The role of hydrodynamics in environmental studies. The case of tidal seas

Environmental studies
Modelling
Hydrodynamics
Water quality
Coastal management

Études d'environnement
Modélisation
Hydrodynamique
Qualité des eaux
Gestion du littoral

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ABSTRACT

The purpose of this review is to highlight the importance and fields of application of knowledge of currents in environmental studies. Several topics are successively addressed: they include current measurement techniques and the possibilities and applications of existing models (dispersion, sediment transport, primary and secondary production...). Some uses in the field of coastal engineering, water quality management, coastal management, oceanographic studies, *etc.* are briefly described.

The conclusion is that knowledge of currents is a compulsory stage in all coastal environmental studies.

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RÉSUMÉ

Rôle de l'hydrodynamique dans les études d'environnement. Cas des mers à marée

La connaissance des courants est primordiale dans les études concernant l'environnement littoral. Le champ d'application est très étendu.

Après avoir brièvement passé en revue les moyens actuels de détermination des courants (mesures), on décrit les possibilités actuelles des modèles (2D, 3D) ainsi que leur champ d'utilisation (études de dispersion, transport sédimentaire, production primaire et secondaire). On décrit ensuite brièvement quelques applications possibles dans le domaine du génie côtier, de la gestion du littoral, des études océanographiques, *etc.*

La connaissance des courants est une étape obligatoire dans toutes les études d'environnement littoral.

Oceanologica Acta, **1991**. Actes du Colloque international sur l'environnement des mers épicontinentales, Lille, 20-22 mars 1990, **vol. sp. n°11**, 29-46.

INTRODUCTION

Until recently man managed the coast without much concern for consequences that were not directly related to his immediate interests. During the last fifteen years, however, public opinion has become sensitive to environmental protection and the increasing development of coastal activities calls for some foresight with regard to the impact of new projects on the environment and the diverse activities already taking place in the zone in question.

Any coastal activity not only uses raw materials or space but also alters the aptitude of the site to support other uses. Projected or established activity, although profitable, could contribute to an eventual economic decline of the whole system or even degrade the coastal zone to an irreversible extent.

In France, the Environmental Protection Law of 10 July 1976 states that "development projects or works, which are undertaken by a public body or which require authorization, must respect environmental considerations".

Studies to determine or predict the impact of such development are largely based on hydrodynamics. Sea currents transport masses of water with their biological and chemical content, mix all these substances (natural or anthropic) and are the source of physical stresses exerted on the sea bed and immobile structures.

RANGE OF PROBLEMS

The coastal activities requiring a knowledge of dynamics include:

Waste discharge

The fundamental problem facing environmental engineers is that posed by the dilution of effluents of all kinds discharged into the sea, and the associated long-term persistence and effects. Waste input can comprise point source discharge (urban and industrial) or non-point source discharge (agricultural). In the latter case, non- point sources are those that provide input into waterways in the form of stormwater runoff from agricultural, urban and forest lands and from baseflow to streams and atmospheric deposition on land and water.

Pollutants may be conservative (trace metals, certain organic pollutants such as PCB, DDT...) or biodegradable. Decision makers should not have the same waste management policy in both cases. In the former case, disposal must be limited to the greatest extent possible whatever the site. In the latter case, the dominant circulation processes of the site or the acceptance capacity of the sea should be taken into account: some wastes can cause problems in sheltered areas but not in exposed zones. This is especially true for nutrients ; in enclosed zones consumption takes place locally as dispersal exchanges are low. Wherever there is large flushing rate, nutrients are transported and diluted by the water mass. If off- shore water is not too enriched (often the case for France) good dispersion of waste can be a solution to its "elimination". If the offshore water mass is already very enriched (as in the North Sea, for example) the problems are merely displaced.

Dredging

The pursuit of economic activity in ports often requires maintenance or exploitation dredging (canal deepening). Dredging cannot be done without impaction the environment. Its most important effects are the following: release of soluble pollutants; modification of currents and salinity regimes following the deepening of a coastal zone; alteration of benthic populations; decrease of photosynthesis as a result of increased turbidity; submerged bottoms and coastal wetlands and tidelands with their associated organisms, are often obliterated by dredging.

Development

Development can include:

Construction of ports, dikes, beaches, groins

They locally modify currents, coastal drift, water residence time, turbidity...,which affect sediment patterns of the seabed (and thus the nature of benthic populations), biological production (anoxia, red tides), nearby seagrass beds.

Dam construction (in estuaries or across rivers)

It regularizes the flow and decreases sediment input; modifies the stratification of coastal waters with consequences on currents, oxygen content of waters...; can change the ecology of a coastal zone and fishing stocks (decrease in freshwater input).

River diversion

The consequences are generally important: increase in the stratification at the river mouth can induce deoxygenation or anoxia of the bottom layer (étang de Berre after diversion of the Durance), changes in the sediment residual drift after stratification may require noticeable increase of dredging (Charleston harbour, *in* Simmons and Herrmann, 1972).

Opening or closing a lagoon or coastal pond

This can have major consequences. The ecology of the site can be completely modified (fresh or seawater, residence time of very different waters, different sensitivity to eutrophization and pollution...).

This brief summary, which is by no means exhaustive, demonstrates the economic importance of coastal development and the conservation of a certain quality of environment.

DETERMINATION OF CURRENTS

Without exception, some knowledge of coastal dynamics is an indispensable stage in understanding the phenomena and the correct organization of research studies. Dispersion reflects, in reality, the current gradients and high frequency turbulence components. The core of the problem is to determine currents at every scale of space and time.

Several techniques are available: direct measurement by current meters; direct measurement by drogue tracking; direct measurement by radar; indirect measurement by observation of tracers of water masses (dye diffusion and artificial radioactive tracers); calculation by hydraulic or mathematical models.

These methods are not equally valid. They have different results and areas of application, but mathematical modelling has recently made considerable progress and is today an indispensable tool not only for decision makers (who have already been using them for several years) but also for the other disciplines of oceanography (chemistry, biology, bacteriology...).

After a discussion of the present state of current determination, some possible developments will be presented: sediment transport, modelization of primary and secondary production. The paper will conclude with some applications of present-day knowledge.

Determination of currents by measurements

Current meter

This technique, much employed a few years ago, presents many disadvantages: difficult and costly deployments; record only what happened at a single point (known as an Eulerian representation); need for mooring of numerous current meters to take into account complex bathymetry which generates a large heterogeneity of currents; .need for long recordings (over one month) to ensure correct interpretation of measurements; frequently erroneous measurements; very low precision: long-term drifts are difficult to extract from the global signal.

Drogue tracking

Drogues equipped with a floating anchor and little influenced by wind can be tracked from land (by a theodolite) or by radiolocation (Argos satellite). Data interpretation is rather delicate but produces what is known as a Lagrangian representation of the currents. However it is difficult to separate the significant part of the signal from the random influence part created by localized gyres of little relevance. Despite improved design, drogues may be sensitive to the wind and cannot be used if the influence of the latter is too important. Such measurements are generally expensive (purchase or hire of buoys, hire of boat for launch and recovery, losses...).

Radar

Measurements of high-frequency radar echoes back-scattered from the sea surface can be used to deduce information on both waves and surface currents. This technique is relatively new and should be used, in the future, as a complement to 3-D models.

For exemple, Prandle (1987) obtained thirty days of synoptic hourly surface current vectors for 84 locations within a nearshore region some 18 km square. The data were separeted into tidal and non tidal notions. It was possible to determine the wind-driven component and the influence of density-driven currents.

Tracers

Dye diffusion in sea water can describe, as a function of space and time, the concentration of a substance dispersed by the combined effects of stirring, mixing and diffusion. This method is often disappointing in the coastal region : it requires a large number of observations, gradients are large, sources are multiple and tracers are often non-permanent.

Remote sensing provides a synoptic view only on the surface and the parameters it detects are short-lived.

Artificial radioactive tracers can give a good representation of general long-term movements.

Determination of currents by hydraulic models

(This subject is beyond the scope of the present paper). Today, hydraulic models are no longer used for current determination except for modelling nearshore field currents and cases where mathematical modelling is not yet competitive as, for example, in the case of sediment transport influenced by current and swell.

Determination of currents by mathematical modelling

In hydrodynamics, a mathematical model is a sequence of calculations resolving the so-called Navier-Stokes equations, which describe the movements of a fluid and its dissolved constituents, and which, in theory, enable almost all sea movements to be described and predicted.

In practice, their solution being extremely complex, it is necessary to simplify them case by case to resolve each problem at reasonable cost.

Usually, the following separation of frequencies is carried out: high frequencies (turbulence); movements of a few hours (tides); long term movements (general circulation).

Scientists also endeavour to reduce the number of spatial coordinates and define one-dimensional (1-D) models (vertical or horizontal co-ordinates), two-dimensional (2-D) models (horizontal and vertical planes) and three-dimensional (3-D) models :

- 1-D current models are adapted to fluvial conditions and are of little interest in sea studies except in estuaries;

- 2-D models are at present the essential tool for applied marine studies. They are very efficient, quick to set up, unexpensive and very precise (Le Hir, 1986; Mauvais *et al.*, 1989; Nihoul et al., 1989; Salomon, 1989);

- three-dimensional (3-D) models are top-range. They are particularly well adapted to marine studies of vertical movements that are often too slow to be measured by current measurements of wind-induced currents, and of the dispersal of fluvial plumes (ex.: Backhaus, 1985; Backhaus and Soetje, 1988; Darras *et al.*, 1987; Manoha, 1989; Lazure *et al.*, 1990...).

