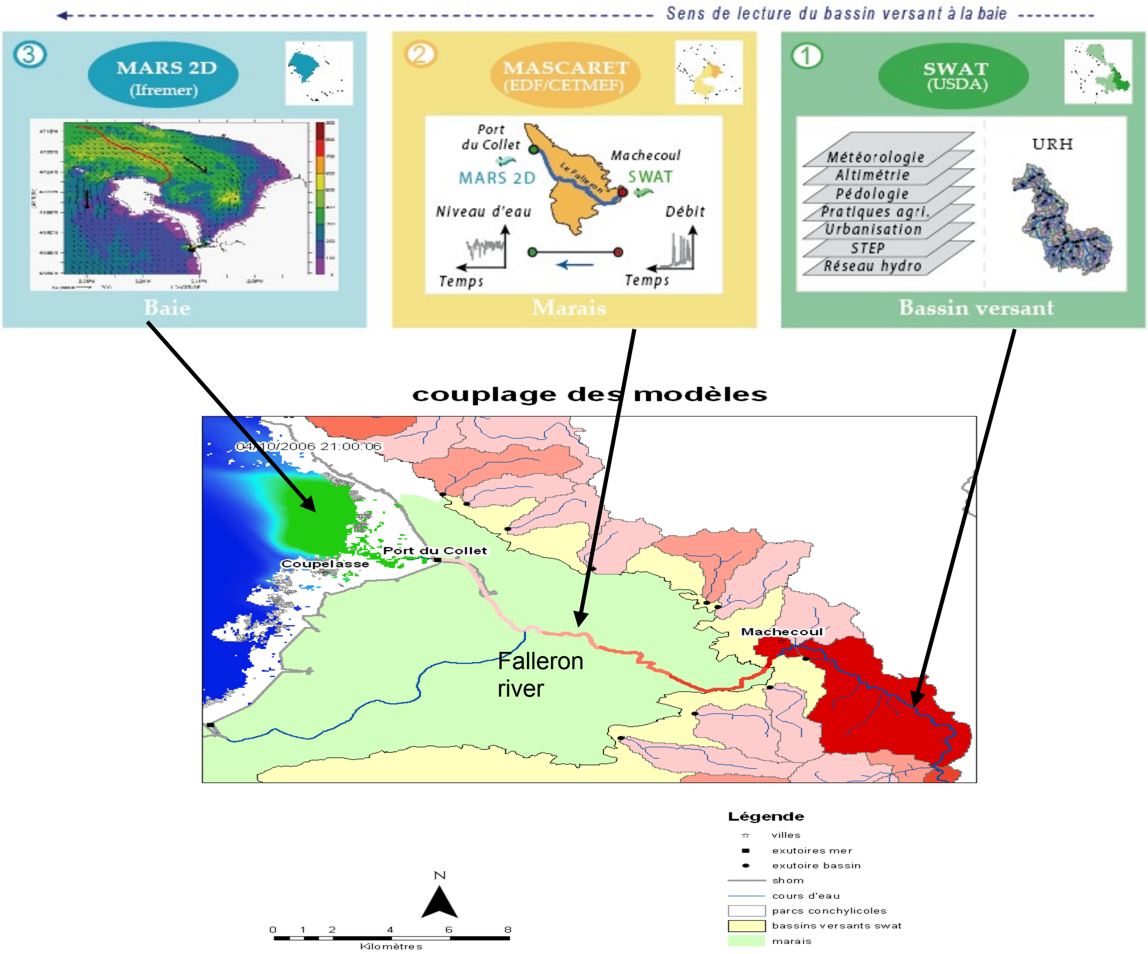

Figure 5 : Coupling circulation models for water and solid flows

- ✓ the hydrosedimentary model **MIKE 21** was used to map the turbid plume observed in the Bay of Bourgneuf in fine detail, notably thanks to refinements made possible by the utilisation of Lidar altimetric data acquired in 2008 on the intertidal zone (Dussauze *et al.*, 2009). The MIKE 21 model was validated (fig. 6) using ground truth data (ADCP, altimeter…) and satellite imagery (Lerouxel *et al.*, 2007).

