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Mathematical Models of Continental Seas

Dynamic processes in the Southern Bight

by

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** The name of "Math. Modelsea" stands in brief for those of the 250 research workers from some 40 laboratories engaged in a nation-wide research and development project in the scope of the Belgian National Programme on the Physical and Biological Environment sponsored by the Department for Scientific Policy, Office of the Prime Minister.

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Chapter I

The Mathematical Model

by

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Foreword

This chapter is a synopsis of the mathematical model which has been the framework of the theoretical and experimental research conducted in the last three years in the scope of the Belgian National Program on the Environment — Sea Project[1].

The successive steps in the construction of the Model have been described in several progress reports and published papers and the details are not reproduced here. A list of references is attached.

A detailed description of the modern concepts and techniques of marine modelling can be found in *Modelling of Marine Systems,* edited by Jacques C. J. Nihoul, Elsevier Publ. Amsterdam, 1974.

The ordering of this chapter closely follows that of the book and the same notations are used.

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[1] Sponsored by the Ministry for Science Policy, Belgium.

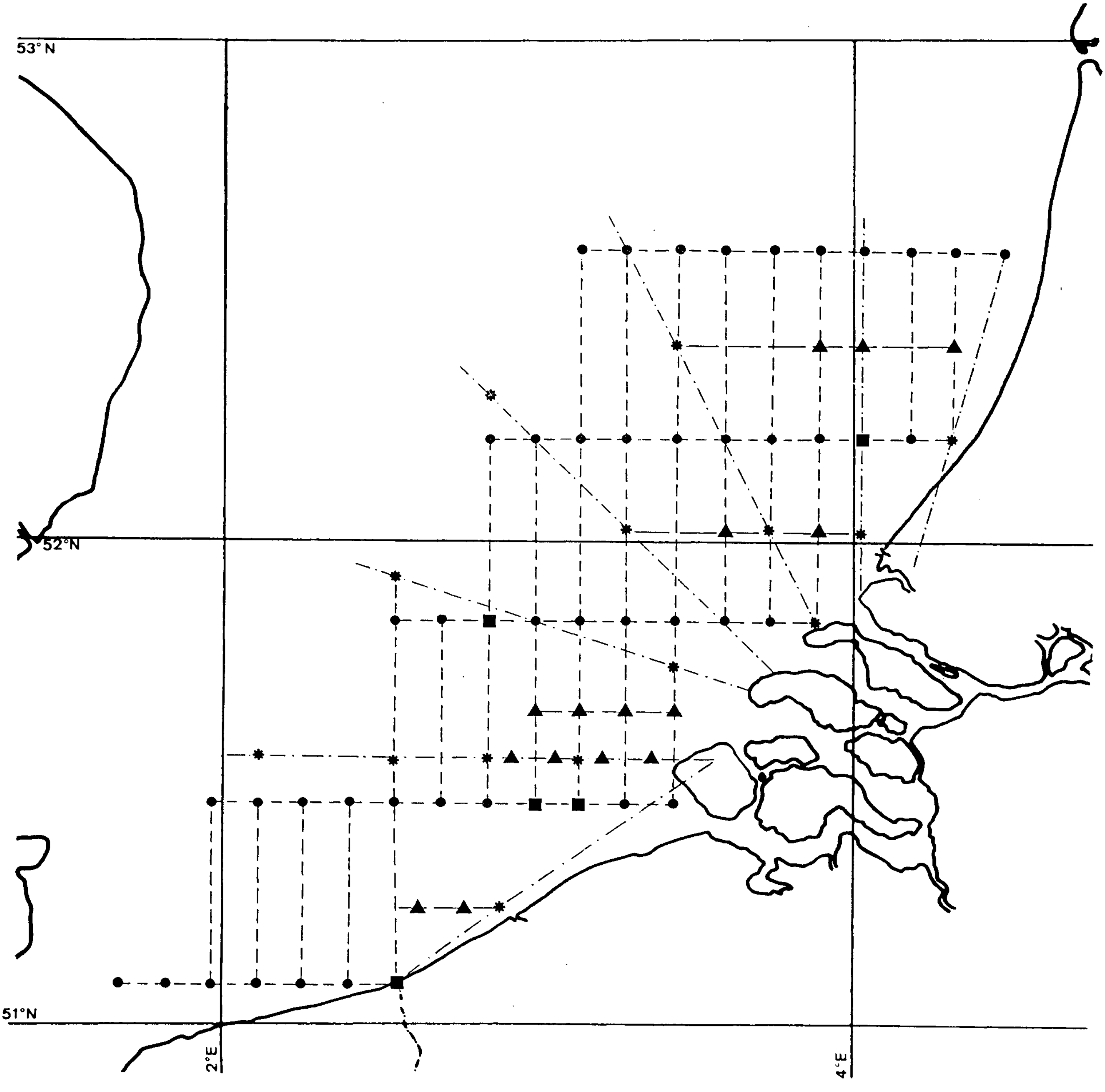

fig. 1.1.

1.- Demarcation of the system

Support

The support of the model is the Southern Bight of the North Sea and the Scheldt Estuary as shown in figure 1.1.

The array of broken lines, dots and squares shows the area where measurements are made several times a year. Data concerning the western part of the Bight are provided by British colleagues in the scope of a general program of exchanges and intercalibrations.

The area in front of the Belgian coast and the Scheldt Estuary are covered by a finer grid of measurements not reproduced on the figure.

The hydrodynamical part of the model is extended to the whole North Sea whenever necessary to provide appropriate Northern boundary conditions for the Southern Bight.

Scope

The primary objective of the model is the study of the space and time characteristics of water motion, surface elevation, temperature, salinity, turbidity, oxygen, nutrients, trace metals, chlorinated hydrocarbons and living species[1].

The situation is summarized in figure 1.2.

Reduction of scope – *Compartments*

Attention is restricted to the most important compartments :

i) dissolved substances,
ii) suspensions,
iii) plankton – phytoplankton,
    zooplankton,
iv) fish – pelagic,
    benthic,
v) shellfish and molluscs,
vi) bottom sediments,

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[1] Petroleum products are examined in a separate program.

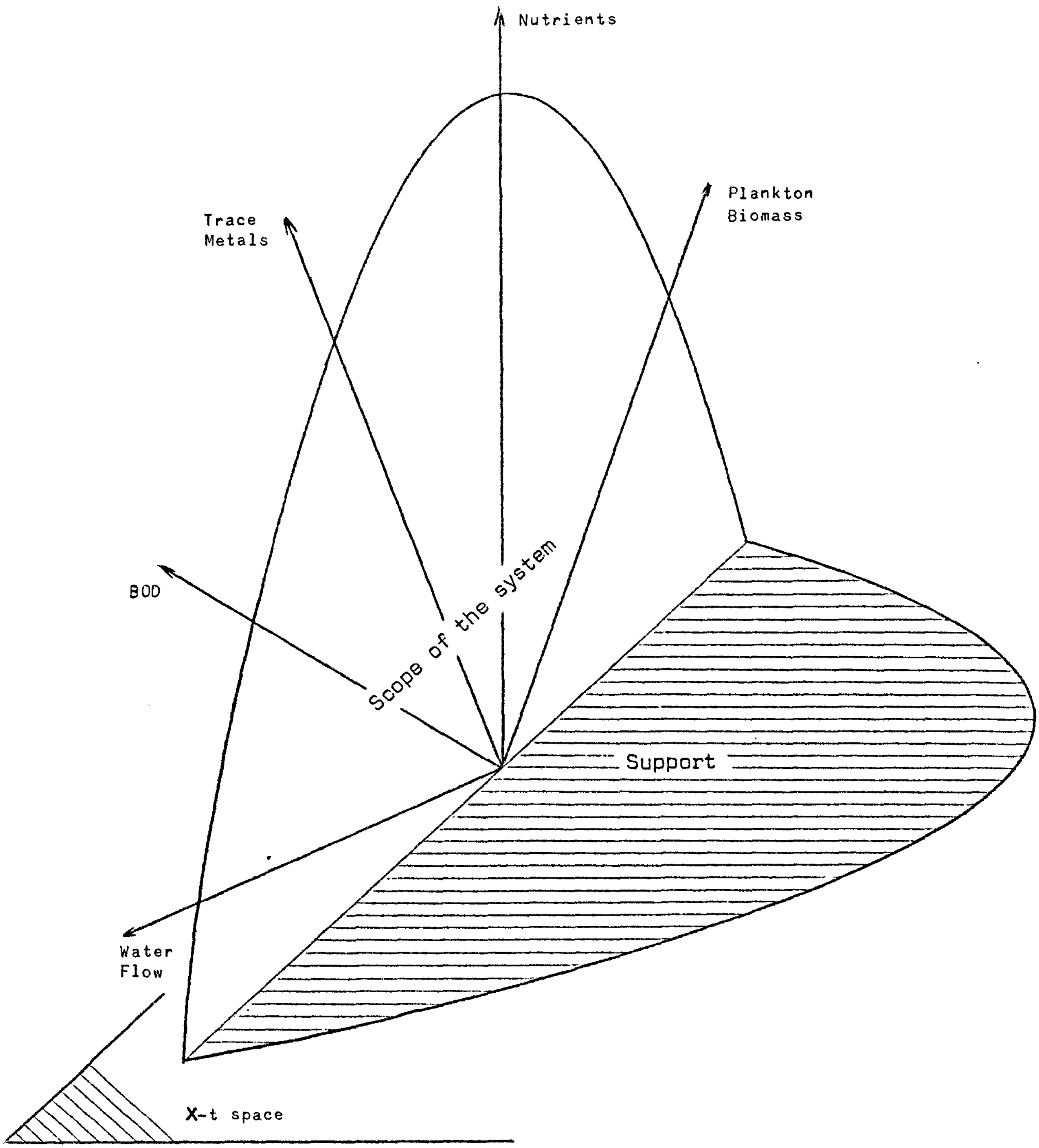
Nutrients
Trace Metals
Plankton Biomass
BOD
Scope of the system
Support
Water Flow
X-t space

fig. 1.2.

vii) macro- and meio-benthos,
viii) bacteria — faecal,
marine heterotrophic,
benthic.

The state variables include the specific mass[1] of each compartment and the aggregate concentrations of the selected chemicals in compartments (i) to (vi).

Selected nutrients : P , N , Si .

Selected heavy metals : Zn , Cd , Pb , Cn , Fe , Mn , Mg .

Selected chlorinated hydrocarbons : pp' DDT , DDD , DDE , aldrine, dialdrine, endrine, lindrane, heptachlore, epoxid heptachlore, PCB .

It must be emphasized here that, although the mathematical model covers all these variables, not every one of them is actually analysed experimentally. In the present state, experimental data are not always available on all chemical concentrations in all compartments at all sampling stations. This may be due to technical difficulties but it is, in most cases, a consequence of the necessity of accepting a hierarchy of priorities in the experimental work and focusing attention to what is most urgently needed (see chapter 2).

The specific masses of compartments (i) and (ii) may be called "salinity" and "turbidity" respectively; the distinction between salinity and turbidity being, in a sense, arbitrary as the experimentalist will call *dissolved* everything which goes through a filter of pre-decided fineness. This must be borne in mind also while interpreting the budgets of nutrients and pollutants in the two compartments.

Reduction of support — *Space averaging*

All over the support except in the Scheldt Estuary the turbulent mixing ensures a uniform density.

While separate three-dimensional and combined depth-averaged and width averaged two-dimensional models are being developed for the Scheldt Estuary, the model for the Southern Bight is further simplified by assuming constant mass density and considering only average properties over the total depth.

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[1] Mass per unit volume.

The mechanical variables are then reduced to the two horizontal components of the depth-averaged velocity vector and the surface elevation.

For the study of specific chemical and ecological interactions, the support may be divided in a limited number of *niches* where similar conditions prevail. In a first approach, one may study the dynamics of the aggregate properties of the niche obtained by further integrating (averaging) over the horizontal dimensions of the niche. Niche (or box) models of this sort have been developed and tested against the experimental observations made in the Ostend "*Bassin de Chasse*", a closed sea basin at the coast which has been extensively studied in the past.

2.- State variables and control parameters

The state variables are defined by the scope of the system as stated above.

As a result of turbulence and other erratic or rapidly oscillating motions of the sea, each variable shows fluctuations around a mean value. Only these mean values are significant for the model.

The evolution equations are written for the mean variables and only the general effect of the fluctuations (through non-linear terms in the basic equations) is taken into account.

The mean variables, *i.e.* the smooth running functions of space and time, obtained by filtering out the fluctuations are denoted by special symbols. A bar over the symbol indicates the average over depth of the mean variable.

In addition to the mechanical variables and temperature, the other state variables represent essentially specific masses or concentrations. (The specific biomass of phytoplankton, the specific mass of copper in solution, suspension or plankton, etc.) These "concentration" variables are noted ρ_a (smooth running part r_a). For convenience ρ_a (r_a) will be referred to as the specific mass of "constituent α"; the word constituent being used in a conventional sense as it may denote a whole aggregate (all dissolved substances ...) or the aggregate content of a compartment in a specific chemical (concentration of mercury in pelagic fish ...).

The mean (smooth running) variables are noted as follows :

		depth-averaged
Velocity vector	u (three dimensional)	$\bar{u}$ (two dimensional)
Flow rate vector		$U = H\,\bar{u}$
Surface elevation		ζ
Total height of water (where h is the depth)		$H = h + \zeta$
Temperature	θ	$\bar{\theta}$
Specific mass of α	r_a	$\bar{r}_a$

"In addition to the state variables, different kinds of parameters appear inevitably in the mathematical description of the system. These may be called *control parameters* as they influence the evolution of the system (hence appear in the evolution equations) but are not predicted by the model itself (no specific evolution equation is written for them).

The first kind of control parameters one thinks of are the *guidance parameters* which are at the disposal of man to manage the marine system according to some optimal design.

Most of the parameters, however, which control the evolution of the system cannot be chosen to conform with man's concern. They are imposed by Nature. These parameters arise from the initial demarcation of the system, the necessity of restricting the state variables and formulating the laws of their evolution in a simple and tractable way. They reflect all the aspects of the natural system of which the model does not take charge; usually because the additional equations required for their prediction would jeopardize the simulation by their difficulty, their dubiousness or simply by increasing the size of the system beyond the computer's ability.

Although they are rarely known beforehand and must be, in most cases, determined approximately by separate models, experimental data or sideways theoretical reflection, the control parameters which result from the closure of the system must be regarded, in the language of the theory of control, as *fixed* and distinct, therefore, from the guidance parameters mentioned above.

The separation between state variables and control parameters is, of course, more or less arbitrary and function of the model's capability and ambition.

For instance, all models of primary productivity (state variables : nutrients and plankton) are controlled by the incident light. In a first stage, the incident light may be taken as a fixed control parameter and be given an empirical value. The model can be refined and give the incident light at every depth as a function of the intensity of light at the sea surface, using the transparency of water as a new control parameter. In an even more perfect version of the model, the transparency of water can be included in the state variables and inferred from the turbidity which itself can be predicted by the model.

The chemical reaction rates may be regarded as control parameters hopefully determined by chemical kinetics, *i.e.* by laboratory experiments or by some fundamental molecular theory conducted in parallel with the model but not part of it.

The dynamics of *translocations* (transfer of a chemical element from one compartment to another) must be given appropriate mathematical form. This cannot be done in general without introducing several control parameters the values of which can only be ascertained experimentally." [1]

To ascertain the value of the control parameters and determine the laws of interaction, complementary variables are measured or calculated. These include, for instance, transparency of water, primary production, diversity and stability indexes, antibiotic effects, etc.

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[1] The text between quotation marks is reproduced from Modelling of Marine Systems, edited by Jacques C.J. Nihoul, Amsterdam, Elsevier Publ., 1974.

3.- Evolution equations

The assumption of uniform sea water density which is justified by experiment (apart from the Scheldt Estuary where slightly different models are being developed) allows a decoupling between the mechanical variables and the others. The hydrodynamic equations can be solved independently of the other evolution equations and the values of the flow velocity determined by the former substituted in the latter which in turn can be solved knowing the interactions between the constituents.

The *hydrodynamic models* which one can develop in this way differ whether one is interested in unsteady sea motions produced by tides and storm surges or in the residual -- "steady" -- circulation which results from the average of the actual flow over a time sufficiently long to cancel out tidal oscillations and transitory wind currents.

The evolution equations for the state variables r_a are coupled through the terms expressing the interactions of the constituent α with other constituents β , γ , ... They also depend on the water motion determined by the hydrodynamic models.

In a first approach, it is rewarding to separate the two effects and study first the dispersion (by currents, sedimentation and turbulence) of a "passive" constituent *i.e.* one which does not have significant interactions with others. Then, to investigate the interactions (*e.g.* the path of a pollutant in the food chain), one can develop *niche models* concerned with mean concentrations over some reasonably homogeneous regions of space. Niche models are not affected by the detailed hydrodynamics of the sea, only its effects on imputs and outputs at the niche's frontiers remain to be known.

Although *passive dispersion models* can only give conservative estimates of the distribution of chemicals and species in the sea and *niche models* can only give an average knowledge of the interactions, they provide nevertheless a first valuable insight into the mechanisms of the marine system.

Of course, the model can combine dispersion and interactions and provide the detailed prediction of the state of the system at all points and time.

However the gigantic amount of computer work which is required to solve large systems of coupled partial differential equations commends that the full scale simulation be restricted to dramatic cases where estimates are insufficient or to special problems (like the dumpings) where, in the area of interest, only a limited number of constituents are involved in a significant way.

The general dispersion-interaction model is described in [Nihoul (1973a)] and subsequent papers. Different simplified forms of this model, pertinent to special studies, are given in the following and illustrated by examples of application.

4.- Tides and storm surges model

i) State variables

Mean depth-averaged horizontal velocity vector	$\overline{u}$
Water height	H

(The surface elevation ζ is given by $H = h + \zeta$ where h is the water depth.)

ii) External forces per unit mass of sea water

Tide-generating force	ξ
Gradient of atmospheric pressure	$\nabla(\frac{p_a}{\rho})$
Wind stress	τ_s
Relation of wind stress to wind velocity v at reference height	$\tau_s = \frac{C}{H} v \|v\|$

iii) Evolution equations

$$\frac{\partial H}{\partial t} + \nabla . (H \overline{u}) = 0$$

$$\frac{\partial \overline{u}}{\partial t} + u . \nabla u + f e_3 \wedge u = \xi - \nabla(\frac{p_a}{\rho} + g\zeta) + a \nabla^2 u$$

$$- \frac{D}{H} u \|u\| + \frac{C}{H} v \|v\|$$

where the e_1 and e_2 axes are horizontal, the e_3-axis vertical and where

$$\nabla = e_1 \frac{\partial}{\partial x_1} + e_2 \frac{\partial}{\partial x_2} .$$

iv) Control parameters

f : Coriolis parameter (twice the vertical component of the angular velocity of the earth)

ρ : specific mass of the sea water

a : horizontal effective viscosity

D : bottom friction coefficient

C : atmospheric drag coefficient

h : depth

v) Interpretation of the evolution equations

The time variation of the velocity vector $\overline{u}$ is the result of

α : advection $\overline{u} . \nabla\overline{u}$

β : rotation $f\, e_3 \wedge \overline{u}$ produced by the Coriolis effect in axes fixed on the rotating earth

γ : mixing by shear effect and turbulence $a\, \nabla^2 u$

δ : friction on the bottom $-\frac{D}{H} \overline{u} \|\overline{u}\|$

ε : acceleration by agents of three different types

$\varepsilon.1$: the wind stress on the sea surface $\frac{C}{H} v \|v\|$ related to the wind velocity v at some reference height

$\varepsilon.2$: the gradient of the atmospheric pressure and of the surface elevation $-\nabla(\frac{p_a}{\rho} + g\zeta)$

$\varepsilon.3$: the external force ξ . The type of external force one has in mind here is essentially the tide-generating force which is generally assumed to derive from a potential. (*i.e.* $\nabla \wedge \xi = 0$). ξ can then be combined with the pressure and surface elevation gradients.

5.- Model of residual circulation

i) State variables

Stream function ψ

The two components of the residual flow rate vector $\mathbf{U}_0$ are given by

$$U_{0,1} = - \frac{\partial\psi}{\partial x_2}$$

$$U_{0,2} = \frac{\partial\psi}{\partial x_1} \ .$$

ii) External forces per unit mass of sea water

Residual stress ϑ

$$\vartheta = (\tau_s)_0 + (\tau_t)_0$$

where $(\tau_s)_0$ is the residual wind stress and $(\tau_t)_0$ the residual tidal stress [Nihoul (1974)]

$$(\tau_t)_0 = [g\zeta_1 \nabla\zeta_1 + \nabla . (H^{-1}UU)]_0$$

where ζ_1 denotes the surface elevation produced by tides and transitory wind forces.

iii) Steady state residual equation

$$\kappa \nabla^2\psi - \frac{\partial\psi}{\partial x_1} \left(f \frac{\partial h}{\partial x_2} + \frac{2\kappa}{h} \frac{\partial H}{\partial x_1}\right) + \frac{\partial\psi}{\partial x_2} \left(f \frac{\partial h}{\partial x_1} - \frac{2\kappa}{h} \frac{\partial h}{\partial x_2}\right)$$

$$= h\ \omega_3 + \frac{\partial h}{\partial x_2} \vartheta_1 - \frac{\partial h}{\partial x_1} \vartheta_2$$

where ϑ_1 and ϑ_2 are the two horizontal components of ϑ and where ω_3 is the vertical component of $\nabla \wedge \vartheta$.

iv) Control parameters

κ : bottom friction coefficient for residual flow

f : Coriolis parameter

h : depth.

v) Interpretation of the residual circulation equation

The space distribution of the stream function ψ is the result of

α : combination of bottom slope and Coriolis effects

$$f \left[\frac{\partial\psi}{\partial x_2} \frac{\partial h}{\partial x_1} - \frac{\partial\psi}{\partial x_1} \frac{\partial h}{\partial x_2}\right]$$

β : combination of bottom slope and bottom friction effects

$$- \frac{2\kappa}{h} \left[\frac{\partial\psi}{\partial x_1} \frac{\partial h}{\partial x_1} + \frac{\partial\psi}{\partial x_2} \frac{\partial h}{\partial x_2}\right]$$

γ : combination of bottom slope and residual stress effects

$$\vartheta_1 \frac{\partial h}{\partial x_2} - \vartheta_2 \frac{\partial h}{\partial x_1}$$

δ : residual stress forcing

$$h \, \omega_3 \, .$$

6.- Passive dispersion models

i) State variables

Depth-averaged concentration of any passive constituent α or depth-averaged temperature ($\overline{c} = \overline{r}_\alpha$ or $\overline{c} = \overline{\theta}$)	$\overline{c}$
Depth-averaged horizontal velocity vector (given by separate hydrodynamic model)	$\overline{U}$
Water height (given by separate hydrodynamic model)	H

ii) Inputs — Outputs

Total input in a water column of unit base (including volume sources, surface and bottom fluxes. If these result in a net output, Λ is negative.)	$H\Lambda$

iii) Evolution equation [Nihoul (1973b)]

$$\frac{\partial \bar{c}}{\partial t} + \bar{\mathbf{u}} \cdot \nabla \bar{c} + H^{-1} \nabla \cdot \left(\gamma_2 \frac{H \sigma_3}{\bar{u}} \bar{c} \, \bar{\mathbf{u}}\right) = \Lambda + H^{-1} \nabla \cdot \left[\gamma_1 \frac{H^2}{\bar{u}} \bar{\mathbf{u}} \, (\bar{\mathbf{u}} \cdot \nabla \bar{c})\right] + \nabla \cdot \tilde{\kappa} \, \nabla \bar{c}$$

iv) Control parameters

σ_3 : migration (sedimentation or ascension) velocity $\sigma_3 = 0$ for temperature and neutrally buoyant constituents

$\tilde{\kappa}$: horizontal eddy diffusivity

γ_1 , γ_2 : shear effects coefficients [Nihoul (1971), (1972), (1973b), (1974)].

v) Interpretation of the evolution equation

The evolution in time of the depth-averaged variable $\bar{c}$ is the result of

α : advection by the depth-averaged velocity $\bar{\mathbf{u}} \cdot \nabla \bar{c}$

β : shear effect correction to the advection taking into account that, as a result of migration, the maximum of $\bar{c}$ may occur in a region of the water column where the actual horizontal velocity is significantly different from $\bar{\mathbf{u}}$ [Nihoul (1973b), (1974)]

$$H^{-1} \nabla \cdot \left(\gamma_2 \frac{H \sigma_3}{\bar{u}} \bar{c} \, \bar{\mathbf{u}}\right)$$

γ : shear effect dispersion [Nihoul (1971), (1972), (1973b), (1974)]

$$H^{-1} \nabla \cdot \left[\gamma_1 \frac{H^2}{\bar{u}} \bar{\mathbf{u}} \, (\bar{\mathbf{u}} \cdot \nabla \bar{c})\right]$$

δ : turbulent dispersion $\nabla \cdot \tilde{\kappa} \, \nabla \bar{c}$

ε : external inputs (or outputs) Λ

7.- Niche interactions model

i) State variables

Averages over the whole niche's space of all interacting chemical and ecological state variables r_α or θ	s_α

ii) Inputs — Outputs

Total input (output if negative) in the niche (including volume sources and fluxes or flows in and out of the niche at the boundaries)	S_α

iii) Evolution equations

$$\frac{ds_\alpha}{dt} = S_\alpha + I_\alpha(t, s_1, s_2, \ldots, s_n)$$

I_α represents the rate of production (or destruction) of s_α by chemical, biochemical or ecological interactions. In general I_α is a function of time and all interacting variables s_β . I_α depends on the particular interactions involved. In many cases, it can be simply approximated by combinations (in sums and products) of simple laws such that

a.	k_α	(constant)
b.	$k_{\alpha\beta} \; s_\beta$	(linear)
c.	$k_{\alpha\beta\gamma} \; s_\beta \; s_\gamma$	(bilinear)
d.	$k_1 \, s_\alpha - k_2 \, s_\alpha^2$	(logistic)
e.	$k_1 \dfrac{s_\beta}{k_2 + s_\beta}$	(Michaeles-Mentem-Monod)

where the k_α , $k_{\alpha\beta}$ and $k_{\alpha\beta\gamma}$ are functions of time and control parameters.

iv) Control parameters

Several control parameters influence the interaction laws and appear in particular in the expressions of the coefficients k_α , $k_{\alpha\beta}$, ...

In some cases, it is simpler to consider these coefficients as resulting control parameters to be determined experimentally.

v) Interpretation of the evolution equation

The niche-averaged value of the state variables r_a or θ changes in time as a result of

α :	input or outputs in or out of the niche	S_a
β :	chemical, biochemical or ecological interactions	I_a .

8.- Examples of applications

8.1.- Tides and storm surges model

The model has been applied with success by Ronday (1973) to the calculation of tides in the North Sea and in the Southern Bight.

Figures 1.3 and 1.4 show a comparison between lines of equal phases and amplitudes according to observation and according to simulation.

8.2.- Residual circulation model

The model has been applied with success by Ronday (1972), Runfola and Adam (1972), Nihoul and Ronday (1974) to the calculation of the residual circulation in the North Sea and in the Southern Bight.

Figure 1.5 shows the residual flows of water masses in the North Sea estimated from observation.

Figure 1.6 shows the calculated stream lines in the North Sea with the assumption of constant depth.

Figure 1.7 shows the calculated stream lines in the North Sea taking the depth variations into account and demonstrating the influence of the bottom slope on the residual circulation.

Figure 1.8 shows the calculated stream lines in the Southern Bight when the tidal stress is neglected.