In every case the models calculate currents, water levels and concentrations of dissolved substances provided the following imperatives are satisfied: knowledge of depths throughout the site; knowledge of fluxes (of water and dissolved elements arriving on the site from river inputs, *etc.*); knowledge at each moment of water depths and concentrations on the perimeter of the studied site.

This final condition is very constraining, as water depths are rarely known with sufficient precision. Scientists often proceed, therefore, by successive approaches according to the detailed sub-model method: an initial large-scale model uses the offshore boundary conditions; a second smaller-scale model then uses the boundary conditions of the previous study and so on. In this way it is possible to determine the currents of a bay or port basin.

Grid size can vary from several kilometres (large-scale model) to a few metres (detailed models). Grids can be regular or variable using the Cartesian coordinates and spherical or cylindrical systems.

Apart from the determination of existing currents, in which it competes with previous methods, mathematical modelling also has the enormous advantage of permitting simulation, *i. e.*, the prevision of a hypothetical situation corresponding to the geometry of a site (canal digging, dike construction) or fluxes introduced to, or excluded, from the studied zone. It is consequently the best tool for development studies.

RESULTS OF MODELS

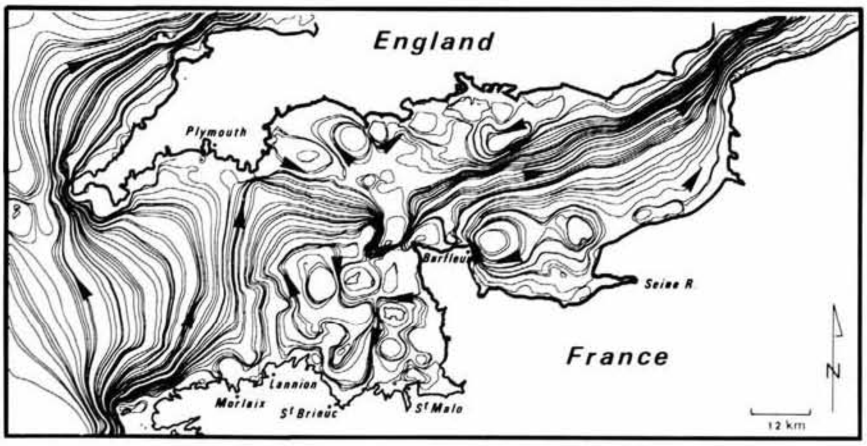
Tidal currents

Tidal mechanisms are the easiest to simulate because they constitute a deterministic phenomenon. Moreover the tide is a barotropic phenomenon, that is, it acts in a uniform manner on the whole of the water layer. It is therefore possible to develop 2-D models (in a horizontal plane) which are now highly-perfected.

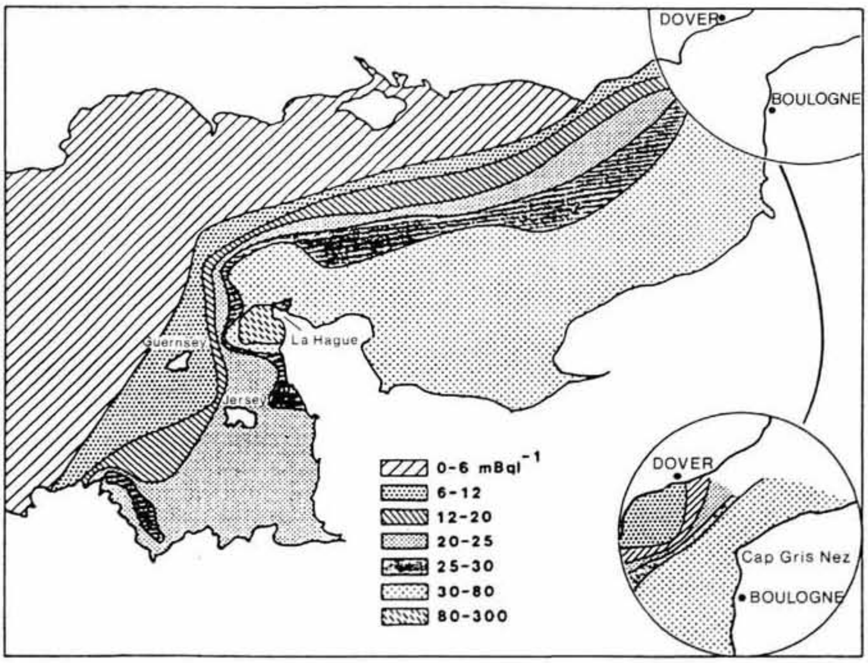
The comparison of calculated with measured currents is a delicate one. In the one case, it is a pin-point measurement; in the other case, the information represents the average current in the grid studied. There is, however, a generally good agreement between models and measurements.

Tidal residual circulation

If the currents of several cycles of tides are filtered by introducing variations due to spring and neap tides to the



a



b

Figure 1

a: Long-term circulation in the Channel (no wind; J.-C. Salomon).
*b: ^{125}Sb dispersion in the Channel (P. Gueguenia*t et al.).

a : Circulation à long terme en Manche (J.-C. Salomon).
b : dispersion de ^{125}Sb en Manche.

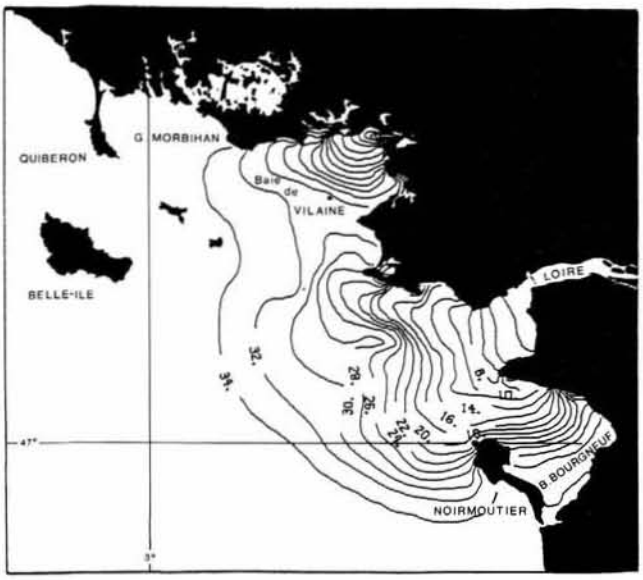


Figure 2

Salinity field near the surface, Loire-Vilaine (J.-C. Salomon, P. Lazure).

Champ de salinité près de la surface dans le secteur Loire-Vilaine (J.-C. Salomon, P. Lazure).

boundary conditions of the models, an average circulation, where tide has disappeared, is obtained. This circulation is induced (excluding the spring-neap tide cycle) by topographic effects, islands, headlands (vortex creation), tidal wave distorsion (propagation at low depth...).

Figure 1 (Salomon *et al.*, 1988; Gueguениat *et al.*, 1988) shows the good agreement between tide residual circulation in the English Channel and the distribution of a radioactive tracer which would be considered permanent (^{125}Sb). The privileged trajectories of transportation correspond to the isolines of concentration. Dispersion and the presence of eddies ensure homogenization between the main trajectory and the coast.

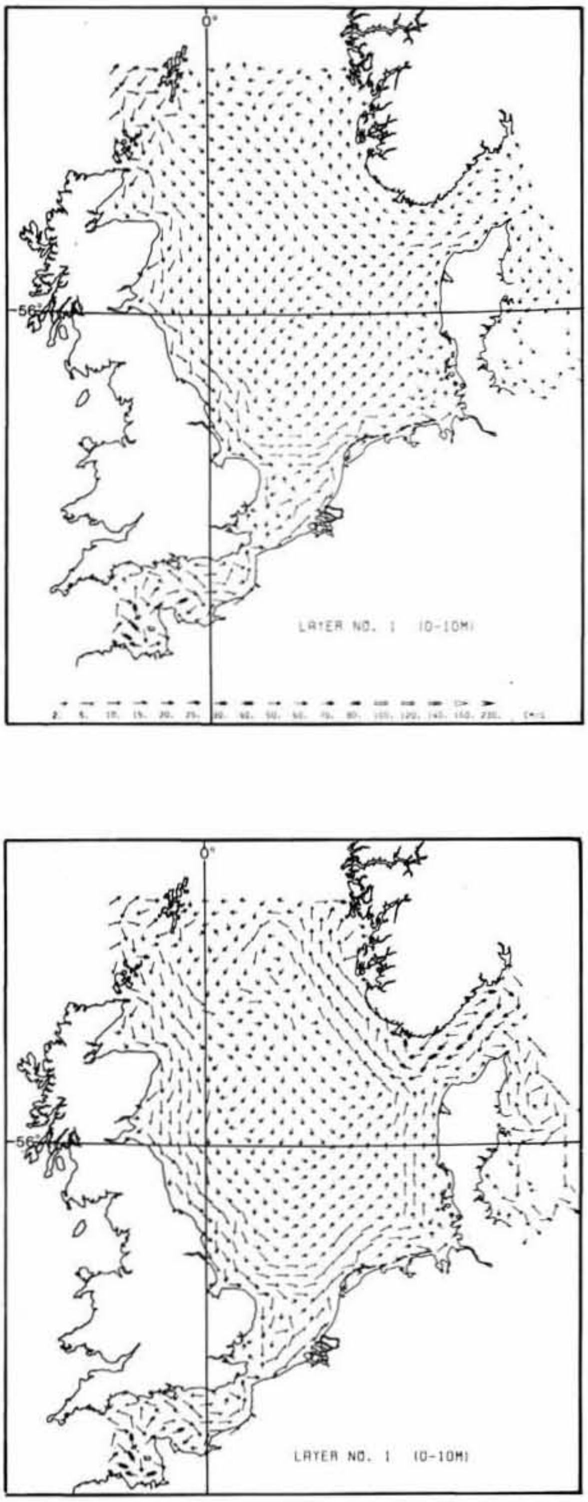
Currents created by differences of density

Fresh water of continental origin mixes with sea water inside estuaries and along the coastal zone. The different salinities create the characteristic circulation of estuary zones: residual circulation directed downstream at the surface and upstream at the bottom. In the coastal zone, geostrophy, friction and density induce helicoidal currents between the surface and the bottom. Natural heating of water in summer creates the same type of phenomenon but on a smaller scale.