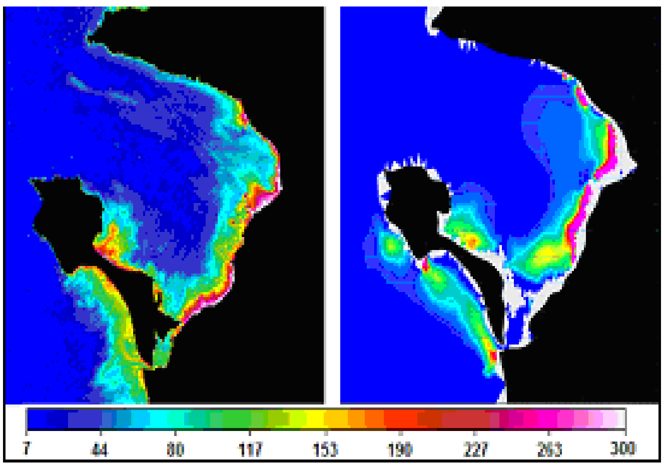

Figure 6 : Turbidity (mg L^{-1}) in the Bay of Bourgneuf. On the left is a SPOT image taken at 11.00 am on 13 December 2005; on the right is the result produced by the MIKE 21 model taken on the same day and at exactly the same time.

The model succeeds in reproducing variations in turbidity intensity in the bay. These variations are partly due to the fact that some bottom sediment can be put back into suspension (due to water turbulence, for example) and this is now taken into account by our model. These data are used as input for the primary production model.

- ✓ The biogeochemical model **ECO-MARS3D** simulates the evolution over time of the three forcing variables from the oyster growth model (Dussauze, 2008) : temperature, the concentration of suspended matter, and the concentration of Chlorophyll *a* (an estimator of food).

- ✓ The oyster growth **biological model** uses data provided by ECO-MARS 3D as input data. A comparison of growth simulations and observations reveals a close match between model and data for the three main compartments of the oyster growth model: gonadal reserves, soma, and oyster-flesh dry weight. The results of the growth simulation indicate a strong spatial variability depending on the oyster producing area, as a function of immersion times and above all turbidity intensity (fig. 7, right). Finally, coupling the model with ECO-MARS 3D allowed us to construct different scenarios with varying stock concentrations of trophic competitors (slipper limpets and wild oysters, fig. 7, left). The ecosystem model now functions with a realistic turbidity signal, and equally well for short term variations (semi-diurnal tidal cycle) as for seasonal variations. This represents a significant improvement in our ability to simulate the way a macrotidal ecosystem operates, and this for ecosystems with some of the highest turbidity levels in Western Europe (Barillé *et al*., 2004).

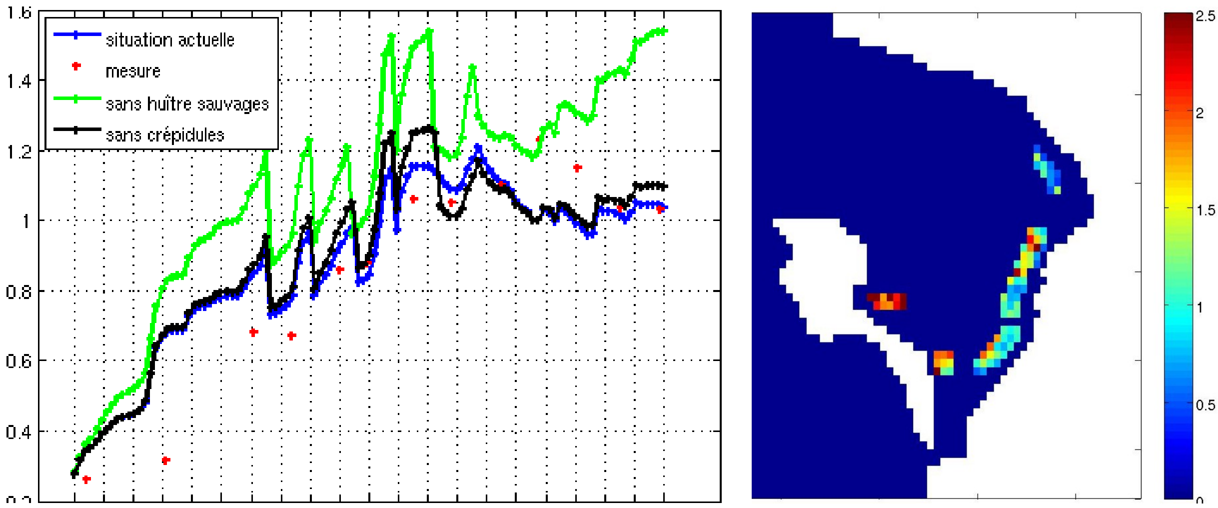

Figure 7 : impact of populations of trophic competitors (on the left *: slipper limpets and wild Crassostrea gigas - March to September 2005. Field measurements : red. Model : current situation in blue, without wild oysters in green, without slipper limpets in black*) and spatial variations in the annual growth of oysters (on the right)