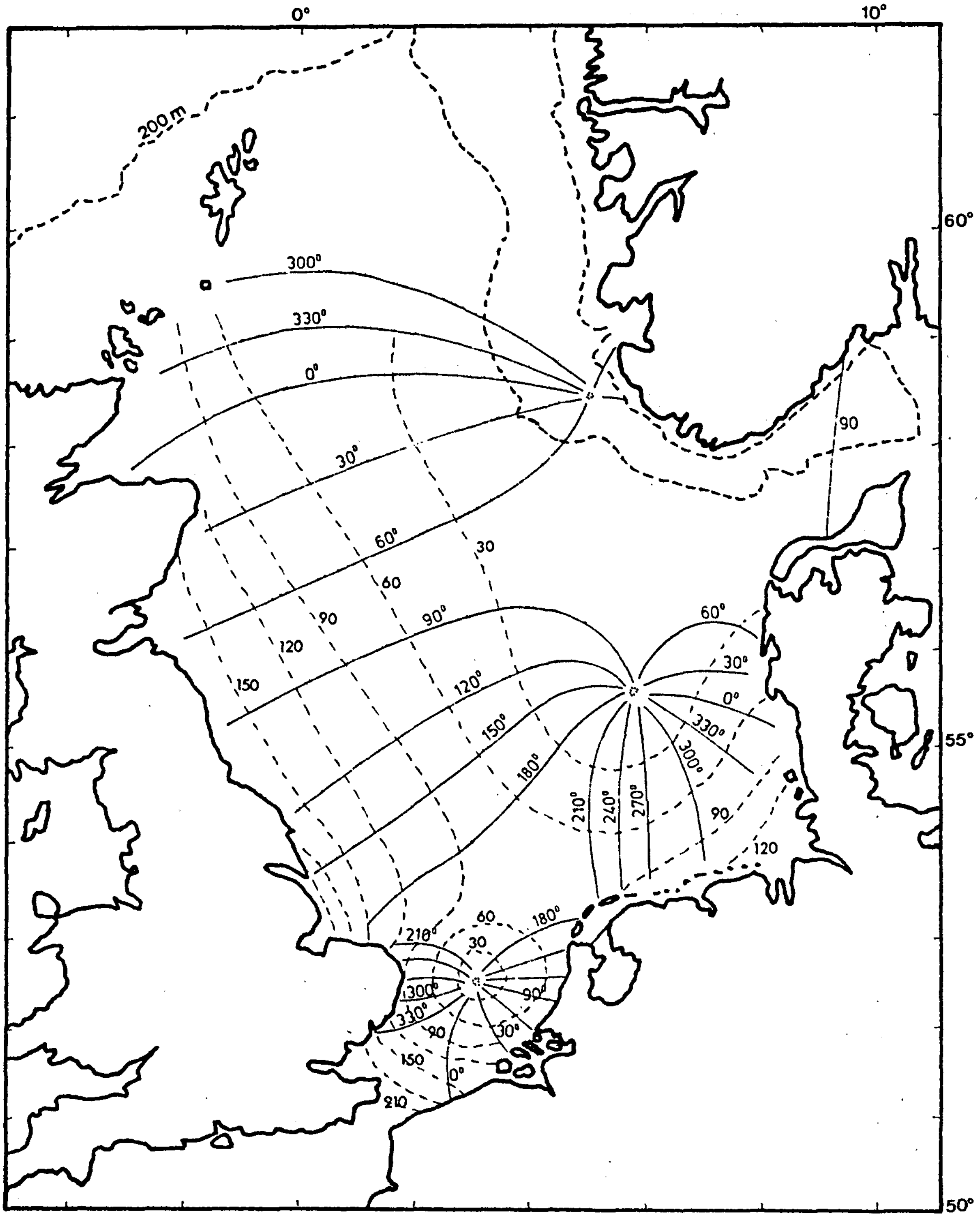

fig. 1.3.- Lines of equal tidal phases and amplitudes in the North Sea according to observations (after Proudman and Doodson, 1924).

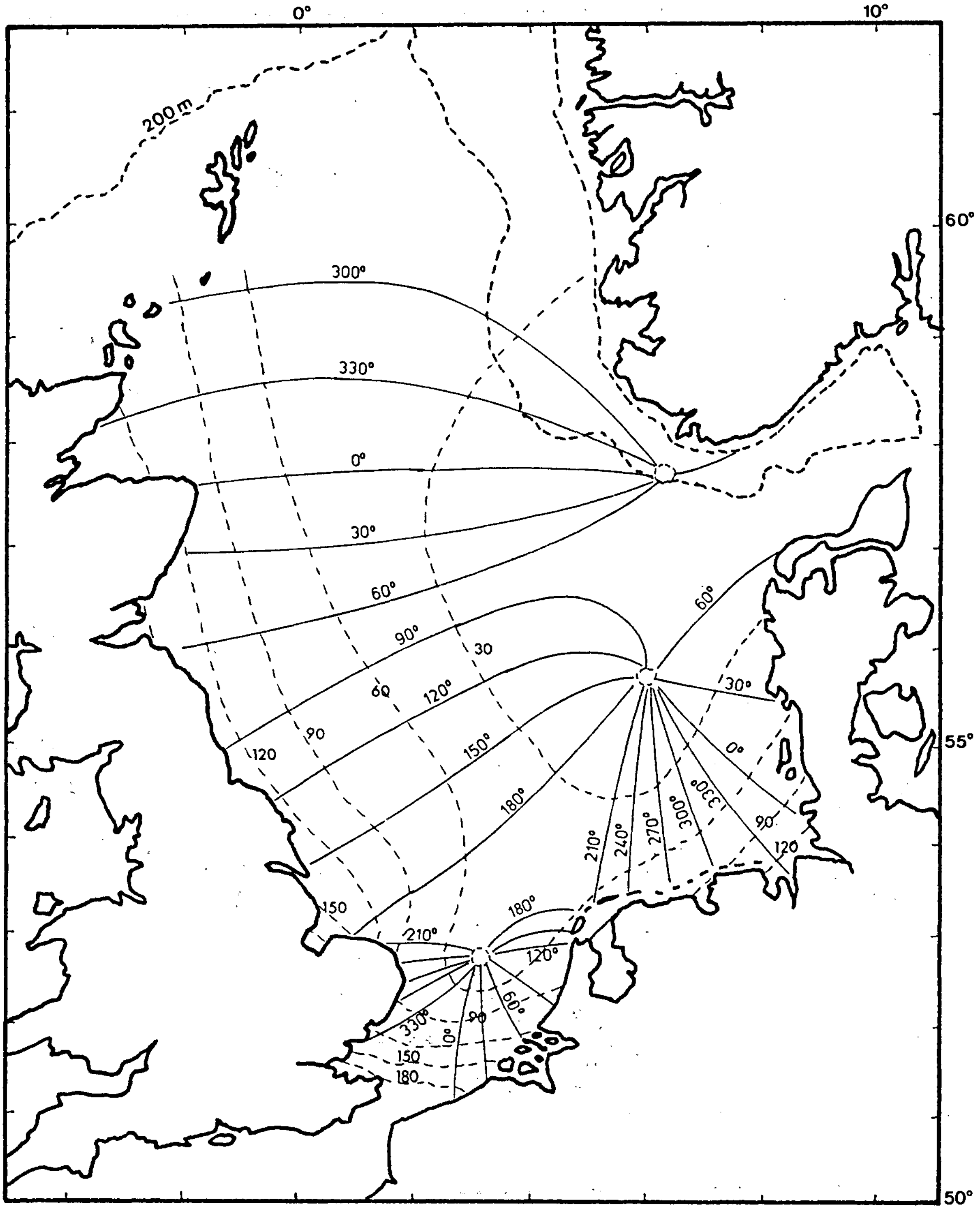

fig. 1.4.- Lines of equal tidal phases and amplitudes in the North Sea according to the mathematical model (after Ronday, 1973).

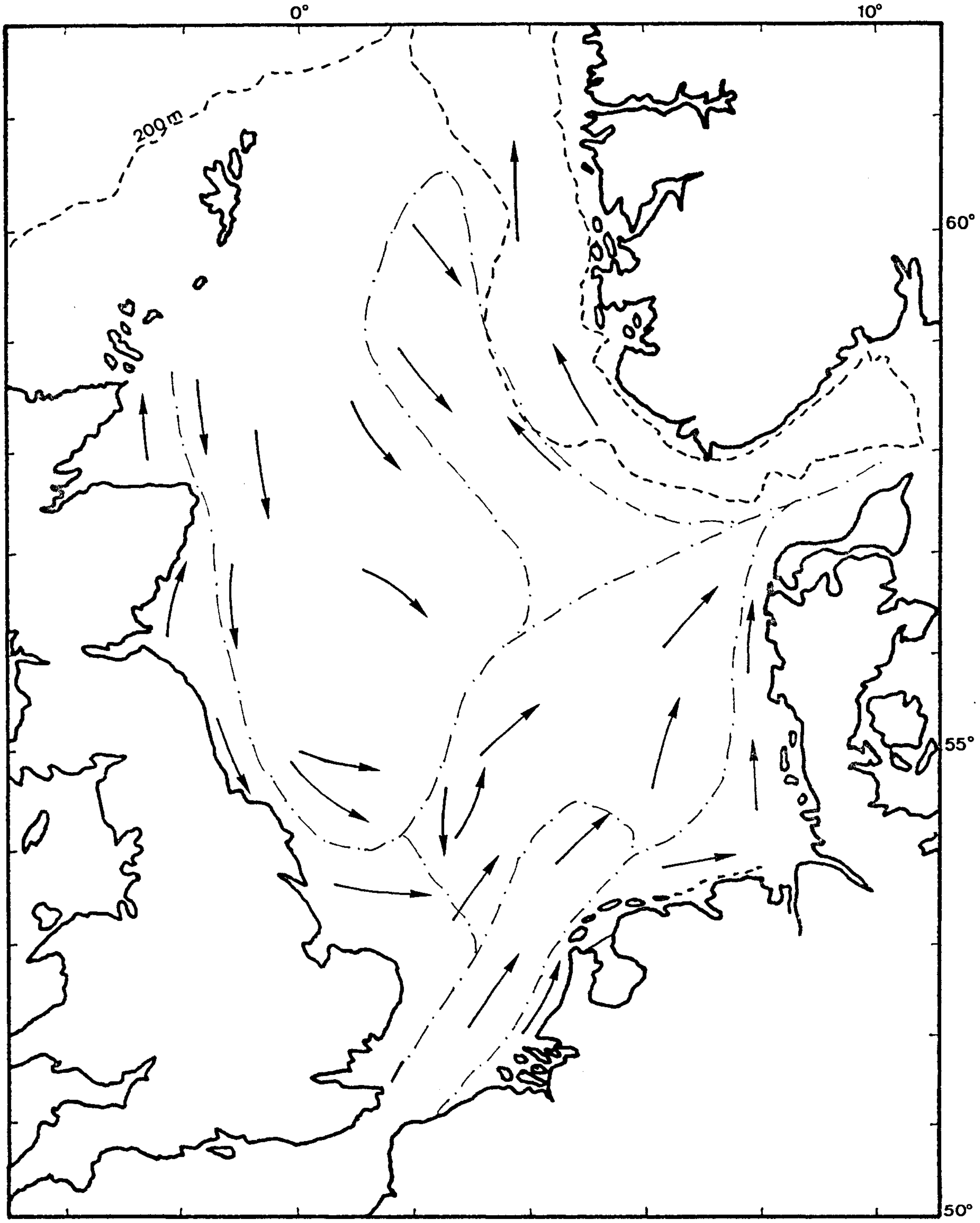

fig. 1.5.- Water masses in the North Sea according to Laevastu (1963).

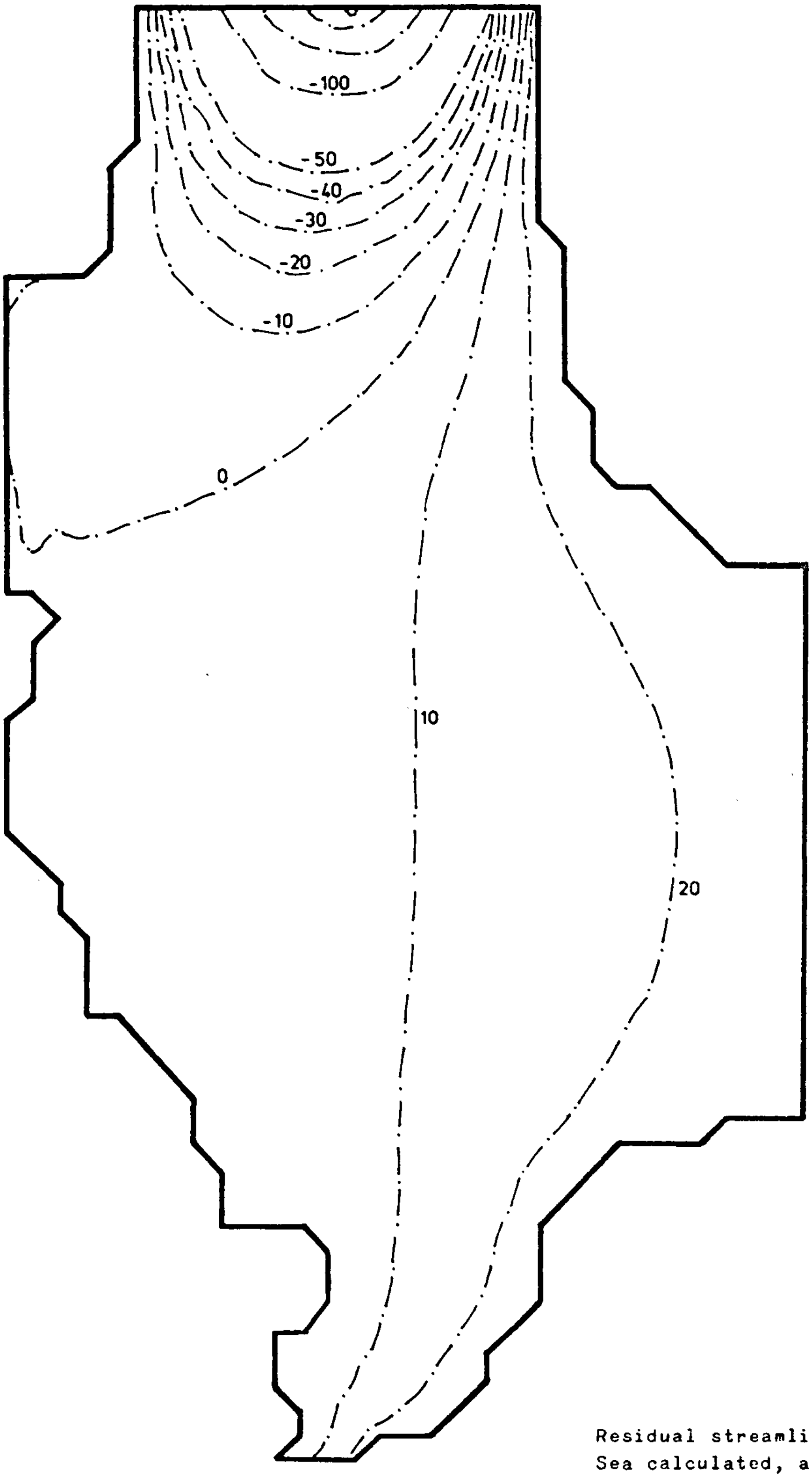

fig. 1.6.
Residual streamlines ψ = const in the North Sea calculated, assuming constant depth (after Ronday, 1972). The actual values of ψ are 10^4 times the indicated figures.

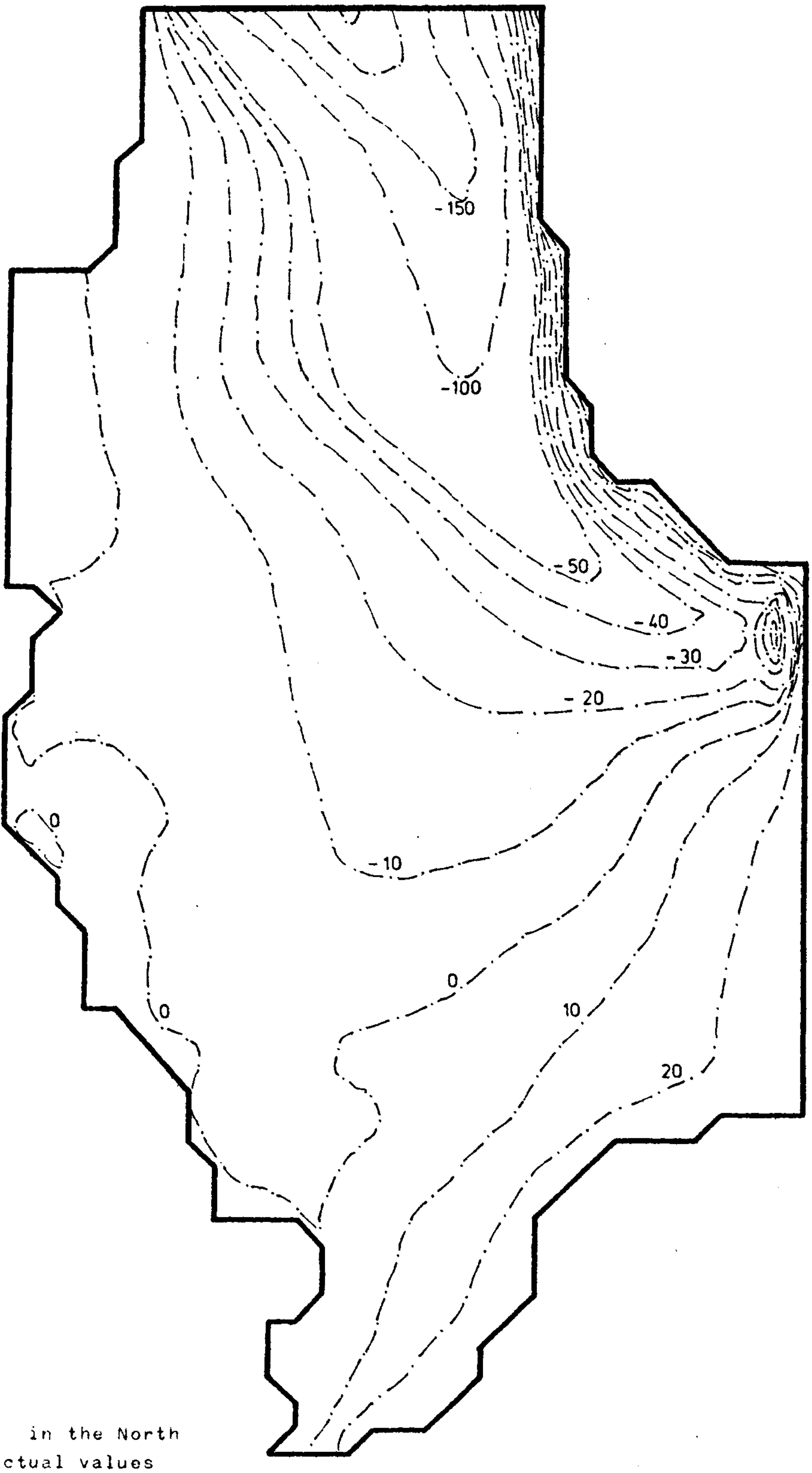

fig. 1.7.
Residual streamlines ψ = const in the North Sea (after Ronday, 1972). The actual values of ψ are 10^4 times the indicated figures.

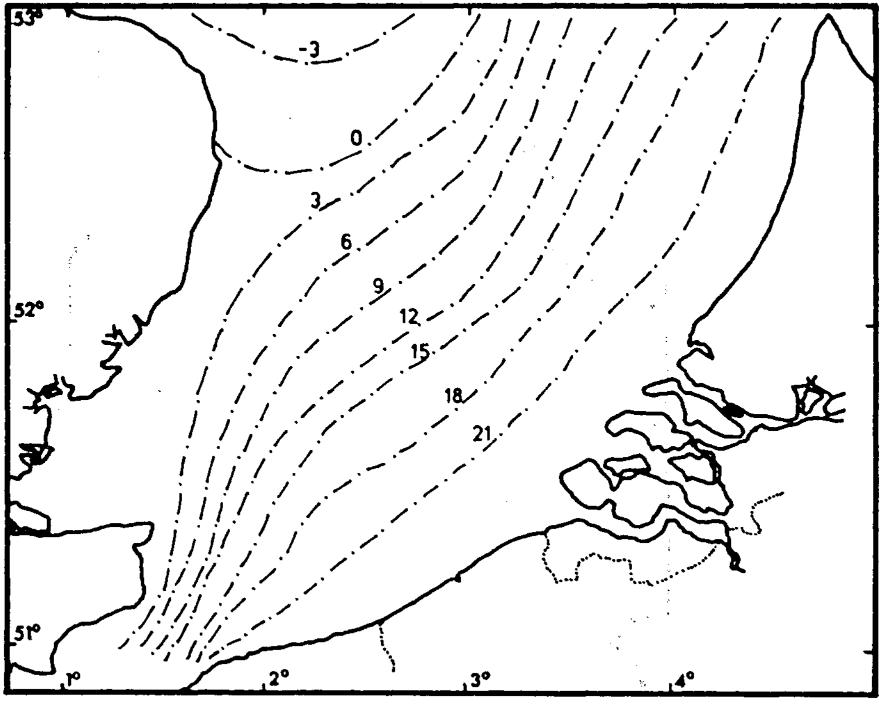

fig. 1.8.- Residual circulation in the Southern Bight without tidal stress. Streamlines ψ = const (in 10^4 m^3/s). (After Nihoul and Ronday, 1974).

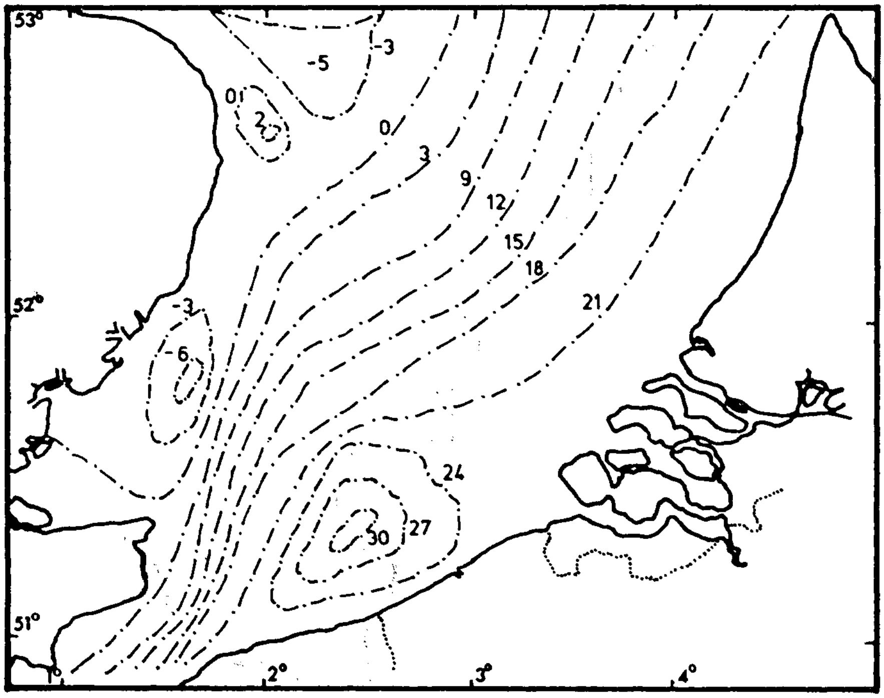

fig. 1.9.- Residual circulation in the Southern Bight with the tidal stress. Strealines ψ = const (in 10^4 m^3/s). (After Nihoul and Ronday, 1974).

Figure 1.9 shows the calculated streamlines in the Southern Bight taking the tidal stress (calculated from the tidal model) into account and demonstrating its cogent influence on the residual circulation.

8.3.- Passive dispersion model

The model has been applied with success by Nihoul (1972) and by Adam and Runfola (1972) to the determination of the dispersion pattern subsequent to a dye release or a dumping.

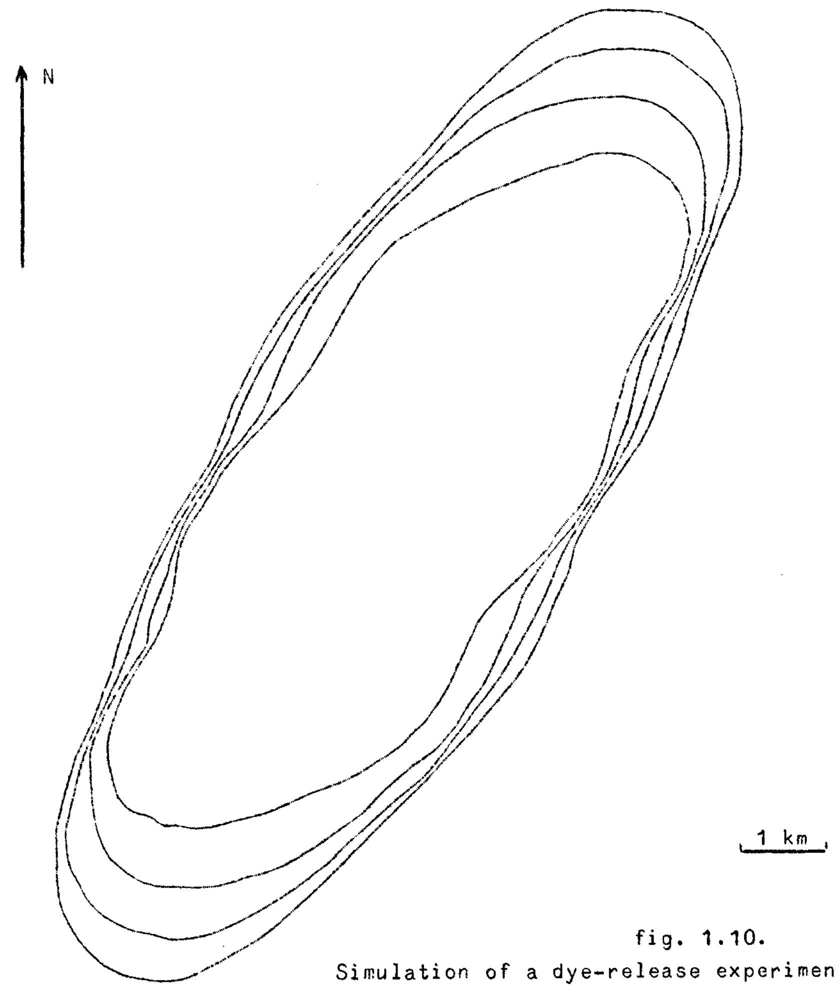

fig. 1.10.
Simulation of a dye-release experiment in the North Sea [after Adam and Runfolla (1972)].
Position : 51°20' N , 1°34' E .
Curves : 1/50 of initial central concentration 48 h - 72 h - 96 h - 108 h after release.

Figure 1.10 illustrates the influence of the shear effect on the anisotropy of the patch of dye.

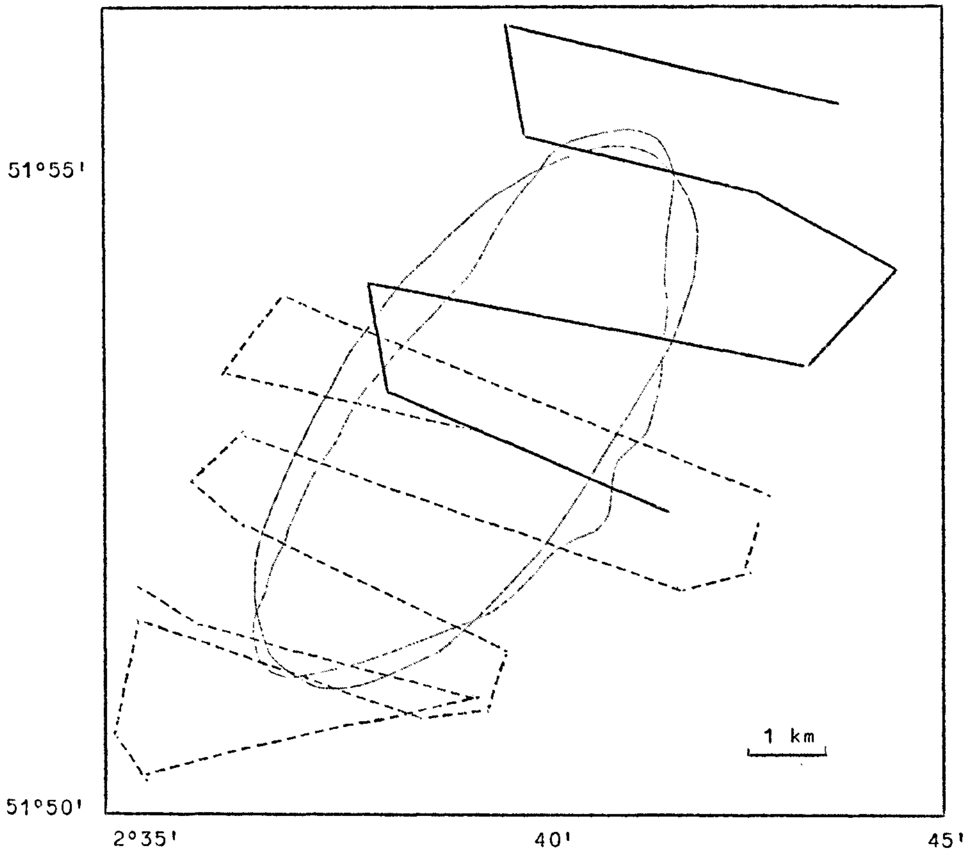

fig. 1.11.
Comparison between observed and predicted shape of a patch of rhodamine B 68 hours after release.
The experimental curve is the irregular curve drawn by Talbot (1970) [The broken piecewise straight lines are the ship's trajectories]. The theoretical curve is the regular ellipse predicted by the simplified model [Nihoul (1972)].