It is obvious that the stratification which provokes vertical currents cannot be simulated with 2-D models which integrate current velocity in the vertical dimension. 3-D models, the development of which is more recent, must be used.

Figure 2 (Salomon and Lazure, 1988) represents the salinity field near the surface in the Loire/Vilaine sector. It is possible, using a 3-D model, to study the modification of currents induced by the salinity gradients. Comparison with Figure 3 shows the modifications induced in the circulation in the North Sea by density gradients (Backhaus and Maier-Reimer, 1983).

Whenever, for reasons of cost, it is not possible to use a 3-D model, 2-D horizontal models, with two layers, can be used. Information is obviously degraded but may be satisfactory.



Barotropic
No wind
No density

Baroclinic
No wind
density

Figure 3

Tidal residual currents (Backaus et al., 1983*).*

Courants résiduels de marée (Backaus *et al.*, 1983).

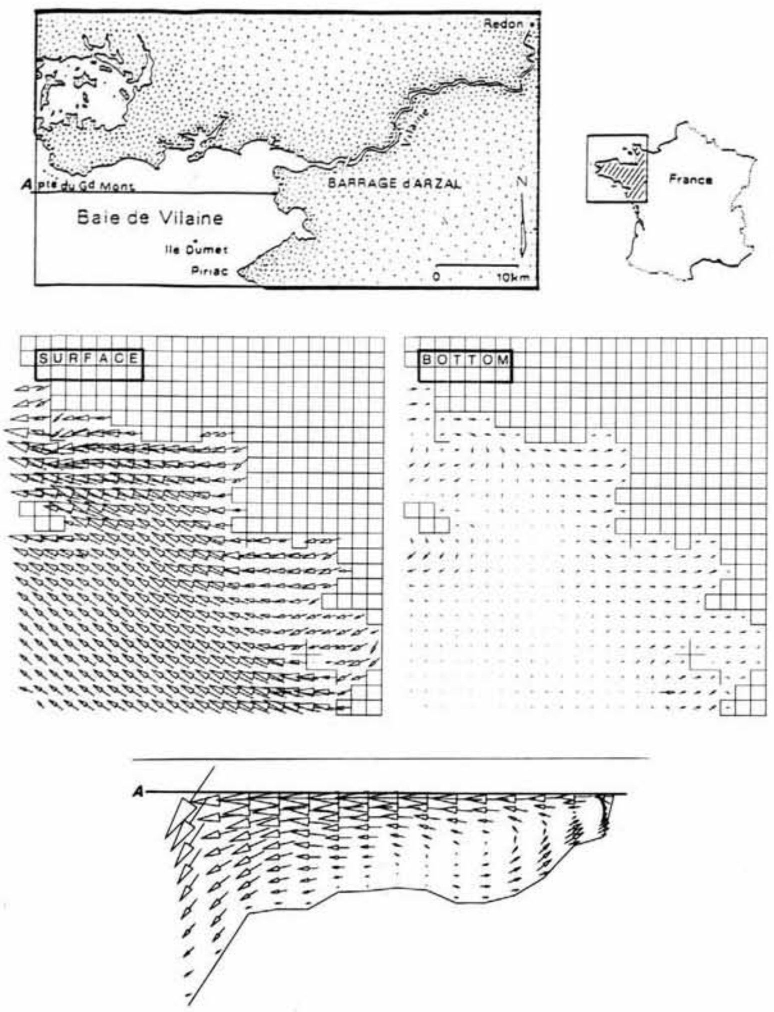


Figure 4

Some horizontal and vertical movements induced by the wind in the Loire-Vilaine sector (P. Lazure).

Courants horizontaux et verticaux induits par le vent dans le secteur Loire-Vilaine (P. Lazure).

Currents induced by wind

In coastal zones, wind is often the main driving-force of long-term movements. It acts on the water surface, which itself transmits part of this force towards the lower layers by turbulence and viscosity. At sea, the current only concerns the first few tens of metres of water. Near the coast, currents are guided by the form of the sea bed. The speed component, which is annulled, creates a depression or an accumulation of waters, consequently a pressure gradient. This in turn is accompanied by vertical movements and geostrophic currents which are superimposed on the original drift.

The result can be complex. It is often difficult to observe because wind is by nature highly variable and weak currents are masked by the tide (whenever present). It is equally difficult to study theoretically because, in contrast with the tide, the vertical dimension must imperatively be introduced into the calculations.

Logically, the study of wind-induced currents requires 3-D modelization. In practice, 2-D models are, regrettably, quite often used as costs are lower and their use much more simple. Results are partly erroneous. Scientific engineers must use 3-D models as soon as possible. However, it is wise to analyze carefully the advantages of 3-D models together with their increased cost.

Figure 4 shows some horizontal and vertical movements induced by the wind in the Loire-Vilaine sector (Lazure and Salomon, 1990).

When we consider only the average modification induced by wind on the general circulation, it is possible to use a 2-D model which will give reasonable results when limited to quite short periods. For long-term general circulation (several months), important precautions must be taken. Besides compulsory use of 3-D models, good meteorological statistics must be available. Backhaus (1985) was able to carry out a simulation in the North Sea for six months. In one calculation, the wind was introduced by its daily average velocity; in another, in the form of its monthly average velocity. Comparison of trajectories obtained by the two simulations over six months showed differences of several hundred kilometres.

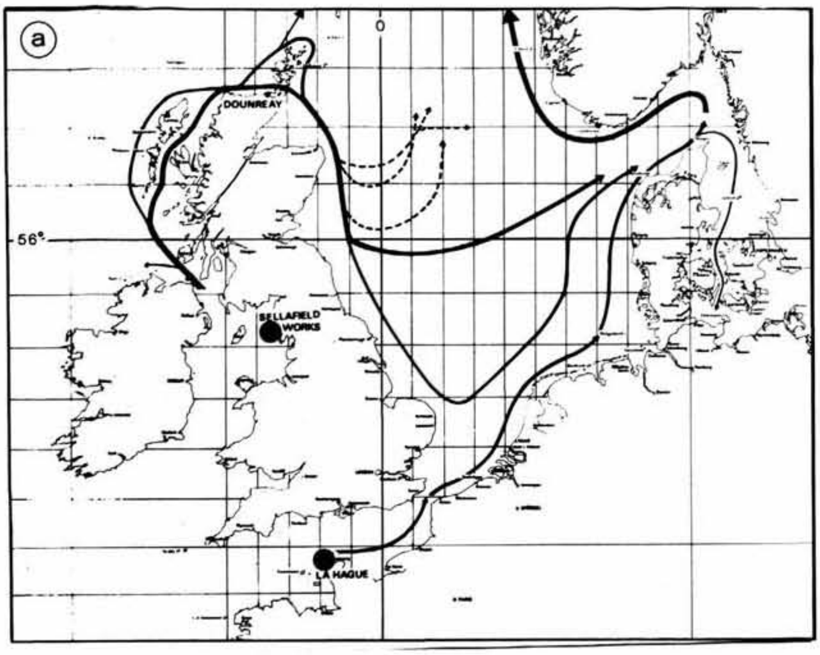
Residual circulation in the North Sea, under different meteorological conditions, has been widely studied, in particular by van Pagee (1986; 1988), Backhaus and Maier-Reimer (1983), Backhaus and Hainbucher (1987), Nihoul *et al.* (1989) and Prandle (1984; 1987).

In the North Sea, tidal residual circulation is sometimes very small. Meteorological conditions thus play an important role in long-term movements of the water mass. Comparison of residual circulation in winter, established by Nihoul (1989), with the map of trajectories of Cs^{137} (Fig. 5) deduced from measurements (Kautsky, 1988) shows the agreement between models and long-term drift.

UTILIZATION OF MODEL RESULTS

Dispersion of dissolved elements in water

Resolution of the advection-dispersion equation permits the calculation, without difficulty, of the dispersion of a dissolved element (pollutant), supposed permanent. Whenever general circulation is strong, dispersion can be treated satisfactorily in a simplified manner. When advection is low, dispersion plays a very important role (turbulence) and must be studied carefully. Figure 6 shows two schematic representations of the concentrations of a pollutant in terms of the relative importance of advection and dispersion.