- ✓ **Economic modellisation** of the functioning of oyster farming activity in the bay of Bourgneuf required us to conduct a survey with enterprises directly, and to gather countable data. This preliminary work enabled us to define 3 types of enterprise, and their respective financial profiles, and this has considerably improved our knowledge of the oyster farming industry in the Bay of Bourgneuf (Le Grel et Le Bihan, 2009). However, some areas of obscurity remain due to the difficulty of accessing information on oyster farming practices.

- ✓ The results obtained with the **DAHU-MAL multi-agents platform** are essentially methodological. Nevertheless, a case study is in progress, and this will enable us to illustrate how activities evolve while taking into account production strategies, the associated spatial organisation, and the different species involved. A simplified version of the model produced by Barillé *et al*. (Haure *et al*., 2008) was implemented within the platform. This initiative enabled us to simulate the impact of turbidity on oyster growth and how production infrastructures might usefully be adapted as a result; it yields a good match with the results obtained by the biological model (fig. 8). Any remaining difficulties are due to the requirement for copious amounts of very varied data to be able to validate the different steps of the production cycle.

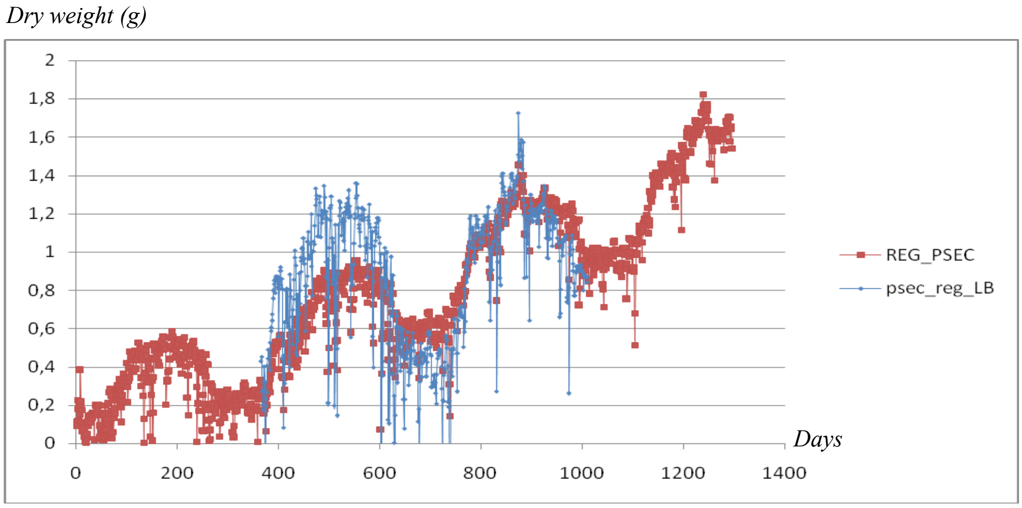

Figure 8 : Variability in dry weight of *Crassostrea gigas* under environmental constraints (T, Chl*a*, suspended matter) over the period 2004-2007. The simulation using a multi-agent model is shown in red, and the simulation using a biological model, in blue.

Conclusion and new perspectives

These results show that it is possible to set up a modellisation chain enabling us to simulate the transfer of water and solids in a continuum made up of different types of environment (drainage basins, coastal wetlands, and coastal waters).
Coupling between the models represents a significant advance in terms of the integration of tools for scenario construction and decisional support.
A scenario integrating all the project compartments has been tested, and opens possibilities for other scenarios such as shellfish culture offshore, the deteriorating quality of coastal waters, or changing agricultural practices.

This new tool will allow us to work with greater precision on problems linked to bacterial concentrations and concentrations of phytosanitary products and their elimination, this being a critical problem in numerous coastal zones.
Nonetheless, there remain new avenues for perfecting this system that could be usefully explored, whether at the thematic level, with the refining and enhancing of some data relating notably to agricultural and oyster farming practices, or at the technical level, with, for example, automated couplings between models.

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