Figure 1.11 shows a comparison between the observed and predicted shape of a patch of rhodamine B, sixty-eight hours after release. The theoretical curve is calculated using a simplified version of the model which fits the best ellipse to the tidal velocity vector diagram.

8.4.- Niche interactions model

The model has been applied with success by Pichot and Adam to the study of chemical, biochemical and ecological interactions in the Ostend *Bassin de Chasse*

Figures 1.12, 1.13 and 1.14 show the evolution of six different forms of phosphorus :

- x_1 dissolved phosphate in sea water;
- x_2 P in non-living matter in suspension;
- x_3 dissolved phosphate in interstitial water;
- x_4 P in bottom sediments;
- x_5 P in plankton;
- x_6 P in benthos.

They illustrate the cogent influence of the non-linear terms in the interaction laws on the existence of a steady state and the time necessary to reach it.

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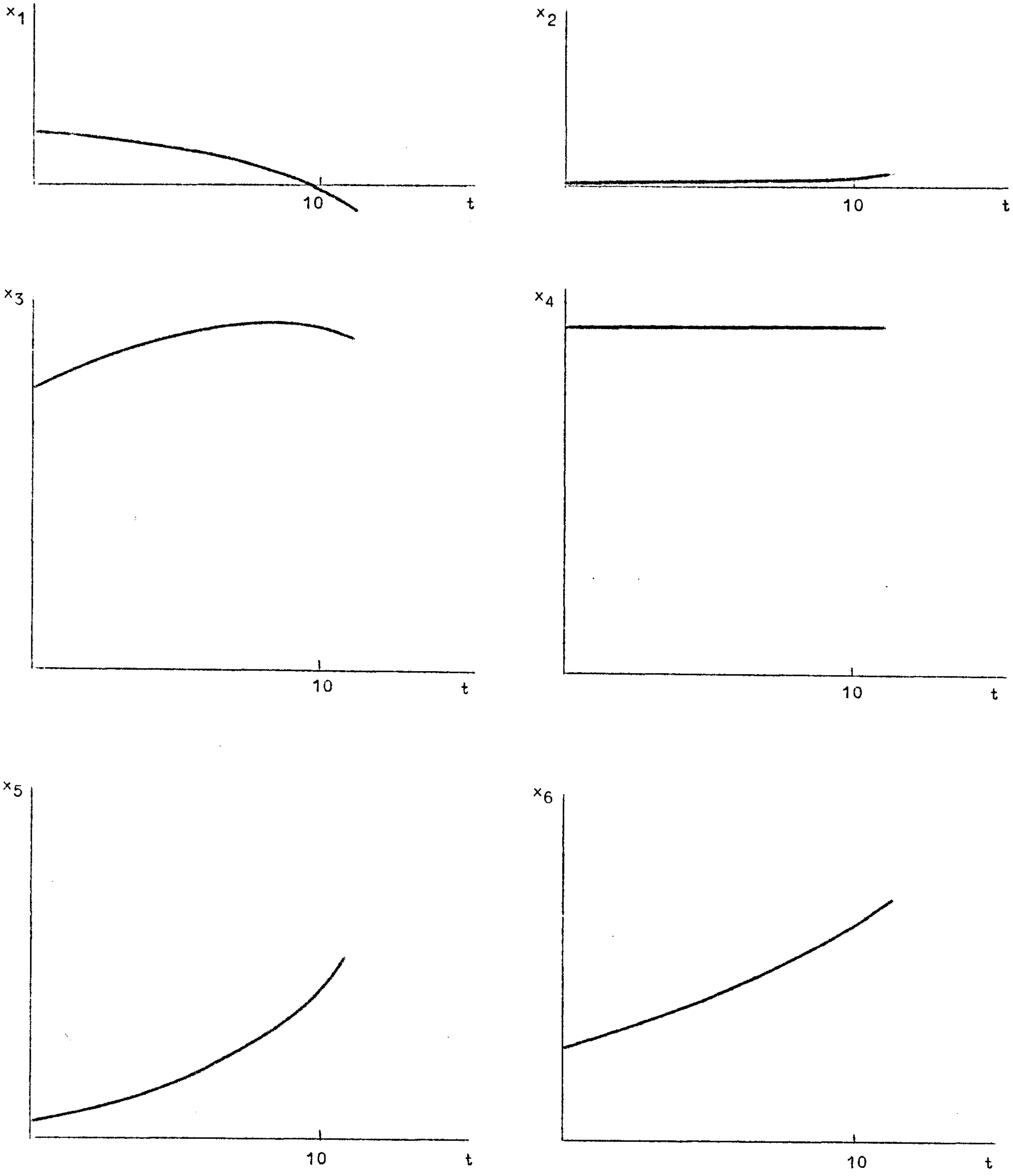

fig. 1.12.
Evolution of six different forms of P in a closed sea basin assuming completely linear interactions [after Adam (1973)].

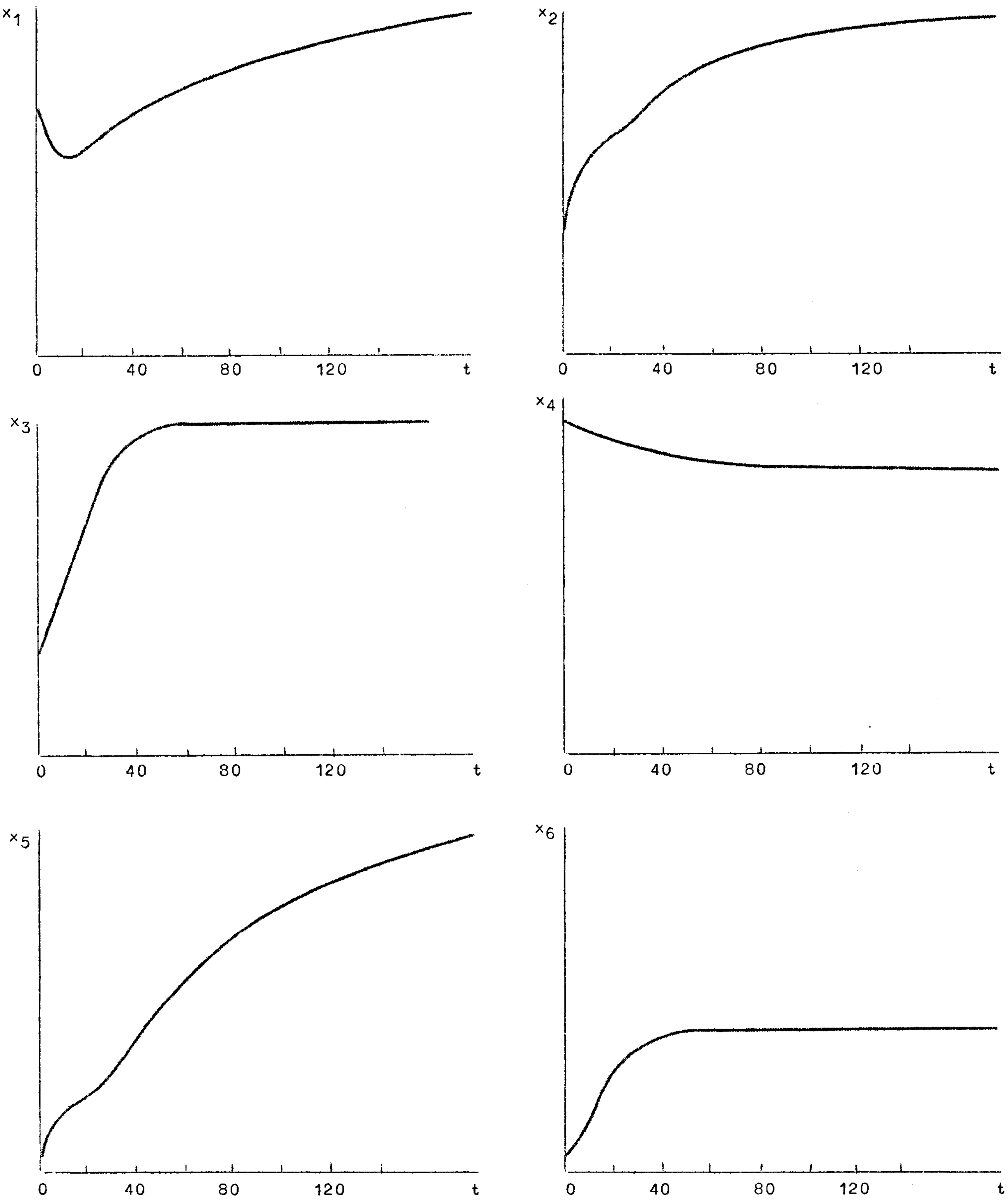

fig. 1.13.
Evolution of six different forms of P in a closed sea basin assuming quadratic-bilinear interactions [after Adam (1973)].

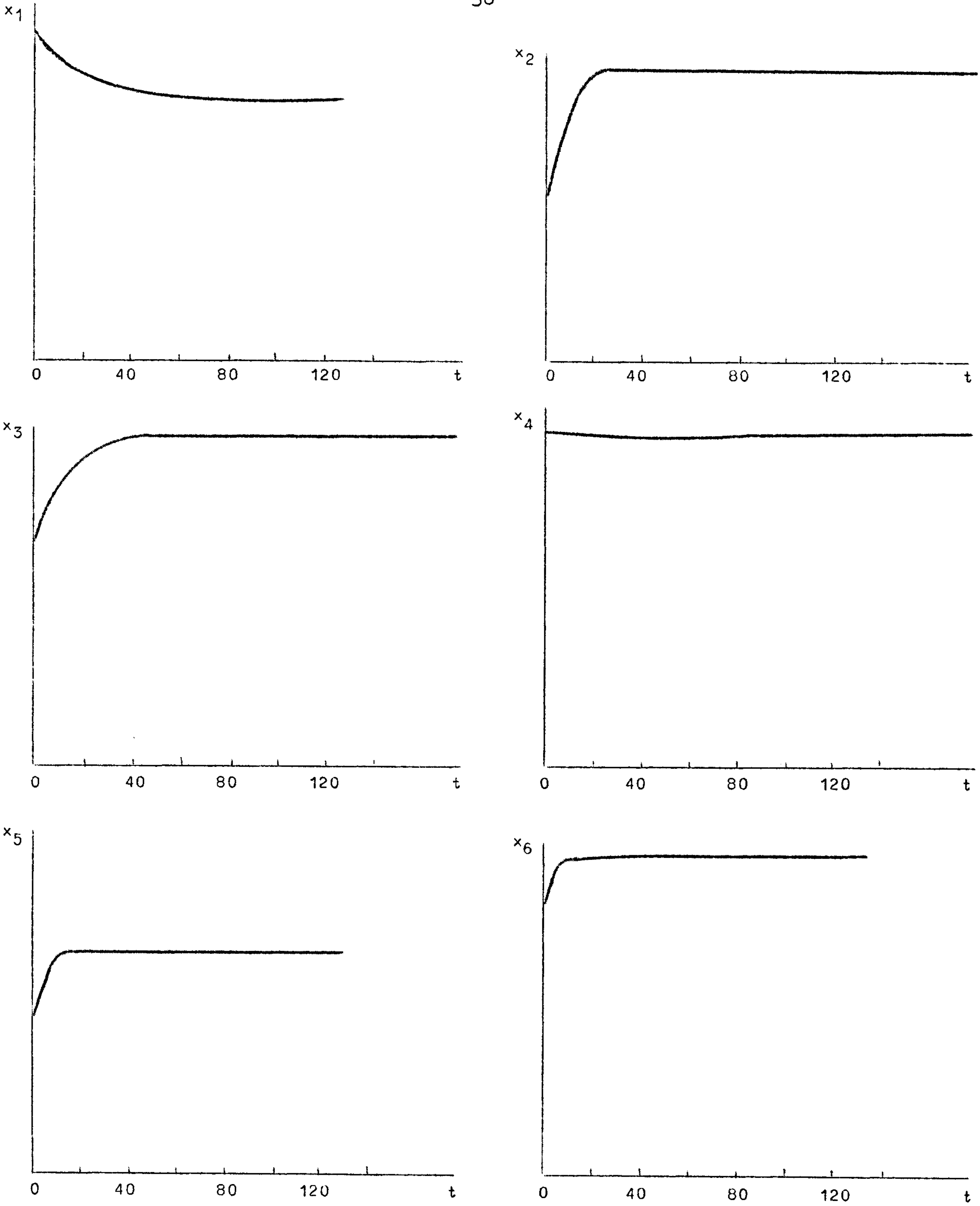

fig. 1.14.
Evolution of six different forms of P in a closed sea basin assuming strongly non-linear interactions [after Adam (1973)].

Programme national sur l'environnement physique et biologique – Projet mer. Progress Reports

N 1 NIHOUL, Mathematical Model for the Study of Sea Pollution.

N 2 NIHOUL, Application of Averaging Techniques to the Mathematical Modelling of Sea Pollution.

N 3 NIHOUL, Mathematical Model, Proc. ICES, Meeting on Pollution in the North Sea, Lowestoft, March 25-26, 1971.

N 4 RONDAY, Etude de la dispersion d'un polluant en mer du Nord.

N 5 NIHOUL, Shear Effect and Eddy Diffusion in the Southern North Sea.

N 6 NIHOUL, Ecosystemology applied to Sea Pollution.

N 7 FRANKIGNOUL, Preliminary report on Air-Sea Interaction.

N 9 ADAM-RUNFOLA, Numerical Resolution of Diffusion Equation.

N 10 NIHOUL, Mathematical Models.

N 11 NIHOUL, A simple Model of Entrainment and Turbulent Diffusion across a Density Interface in the Ocean.

N 12 FRANKIGNOUL-STRAIT, Coherence and vertical Propagation of High-frequency Energy in the Deep Sea.

N 13 RONDAY, Etude de la circulation résiduelle en mer du Nord au mois de janvier.

N 14 ADAM-RUNFOLA, Numerical Methods for the Computation of Shear Effect Diffusion.

N 15 RUNFOLA-ADAM, Residual and Wind-driven Circulation in the Southern Bight.

N 16 DUBOIS, A new Statistics of Ecosystems.

N 17 RONDAY, Modèle mathématique pour l'étude de la circulation due à la marée en mer du Nord.

N 19 PICHOT-HECQ, Exploitation des données au point fixe M06 par corrélations croisées.

N 20 NIHOUL, Diffusion of Turbidity by Shear Effect and Turbulence in the Southern Bight of the North Sea.

N 21 DUBOIS, Diversity of space-time dependent fluctuating Distributions of Species.

N 22 I DROISSART-SMITZ, Applications du calculateur hybride aux problèmes écologiques.

II LEROY, Modèles non-linéaires d'interactions écologiques.

N 23 GENET, Développement économique optimal de régions frontalières affectées par une pollution transfrontière.

N 24 DUBOIS, The Behaviour of the Index of Fluctuations D in the Volterra-Lotka Model.

N 25 NIHOUL, Interactions at the Sea Boundaries as a Handicap to Modelling.

N 26 LAMBERMONT-LEBON, On a new Derivation of the Erosion Flux induced by a Turbulent Flow.

Chapter II

Data Acquisition and Processing

by

Georges PICHOT

Foreward

This chapter is based on "The Belgian Automatic Oceanographic and Meteorological Data Station" by G. Pichot, A. De Haen and J. C. J. Nihoul, Symposium on Offshore Data Acquisition Systems, Southampton, Sept. 16-18, 1974. The author is endebted to the Belgian Navy for the help he received in collecting the data for the preparation of this report.

1.- Ships survey

The Belgian Navy provided five ships whose characteristics and activities are summarized in table 2.1. The main cruises consisted in the study

- of 25 points distributed on rectangular or radial networks (see fig. 1.1) and surveyed regularly, at least every season. Particularly, the important cruise of September-October 1973 was one of our contributions to the JONSDAP 73 (Joint North Sea Data Acquisition Programme) exercise in collaboration with the United Kingdom and the Netherlands.
- of some characteristic points of open sea and coastal waters (see fig. 1.1), considered as fixed stations and continuously surveyed during a week, in 1973.

Table 2.1

Name of the ship	Type	Length (m)	Crew	Scientists	Number of effective working days at sea			Total
					1971	1972	1973	
MECHELEN	M.S.C.	44	28	11	74	76	78	228
ZENOBE GRAMME	Ketch	28	13	3	26	32	42	100
HASSELT or HERSTAL or KORTRIJK	M.S.I.	34	12	1	37	125	80	242
Total					137	233	200	570

- of 1200 points for a unic sedimentological survey.

The results of all these cruises and their discussion are the subject of all the following chapters.

2.- Currentmeter stations

Our Plessey MO21, NBA DNC2A and VACM-AMF currentmeters were only received since August 1973 and used for the first time during Jonsdap 73.

Figure 2.1 shows the deployment of automatic stations during this exercise. Our programme assured two stations at 51°14' N 2°28' E and 51°31' N 2°25' E and contributed to the rigs of instruments intercalibration and of spatial coherency check with the KNMI (De Bilt).

The schema of the used mooring is reported on figure 2.2.

For example, the results of the bottom meter of the station (51°31' N , 2°25' E) is given, after decoding and translating its magnetic tape, fig. 2.3 where the upper and lower diagrams represent the phase and the amplitude of the current. One identifies :

- an oscillation of 12.4 h period which is the principal lunar tide M_2 .
- an about 14 days modulation which is the beating between M_2 and the principal polar S_2 .

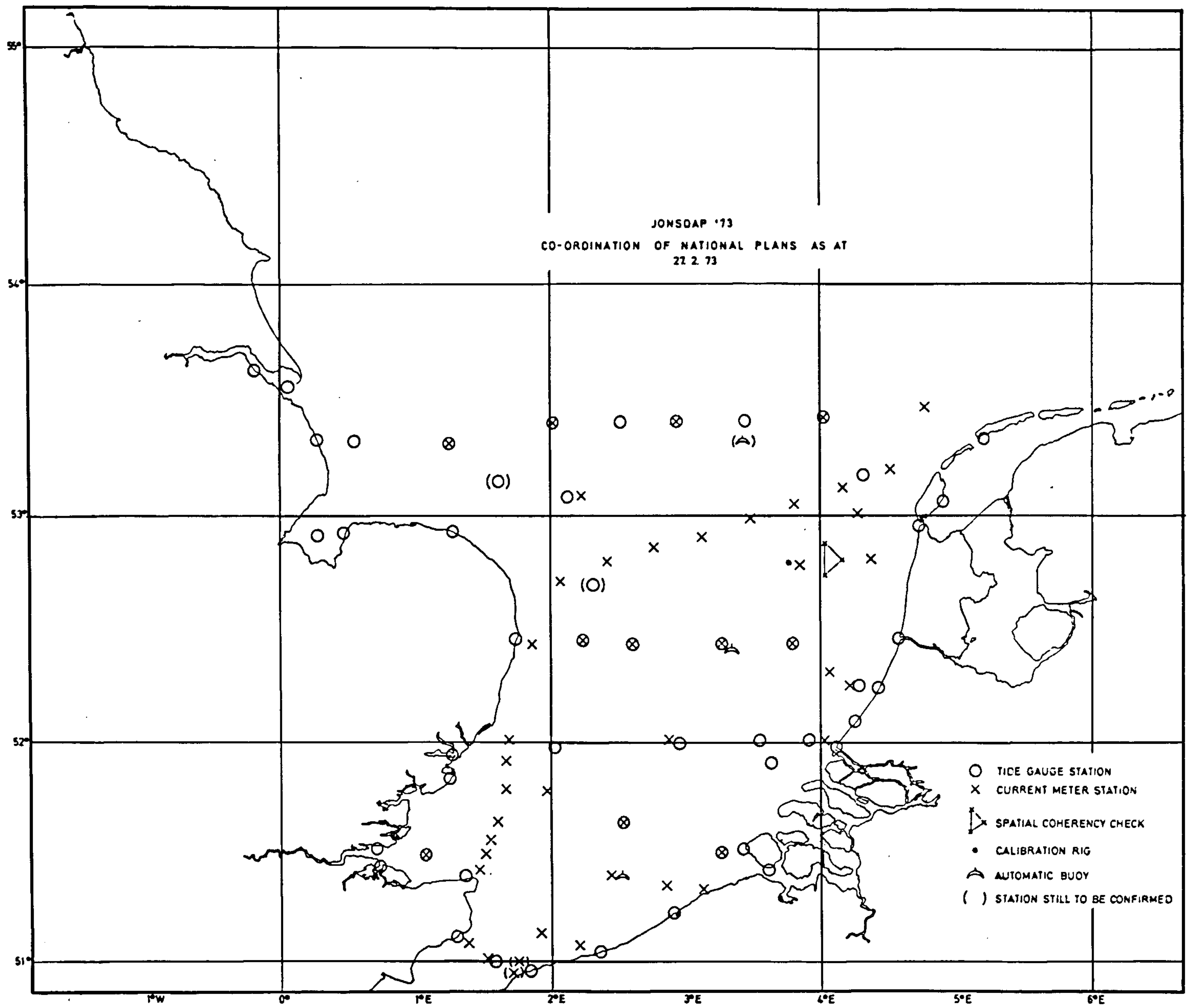
JONSDAP '73
CO-ORDINATION OF NATIONAL PLANS AS AT
22 2 73
55°
54°
53°
52°
51°
1°W
0°
1°E
2°E
3°E
4°E
5°E
6°E
○ TIDE GAUGE STATION
× CURRENT METER STATION
SPATIAL COHERENCY CHECK
• CALIBRATION RIG
AUTOMATIC BUOY
( ) STATION STILL TO BE CONFIRMED

fig. 2.1.

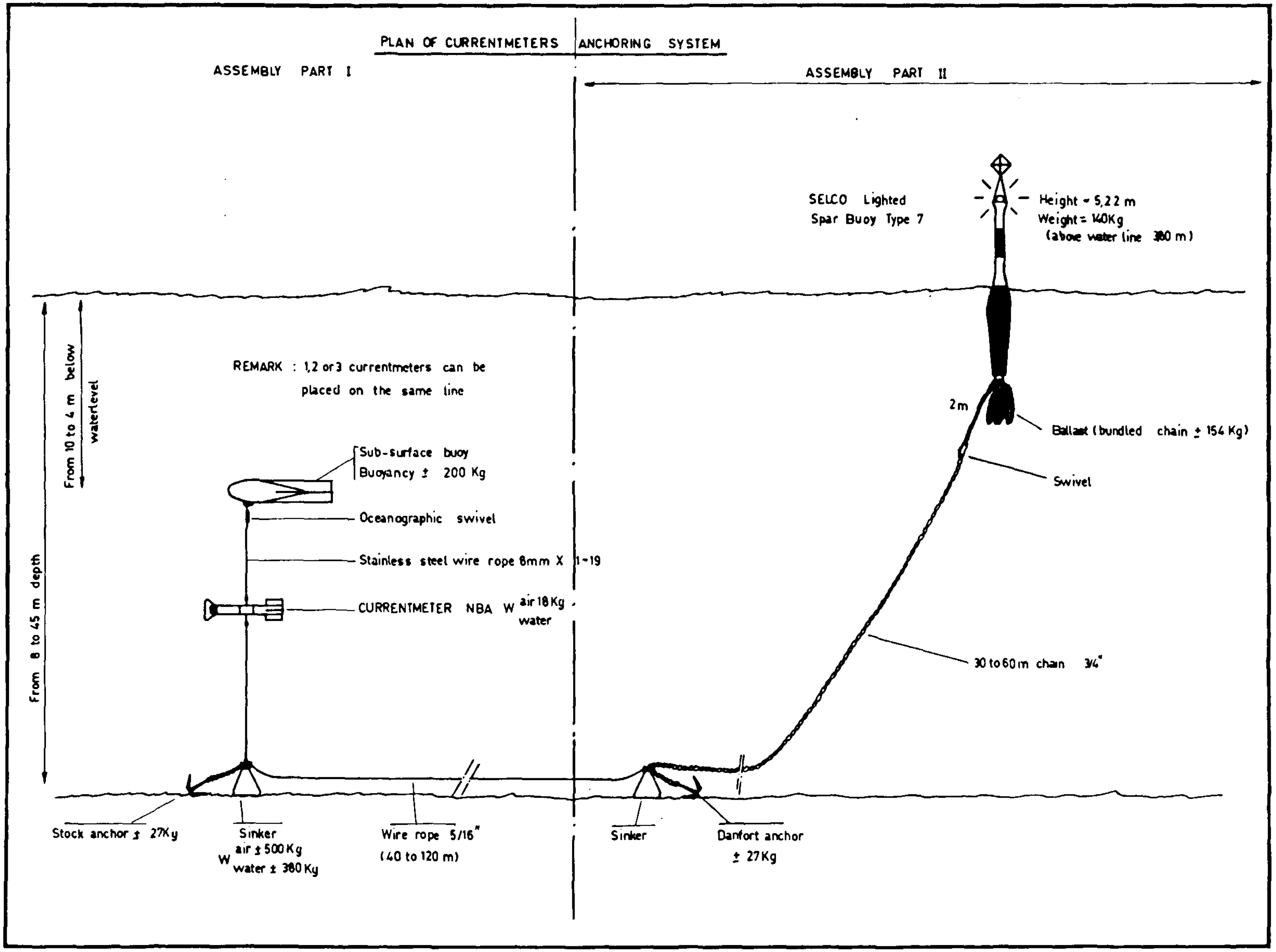
PLAN OF CURRENTMETERS ANCHORING SYSTEM
ASSEMBLY PART I
ASSEMBLY PART II
SELCO Lighted
Spar Buoy Type 7
Height - 5,22 m
Weight = 140Kg
(above water line 380 m)
REMARK : 1,2 or 3 currentmeters can be
placed on the same line
From 10 to 4 m below waterlevel
From 8 to 45 m depth
Sub-surface buoy
Buoyancy ± 200 Kg
Oceanographic swivel
Stainless steel wire rope 8mm X 1-19
CURRENTMETER NBA W air 18 Kg water
2m
Ballast (bundled chain ± 154 Kg)
Swivel
30 to 60 m chain 3/4"
Stock anchor ± 27Kg
Sinker
W air ± 500 Kg water ± 380 Kg
Wire rope 5/16"
(40 to 120 m)
Sinker
Danfort anchor
± 27Kg

fig. 2.2.