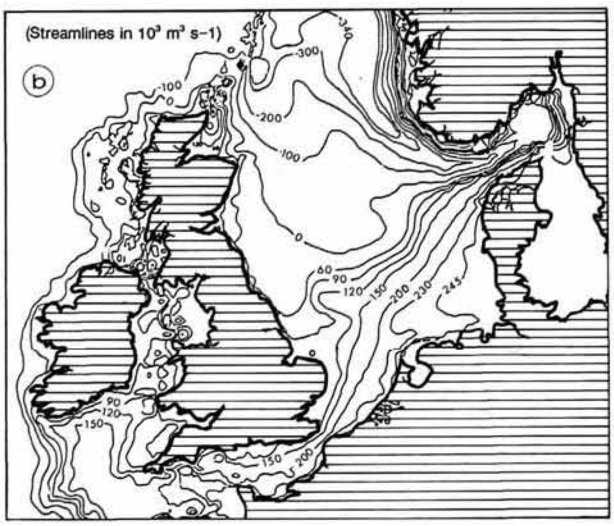


Figure 5

a) Comparison between transport routes of Cs_{137} deduced from the measurements of the activity concentration distribution in the years 1971 to 1984. Dotted lines indicate temporary different transport routes (H. Kautsky).
b) and calculated residual circulation in January (J.C.J. Nihoul et al.*).*

a) Trajectoires des rejets de Cs_{137} déduites de mesures d'activité. Les pointillés indiquent des trajectoires temporaires (H. Kautsky).
b) Circulation résiduelle en janvier (J.C.J. Nihoul *et al.*).

For non-permanent dissolved constituents, the laws of consumption or disappearance must be introduced into the model. As these laws are less well-known than the law of physical dispersion, they are generally the parameters which limit the performance of the model. The model permits simulation of different laws of consumption and dispersal, and the consequent enhancement of relevant knowledge. Figure 7 (Salomon and Pommepuy, 1990) shows the simulation of enterobacteriae wastes. Analysis of these results linked with on-site measurements shows, on the one hand, that physical dilution of effluent plays a more important role on concentration than die-off rates and, on the other hand, that survival times vary from a few hours to a few days (die-off is low in high turbidity, moderate sunshine, large concentrations of nutrients and organic matter...).

The fate in the sea of a warm water mass (*e.g.* from a nuclear power plant) can be assimilated to that of a non-permanent dissolved pollutant ; exchanges with the atmosphere are treated as disappearance rate. Numerous 2-D and 3-D models of thermal plumes have been developed. Figure 8 (Manoha, 1989) shows a 3-D simulation of the plume for the Gravelines nuclear power plant. Measurements carried out on the power plant site confirm the results of modelling, principal differences occurring at slack tides.

Dispersion of elements associated with particles

Numerous pollutants are adsorbed on particulate matter especially on the fine grain fraction of sediments (mud and organic matter). By adsorption to certain material the laws of decreasing bacteria or viruses can be modified. It was possible to show very long survival times (die-off rates of fourteen days with a maximum value of forty days). Besides advection and dispersion, the settling of particles, the deposition rate and resuspensions must also be taken into account. At depths of less than 20 m, there could be resuspension caused by swell. In order to study an average

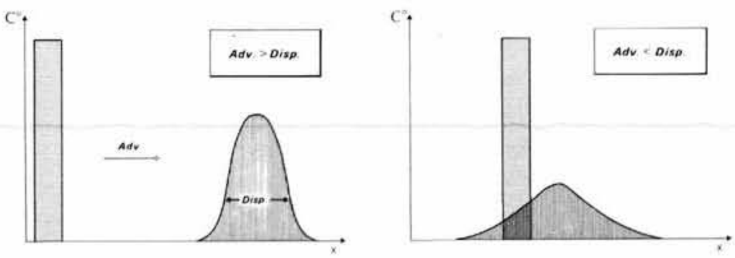


Figure 6

Relative importance of advection and dispersion (J.-C. Salomon):
- whenever general circulation is strong, dispersion can be treated satisfactorely in a simplified way;
- when advection is low, dispersion plays a very important role (turbulence) and must be studied carefully.

Importance relative de l'advection et de la dispersion (J.-C. Salomon).

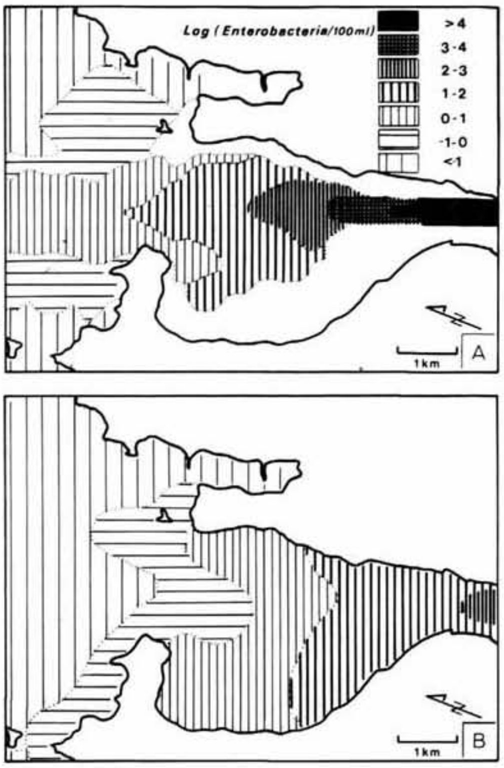


Figure 7

Enterobacteria concentration modelling at low and high tide in the Bay of Morlaix (J.-C. Salomon and M. Pommepuy).

Modélisation de la concentration en entérobactéries à basse mer et pleine mer en baie de Morlaix (J.-C. Salomon, M. Pommepuy).

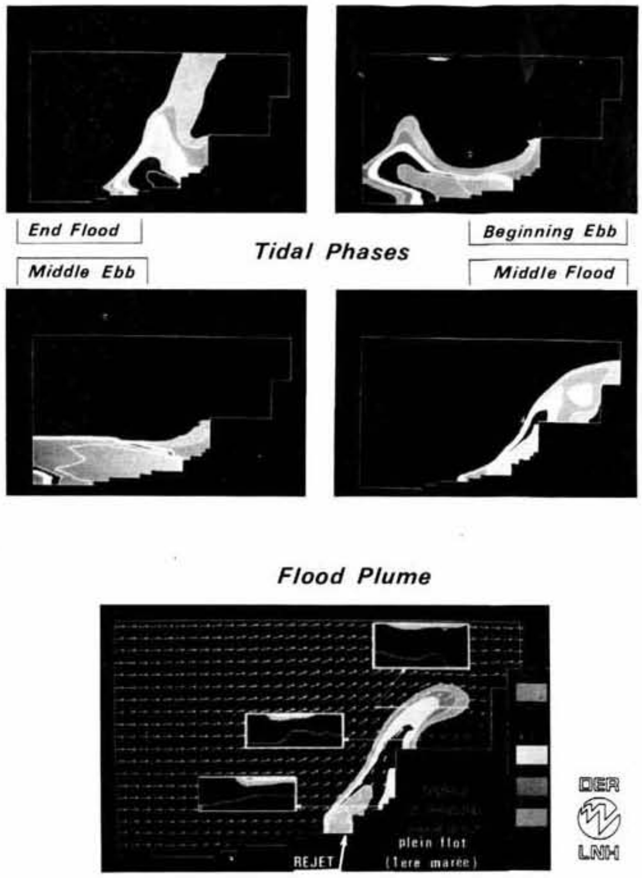


Figure 8

Gravelines nuclear power plant: 3-D thermal plume simulation (L.N.H.).

Centrale de Gravelines : simulation tridimensionnelle du panache direct (L.N.H.).

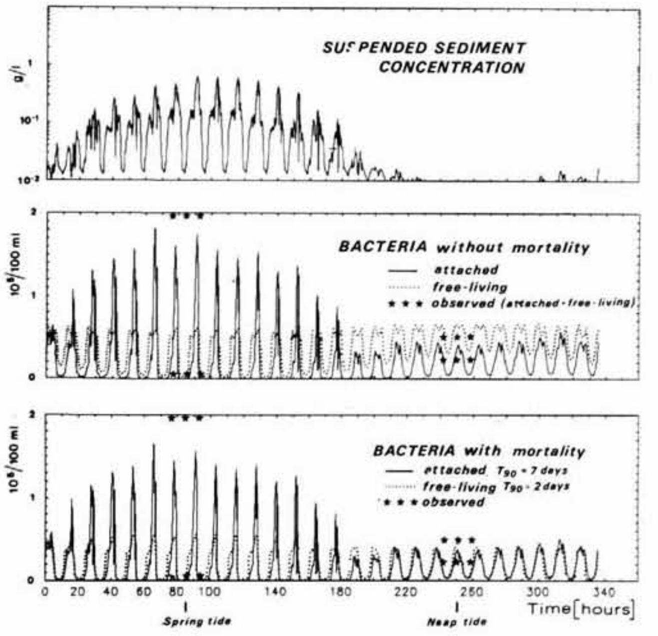


Figure 9

Suspended load and bacteria concentration (free living and attached). Bay of Morlaix (P. Le Hir).

Concentration, en un point, des matières en suspension et des bactéries (liées et libres). Baie de Morlaix (P. Le Hir).

transportation the action of currents is often studied without taking into account the effects of swell.

Figure 9 (Le Hir *et al.*, 1989) represents the enterobacterial concentrations obtained by disassociating the part of free bacteria from those adsorbed on the sediment in the Morlaix river.

Transportation and dispersion of sediments

Movements of fine sediments are usually distinguished from those of coarse sediments (*e.g.*, van Rijn, 1989).

Coarse sediment (sand and gravel)

They behave more simply than mud (whenever they are not mixed with mud). They are not altered and do not flocculate. They are partly transported in suspension (the finest) and partly near the bottom by bed load transport.

Their movement cannot, however, be described with precision. Numerous experimental results have been obtained in laboratories in order to determine the quantities transported in terms of a certain number of parameters (current velocity, shear stress, mean grain size...). Unfortunately, divergence with experimental results is large and no formula is really satisfactory.

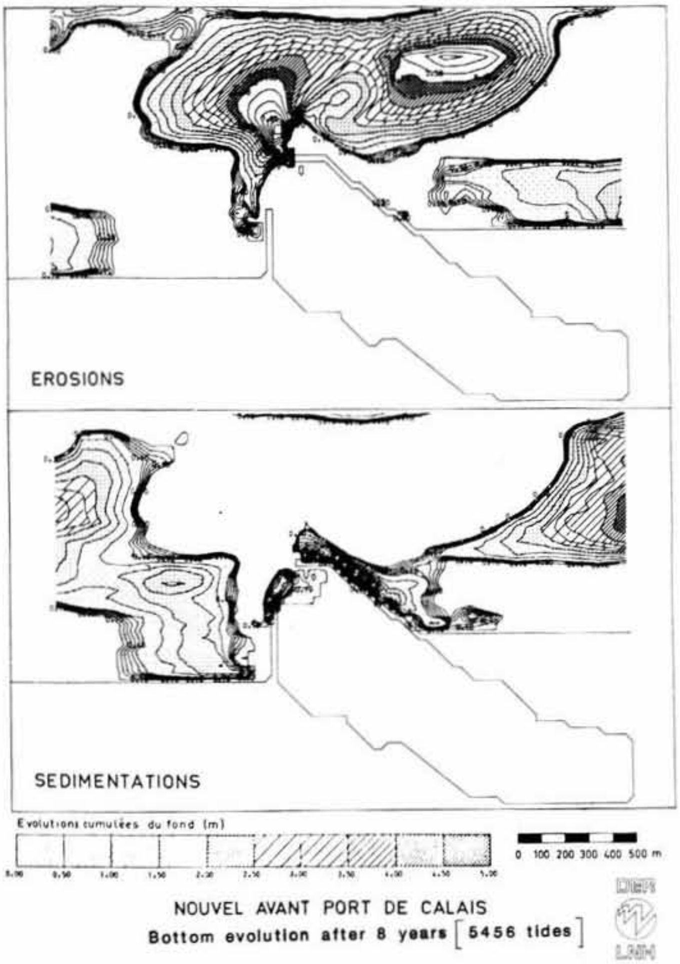


Figure 10

Sand transport simulation (L.N.H.).

Simulation du transport de sable (L.N.H.).

Moreover, in shallow depths, swell intervenes.

It is, therefore, difficult at the present time to make long-term forecasts. However some attempts at "half-forecasting" have been made, based on linkages between the results of modelling and techniques of extrapolation of phenomena viewed on site (*e.g.* de Vriend *et al.*, 1989).

In a few special cases (when, for example, the introduced perturbation is very large, one may hope to obtain an idea of short- and mid-term evolution. Figure 10 (Pechon, 1988) shows the results of a simulation carried out at Calais harbour.

The introduction of 3-D modelling has permitted investigation of the problem of the equilibrium of a sedimentary particle, in the water mass, and results have been improved. The problem at present is one of cost. Results of models are encouraging, and long-term forecasting should progressively improve.

The problem of linking models of current and swell remains. Some trials are being carried out (*e.g.* Andersen *et al.*, 1988), but for many years to come mathematical modelling of sand transports will require numerous *in situ* observations.

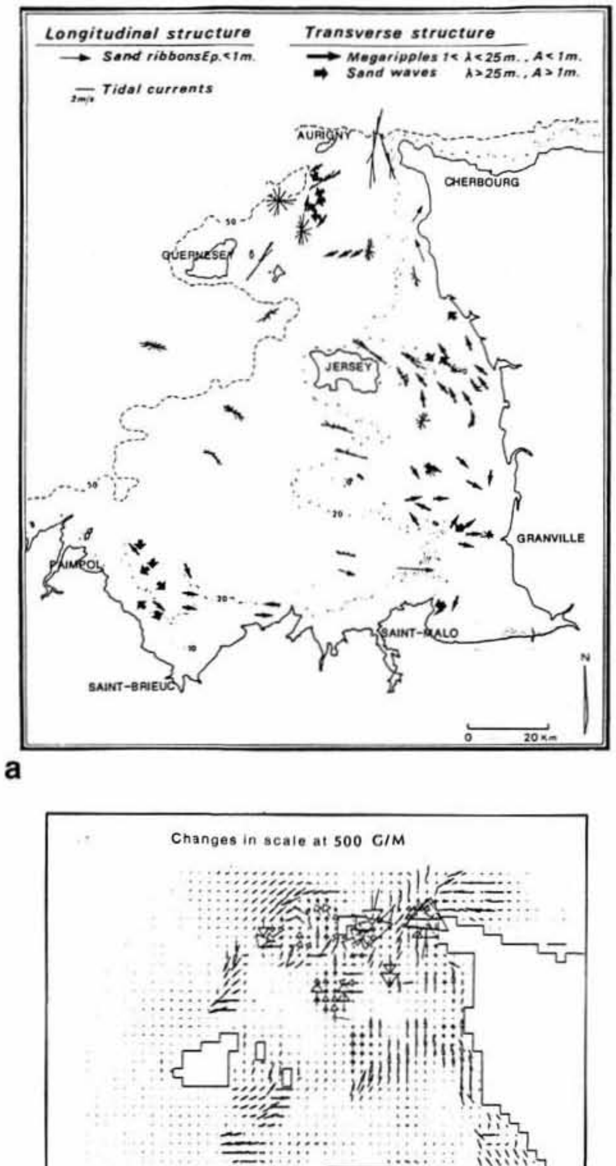


Figure 11

a: Sand transport (P. Bassoullet and P. Walker): side-scan sonar interpretation.
b: Bed load transport and suspension calculation (A. Orbi). Spring tide.

a et c : Comparaison des résultats du sonar latéral et du transport théorique de charriage (P. Bassoullett et P. Walker ; A. Orbi).

From the results of analytical and empirical models adapted to sandy sediment it is possible to calculate theoretical instantaneous flows from bedload transport. Generally there is good agreement between the maps of

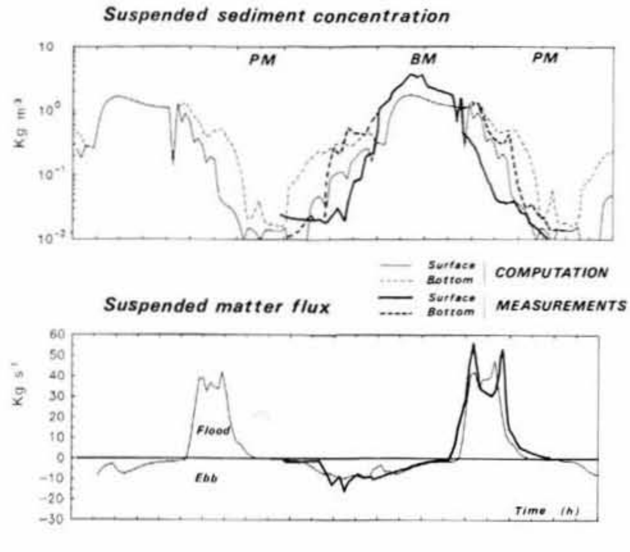


Figure 12

Suspended matter: measured and calculated (P. Le Hir).

Matières en suspension : mesures et calcul (P. Le Hir).

the distribution of superficial sediment and maps of theoretical bedload transport. In the Gulf of St Malo, for example, studies carried out by IFREMER have shown that there is stability almost everywhere. For spring tides only a few points are in a bedload movement situation at the moment of tides. Comparison of these results with information obtained using side-scan sonar data (movements of sandy beds) shows very good agreement (Fig. 11; Bassoullet, 1986; Orbi, 1986).

Fine grain (or cohesive) sediments (muds)

They are measured in tens of micrometres. They form aggregates and flocs and, through mixture with water, cause fluids to have complex properties (plastic, thixotropic...). Suspended in water, they settle slowly with large variations in the rate, according to their physical state and that of their environment. When these sediments are resuspended, their behaviour can be considered as that of a dissolved constituent on which a settling rate has to be applied. The estimation of the fluxes of sediment from the seabed to water and vice versa is very difficult (Le Hir *et al.*, 1989 *a* and *b*). Another problem is to manage the sedimentological compartment of the bed. In the course of time, these materials age, settle, lose part of their water structure and change chemically. It is, therefore, difficult to make long-term forecasts. In estuaries, turbidity maxima have been reproduced correctly (Markofsky and Lang, 1989). For short periods, the results may be good (Fig. 12, Le Hir *et al.*, 1989). As shown in the previous chapter, concentrations of pollutants associated with particle matter can be simulated.

Primary production

Numerous models of primary production of very different complexities now exist (*e.g.*, Billen et Lancelot, 1988; Fransz, 1985; Jorgensen, 1986). The simplest reproduce the nitrogen cycle without remineralization in the sediment. The most sophisticated simulate nitrogen, phosphorus and silicium cycles and to a certain extent take exchanges with sediment into account.

The limiting elements for development of certain species (N or P) can be shown, including silicium for diatom/flagellate development. Most models deal with chlorophyll biomass, so it is usually necessary to take advection, the parameter essential for the availibility of nutrients, into account. Some models use dynamics results directly. Most deteriorate information and use boxes. Current results are thus transformed into the flux from one box into another. This loss of information which introduces an artefactual dispersion is regrettable. But it may be noted that time scales for primary production are from several weeks to several months. The use of 3-D models over such periods is onerous. It is, however, possible to use a Lagrangian model of residual circulation. Evolved models of primary production include exchange with sediment (nitrogen remineralization). Moreover, it is obvious that the benthic ecosystem and particularly its algal biomass has a retention effect in relation to the water mass as shown by Riou and Gosse (1989; Fig. 13).