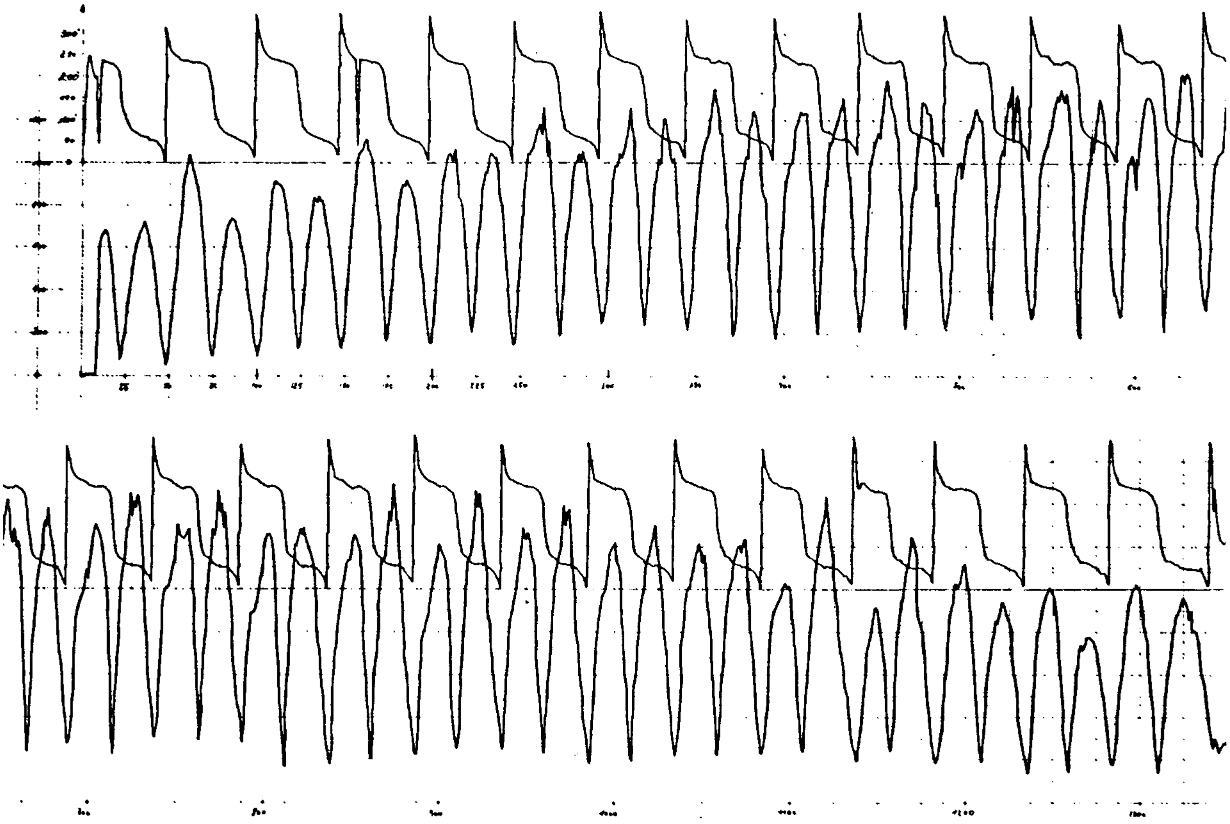

fig. 2.3.

- a daily maximum of speed due to the principal lunar diurnal tides O_1 .
- the difference between two successive maxima which is decreasing with an increasing amplitude probably due to an interaction of M_2 , S_2 and O_1 .
- the speed maximum of neap waters in opposition direction of these of spring waters due to the topography of this area.

3.- Automatic oceanographic and meteorological data stations

Because the model requires continuous knowledge of the boundary conditions, the acquisition of automatic and meteorological data stations was decided.

An *ad hoc* working group was set up to conduct a market survey. It considered the following buoys : Comex (Telem 150, HSB/1 and Borem), Sysna, Selco (type 6,7,12 and 17), Simrad (SBI, MET and satellite commanded), Hagenuk (UBA and Stamob), LCT (L55), Dornier, General Dynamics, Saclantcen and came to the following main conclusions :

1. The scarce, irregular and geographically scattered demand in this new field led to a lack of industry involvement, real competition and normal market conditions.
2. In spite of large publicity statements, most of the systems had at our own knowlegde not thoroughly, if ever, been experimented.

The buoy was required to be big and robust enough to carry safely a great amount of all kinds of sensors, to be easily noticeable by ships and to survive long periods of unattended operation in all seasons. The French Sysna buoy appeared to be the best compromise between our programme's requirements and its financial possibilities.

The electronics was designed and developed by ourselves. It is quite sophisticated so that it can receive and treat nearly any form of sensor signal, operate a certain level of pre-processing (numerical integration, vectorial projections, sums, etc.) and monitor the buoy itself (energy levels, movements, safety, etc.).

General Description of the SYSNA Buoy

The float of the Sysna buoy is a disc of 3 meters in diameter and 1.5 meters thick. Its important own stability is further increased by a 900 kg fixed ballast contained in the short elliptic stream-lined tail and also by a 1500 kg mobile ballast suspended at 8 meters below the buoy at the end of a V-shaped synthetic fibre line. This mooring chain is attached underneath this ballast.

Four hatches are symmetrically disposed on the flat deck of the buoy, around the center. They cover the cylindrical wells which contain the battery racks. A fifth hatchway gives access to the inner space of the buoy. Two easily accessible, 1 meter high, standard 19 inch instrument racks are mounted on each side of this compartment. Although they support the complete electronics, the transmitter, the control and distribution panel and some dry batteries packs, abundant space is provided for additional equipment. In addition, several smaller, completely sealed-off compartments can keep the platform buoyant in case of flooding of the main chamber.

The central, 8 meters long, tubular mast is guyed by four stainless steel cables. It supports a tubular structure to which are fixed the flashlight, the radar reflector, the antenna system and the meteorological sensors. Two wind generators are symmetrically attached to the mast, halfway up, in order not to disturb the meteorological measurements. Under normal conditions only one of them can keep the batteries fully charged.

The buoy and its mooring are shown in figure 2.4 and table 2.2 summarises its characteristics. The buoy and the mast are made of sea water resistant aluminium alloy. All precautions have been taken in order to avoid galvanic corrosion of the submerged parts.

Table 2.2

The SYSNA Buoy

Mechanical characteristics	
Overall diameter of the float	3,021 mm
Height of the float (including small ballast tail)	2,180 mm
Maximum height inside	1,580 mm
Mast length	8,100 mm
Mast diameter	150 mm
Displacement	2,000 kg
Float volume	10 m^3
Stability	2 t.m
Rolling period	2.8 s
Heave period	1 s
Spare buoyancy (with 1 ton of batteries and equipment)	7 tons

Materials used

Buoys : AG4MC aluminium alloy, specially resistant to marine corrosion. Tubes : AG3 . Cast parts : AS 13 74 . Guys and guy fixings : stainless steel 316 (18/12 Mo).

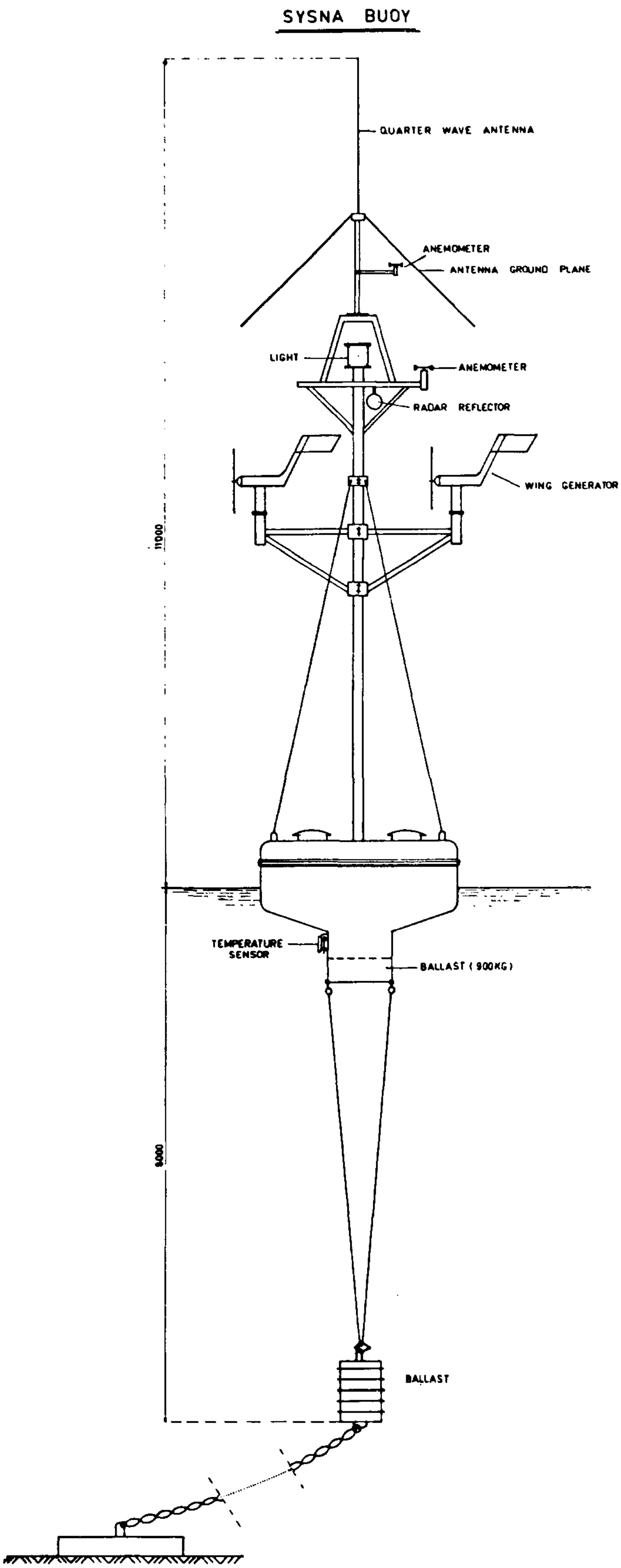
SYSNA BUOY
QUARTER WAVE ANTENNA
ANEMOMETER
ANTENNA GROUND PLANE
LIGHT
ANEMOMETER
RADAR REFLECTOR
WING GENERATOR
11000
TEMPERATURE SENSOR
BALLAST (900KG)
9000
BALLAST

fig. 2.4.

Power Supply

Because of the general use of "COSMOS" type integrated circuits in the "Data Acquisition System", its power drain has been kept very low and is of the order of 3 watts. The used voltages are + 24 volts and - 18 volts for the D.A.S. and + 24 volts for the radio transmitter, the sensors and the light.

1) Wind generators

Two AEROWATT type 24FP7 wind generators are the buoy's main energy source. Under normal conditions, the battery buffered output of only one of them is sufficient to maintain the whole buoy system including the powerful flashing light in operation.

Their main characteristics are :

a) Electrical

- direct drive permanent magnet two phase alternator. The output is converted to DC by two built-in diode bridges;
- rated power output : 24 watts (for a 7 m/s wind speed);
- rated voltage : 24 volts.

b) Mechanical

- propeller : directly mounted on alternator shaft;
- two lightweight specially treated wooden propeller blades;
- variable pitch automatically controlled by wind pressure;
- average starting wind velocity : 3 m/s ;
- maximum rotation speed : 1200 rev/m ;
- overall length : 1530 mm ;
- propeller diameter : 1000 mm ;
- total weight : 20 kg ;
- wind drag at 30 m/s : 26 kg .

2) Rechargeable batteries

The inconvenience of wind generators is their irregular output. This is why they are buffered by 24 V , 195 A hours lead acid batteries. This set gives the buoy system an endurance of 7 days at full performance in the complete absence of wind by total generator breakdown.

3) Expendable batteries

A small set of dry Mallory Duracell alkaline manganese batteries provides a negative 18 volts, 20 A hours power supply for operational amplifiers and various other circuits requiring a negative polarisation. As a simplification this negative voltage will be provided in the future directly from the mains 24 volts by a solid-state DC-DC converter.

A powerful set of 24 volts 4000 A hours Cipel zinc-oxygen expendable batteries with KOH liquid electrolite previously was the primary energy source of this type of buoy. These batteries have shown to be expensive, cumbersome and unreliable, if not dangerous, when used on a buoy. More compact and safer marine type Nickel-Cadmium rechargeable batteries have been purchased to replace them. They will be connected to the wind generators.

4.- The data acquisition system (D.A.S.)

General description

The basic unit consists of a signal scanner and an A to D converter for analog inputs, and of a code adaptor and a digital multiplexer for the digital inputs. Auxiliary circuits adapt a wide range of input signals, numerically integrate certain parameters, record the time of the measurements, etc. The general use of "COSMOS" integrated circuits lead to high reliability and very reduced power requirements.

1) The analog to digital converter

It is a precision, crystal controlled time interval meter. Its standard *analog input* is a series of frequency modulated pulses. Its *digital output* is in BCD code and is fed to the transmitter's modulator.

2) The scanner

An electronic 32 channel switching device successively interrogates the oceanographic and meteorological sensors. This switching affects not only the sensors output signal but also its power supply in order to reduce power drain, drift due to sensor self-heating and to eliminate possible cross talk on signal cables. Power is provided a certain time before the actual measurement to the integrating channels as well as to the sensors which need warming up.

3) The input adaptors (signal processing)

a) F.M. signals

Each of the scanner's input channels is made to receive a series of frequency modulated pulses. Amplifiers, limiters and pulse shapers allow the processing of any F.M. voltage. In addition, a series of dividers adapt the scale to a wide range of frequencies.

b) D.C. voltages

They are measured by the channels equipped with voltage-to-frequency converters.

c) Digital inputs

By means of buffer memories and under scanner clock control, the system can also directly receive, process and dispatch the information from sensors or sub-systems already equipped with digital outputs.

4) The numerical integrators

For accurate integration over long periods, the F.M. signals are stored in individual digital counters. These operate simultaneously and the integration time is set with precision by the general quartz oscillator clock. The digital output of these counters is then multiplexed under scanner control.

Technical characteristics

1) The analog to digital converter

It is a time interval meter counting the number of reference pulses issued by the precision quartz oscillator between two successive signal pulses. This way it converts the analog F.M. signals from the sensors into a number presented in parallel digital form. This time interval meter, as well as the integration modules, uses the B.C.D. 8.4.2.1. code. Accuracy :

FM signals : 10^{-5} ,

DC voltages : 10^{-3} ,

Full scale resolution : 10^{-6} .

2) <u>The scanner</u>

a) The scanner now has 32 channels. Possible extension up to 64 is provided.

b) A front panel selector limits the number of channels to be interrogated. It adapts the scanner to the actual number of sensors.

c) A "Single Channel Repeat" selector blocks the scanning cycle on any desired channel, excluding all the others. This facility is used for testing or calibrating a given sensor.

d) For easy data processing, prior to the radio transmission the corresponding channel number is added in front of each measurement.

e) The interrogation speed can be adjusted from 1 to 10 seconds per channel. The actual speed of 1 channel per second seems to be a suitable compromise between radio band width considerations on one side and short transmission time and a reasonable simultaneity of the measurements on the other side.

f) The normal sequence of an interrogation cycle is :

Channel N°	
1	: Buoy identification number;
2	: Time of the measurement cycle : (day, hour, minute, second);
3	: Control fixed frequency;
4-7	: Digital inputs;
8-11	: Voltages or frequencies to be numerically integrated;
12-22	: Voltages;
23-32	: Frequencies.

Thanks to the modular structure of the system, the sequential order as well as the number of channels of each type can be modified.

g) The interval between cycles is adjustable from "continuous" to one cycle a day. Intervals of half an hour for testing and of three hours for normal operational use seem most adequate.

3) Timing unit

This general time base is controlled by a 100 kHz crystal oscillator. It delivers the reference pulses for the counters as well as the time of day. It controls the integration periods, the scanning rate, the cycle repetition rate, etc.

4) Input signals

a) Frequency modulated alternating current or pulses. Dividers allow to measure signals over 30 MHz.

b) DC voltages 0-10 mV , 100 mV , 1 V and 10 V ; input impedance : 100 kOhm .

c) Voltages and frequencies to be numerically integrated during 1 , 10 or 30 minutes .

d) B.C.D. coded parallel digital inputs.

5) Output signals

Binary coded decimal "8.4.2.1" code, serial output.

6 measurement digits	24 bits
2 channel number digits	8 bits
channel separation	8 bits
Total	40 bits

To reduce the number of transmission errors due mainly to interference or fading, the self correcting "Hamming" code is used. The additional parity bits needed bring the total length of one measurement to 80 bits.

6) Modulator

This unit transforms the "clock" and "information" pulses delivered on two lines by the D.A.S. into a Pulse Length Coded 2500 Hz modulation subcarrier which is then applied to the transmitter's input.

7) Dimensions and environment

The complete unit can be contained in a 36 cm diameter, 50 cm long cylinder. Operating temperature ranges from - 2 to 40 °C with standard integrated circuits.

5.- Data Transmission

The data are transmitted to Ostend by a 10 watt completely transistorized FM transceiver operating in the lower VHF band (Mobilophone CMT Phillips). A complete transmitter-receiver is used as well on the buoy as at the receiving station for two main reasons :

- equipment standardization and interchangeability;
- possibility of a bi-directional radio link for future remote control and selective interrogation.

The essential characteristics are :

Dimensions : 70 × 235 × 235 mm ;
Weight : 3 kg ;
Power requirements : 24 V DC (21.1 to 31.7 V) ,
transmission 2 A (48 W) ,
receiving 0.12 A ;
Transmitting frequency : 31.850 MHz ;
RF output power : 10 watts;
Modulation : Phase modulation;
Encoding : P.C.M. applied to 2500 Hz subcarrier;
Antenna : Quater wave fiberglass whip and ground plane elements;
Range : 80 km minimum.

6.- Sensors

For the moment, the buoy is only equipped with some sensors which are known as the most reliable at sea. They measure wind speed, wind direction, barometric pressure, waves (Datawell heave sensor), air temperature and water temperature. The two latter ones are built and calibrated by ourselves.

Other sensors, and sometimes the most interesting ones, are still in an experimental phase, not yet miniaturised, cumbersome and energy greedy. Their long term fiability is not warranted in reason of corrosion, fouling and shocks.

Sensors for direct and reflected light, pH, dissolved oxygen, heavy metals by accumulating, phytoplankton activity by autoradiography are at present in research and development.

7.- The data processing computer

A data processing computer is installed in Ostend and linked to the receiving radio station. It is a Hewlett Packard Type 2100 computer with a 32 k words of 16 bits core memory. The various peripherals and input-output devices such as fixed and removable disc, magnetic tapes, teleprinter, fast tape puncher and reader, Tektronix CRT video display, 30 cm and 80 cm Calcomp plotters, Tally line printer, etc. make this relatively small computer specially suitable for receiving large amounts of data in all kinds and to output them after processing in any desired format.

The principal processing phases are :

- transcoding of the received binary data,
- putting in order the digits, the numbers and then the measuring cycles,
- dispatching of the data arriving from different stations,
- synchronisation and introduction or correction of the time scale,
- translation of the received numbers into proper parameters, by means of the calibration equations,

- control of the data : listing, display on video tube, automatic plots, statistical methods,
- editing, after manual or automatic error detection,
- concentration of the data : weighted averages, numerical filters,
- statistics, correlations, power spectra, ...

It is very important that most of these operations can be carried out "on line" and the remaining ones as soon as possible after reception of the data in order to detect any instrumental malfunction immediately and to make them available for a direct, easy and efficient use in our mathematical models.

Chapter III

I. Detrital Sedimentology in the Southern Bight of the North Sea

by

F. GULLENTOPS

During 1972 and 1973 some 1200 samples were analysed taken at regular intervals, mostly with a Van Veen sampler, in the Southern Bight of the North Sea. The sampling net is indicated on fig. 3.1, together with the essential isobaths as synthetised by Houbolt and put graciously at our disposal.

Analytical procedure and calculation of used parameters has been presented in our report : Analytical Flowsheet for Detrital Sediments (1972).

In this progress report, five maps will be commented upon, representing the distribution of five parameters which have proved to be of significance. Instead of giving long tables with the 5 × 1200 parameters, the results are presented on the maps with a system of symbols which allow a close enough identification of the exact values. For each map are successively discussed in A, the choice of the parameter, in B comments on the distribution, in C interpretation of the facts.

fig. 3.1.

1.- Gravel

A.-

When the history of the North Sea, as far as known, is taken into account it can be stated that gravel occurring on the actual seabottom may have four origins :

1) Fossil gravel sediments deposited subaerially during glacial low sea-level stages as fluvial or fluvio-glacial sediments.

2) These continental sediments reworked by the transgressive sea during sea level rise at the transition to an interglacial stage. Most effective will have been the Flandrian transgression but it must be foreseen that also the earlier Eemian transgression has left relicts.

3) Erosion of the sea by wave abrasion or tidal current erosion of all types of earlier deposits as well as the tertiary and cretaceous subsoil to form a residual lag-gravel, being a concentration of all elements too heavy to be transported by these currents.

4) New gravels brought in by the actual rivers or modern coastal cliff erosion.

This analysis shows that gravel occurrences on the actual seabottom are an indication for high wave activity or current velocity that bring about either actual erosion or prohibit actual sedimentation.

B.-

Fig. 3.2 shows a strong concentration of gravel occurrences.

North of 50°40' N and along the south-eastern shore only a very limited number of samples contain some coarser particles. Only one sample contains more than 10 % , seven samples contain between 2 and 8 % . These samples occur dispersed, apart from one SW-NE trending pattern 45 km east of Outer Gabbard, and it is to be stressed that north of the Rhine mouth not a single gravel was found in a broad area 75 km out of the coast.

In the southwest the gravel samples are strikingly more abundant and their gravel content also very high, up to 100 % . Most of the occurrences are grouped and can be easily outlined. In doing this the topography is important as obviously the gravel occurs in the swales

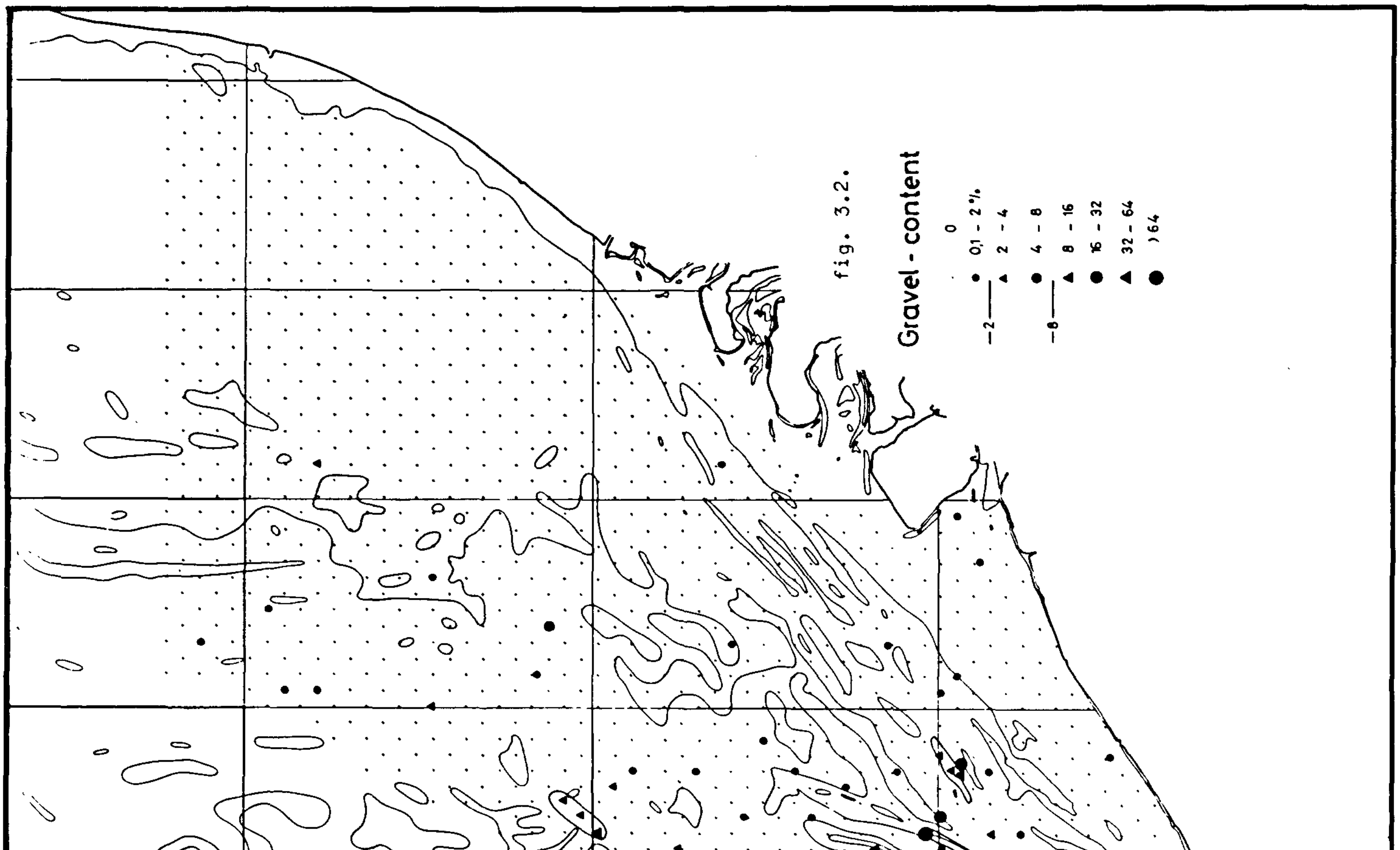

fig. 3.2.

between the sandbanks. The density of gravel samples allowed to outline two gravel classes 2 - 16 % and more than 16 % . The map shows two cartographic expressions of the gravelly sediments.

1) In the Hinder Banks and the northern Flemish Banks the gravels occur in narrow, elongated, enclosed stretches in the swales between some banks. The gravelly sediment is only present in the deeper swales and occurs in the eastern part at a swale depth of 30 m , deepening between Oost and West Hinder to 40 m and along the Fairey Bank to 45 m . In the same direction exists a definite trend towards higher gravel percentages.

2) In the southern Flemish Banks and in the Sandettie Falls area an inverted situation exists. The majority of the bottom is now gravelly and the much more individualized sandbanks stand out clearly. The gravel patches are not only larger but also higher percentages of gravel occur and several samples were pure gravel. The depth oscillates between 50 and 60 m and the purest gravels correspond to the deepest parts.

It must be stressed that the western boundary lines have only a limited value as they coincide with the extent of the sampling.

C.-

The map refines the distribution map of gravels given by Veenstra (1969). It shows that in the southern part of the Southern Bight exists a generalized gravel surface which lies at a depth of 60 m in the central, deepest channel and rises at first rapidly then slowly to - 30 m . It may be assumed with certainty to continue in the gravel layer which was found generalized by Briquet (1931) between the tertiary subsoil and the pleistocene cover in the coastal plain of northern France and Belgium, at the same depth of - 30 m .

The origin of this gravel layer will be studied in a future step by analyzing its petrographic composition. Veenstra (1969) who had not such abundant material indicates already a distinction between the eastern part with a majority of gravel reworked out of the local tertiary subsoil, and the marked appearance of foreign gravel in the deeper central portion. Its occurrence shows certainly the existence of actual tidal currents strong enough to prohibit sedimentation, eventually to erode the subsoil.

2.- Shells and shell fragments

A.-

The amount of shells or shell fragments has been determined on the fraction coarser than 2 mm . No attempt has been made to distinguish between living organisms, whole shells or commuted shells. This means that high shell percentages do not necessarily point to high biological activity. They can also originate through current accumulation of shell debris.

Low shell percentages are certainly an indication of low biological activity, but might also be influenced by rapid sedimentation.

B.-

The analytical results are shown on figure 3.3. After study of the distribution it was found that the data could significantly be grouped in three classes :

- less than 0.2 % : those containing no shells at all or only 0.1 % in the group 0.1 - 2 % ;
- from 0.2 to 8 % ;
- more than 8 % : grouping all the very shelly samples; only ten contained between 32 and 64 % ; only one, taken in a shell bank, contained 100 % .

In delineating the groups the principle was followed that at least two samples in the same group were necessary. This minimum requirement occurred only 6 times. This means that generally large patches have similar composition and proves that the analytical results are worthfull.

The cartographic expression shows immediately two results. There is no significant relation between bottom topography and shell content as the boundaries do not follow the bathymetric picture.

There is a definite trend in diminishing shell content from south to north and from deep water to the coast.

1) Areas without shells

A first very conspicuous configuration is the regular occurrence of shell-free sediments along the coast with tonguelike projections into

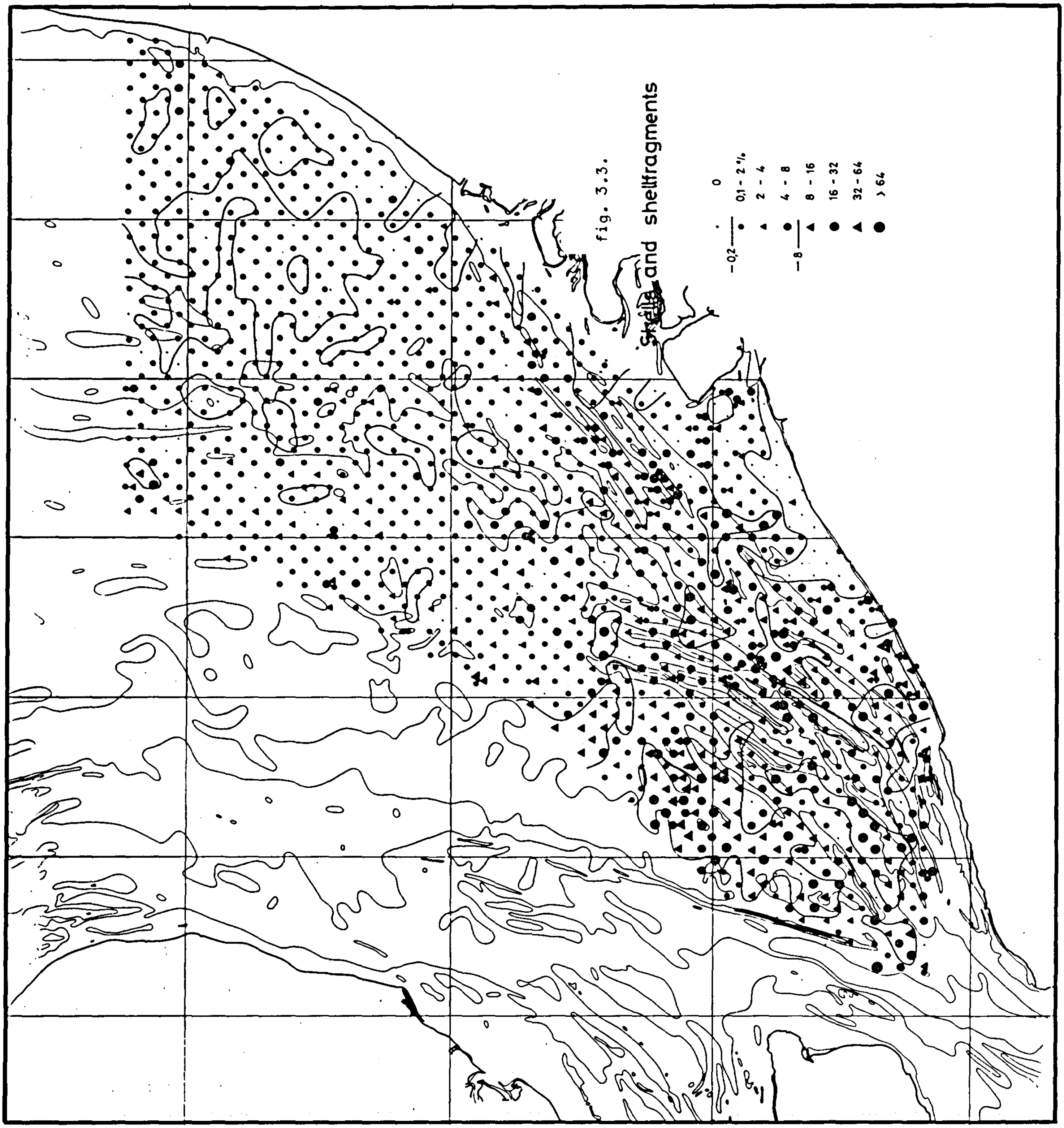

fig. 3.3.

Shells and shellfragments

the sea. The patch before the eastern Belgian coast and along the south bank of the Scheldt mouth is the most important and is at the same time the most shell-free as 85 % of the samples are of the class 0 . Towards the south a small patch extends out of the Yzer mouth and in front of Dunkerque. Towards the north up to Scheveningen the areas are not contiguous along the coast and are limited to individualized tongues. At the same time they are less shell-free as 75 % of the samples have a 0.1 % shell content.

In open water there is also a remarkable change in pattern from south to north. In the south two well defined stretches occur corresponding to two sandbanks, together with isolated low values in the distribution of which no correlation could be traced. Further north the area of shell-free sediments increases with 98 % of the samples in the 0.1 class. Out of the North-Holland coast a very large uniform area exists which dissolves into isolated patches towards the coast as well as towards the deeper sea.

2) Areas with high shell content (> 8 %)

Those are clearly located in the southern part of the map. A large stretch exists in the deepest part between Falls and Sandettie. It breaks up into isolated but large areas towards the coast. One of them touches the coast at the Belgian-French border and is responsible for the very shelly beaches there. The same pattern exists towards the north and more rapidly in front of the Scheldt estuaries. North of 51°45' N only a few isolated values occur just above 8 % excepted the small patch west of Brown Bank.

3) Areas with intermediate shell content (0.2 – 8 %)

As an intermediate class it occupies evidently the remaining space. Nevertheless the detail symbols allow to stress some trends. The surface occupied by this group is much larger in the north. Furthermore the southern half is predominantly characterized by values between 4 and 8 , while north of 52° N they are dominantly below 2 , the exceptions being located west of Brown Bank and in front of the Yser-mouth.

C.-

The literature is very silent on this type of parameter although for the interpretation of actual sedimentation and for the understanding of fossil deposits it can be important. An explanation of the observed data can only be tentative.

1) If a certain shell content in these undeep and well aerated waters can be estimated as normal then it must be explained why a general trend towards less shells from south to north is present. This might be due to changing ecological conditions, becoming less favorable. Diminishing tidal range, and so diminishing tidal currents, towards the north should have a bearing on the oxygen-content and might diminish population density. However shell percentages are an integration in time of population density. For the same population density the shell percentage will decrease with increasing rate of sedimentation. It was indeed seen qualitatively that, except for a few pure shellbanks, high shell percentages had relatively much more shell fragments, indicating their reworked and even transported character. It becomes obvious that the southern part is a more stable sea bottom with slow sedimentation rate and that this changes abruptly north of 51°45' N . The fact that in the south the lowest shell percentages (even two stretches of 0 %) lie on the ridges indicates a more rapid sediment renewal on these ridges, offering a less stable environment. The high shell content is correlated to the bank topography and the intervening gravelcovered swales all due to the same high tidal current system.

2) The extremely low shell percentages (group 1) can then be explained in the first place by rapid sedimentation rate exemplified by two ridges in the Flemish banks. The big area of the coast of North-Holland corresponds with the zone in which Houbolt (1968) found extensive transverse mega-ripples indicative of a regular bottomsand transport corresponding with sediment renewal and high sedimentation rate. This coincidence corroborates the validity of the explanation.

Clearly however the patches along the coast with their tonguelike projections into the sea cannot be explained by high sedimentation rates. The large one in front of the Belgian coast coincides with mud sedimentation.

The rate of this sedimentation is not yet known but can hardly explain the low shell content which is mostly 0 . Furthermore the delimited areas do not coincide with any special relief form.

Obviously they are related to the different river mouth of Rhine and Scheldt. More precisely each tongue can be traced to a mouth with a net tendency towards a south-western deviation. This is in agreement with ebb-current direction and shows that these shell-poor zones are correlated with the outcoming watermass of the estuaries.

In certain conditions this could be due to the inflow of fresh water. However, excepted for the Rhine mouth, all these estuaries have nearly the same salt content as the sea. So other physico-chemical characteristics of these waters, pollution, must be the reason. In this hypothesis it would be worthwhile to verify if the tongue north of Europoort is not due to affluents from the large urban area of The Hague. It merits to be signaled that the Yser mouth is completely devoid of this negative influence and on the contrary high shell percentages occur there. This means that the Amsterdam urban area does not send into the sea pollutant effluents.

Because the same pollution holds true for the Yser estuary in the extreme south-west the same explanation must be valid for the large shell-free area off the Belgian coast.

The tidal ebb-current brings the Scheldt water to the south-west and its effect is reinforced by effluents from the coastal urban areas. These coastal waters are then taken up by the stream pattern in the more open sea and swept to the north by the flood current.

3.- Sand percentage

A.-

It is necessary to recall that the sand percentage is not defined here as the percentage on the total sample. In the flowsheet used [Gullentops (1972)], particles coarser than 2 mm are first sieved off, and the fraction finer than 2 mm is then decalcified. The remainder, considered as the total detrital non-calcareous sediment, is then divided at 62 µ into the sand fraction and the suspension fraction. The map (fig. 3.4) depicts in this way the distribution of the sand percentage and at the same time of the complementary mud percentage.

The numerous analytical classes distinguished by symbols could again be united in three significant groups : from 100 to 98 % sand, between 98 and 68 % and less than 68 % sand.

B.-

The distribution of the three groups is significant :

1) Pure sands : 100 – 98 %

90 % of the samples fall in this category and more than half of them contain more than 99 % sand. This means that only a negligible amount of mud is trapped in the sand pores or might even have adhered to the grains and was loosened by the analytical procedure. Dispersed into this area occur some twenty single sample points in which the mud content reaches up to 5 % and which were not outlined. They are all situated in deeper parts of the irregular bottom topography.

2) Mud bottoms : less than 68 % sand

Most of the samples in this group contain less than 36 % sand and are true muds. They are concentrated south west of the Scheldt estuary and a small path south west of the Rhine mouth. The outlining of the areas suffers from the sample distances and does not sufficiently take into account the detailed bottom topography.

Two patches occur in the Scheldt estuarine funnel along the flood and ebb-channels. A big area occurs in front of the eastern Belgian coast and has strikingly the same form as the shell-free area. The same holds true for the patch in front of the Yser mouth.

3) Muddy sands : between 2 and 32 % mud

This type of sediment occurs essentially in front of the Belgian coast as an extension of the pure mud bottoms and is also present elongated stretches at some distance from the coast in the swales between the

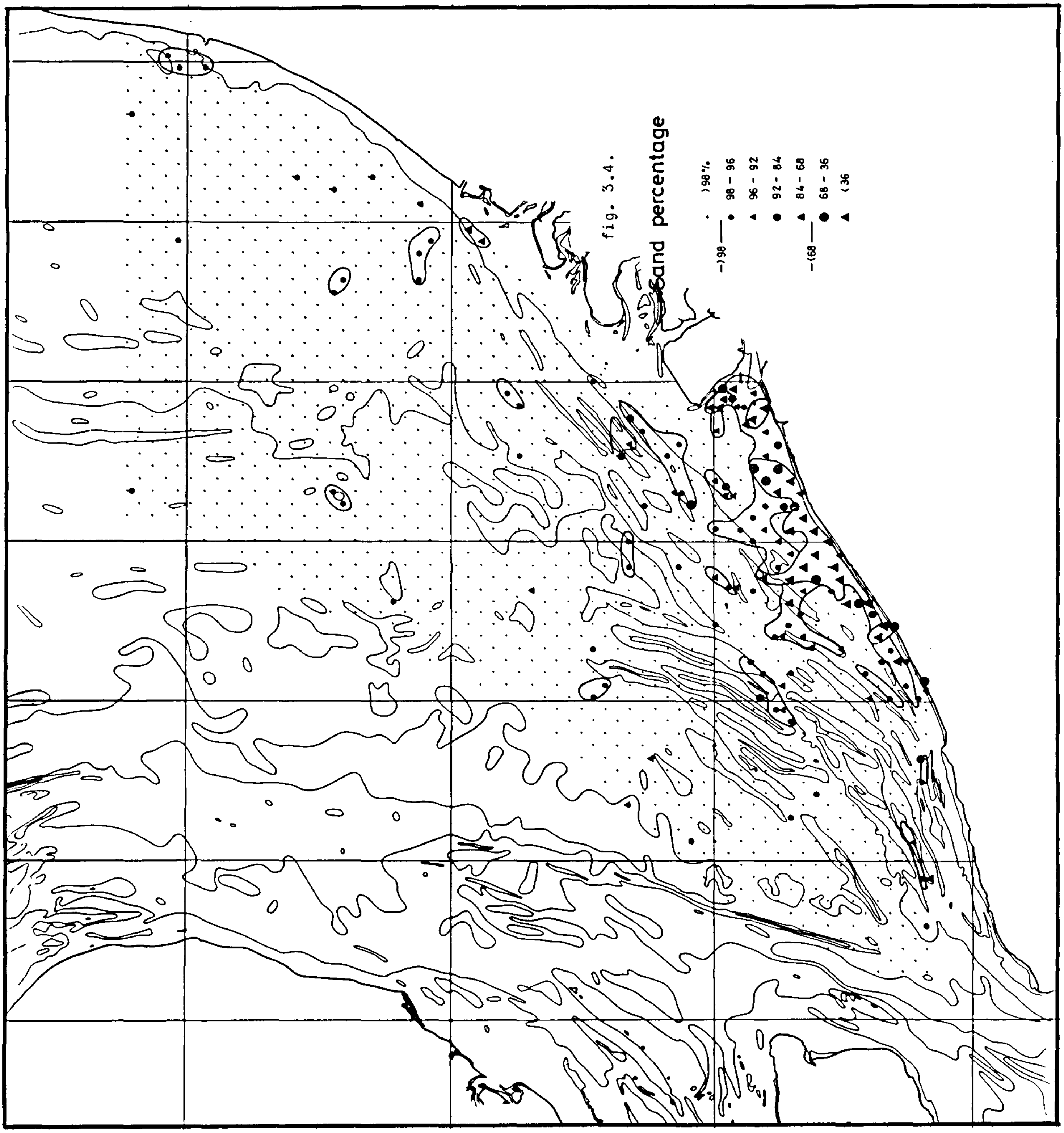

fig. 3.4.

Sand percentage

Zeeland and Flemish Banks. Further north only small patches occur, the most important ones before the mouth of Rhine and Yser. Remarkable is their practically complete absence in the open but also deeper sea.

C.-

1) The extremely low mud content in the greater part of the sampled area shows that in general the energy on the seabottom is sufficiently high to prohibit permanent deposition of mud. It has been shown [Moens (1972)] that in the open North Sea the suspension load of the sea water is rather low, with a mean of 3 mg/ℓ , but that after stormy weather this may increase considerably. The low suspension load in the middle of the Southern Bight was already shown by Maff (1957). The axe of minimum of turbidity corresponds rather well with the axe of maximum of salinity which correlates with the inflow through the Channel of clearer Atlantic water with higher salinity. This minimum correlates at the same time with greatest water depth and so lowest tidal current velocities.

Two forces may be responsible for the lack of permanent deposition. Tidal currents are strong and their force is depicted by the median grain size of the transported sands. Around current reversal the velocity drops however sufficiently to allow some fall out of suspended material. Current erosion will depend on the mechanical characteristics of the freshly deposited mud. Wave induced bottom turbulence is certainly more powerful to bring freshly deposited muds back in suspension. Maximum waterdepth in the sampled area is 60 m , which corresponds approximately to half the mean wave length. As stormy weather is generally produced by north west wind directions corresponding to maximum fetch, high wave bottom turbulence may be expected up to this depth.

It can be concluded that wave turbulence may be considered as the primary factor to inhibit permanent mud deposition and that tidal currents are responsible for the stepwise transportation of the suspended material to deeper parts of the sea where it will be out of reach of wave bottom turbulence.

2) The large mud content in front of the Belgian coast has been studied by Bastin (1973) and by Moens (1973).

In the large context of a sandy Southern Bight this distribution is very conspicuous. Two questions need to be answered : Which is the source of this mud and why is it deposited there?

a) The source of the mud will have to be found by detailed analysis of its grain size, mineralogy, physico-chemical properties and composition of its organic compounds. However this research can be guided by the consideration of three possible hypothetical sources.

- Bastin (1973) has put forward that the mud can derive from the local sea erosion of the underlaying tertiary clays. At a depth of - 30 m occurs under the modern seafloor sediments and ridges the abraded surface of the tertiary subsoil in which clays of eocene and oligocene age are predominant. In the deeper swales and channels this subsoil might be reached and eroded by the strong tidal currents or as Professor Faas[1] suggested by biogene erosion such as crab burrowing. Until now no outcrops have been located and it is doubtful that they could account for the large amount of mud deposited.
- The tidal inflow through the Straits of Dover brings in Atlantic water which has a low turbidity [Lee and Folkard (1969)] and hence a low suspension sediment load. Coastal waters are more turbid and can bring suspension load to the north. However the coast to the south is essentially composed of sand beaches and chalk cliffs and the Somme is the first somewhat important stream. So a southern coastal water mud source is real but can difficultly account for all the mud deposition. It may be stressed that continued development of harbour and industrial activity in the Calais-Dunkerque area might in the future have an increased effect on sediments along the Belgian coast.
- Ebb current outflow from the Scheldt estuary can lastly contribute. The actual upper Scheldt annual suspension load has been estimated by different authors [Gullentops (1973), Bastin (1973), Wollast (1971)] as between 1 and 2 million tons of mud. The percentage of this load finally carried out to the sea must historically have increased because

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[1] Oral communication.

the surface of the natural tidal flat sedimentation areas in the estuary has continuously been reduced by endiguing. In recent times the output has been increased artificially by the channel dredging activities for the Antwerp harbour. As this Scheldt estuary exists only some 1500 years and the important human interference only a few centuries, the mud deposition before the coast should also be historical if essentially related to the Scheldt. Up till now the mud sedimentation has not expressed itself in a typical morphological appearance but seems to drown the coastal sand ridge topography. This would be in favour for a recent development. A program for coring the mud sediments and studying their age and evolution of characteristics with depth will try to answer this question.

b) An explanation of the mud sedimentation must also explain why it is not eroded again. Here also a final answer is not yet available but a few hypotheses can be formulated.

- Sedimentation of mud is enhanced by the amount present. If concentration of suspended matter is very high floculation and aggregation of particles will increase. By biological activity aggregates can be formed and held on the bottom in such a way that there is a net surplus of sedimentation on renewed erosion. Shell life was seen to be very low in this area but other organisms as worms, especially Polydora, can be responsible.
- Bottom depth is rather low in these coastal waters, not exceeding 20 m . Wave turbulence should be very high and indeed coastal water turbidity is high [Moens (1973)]. However wave height is considerably reduced by the numerous north east tranding Flemish and Hinder Banks which cause the long swell to break. This coastal zone is in the wave shadow and experiences a much lower energy. These pre-coastal ridges tend to produce sublagoonal conditions in their shadow.
- Bastin (1973) and Moens (1973) studying the residual tidal currents found that this mud area was characterized by low residual currents which means that the turbid waters do remain in the area with only very low escape possibilities near the Wandelaar Bank.

If placed in the macromorphological situation it could be deduced from the trend of Flemish and Hinder Banks that the major tidal current direction, created by the Channel funnel, deviates from the coast. This combined with the tidal pump action of the Scheldt estuary might create in front of the Belgian coast a clockwise gyre in residual tidal currents with low escape possibilities of mud towards the north.

The mud area could *in globo* be explained by the tendency to form an outerlagoon behind the prelittoral ridges in which increased suspended matter arrival tends to be preserved by the current pattern is floculated and aggregated by biological activity and preserved from net erosion by weakened wave activity.

3) The class of medium mud content is in fact much narrower than the theoretical 98 to 68 % of sand. Indeed, the great majority of samples in this class contain only between 2 and 6 % of mud. Although the grab samples do not allow for stratification observations it can be argued that this mud is not present as a general mixture with the sand but as fine mud layers; they can be interpreted as sedimented during periods of slack currents combined with low wave turbulence. These layers could either be temporarily sedimented and sampled before renewed erosion or covered by the progression of sand waves and so represent a more definite sedimentation. For the more extensive patches the second hypothesis is more likely. Those lying in the neighbourhood of the mud areas can be regarded as extensions of this sedimentation and might indicate the danger of an extended mud cover in the future.

4.- Carbonate content

A.-

To distinguish eventually different types of carbonate origin the carbonate content was determined on a shell-free basis. It was determined by acid digestion on the sediment fraction smaller than 2 mm . The analysis results are expressed by symbols in seven classes with logarithmic boundaries. These could be grouped after study of the distribution in three meaningful groups : less than 4 % , from 4 to 12 % and more than 12 % . It was found indeed that in the class

8 – 16 % the samples with more than 12 % occurred in the same cartographic areas as the group above 16 % and was genetically related.

B.-

Figure 3.5 shows a striking distribution pattern, with a very strong trend to low carbonate content from south to north.

1) High carbonate content above 12 % occurs only south of 51°35' N . It falls clearly in two areas. The first follows the deepest water. It has very high percentages in the south up to 50 % and breaks up into patches towards the north.

The second lies along the coast, a smaller area in front of the Belgian-French border, a larger off the Belgian coast. The last one has several norrow protrusions towards the north, the image of which may not be exact due to the distant sampling.

2) Medium carbonate content (4 – 12 %)

South of 51°45' N the whole remaining area is taken by the medium class and the sharp boundary towards the north illustrates well the diminishing carbonate gradient in that direction. Inside the class values are higher in the south and gradually towards the north more samples occur with low carbonate content. Only two patches of low content can however be delineated in the area.

North of this line only three small patches of medium content can be delineated in the open sea. Along the Dutch shore however the medium class is well represented by small patches in front of the northern delta exits, a bigger one in front of the Rhine mouth and a more important one in the extreme north east near the Yser mouth.

3) Low carbonate content (less than 4 %)

Occurring only in the norther part. The diminishing trend is further accentuated by the predominance of the class 2 – 4 % in the southern part and the predominance of the class 0.2 % in the northern part. Towards the coast there is a definite increase as between Rhine and Yser mouth only values in the higher 2 – 4 % occur.

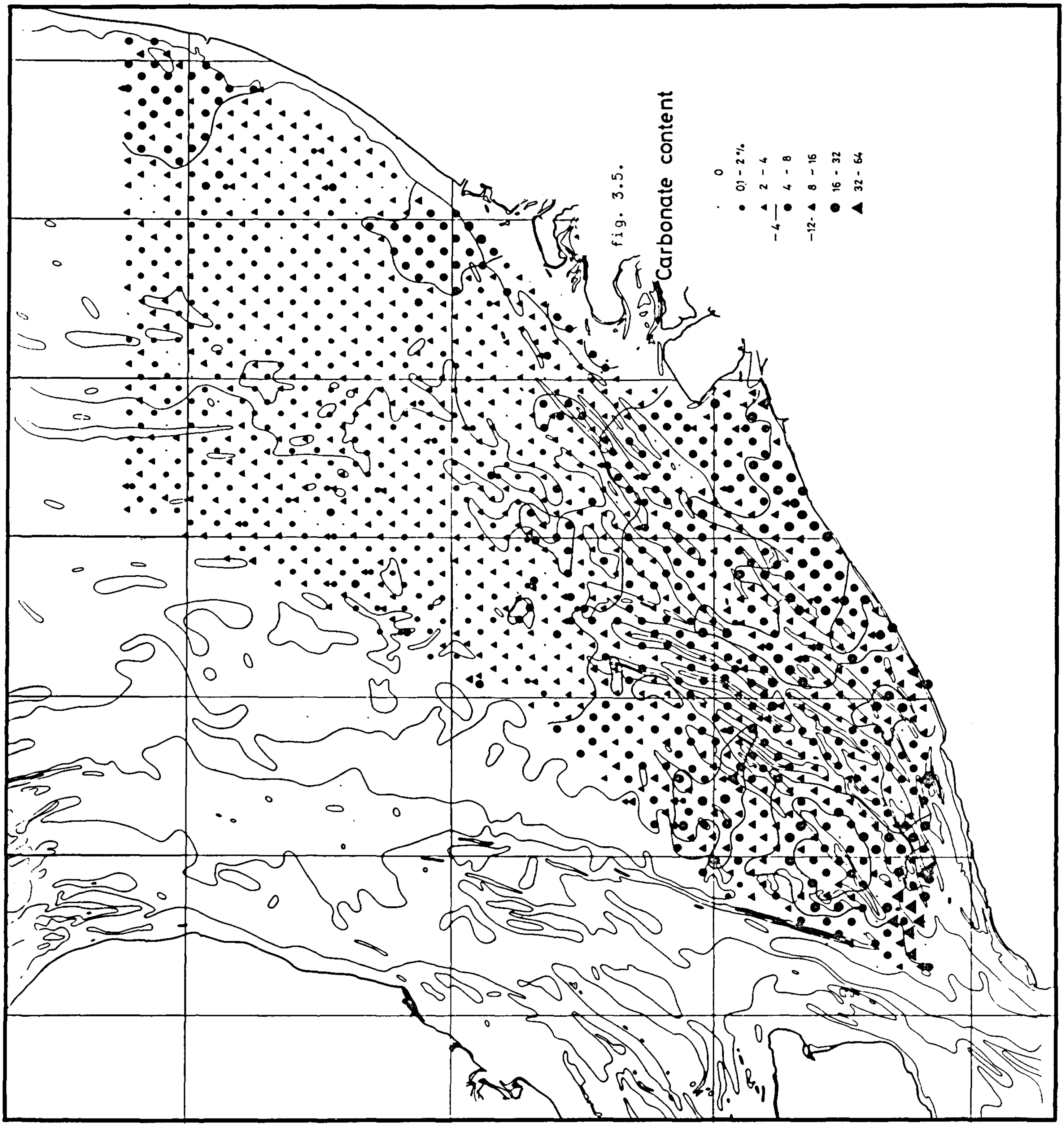

fig. 3.5.
Carbonate content

C.-

The major trend of diminishing carbonate content towards the north corresponds exactly with the trend in shell percentage as does the sharp boundary between north and south. This makes it clear that a positive correlation exists between shell content in the total sample and carbonate content in the fraction smaller than 2 mm . It shows that the carbonate content is due essentially to biological activity and is formed by commuted shells and microfossils. Highest values occur along the central axis with extremes of more then 50 % in the south. Influence of eroded chalk cannot be excluded here. Also the area before the Belgian-French border corresponds with high shell concentration. In this fraction smaller than 2 mm the high percentages can less be explained as lag deposits. Small platy shell fragments have indeed a higher transport capacity than equal quartz grains. This would indicate that the diminishing trend towards the north is essentially caused by less abundant mollusc life.

The three carbonate-rich areas before the Belgian coast, the Rhine and Yser mouths cannot be explained in the same way. Before the Belgian coast the area corresponds largely with a shell low or even shell-free area, and at the same time with predominance of mud, the carbonate is high and values between 20 and 30 % are frequent. This means that the carbonate is essentially present in the mud fraction. Its origin can be shell-flower but it cannot be excluded to be of local biochemical origin. The inflow of Ca-rich Sheldt waters and the presence of muds rich in organic substances may create physico-chemical conditions favourable for the development of calcareous nanno-organisms or even $CaCO_3$ precipitation.

The same relation with Rhine-Meuse waters holds in front of Rotterdam. The area is however much smaller. In this constellation can be seen a different behaviour of Scheldt waters which are trapped by the outer-lagoonal configuration while Rhine-Meuse waters are easily dispersed in open sea.

The area before the Yser mouth is again different and corresponds clearly with good biological conditions and correlates with higher shell percentage and low mud content.

To test these hypotheses the carbonate content will be further analysed by studying the grain size distributions of the carbonate, its mineralogical nature in the different fractions and the biological or chemical origin of the particles.

5.- Mean grainsize of the sands

A.-

The sandfraction is the load transported along the bottom. Its grainsize should be in equilibrium with the currents present when the sand is now being transported. A measure of central tendency of the sand should then depict the current energy on the seabottom.

After eliminating from the total sediment the gravel fraction, the suspension fraction, the carbonate and organic content, the pure sandfraction is obtained. As a measure of central tendency was chosen as a first approach the median, determined graphically on the cumulative curves of the sandfraction.

In figure 3.6 the obtained values are indicated by symbols referring to median grainsize classes based on a logarithmical series. After studying the distribution pattern 4 major groups were distinguished and named :

- Median finer than 175 µ : very fine sand;
- Median between 175 — 250 µ : fine sand;
- Median between 250 — 350 µ : coarse sand;
- Median coarser than 350 µ : very coarse sand.