Having simulated primary production, it is possible to determine the oxygen content of the water mass, the oxygen content depending on benthic demand, plankton respiration and atmospheric exchange. Chapelle (1989) was thus able to reproduce the anoxia of 1982 in the bay of Vilaine which provoked a high fish mortality. Figure 14 gives a conceptual drawing of the biological model (the phosphorus cycle is in preparation), the box-model, the percentage of variations of minimum oxygen in the bottom boxes according to the 1984 simulation.

Figure 15 represents the annual cycles of salinity, mineral nitrogen, phytoplankton and oxygen saturation percentage.

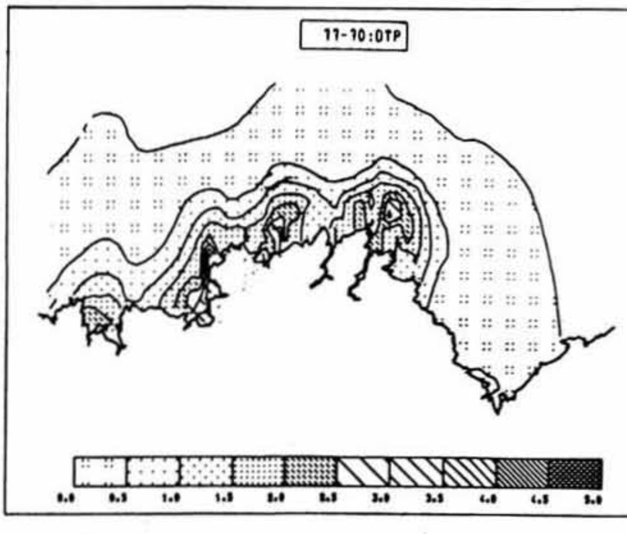


Figure 13

Difference between annual phytoplankton (g C/m²) production rate according to: - coastal model; - coastal model with initial macrobenthic algal vegetation reduced by 50 % (J. Riou and P. Gosse).

Différence de production annuelle de phytoplancton (g C/m²) entre : - le modèle côtier ; - le modèle côtier avec une végétation algale macrobenthique réduite de 50 % (J. Riou, P. Gosse).

Modelling of the plankton ecosystem

These models are intended to understand the laws governing the succession of species in the pelagic ecosystem.

Nutrients ——> Phytoplankton ——> Herbivores ——> Carnivores

Initially relatively simple, they become more and more complex until they reach a very high degree of sophistication. The quality of the model depends, of course, on the relevance of the process introduced : vertical diffusion, temperature, growth rate, growth limitation, mortality rate, assimilation rate, sedimentation of diatoms depending on the concentration of silicate and population age, storage of silicium by diatoms...

Biological knowledge plays an increasingly important role as the model becomes more complex.

So the Andersen and Nival model (1989) supposes that copepods prefer flagellates to diatoms, but capture more dinoflagellates than microflagellates, and that copepods have a better filtration rate when the prey are larger in size.

Results are remarkable. Figure 16 shows the results of one 40-day simulation off the British Columbia coast. One can see the good agreement with silicate, nitrate, diatom measurements. Agreement is not so good for other parameters.

These results were obtained in a confined area vertical stability being the only dynamic parameter. Trials are now taking place to link this biological model to a 3-D circulation model.

Secondary benthic production

In the coastal zone, secondary benthic production is largely dependent on the detritic compartment of diverse origin: phytoplankton, grass beds, macroalgae, marshland, river inputs... Waste matter being principally produced outside the study area, a knowledge of dynamics is therefore essential.

Numerous models have been produced for benthic populations (localized monospecific models for the same geographical zone). These so-called "population dynamics" models interpret growth and mortality rates in the life span of one cohort. The production of the population is equal to the sum of the production per cohort. Recruitment is usually considered constant, which is a severe limitation on the realism of the model. However, this approach has supplied numerous production/biomass relations which can be used in specific models.

The integration of the benthos in ecosystem models is recent. Brylinski (1972) introduced, in his English Channel steady state model, benthic fauna in the form of a single compartment. Kremer and Nixon (1978) introduced several macrofauna (bivalves, decapods, sponges, endofauna) compartments into their simulation of Narraganset Bay. The most recent models introduce the bacterial compartment, both as a trophic source and a remineralization element for organic matter (Chardy, 1988). Although the exchanges within the macrobenthic compartment can be correctly simulated by a pinpoint model, the role of microbiota and the pelagos-benthos coupling (or sediment-water column) remain, on the other hand, very difficult to determine. It seems, however, that the role of the benthos in coastal ecosystem models is becoming more and more important in as much as a significant part of the regenerated primary production is attributable to it.

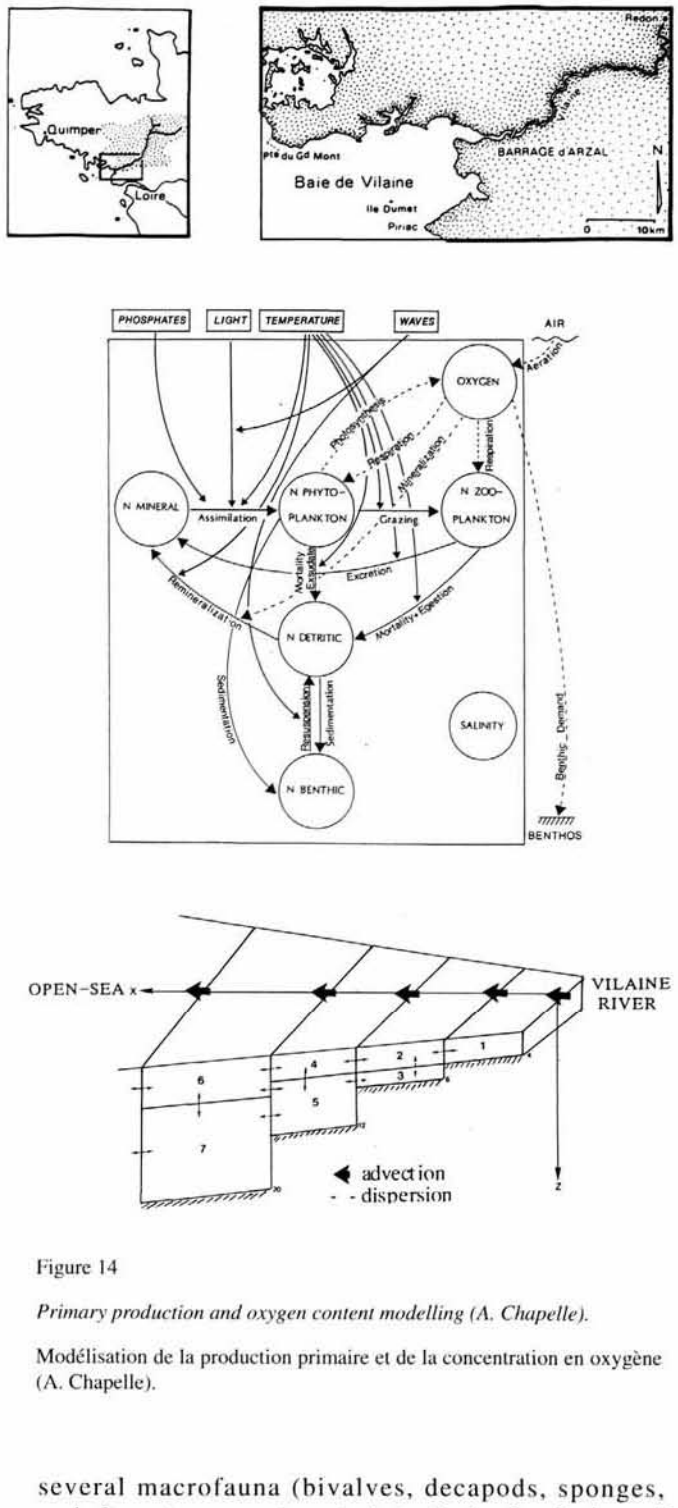


Figure 14

Primary production and oxygen content modelling (A. Chapelle).

Modélisation de la production primaire et de la concentration en oxygène (A. Chapelle).

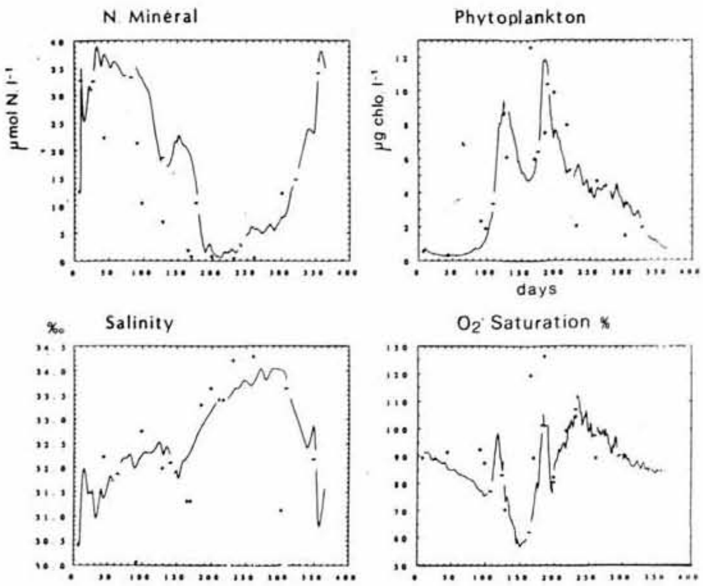


Figure 15

Modelling results (A. Chapelle).

Résultats de la modélisation (A. Chapelle).

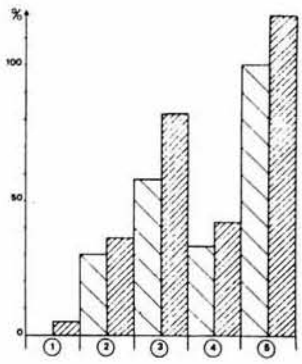
1) Without zooplankton respiration.

2) Without benthic oxygen demand.

3) Without phytoplankton respiration.

4) Without remineralization.

5) Without pelagic demand.



APPLICATIONS

The present possibilities concerning current determination, dispersal of constituents and biological production associated with nutrients have just been briefly described. What are the existing applications? It is difficult to provide an exhaustive reply, as the domain in question is very large, but models are used in:

Coastal engineering

Here, modelling elucidates the influence on currents and sedimentary dynamics of construction work, groins, dikes, estuary dams, building-up of coastal zone, canal deepening, coastal erosion protection (although in this question, swell is often the principal parameter; *e.g*;, Leentvaar and Nijboer, 1986).

Water quality management

The aptitude of a site to receive a certain quantity of pollutants depends largely on its mixing capacity. Figure 17 shows, for one bay, the different impacted surfaces in relation to different input locations.

It is also possible, through modelling, to determine the respective influences of different waste inputs in a given zone.

We can then determine which input must be controlled in order to maintain a satisfactory bacterial quality of the coastal zone.

When sensitive zones (shellfish area, beaches) are near waste outfalls, it is possible to define release times which optimize sensitive zone protection.

Other issues that can be examined include:

. Disposal of dredged sediment : where? when? how much (*e.g.*, Mommaerts *et al.*, 1987)?

. Fish farm effluent disposal : breeding biomass tolerance in a coastal zone

. Maritime construction works.

Knowledge of residence times of water is fundamental idea to fight against eutrophication : in a particular area, a weak flushing rate will induce a local consumption of nutrients, but a large flushing rate will permit the dilution of nutrients in the water masses before being assimilated by vegetation.

It has been shown (Menesguen and Salomon, 1988) that macroalgae proliferation (ulva) inside the bay of St. Brieuc is certainly due to nutrient inputs, but also to the trapping of the coastal water mass which has difficulty diluting with offshore water. It seems that nitrogen reduction has more important consequences on ulvae biomass than phosphorus reduction. Figure 18 gives Lagrangian residual circulation in the bay of St. Brieuc, areas of ulvae proliferation and biomass reduction in relation to nitrogen and phosphorus decreases.

Present-day tools are not totally predictive: for a given site it is not possible to determine precisely the carrying capacity of the area (*e.g.* algal mass blooms, anoxia). It is foreseeable that in the medium term percentages of risk will be obtained in relation to sea agitation, winds, freshwater inflow and, of course, flushing time.

Coastal management

Determination of the biotic capacity of a cultivated shellfish area

Is is economically interesting to know the optimal possible biomass in a cultivated shellfish area. Below this biomass, maximum benefit of available nutrients is not achieved. Above, growth slows and certain illnesses can appear.

The Marennes-Oleron basin is the largest French cultivated shellfish area (40 000 metric tons of oysters per year). Numerous *in situ* studies, as well as a numerical model of oyster growth, have highlighted out the primordial role of phytoplankton flux in the growth yield of shellfish stocks. One part of this food comes from outside the area and is brought by currents. Another part is produced inside the area thanks to the nutrient input of the diluted plume of the River Charente (Héral *et al.*, 1983; 1988; Bacher, 1989).

A model is at present being set up to determine primary production inside the basin, consumption of phytoplankton by oysters and oyster growth. The estimate of optimal yield for the basin is expected. A simple model of the nitrogen cycle without the oyster compartment has already been linked to an advection dispersion "box" model. Figure 19 shows the implantation of the "box" system and the first results of the simulation of chlorophyll concentration (Menesguen, 1989).

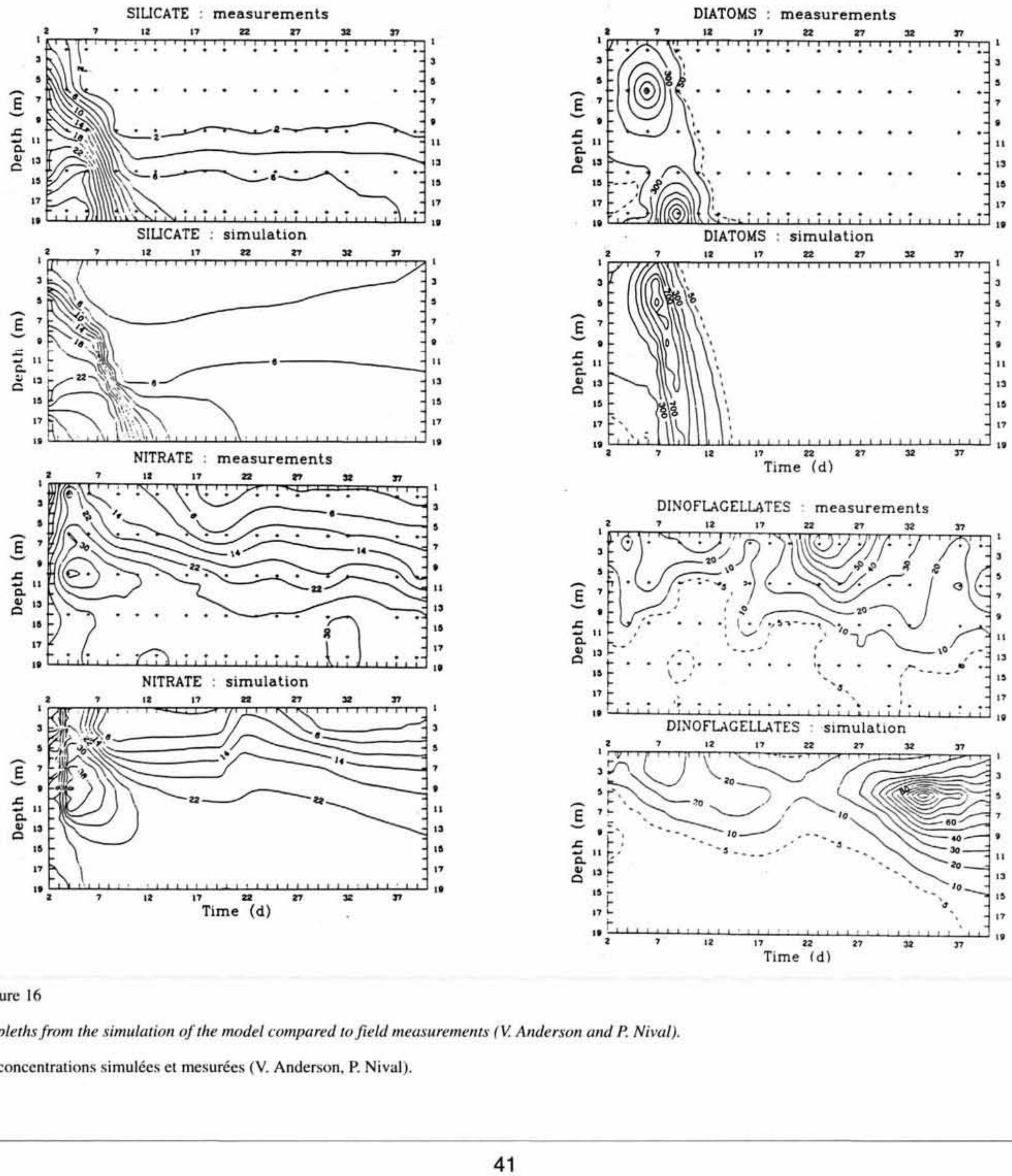


Figure 16

Isopleths from the simulation of the model compared to field measurements (V. Anderson and P. Nival).

Isoconcentrations simulées et mesurées (V. Anderson, P. Nival).

Figure 17

Different impacted surfaces in relation to the input point (J.-C. Salomon).

Influence du point de rejet sur la contamination d'une zone côtière (J.-C. Salomon).

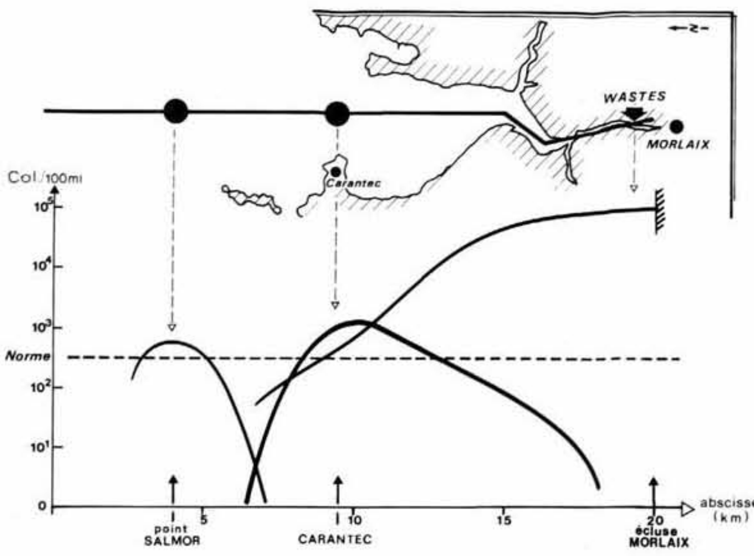
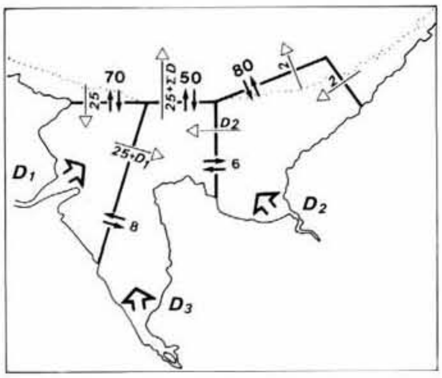


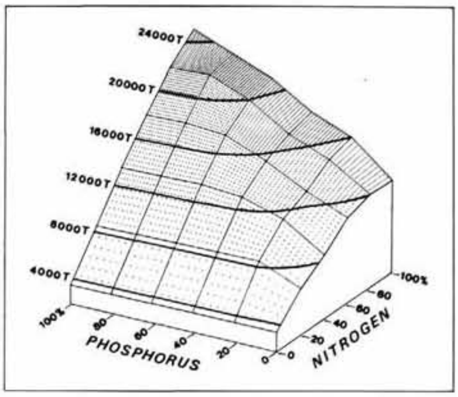
Figure 18

Ulva mass growth modelling (Bay of St. Brieuc; A. Menesguen).
a: Advective and dispersive fluxes through the box model.
b: Expected variation of the maximum summer biomass according to different levels of reduction of N- and P- inputs.
c: Map of calculated lagrangian residual currents and stranded ulvae.