In delineating the different areas greater difficulties were encountered than for the other maps. This was especially so in the southern ridge region. This could be expected because current velocities differ considerably in the swales, on the flancs and on the top of the ridges and sampling is too distant to give an information on this detail. Nevertheless a significant picture was obtained.

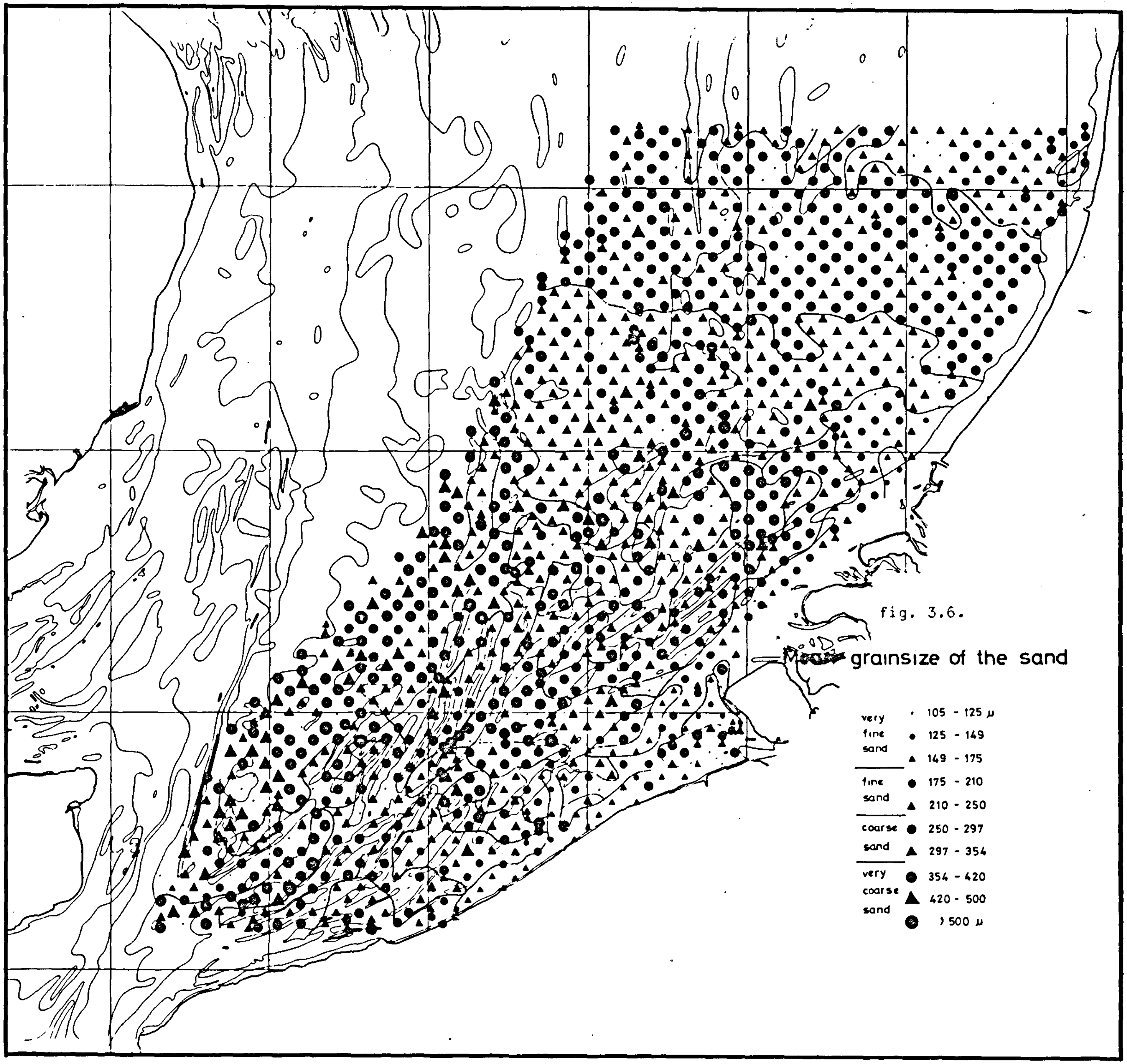

fig. 3.6.

~~Mean~~ grainsize of the sand

B.-

1) Very fine sands

The very fine sands are strikingly only located along the coast. Two small patches occur in the neighbourhood of Rhine and Yser mouth. By far the biggest area is to be found along the Belgian coast, and on and in front of the triangular funnel plate of the Scheldt estuary.

2) Fine sands

At the northern border of the map appears a concentration of fine sand values approximately limited at 52°30' N . Further down the coast a large bulge is located at the Rhine-Meuse mouth and is continued by a small ledge along the coast up to the Scheldt estuary. In front of the Belgian coast this zone broadens but is at the same time interrupted by coarser sands in the Flemish Banks. In more open sea only one small area occurs south of West-Hinder Bank.

3) Very coarse sands

The very coarse sands follow an opposite pattern. The biggest area lies at the south-western border and coincides with the deepest water.

It is not only the largest area but it has the highest concentration of sand-medians above 420 µ . Other areas occur in the deeper swale between Sandettie and Flemish Banks and between the Hinder and Zeeland Banks.

North of the Zeeland Banks a few patches occur the largest one immediately to the north-east of them and located very close to the coast. North of 52° N only isolated samples of the very coarse sand occur.

4) Coarse sands

This class fills up the rest of the map as an intermediate zone but close inspection allows to separate it in two subclasses : the median between 250 – 297 µ and between 297 – 354 µ which will be named here medium-coarse and rather coarse.

North of a rather sharp line approximately at 52°12' N the great majority of samples is of the medium coarse subclass. Immediately south the rather coarse subclass is dominant with appearance of very coarse samples.

Further south once that the ridge topography starts this subdivision is much less meaningfull and gives only an indication that which subclass is more frequent. In this way the Zeeland Banks, the eastern Flemish Banks and Sandettie belongs to the medium coarse subclass, while the Hinder and western Flemish Banks are rather coarse.

C.-

The description has made it clear that the major trends in grainsize distinguished by Jarke (1956) are present, but more samples have refined and at the same time complicated the picture.

When trying to find explanations for this distribution it must first be stressed that we conceive the sampling of the uppermost sedimentlayer to have touched only material which is in equilibrium with actual conditions, either modern sediments on sedimentation areas or lag sediments on erosion areas.

A first major trend is the diminishing grainsize towards the north clearly shown by the parallel lines which separate the classes, coarser than 350 μ south of 52° N , coarser than 300 μ south of 52°12' N , coarser than 250 μ south of 52°25' N . This regular succession corresponds with a general rather flat bottom topography, characterized by megaripples progressing towards the north [Houbolt (1968)]. As bottom depth is uniform in this direction this change must be correlated with diminishing velocity of tidal currents as the tidal range diminishes from 3 to 1.5 m .

Note that in this area tidal currents are neatly opposite with a net residual current in NNE direction perpendicular to the grainsize limit-lines. In terms of sediment transport the grainsize fall from 350 to 250 μ should correspond with a velocity drop of one third.

In the southern ridge topography the picture is more complicated. The very coarse sands occurring in the deepest parts and in the swales between the ridges correlate often with high gravel and shell percentages and must be interpreted as lag deposits. All finer grainsizes are swept away. Problematical are the coarse patches surrounding the Zeeland Banks and which are in less deep water. Some of these might be depositional areas or represent fossil sediments.

The ridges have a great variation in grainsize which depends on the part of the ridge where the sample was taken as shown by Houbolt (1968). Nevertheless several families can be recognized.

- The coarsest ridge systems are the northern Flemish Banks and the Hinder Banks. Their direction is parallel with the tidal currents which are perfectly opposite with a net transport to the north.
- Less coarse is the Sandettie Bank situated in very deep water and its grainsize has a relation to the Falls. Sandettie is known to be fastly moving and is the major obstacle in the Channel route. Together with the Falls Van Veen (1936) considered it to be a broken up ebb-parabolic.

Another hypothesis would be to derive Sandettie material from the Falls. The rest currents in the Falls seem to be directed to the south with protrusion of the bank into strong channel currents. The sand here is taken up and swept to the north, building up Sandettie on the other side of the current axis with rest currents to the north. Mineralogical research will be conducted to verify this hypothesis.

The eastern Flemish banks are also less coarse corresponding with less energy. The same is true for the Zeeland banks. These have a topographical trend at an angle with the Hinder system which would favour the explanation of Houbolt (1968) as being stabilized fossil forms. We believe the actual tidal currents to be too strong to preserve ridges with which they are in desequilibrium. Their direction should then be an influence of the tidal pump system of the Scheldt estuaries on the general long-shore tidal current system.

The map demonstrates however another significant fact. In the open northern part the seabottom energy diminishes practically not along the coast. Only at the Yser mouth in the lee of a small bank the grainsize is finer and in front of the Rhine-Meuse mouth, due to local output.

However, in the southern part together with the development of the ridge topography the fine coastal sandy sediments become important. Highest energy is not situated along the coast but in the distant tidal ridges, this proves that wave energy is less important here than tidal currents for sedimentation.

6.- General conclusion

Sedimentation in the Southern Bight of the North Sea is essentially organized in response to a current system due to the funnel shape starting in the Straits of Dover.

In the southern part high current velocities are responsible for arranging the mobile very coarse sand in parallel ridges with swales in which lag deposits, gravel and shells, dominate. The lateral tidal pump system of the two Scheldt estuaries is responsible for the deviation of the ridges in front of the eastern Belgian coast. In this triangle finer sands are in equilibrium with lower energy. In the northern part sand size diminishes parallel to the coast proportional to lowering current velocity. Abruptly a new equilibrium is established with a flat bottomed sea without longitudinal ridges but with much smaller transverse megaripples. This system holds true up to the immediate neighbourhood of the coast proving that sedimentation is not organized by a wave model perpendicular to the coast, but by a current model parallel to the coast.

The Southern Bight is strikingly free of muddy sediments indicating that currents and here also wave turbulence are high enough to allow only temporary decantation but no final deposition. Only in front of the Meuse-Rhine mouth increased fluvial input of suspension material influences the bottom sediments. The big exception is the low energy triangle in front of the eastern Belgian coast in which muddy sedimentation is developing to a considerable extent due to local affluents as the Yser but mostly to the suspension material dragged out of the Scheldt estuary by low tide and trapped in this area.

ERTS-A, remote sensing documents, proved this fact strikingly showing a suspension plume in front of the Rhine mouth and a huge turbid area in front of the eastern Belgian coast connected with an extremely turbid Scheldt estuary.

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II. Suspended Matter

by

M. MOENS

In our previous report (1972) we already showed that a water mass with a high suspended matter content persists off the Belgian coast. Mean concentration attained 10 mg/ℓ [fig. 1 (1972)] and more during different campaigns held however at Beaufort < 8 . These concentrations can be attained in two ways :

i) hydrodynamic processes can create a concentration increase from sediment sources,

ii) constant reworking of underlying mud layers can cause increased turbidity.

The part of the North Sea under consideration has a diurnal tidal system. In some places velocities of 2 knots (± 100 cm/s) are attained (Scheur). However a more or less extended mud layer is found under these turbid waters [Bastin (1973)]. The muddy area extends from one or two km from the coast to some 20 km into the sea at its greatest extension (fig. 3.13). Depth is always less than 20 m .

Thus, hydrodynamic conditions must be such that accumulation and preservation of this mud is possible.

Many have worked on the relationship between water velocity and sedimentation erosion. Partheniades (1965) came to the conclusion that there must be a "critical velocity above which all clay stays in suspension and under which all clay settles". In his experiments, this happened at 0.5 ft/s (15 cm/s) . He stated however that turbulence should be much less in open water than in his laboratory flume at the same velocity. Terwindt and Breusers (1972) put forward that sedimentation in the North Sea starts as soon as the velocity 0.5 m of the bottom falls under 20 cm/s .

As the determination of near bottom velocities in the area had to be calculated on the basis of surface velocities, we take 20 cm/s at 1 m above the bottom as a possible critical velocity for the sedimentation of mud.

Terwindt, Breusers and Svasek (1968) found a critical shear stress of 1.1 N/m^2 for sand-clay laminations in the Haringvliet.

Table 3.1 compiles the results of some authors. We did not have the opportunity to take undisturbed samples. Mixing with underlying sand in sampling laminated sand-mud deposits may be occurred. This means that we cannot give an hydraulic valuable granulometric composition of the mud.

Table 3.1

Critical water velocities after some authors

Authors	Composition z = sand s = silt k = clay	U_c^* (cm/s)	U_{50} V at 50 cm off the bottom	U_{100} V at 1 m off the bottom
Partheniades (1965)	no sand	0.8	21	22
Terwindt, Breusers and Svasek (1967)	50% z 30% z 20% z	3.3	97	103
Terwindt and Breusers (1972)	37% z - 2 h	1.9	53	56
	2 1/2 h	2.1	59	63
	7% z - 2 h	0.8	21	22
	2% z - 2 1/2 h	1.4	38	41
	37% z - 1/4 h	0.7	18	19
	1/2 h	1.2	32	34
	1 h	1.75	49	52
	2 h	2	56	60

Terwindt and Breusers (1972) results could be applied to the situation off the Belgian coast as circumstances, comparable with those occuring in their experiments are found here. A critical velocity of 60 cm/s at 1 m above the bottom or U_c^+ of ~ 2 cm/s could be an acceptable value.

Thus, we put forward that at places where V_{100} (velocity at 100 cm above the bottom) does not exceed 60 cm/s and falls for some time below 20 cm/s , mud layers can very probably be formed and preserved.

On the basis of the *Stroomatlas* of the *Ministerie van Openbare Werken* V_{100} are calculated by means of the Van Veen (1936) equation :

$$V = a \sqrt{h}$$

with V the velocity at a m above the bottom, a the velocity at 1 m above the bottom and h the depth, based on MLLWS and the amplitude.

It seems that off the Western Belgian coast, the longest period with the lowest velocities is slackwater before flood.

This means, as the water turns anti-clockwise that settling is most intensive when the watermass moves in the seaward direction. So, export of mud towards the sea is difficult and concentration towards the coast is favorized.

For the *Stroomatlas*-stations, the velocity-vectors are added for every hour from 6 hours before to 6 hours after high water. The results are shown in fig. 3.7 and 3.8, for spring and neap tide. The western part of the area has a NE to E directed resultant. Material that stays in suspension will thus be transported along or towards the coast.

Tidal streams along the eastern part of the coast are much stronger. The resulting direction is S to SW here. Export of muddy suspended material can occur in the neighbourhood of the Wandelaar, especially at spring tides. Water velocity does not fall under 20 cm/s then, and the resultant stream direction is seaward.

As already shown by Bastin (1973), the Belgian coastal area is a place where spring and neap tide reststreams meet.

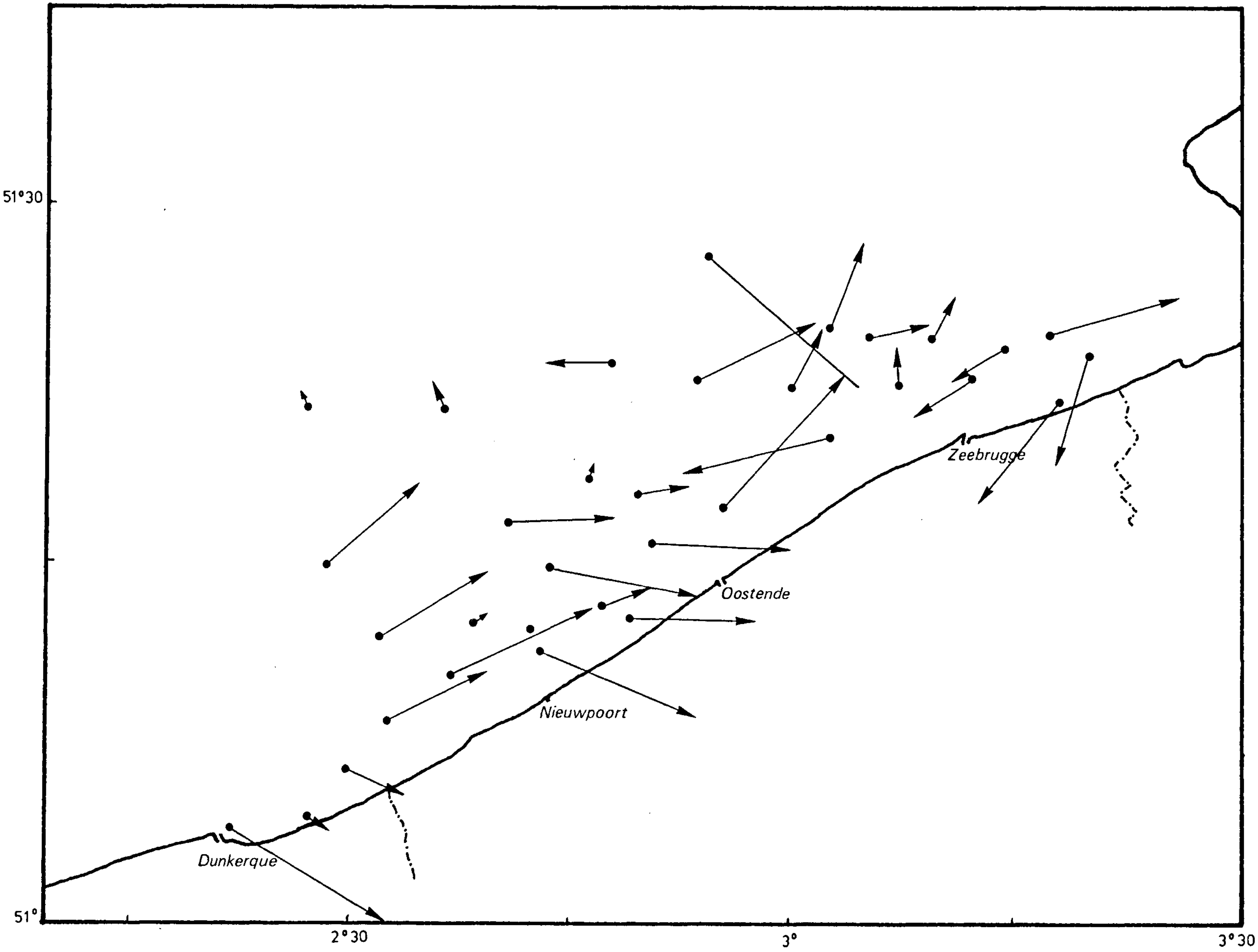


fig. 3.7.- Results of tidal currents taken over a spring tidecycle (12 hr) (from "Stroomatlas"). 1 km = 0.5 cm .

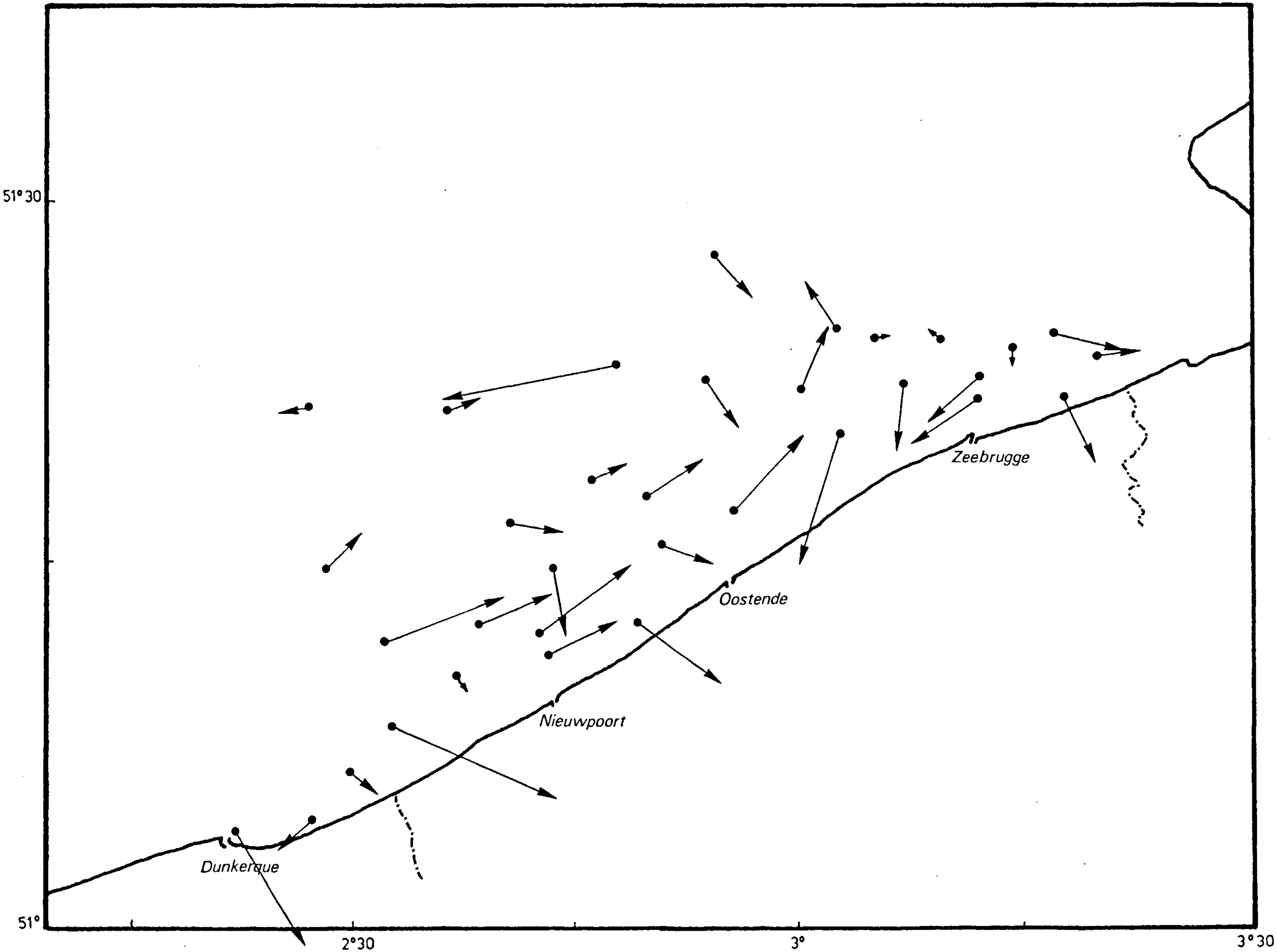


fig. 3.8.- Results of tidal currents taken over a neap tidecycle (12 hr) (from "Stroomatlas").

We already mentioned that this area is usually more turbid than surrounding waters.

Draper (1966) and McCave (1971) showed that wave action is highly effective at depths of less than 15 to 20 m . We thus know that the area under consideration is regularly reworked by waves.

The higher concentration of suspended matter can be explained by the constant and periodical reworking of this material.

Based on the *Stroomatlas*, the figures 3.9, 3.10, 3.11 and 3.12 were drawn. They show the distribution of minimum and maximum velocities at 1 m above the bottom at spring and neap tides (V_{100}^{min} and V_{100}^{max}). The aim was to correlate mud distributions and hydrodynamic conditions.

One can see that, apart from the Scheur, V_{100}^{max} and V_{100}^{min} during spring and neap tides are almost always lower than 50 cm/s and 20 cm/s .

A zone of changing with along the coast has at all times slack-water velocities lower than 10 cm/s . Slackwater sedimentation should occur if it is not inhibited by wave action.

Off the eastern part of the coast, V_{100}^{min} is always higher than 20 cm/s . Mud sedimentation is less probable than elsewhere.

V_{100}^{max} increases during spring tides from 50 cm/s off the western part of the coast to more than 100 cm/s at the Scheur. Current strength is high enough to cause erosion of mud provided its consolidation is not too high.

It is apparent that in a near coastal zone sedimentation of mud can occur during spring tides and during neap tides as well. Probably in the western part the mud is less subject to erosion by streaming water. Nevertheless, stirring up by waves will make this material available to transport. A comparison between the figures 1 (1972) and 3.10 of the actual report shows that the area with the highest current velocities is also more turbid than surrounding zones.

Some elements were lacking to explain the high suspended matter concentrations. For instance, the resulting current direction of the velocities between ± 20 cm/s and 60 cm/s must be as useful indication of transport of fine grained material. The position of a water particle after one tidal cycle is also a very important aid, as well as good

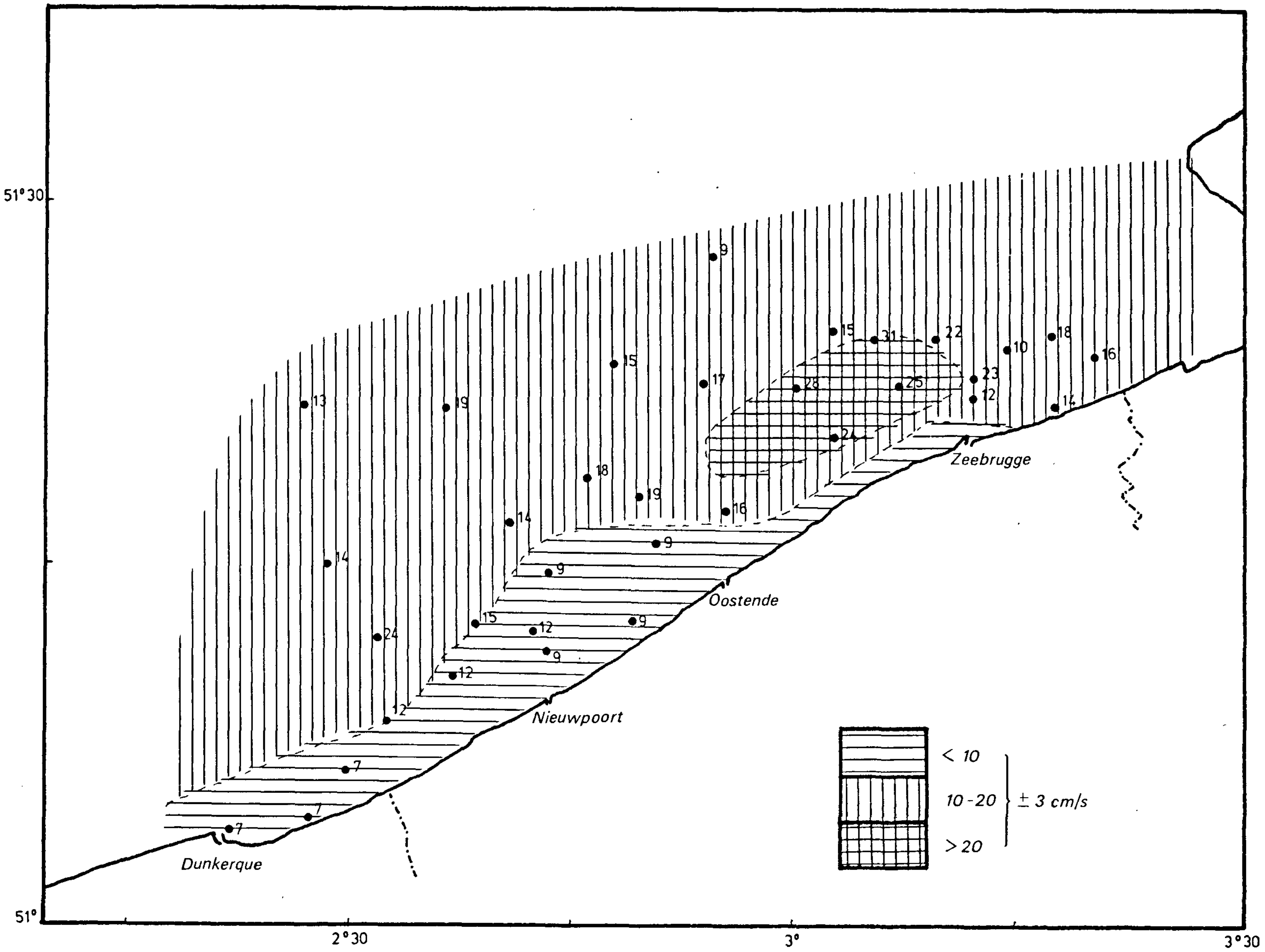


fig. 3.9.- Distribution of the V_{100}^{min} at springtide (minimum speed at 1 m from the bottom).

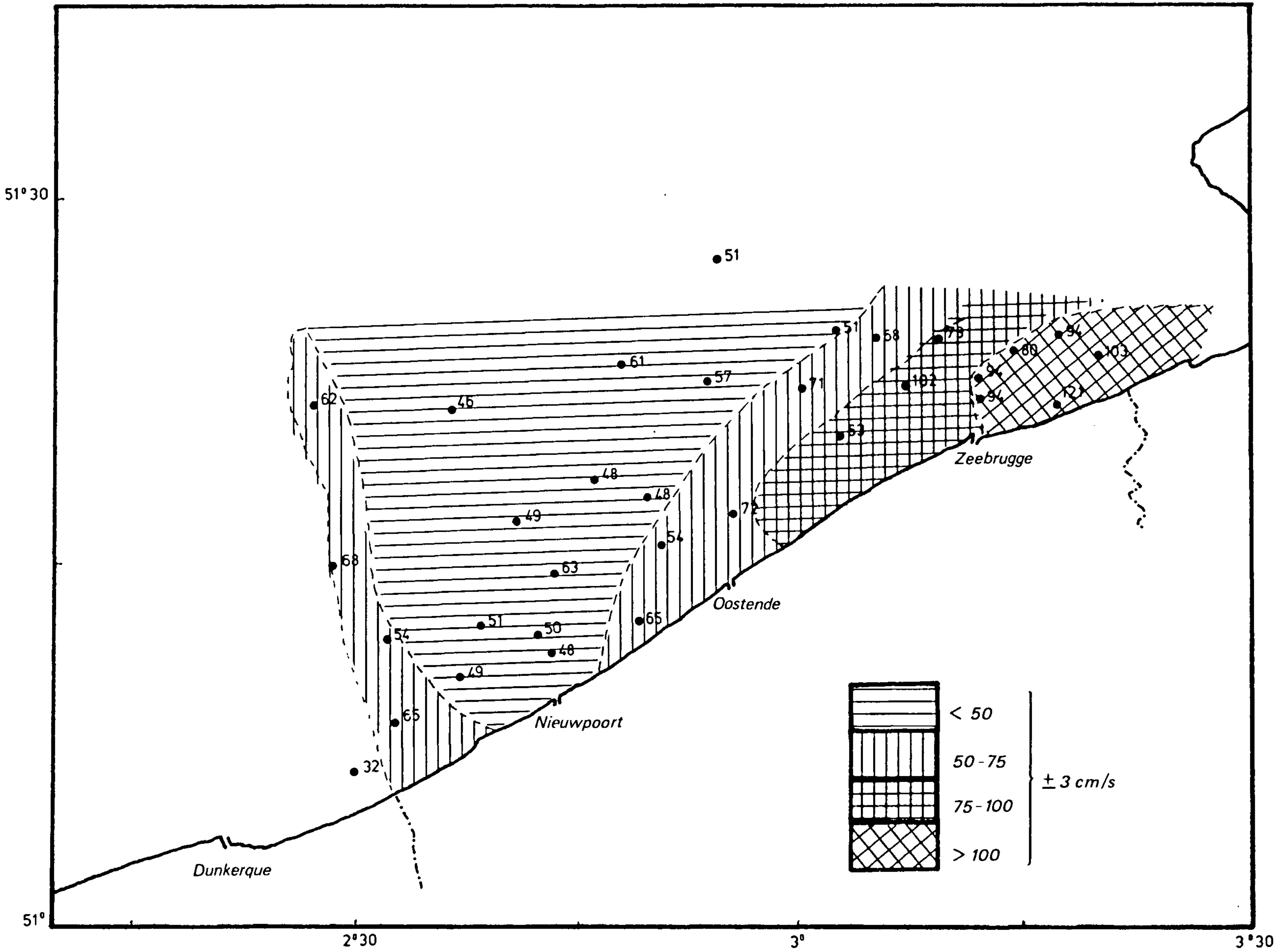


fig. 3.10.- Distribution of the V_{100}^{max} at springtide.

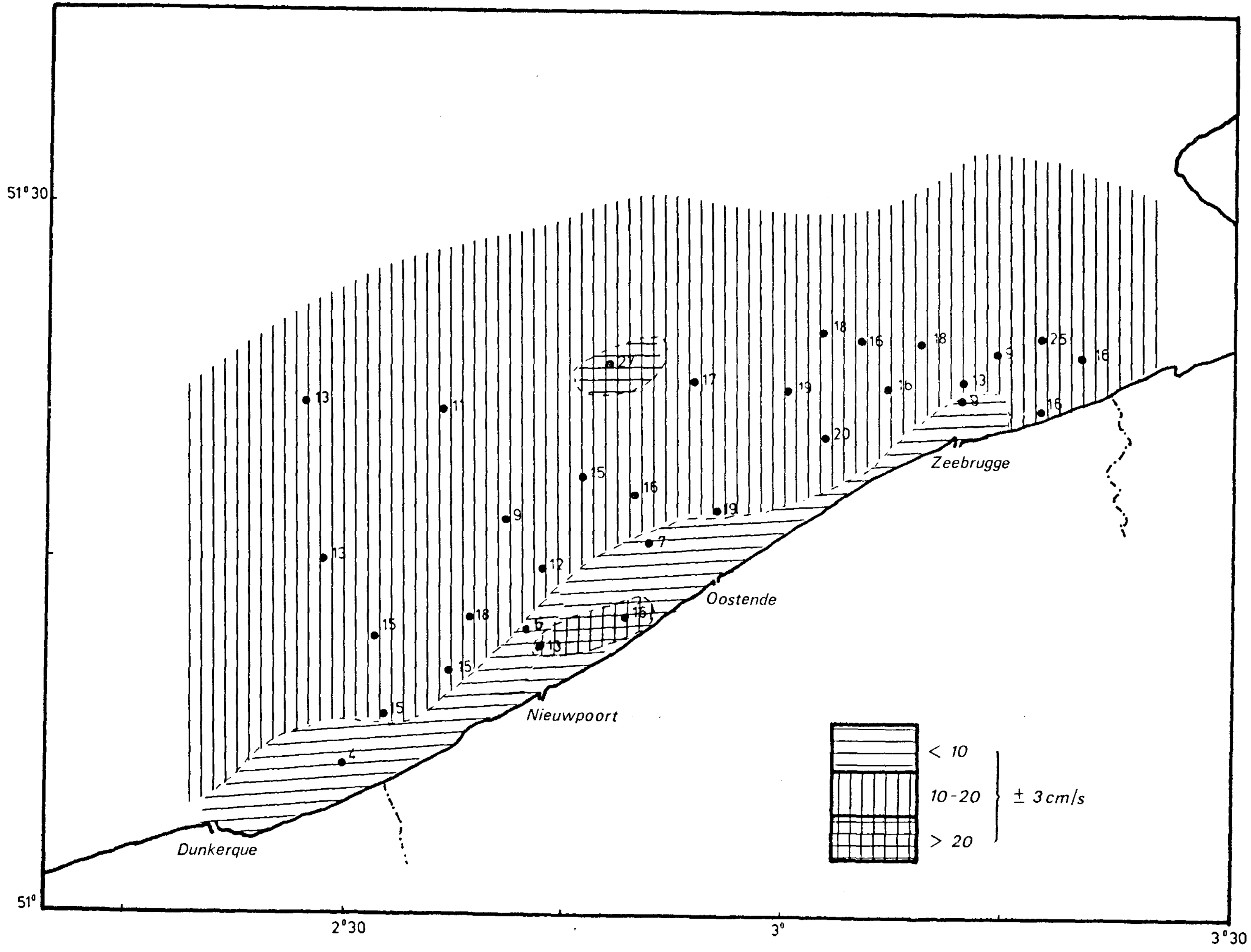


fig. 3.11.- Distribution of the V_{100}^{min} at neaptide.

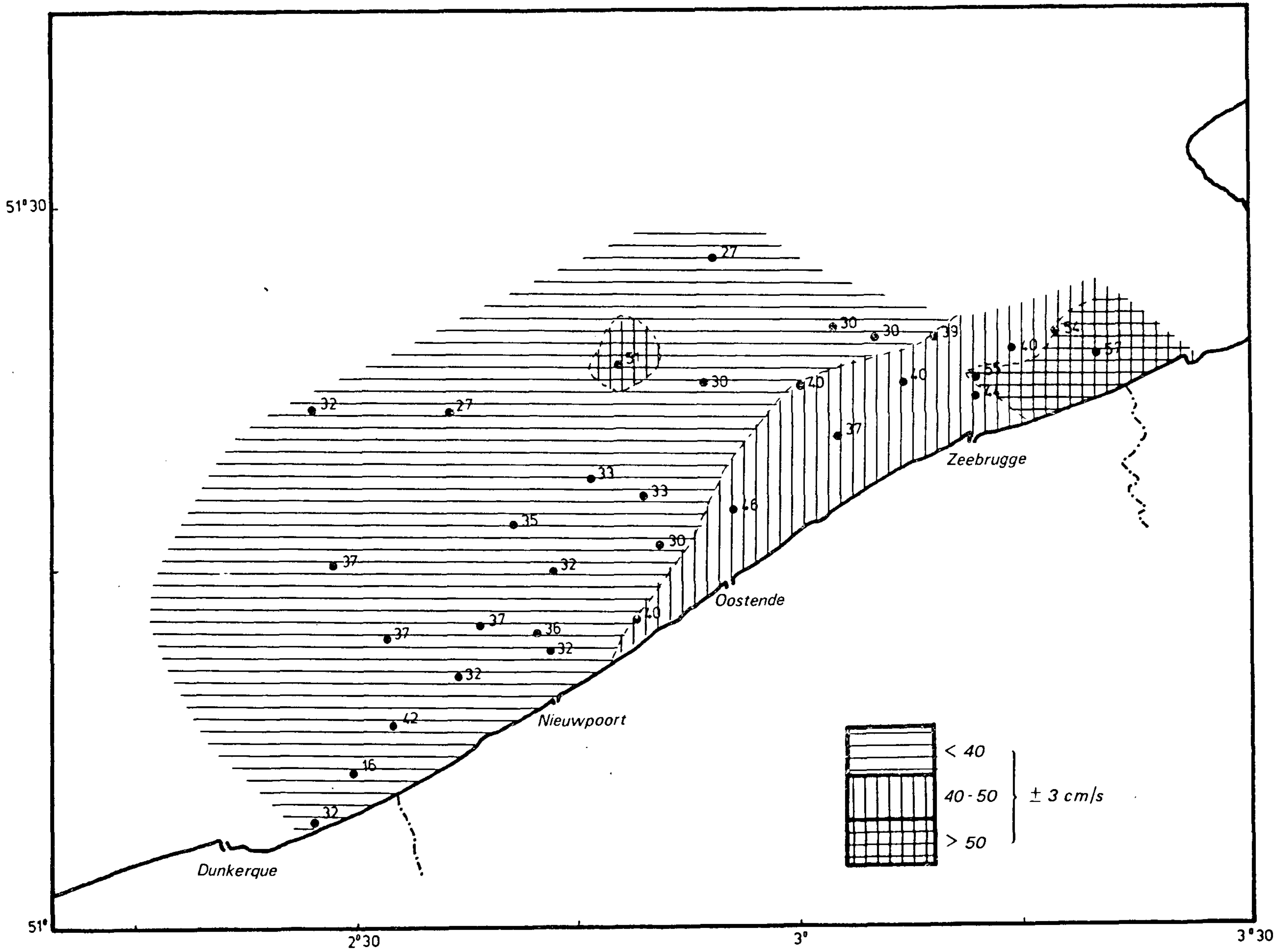


fig. 3.12.- Distribution of the V_{100}^{max} at neaptide.

wave action observations. Grainsize distributions of the suspended sediment is unknown too. Samples gathered by centrifugation were too small to accomplish a classic analysis. Besides, this material was so hard to peptisize that the obtained results are unreliable.

III. Bottom Sediments

by

M. MOENS

Figure 3.13 shows the distribution of mud in the vicinity of the Belgian coast. In general, only one grab sample per station was available to us. Of course, the aim of this map is not to delineate the bodies of mud accurately. Bastin (1973) drew his map on the basis of continual sampling, a much better method for that purpose. Our mode of sampling is of course better fit to establish differences in physical and chemical properties of the sediments.

Sedimentary facies differences between different areas can only be studied by undistributed samples. Fine grained sediments in the area under consideration probably in places consist of layered sand and clay or mud.

A grab can homogenize a sample in such a way that a false granulometric image appears. Our figures thus only represent the overall granulometric composition of the samples and no further conclusions should be drawn from them such as shear stress, water content, compaction, etc.

A sample with 30 % , > 63 μ (global analysis) could have been taken on a clay or mud layer with a sandy layer some 10 to 15 cm underneath. This appears on the distribution diagrams as bi- and even polimodal distributions.

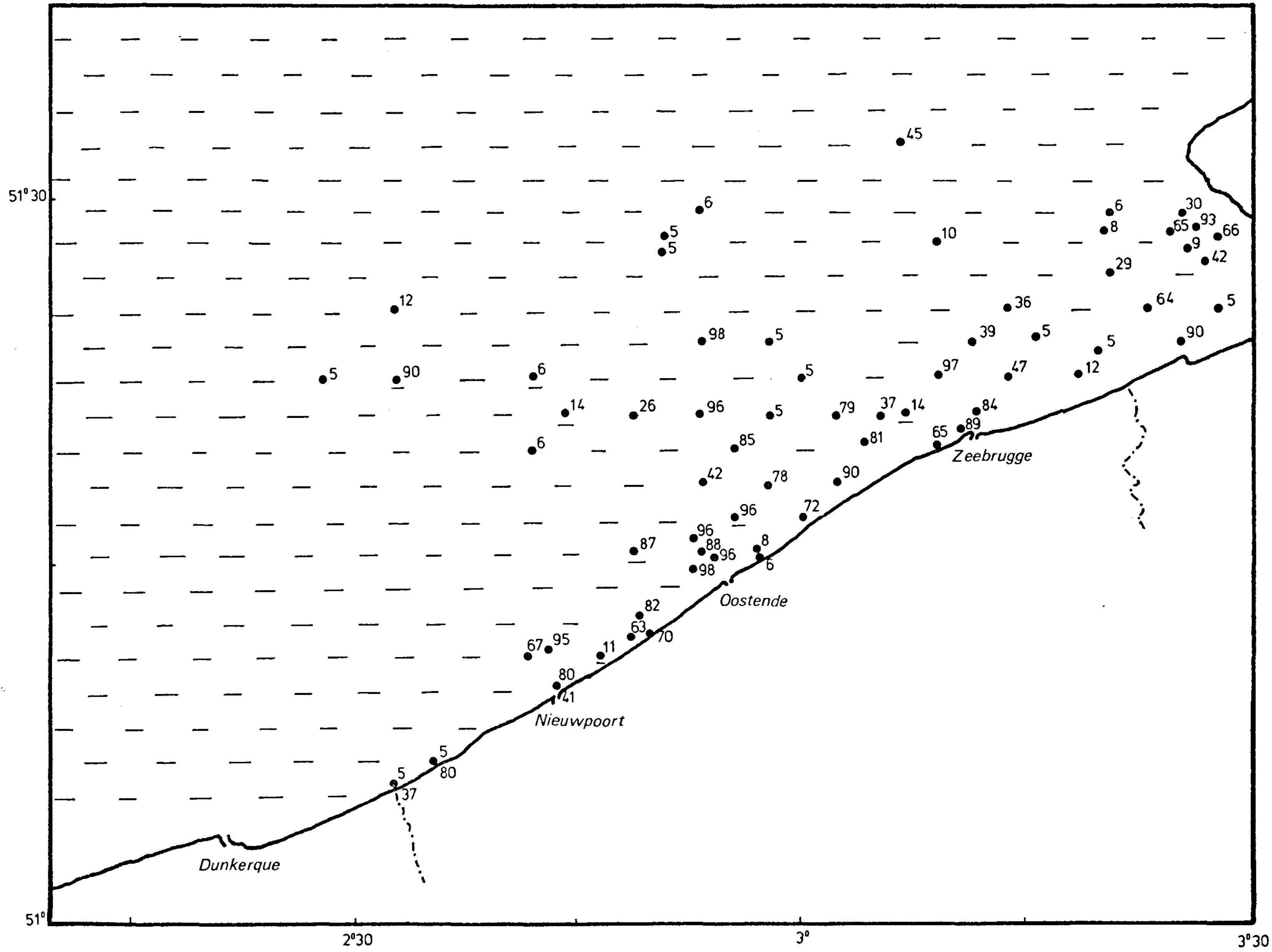


fig. 3.13.- Distribution of mud before the Belgium coast expressed in % silt and clay per analysed sample.

Granulometric analysis was obtained by the method described in the report *A flowsheet for analysis on recent detrital sediments* by F. Gullentops (1972). As to the accuracy : the screens of 63 μ and 32 μ were controlled on sieve opening. Reproductibility of the applied decantation method was found to be at least 1 % . Nevertheless, granulometric analysis for the fraction > 32 μ was only executed as soon as the sample contained more than 5 % > 63 μ .

A comparison between the figures 3.13 and 1 (1972) shows that the turbide area reflects the distribution of mud on the bottom. This is still more apparent on the fig. 2 (1972). A turbidity-muddy bottom sediments link is apparent.

A comparison between the figures 3.9, 3.10 and 3.13 teaches us that mud is lying in places where current velocities of more than 60 cm/s are possible and V_{100}^{min} does not fall under 20 cm/s .

The coastal zone which is a favorable area for sedimentation of fine grained material as to current strength, is subject to intense wave activity.

The most persistent wind directions are those of the western sector. The strike of the sand banks is such that the area beyond is protected against long waves.

Nevertheless, it seems that the mud is situated in a zone of partly high current and wave energy. We think that mud sedimentation must occur because of high turbidity. McCave (1971) has already drawn the attention to the fact that irrespective hydrodynamical conditions, settling of mud can start if suspended sediment concentration (mud) is high enough.

The presence of mud in the Belgian coastal waters can be explained by :

1) Streaming water

Concentration and transport of suspended matter towards the coast by residual currents. Most probably, the current direction, resulting from the vectoral addition of the velocities between the eroding and settling current strengths will point in a coastal direction.

2) Wave action

Waves can induce a translating movement in slightly consolidated mud in such a way that this mud is transported without being brought into suspension [Migniot (1968)]. We think that this mechanism should be taken into account here as well.

Nevertheless, reworking by waves keeps turbidity high in some places. In this way, new material becomes available for transport. The high suspended matter concentration area [fig. 1 (1972)] reflects bottom morphology as well. Undeep water extends well far into the sea off the Scheldt mouth, as muddy bottom sediments do.

We think current patterns are of primary importance; they cause high concentrations and induce sedimentation.

Partheniades (1965) and Migniot (1968) have already drawn the attention to the fact that fine grained material will not only be resuspended by waves but grain size distribution will also drastically be reduced (mean fall velocity 5 times smaller). In this way this material becomes extremely fit for transport. Furthermore, it seems to us that sedimentation and erosion are coupled to spring and neap tide periods.

V_{100} of 40 cm/s and more are, during neap-tide only, reached in the Scheur and off the eastern part of the coast. At this time mud-layers can be laid down and preserved so that the degree of compaction can increase. In this way these sediments become more resistant to erosion which can possible occur at the next spring tide.

Figure 3.13 shows that "mud" is always a mixture of silt, clay and sand. The mean of the median of the fraction $> 63\ \mu$ is $176\ \mu$.

Figure 3.14 shows that there is a loose correlation between the grainsize of the sand and its weight percent in the sample : the sandier it is, the coarser it can be. Sand content can thus be correlated with current-strength — wave action, as under these conditions coarse material can be transported.

In the triangular diagram (fig. 3.15) a wedge-shaped dot concentration appears from the sand-corner to the opposite silt-clay side. This means that in our samples a more or less fixed ratio exists between the silt and clay content : ± 65/35 . Both fractions have been transported together in suspension as more or less homogeneous grain complexes.

Samples with a sand content of 35 to 50 % seem to be absent. We think this is due to the admixture of loess-silt. A still closer

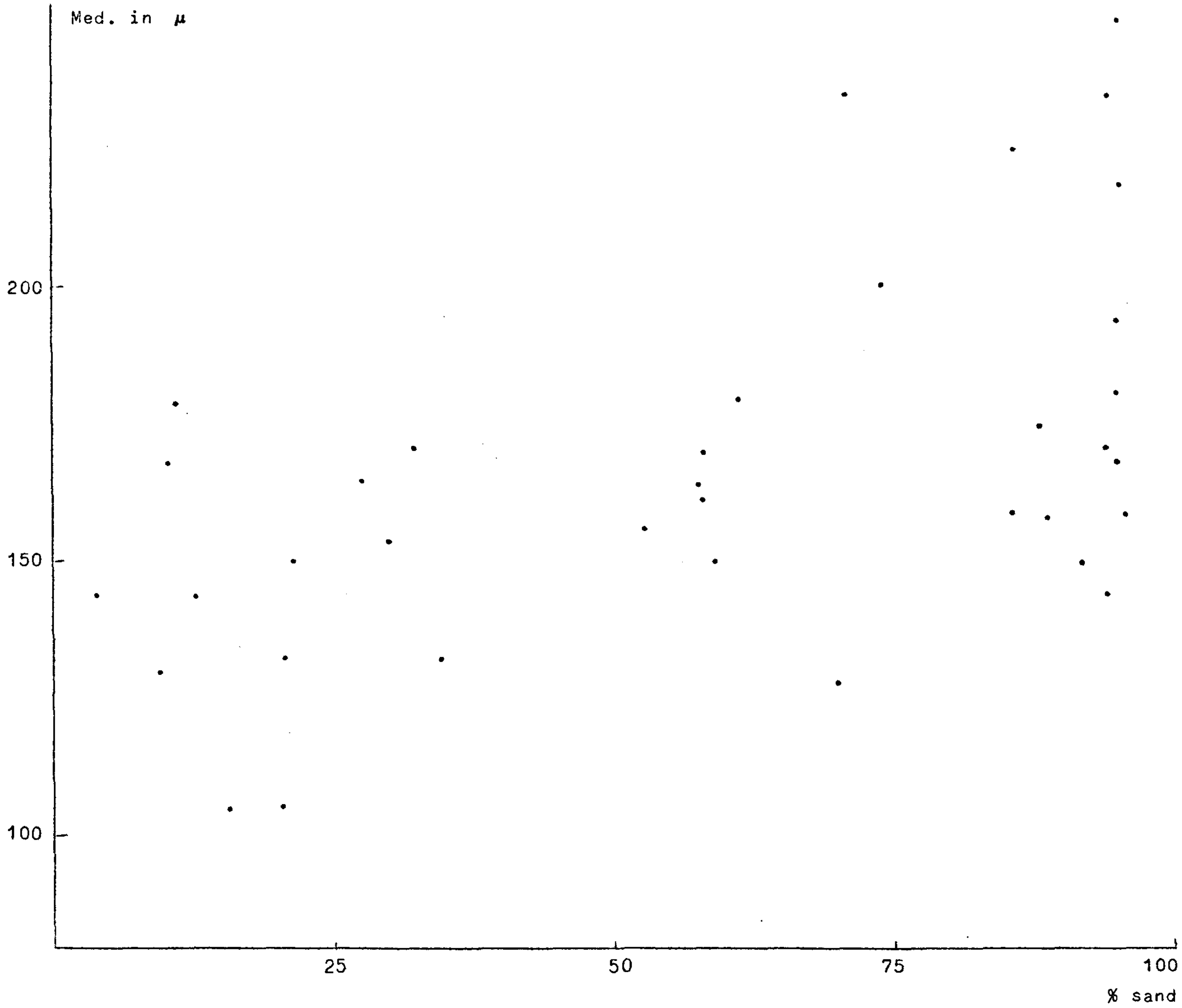


fig. 3. 14.
Relation between the median of the sand fraction and the per cent sand present in mudholding samples.

relationship exists between the fine silt fraction and the clay fraction (fig. 3.16) : the silt-clay ratio is 55/45 .

Samples with more than 45 % < 16 μ show a less good correlation. We think that the admixture of silt is responsible for this too.

However the coorelation between the fraction $\tilde{<}$ 2 μ and 2 - 16 μ shows again that clay is not deposited separately, but always settles as a mixture of coarser material.

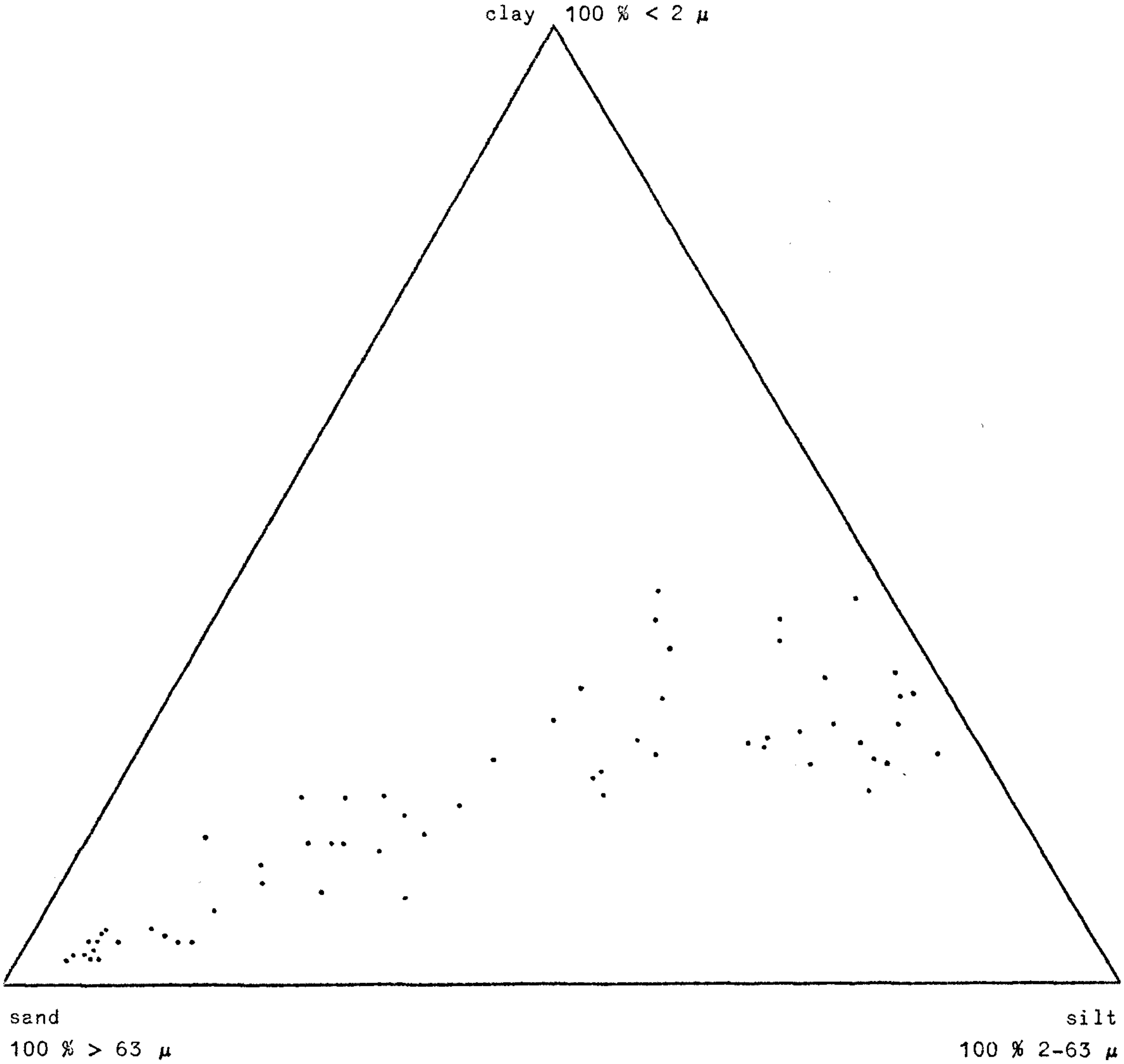


fig. 3.15
Proportion of sand-silt-clay composition of bottom samples.