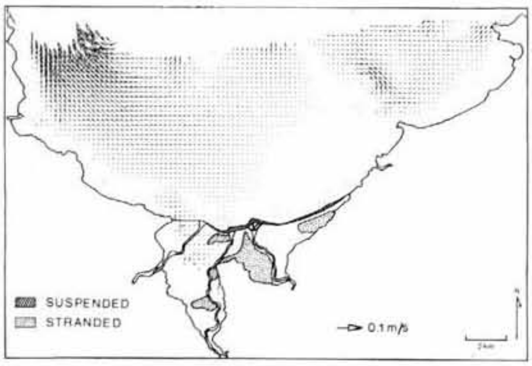
Modélisation de la croissance des ulves en baie de Saint-Brieuc (A. Menesguen).
a : flux à travers les boîtes du modèle.
b : réduction simulée de la biomasse maximale en fonction d'un abaissement des apports d'azote et de phosphore.
c : carte de courants résiduels lagrangiens.



Advective and dispersive fluxes through the box model



Expected variation of the maximum summer biomass according to different levels of reduction of N- and P- inputs.



Map of calculated lagrangian residual currents and stranded ulvae.

Oceanographic studies

A large number of marine species have a pelagic larval stage (mussels: three to four weeks; seascallops : three weeks; oysters : fifteen days to three weeks; sea urchins : three to four weeks; crayfish : several months). Since these species spend part of their life cycle away from the benthic region in the overlying water column, the ultimate fate (when the free-living larvae leave the water column to develop into a benthic adult) of these larvae depends on residual circulation. In some exceptional conditions (wind...), there could be no recruitment as larvae are transported into an unfavourable benthic habitat.

Examination of residual circulation chart of shelf seas, the English Channel for example, shows the presence of many gyres. When the period of gyres is different from that of larvae production, a species can only be maintained by linking two or three gyres which fertilize each other (Salomon, 1989 *a* and *b*).

Models are now capable of reproducing fronts and upwellings (Nihoul, 1989). These zones are biologically interesting because they are highly productive. They are dominated by phytoplankton primary production.

Some coastal ecosystems near large estuaries are sometimes in a relatively satisfactory state despite enormous pollutant input from the estuary. This is the case for the "baie de Seine". According to Cabioch *et al.* (1989), there is apparently a double paradox : quasi normal marine populations in structure and function in the immediate proximity of an estuary subject to strong perturbation impulses (high riverflow and pollution).

The current hypothesis concerning this anomaly is as follows: population settling phase (spring and summer recruitment) takes place during marine dominant input through bottom residual circulation as it converges towards the estuary (about 5 cm/s). The seabed adjacent to the estuary is supplied with larvae originating in the external zone (or other distant areas of the same nature), and so renews its populations whatever the perturbation suffered by local adult populations; perturbations of benthic communities by high riverflow and pollution are predominant during winter and only participate in the normal decline of such populations in any circumstances at this period (and of recruitement mortality).

It thus seems that this phasal discordance between the period of settlement of populations and major perturbations together with the predominance of marine input in a recruitment period explain both the permanence of marine populations so close to the estuary and the interannual regularity of its kinetics.

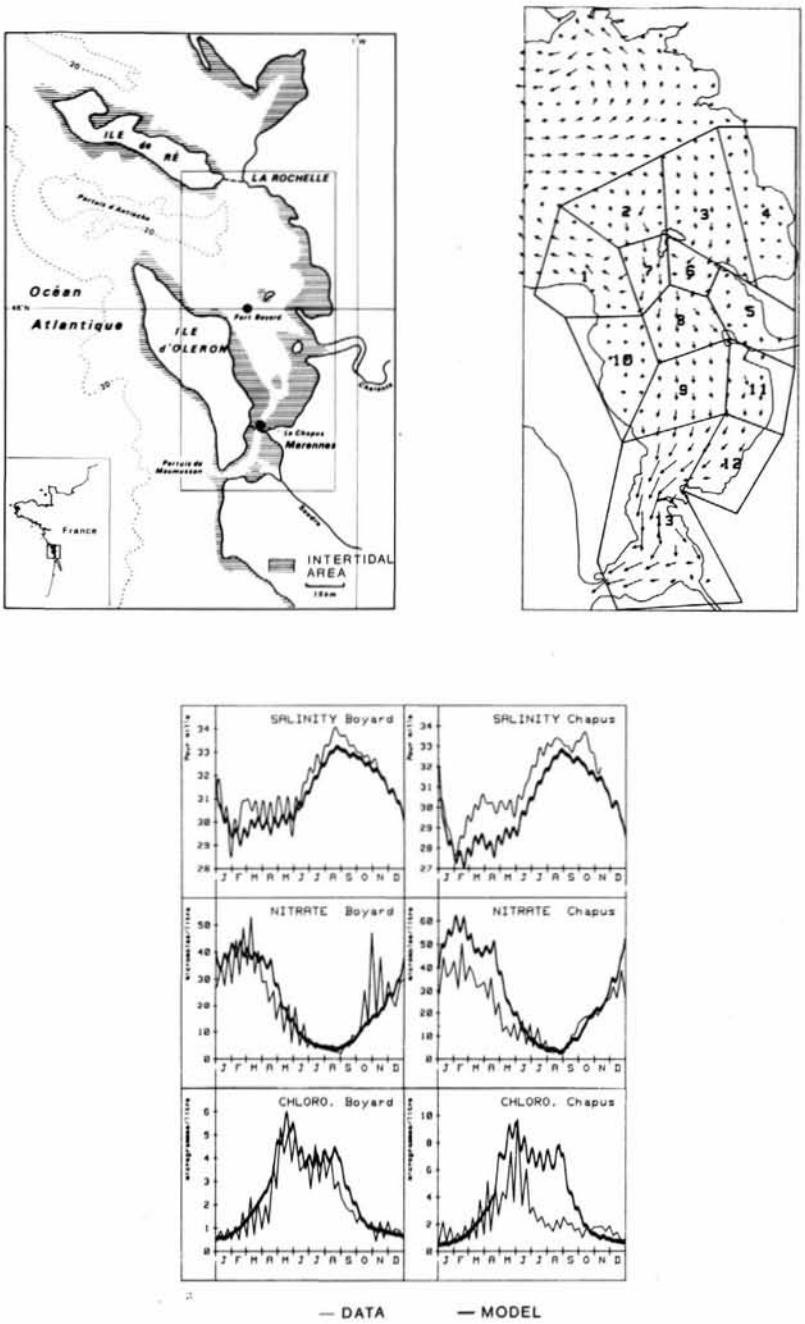


Figure 19

Primary production modelling in an oyster culture zone (Marennes-Oléron, France; A. Menesguen).

Simulation de la production primaire dans une zone de culture marine (Marennes-Oléron ; A. Menesguen).

Helping decision making in case of accident

From the density of a chemical pollutant (oil or other) accidentally introduced into the environment, it is possible to predict its displacement and elaborate a coastal protection strategy. In case of pollution by light hydrocarbons, treatment of the spill (thickening in order to sink them) in estuarine zone must be avoided : by passing into the lower level they will cause upstream contamination.

Investigation of residual currents can serve as a precise tool in the search for floating wrecks.

CONCLUSION

As has been shown, the range of applications of coastal dynamics is huge. Present results are important and show that oceanography is resolutely engaged on this path of quantification based upon a better understanding laws of nature. Besides the "traditional" aspects of coastal engineering where results have been used for several years (waste dispersal, erosion-sedimentation), a new field of activity is opening up to shelf sea physicists who must now combine their efforts, with those produced by other scientists (*e.g.* marine biologists, chemists, microbiologists etc.) in suggesting ways of rendering current coastal development as compatible as possible with the preservation of coastal ecosystems and with the perpetuation of coastal resources. Given the importance in our society of the problems related to environmental protection, it may be imagined that in a few years time, the results of coastal dynamics will have numerous applications: in particular they will permit the taking of decisions.

Dynamic modelling has reached a high degree of precision and is generally reliable. But sophisticated models (which only omit a few terms from the equations) are costly. Any particular application necessitates determination of the type of simplification to be introduced: too much, and results are false; too little, and costs rise. There will therefore have to be a delicate choice involving, in each case, the judgement of an experienced modeller.

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