To illustrate grainsize variations in the area, two profiles were drawn (fig. 3.17). Stations that were repeatedly sampled are presented here with their mean values. Dotted lines interconnect stations with an appreciable mud-content. The profile along the coast shows clearly that mud-content of the samples increases towards the midcoast. The maximum is reached in the vicinity of the station 1113 (De Haan). A clay percentage of 25 % is frequently found (fig. 3.17). Coarse and medium silt content suddenly increase from 1167 to 1207. Samples with the same

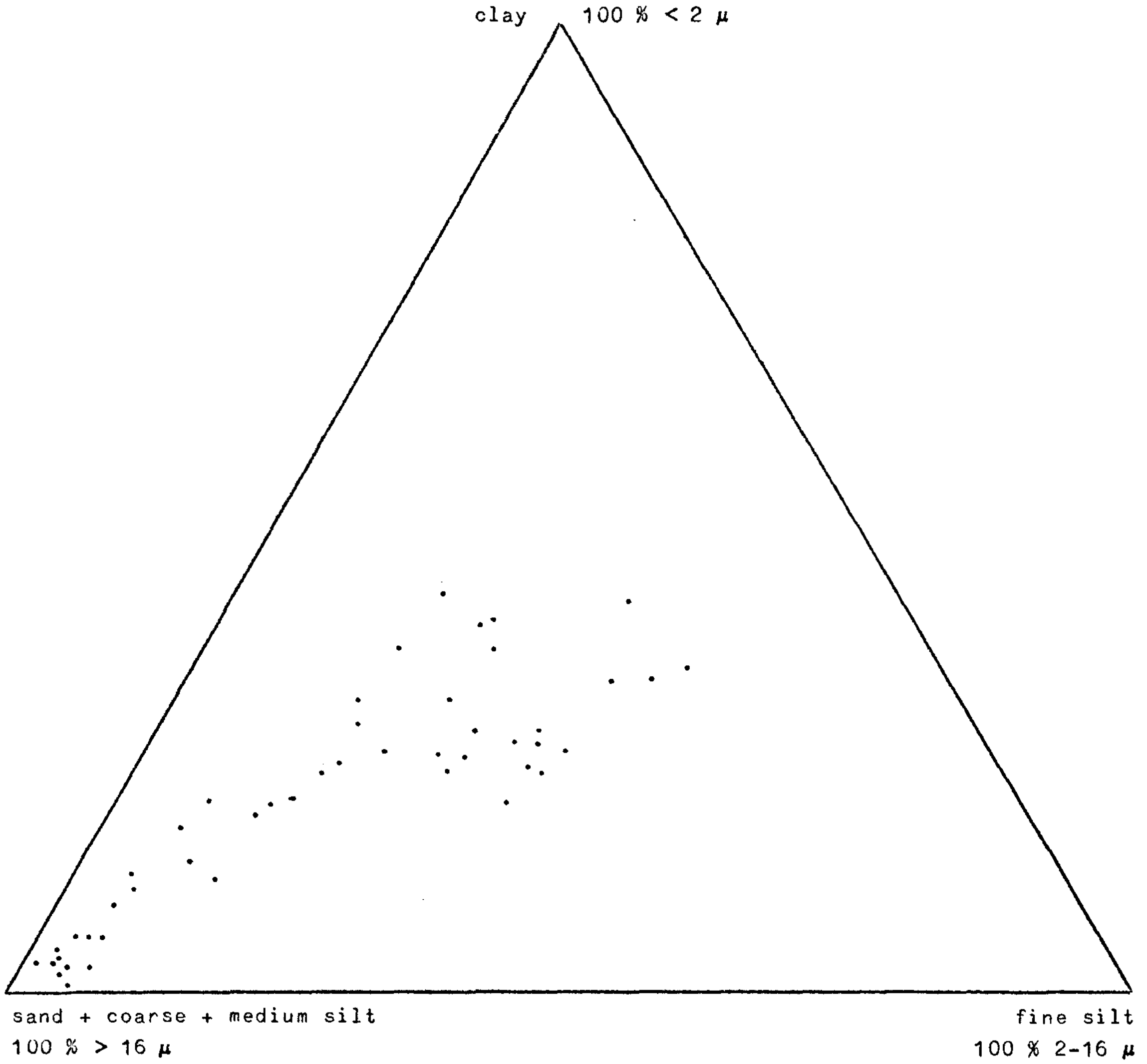


fig. 3.16.
Relation between fine silt and clay in bottom samples.

important coarse and medium silt fractions were found in the Scheldt mud during a separate investigation. We think Scheldt material may be present in the 1207 station.

The relationship between fine silt and clay is obvious in the second profile. Here clay content reaches 40 % .

To clarify the relationship between the different fine fractions, four parameters were calculated : Scr, Scmr, Cr and Ocr. Moreover they may contain some information about the provenance of the material.

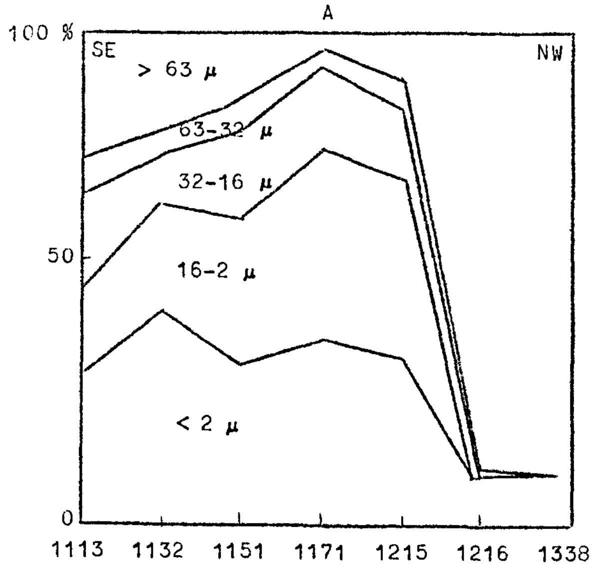
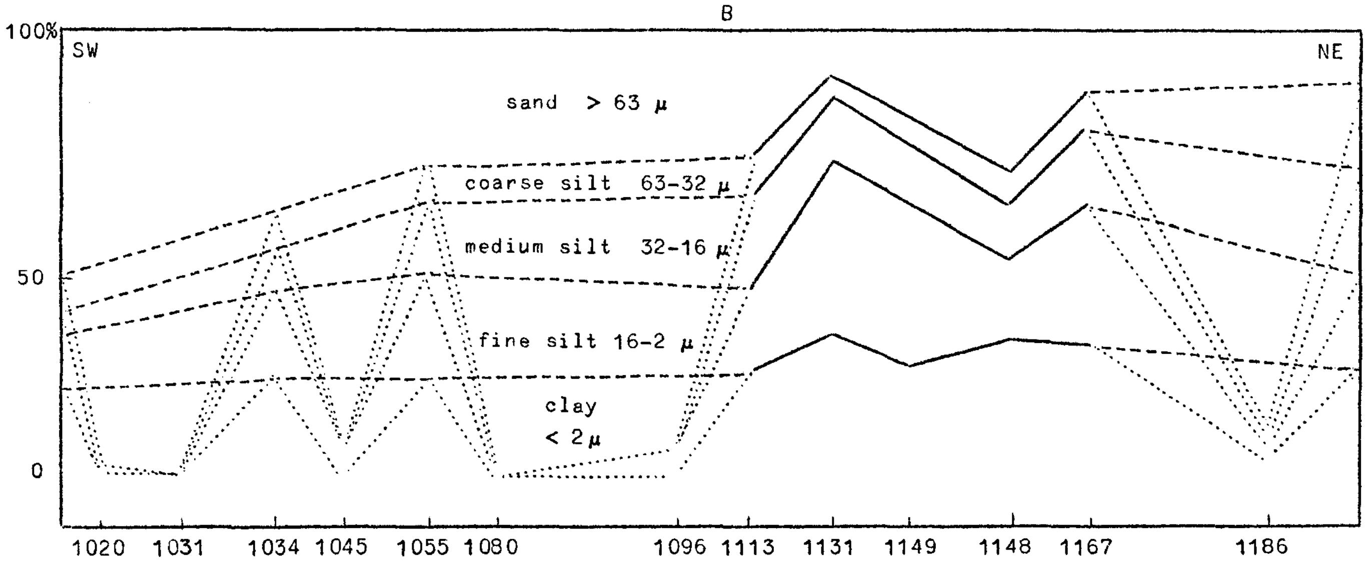


fig. 3.17.

A.- Graindiameter profile normal to the coast in De Haan.

B.- Grain diameter profile along the coast from De Panne to the Schelde mouth.



A brief discussion of the figures 3.18, 3.19, 3.20 and 3.21 is held here.

$$\text{Scr} \; : \; \text{silt coarse ratio} = \frac{\text{fraction } 63-32\ \mu}{\text{fraction } < 63\ \mu}$$

gives the contribution of the coarse silt fraction to the < 63 µ fraction. Values range from 0.01 to 0.29 ; the mean is 0.12 .

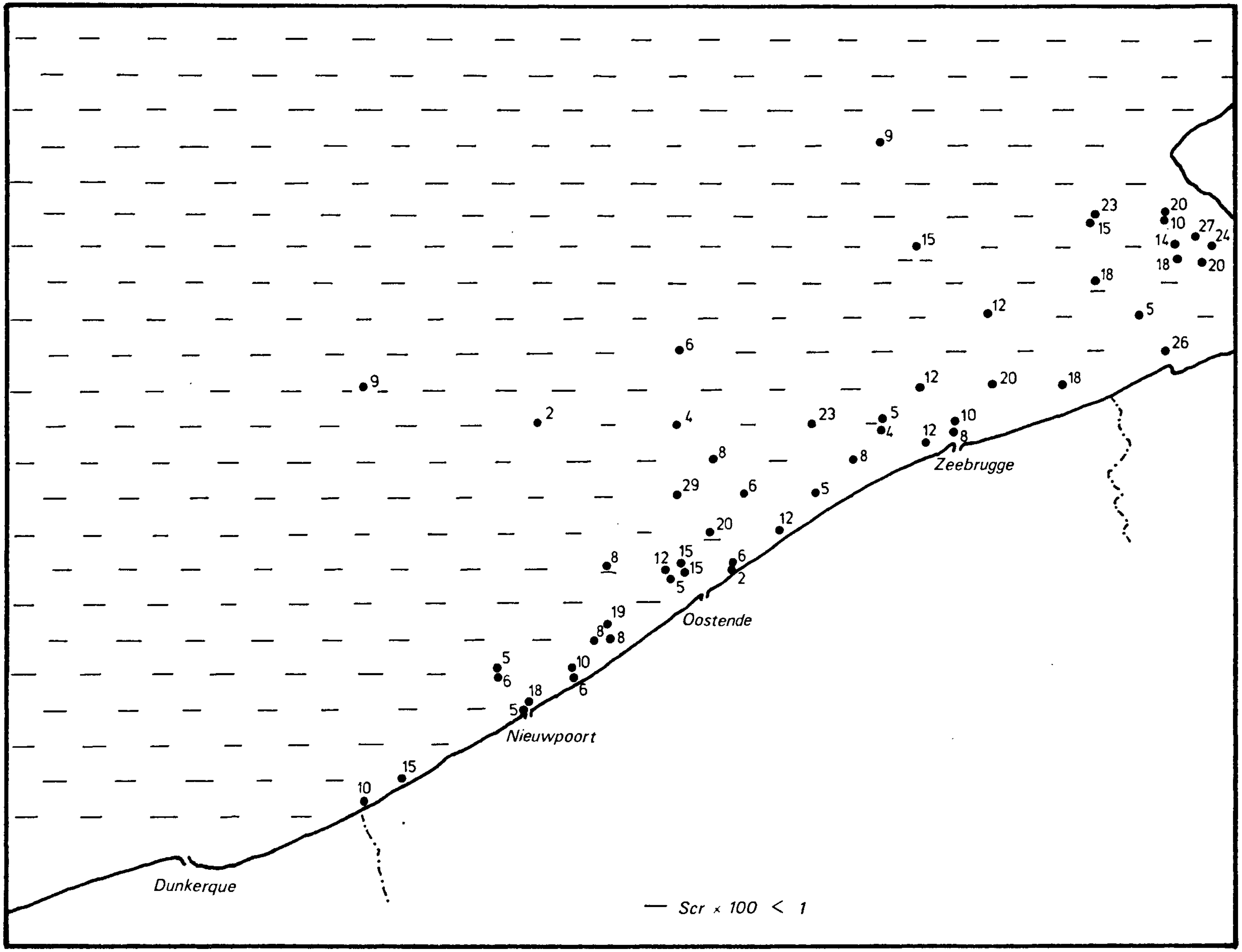


fig. 3.18.- Scr x 100-parameter of the bottom samples.

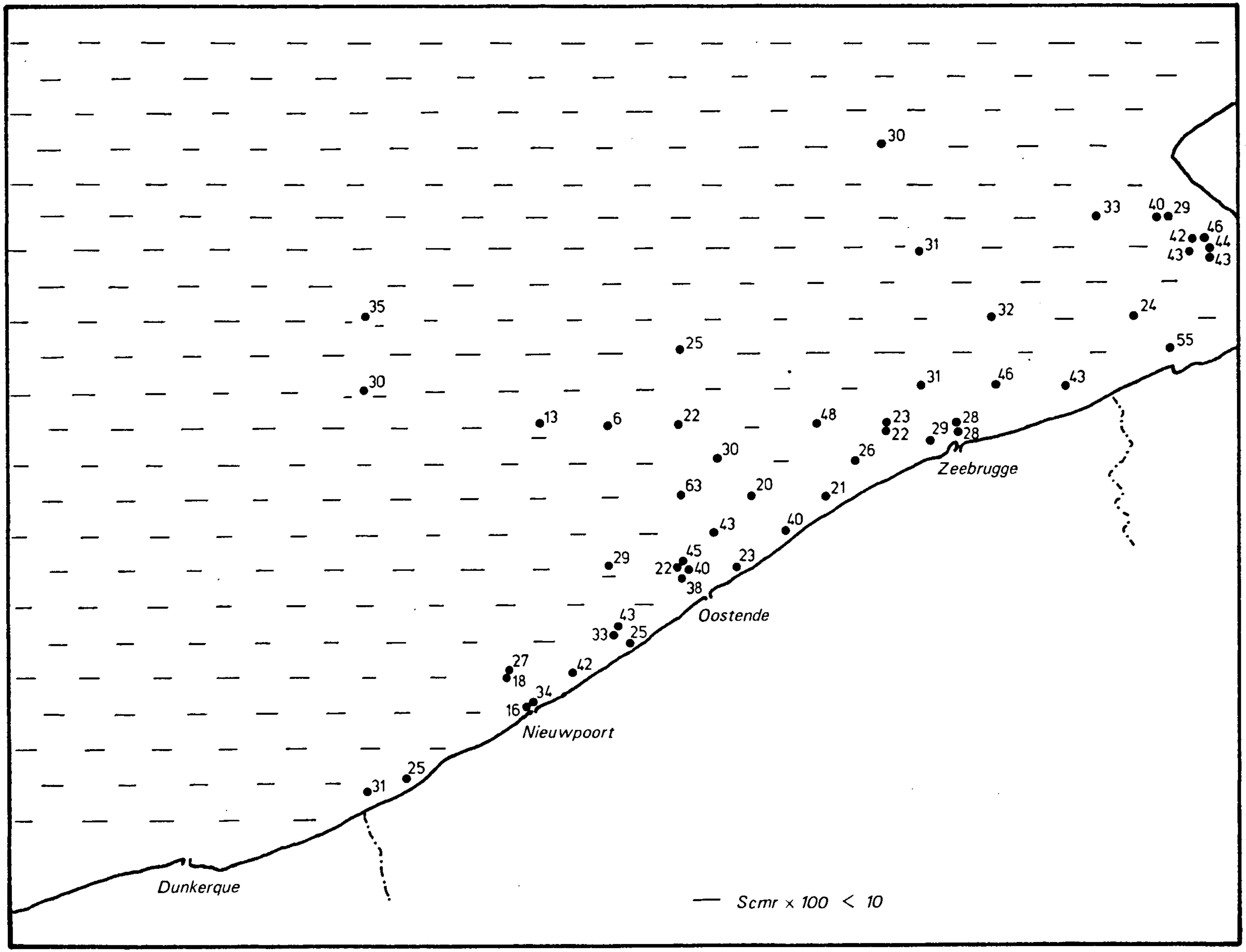


fig. 3.19.- Scmr x 100-parameter of the bottom samples.

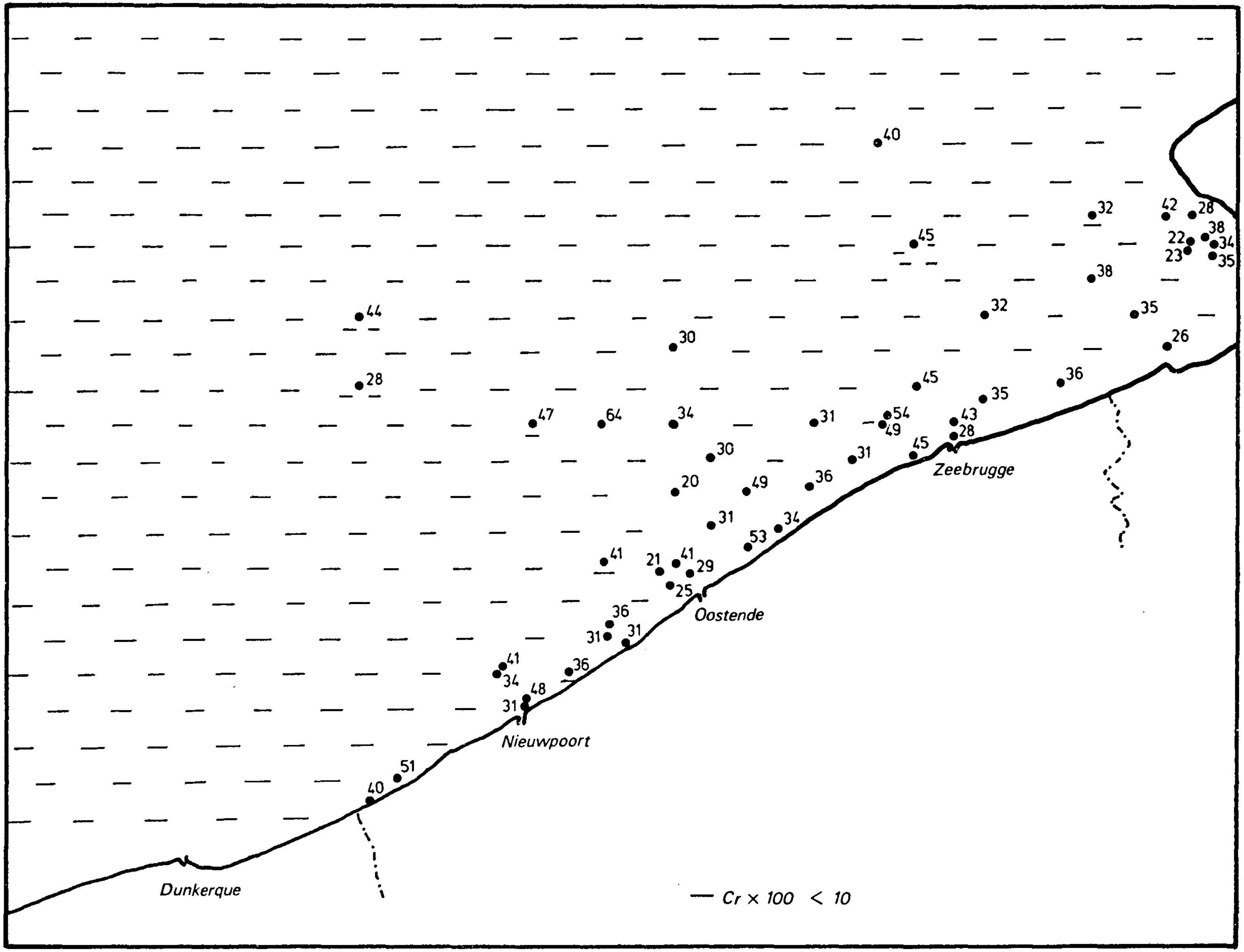


fig. 3.20.- Cr x 100-parameter of the bottom samples.

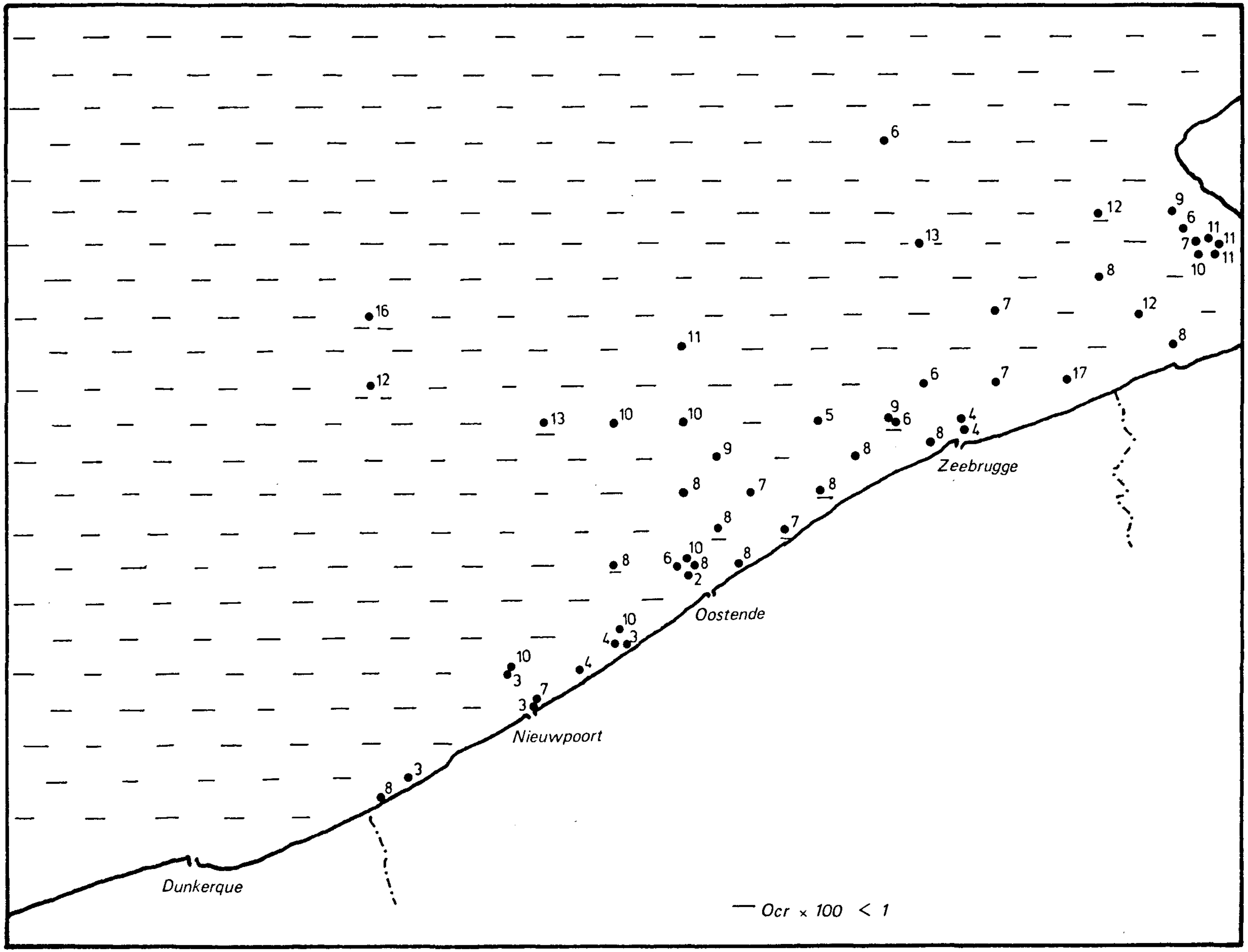


fig. 3.21.- Ocr × 100-parameter of the bottom samples.

This value is appreciably lower than the mean of the corresponding Scheldt mud parameters : 0.30 . At the stations 5 and 7 however, parameters with such high values possibly point to the presence of Scheldt material in these places. We think this should be almost certain at station 5. However, we cannot explain the high coarse silt content of the sample 1133.

$$\text{Scmr} : \text{silt coarse and medium ratio} = \frac{\text{fraction } 63-16\ \mu}{\text{fraction } < 63\ \mu}$$

records the contribution of coarse and medium silt in the suspended material Ps (fraction < 63 µ). The Scmr values are situated between 0.06 and 0.63 with a mean of 0.32 . Again, these are lower values than those of the Scheldt sediments : ± 0.55 . The Scmr-value distribution is bimodal with a first mode around 0.25 to 0.30 and a second around 0.40 to 0.45 . High values are found again around the mouth of the Western Scheldt and along its western extension. This could be due to the discharge of loess-rich material by the western Scheldt. A certain export of fine-grained material by the Scheldt thus seems possible. Hitherto, deposition of his muddy sediments into its lower part has always been assumed.

At the stations 1049, 1065, 1113, 1114 and 1133, high values were found with a maximum of 0.63 at 1133.

$$\text{Cr} : \text{clay ratio} = \frac{\text{fraction } < 2\ \mu}{\text{fraction } < 63\ \mu}$$

reflects the contribution of the clay fraction to the fraction < 63 µ .

Cr-values fluctuate between 0.22 and 0.64 with a mean of 0.36 , which is a higher value than for the Scheldt : 0.30 . This might point to the fact that in contrast with the coarser fractions (silt), the fine material (clay) is preferably discharged into the sea.

Some kind of sorting mechanism must thus be active in the lower Scheldt.

High Cr-values were found at the stations 1168, 1188, 1148, 1132, 1172, 1173 and 1007. Here, a more or less clay-rich sedimentation must exist.

We also found that the Cr-parameter is subject to strong variations. Silt-rich as well as clay-rich mud can be found in one and the same station (N° 1097 and 5, for example). This makes us think that the numerical values of this ratio may be strongly influenced by local and temporary hydrodynamical conditions, rather than by the provenance of the material.

$$\text{Ocr} \;:\; \text{organic clay ratio} \;=\; \frac{\text{organic fraction} \quad (H_2O_2)}{\text{fraction} \;<\; 2\ \mu} \;.$$

It is presumed that organic material is found in the clay-fraction, therefore the organic fraction is expressed as a percentage of the clay fraction. The Ocr-values fluctuate between 0.02 and 0.17 , the mean is 0.08 . The corresponding value for the Scheldt basin is 0.24 .

Seawater is generally oversaturated with oxygen, so the oxidation of organic compounds is easier in seawater than in riverwater.

Values for this parameter higher than the mean were found at the Scheldt mouth in N° 1186. When reworking occurs, organic matter in the sediment is repeatedly brought into contact with oxygenated water. So farther offshore in deeper parts of the sea where no reworking occurs, a higher organic matter content of the clay appears : N° 6, 1173 and 1941.

The optical investigation of the light mineral decalcified fraction was started as well. The most abundant grains of course are quartz (60 to 70 %), feldspars (± 20 %), silex (to 10 %). Chlorite, glauconite, silex and heavy minerals are the less important grains. Carbonate material easily makes up 50 % of the sample when not treated with HCl .

The countings are too incomplete to allow interpretation. Results can be found in Table 3.2. We can say that at this first glance the muds of the Belgian coast seem to be mineralogically homogenous. This is in accordance with the ratio analysis.

Remarkable anyway is the relative high chlorite content.

Table 3.2

% light minerals - composition per sample of the 32-63 μ fraction
(% quartz = 100 % - sum of the percentages of the other minerals)

Mineral species	Sample number															
	1007	1283	1113	1034	1131	1151	1097	1168	1114	1050	1149	1187	1065	1098	1132	1188
Orthoclase	9	9	10	10	6	9	7	8	6	9	7	6	6	9	7	9
Plagioclase	8	5	5	6	5	10	10	7	8	10	10	9	5	8	9	7
Silex	7	3	5	3	No executed											
Chlorite	5	3	5	4												
Glauconite	2	1	1	2												
Heavy minerals	1	3	1	2												
Opaque	3	2	4	2												
Quartz	65	76	69	71												

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Chapitre IV

Le comportement de nutrients dans l'estuaire de l'Escaut; cas de la silice et de l'ammoniaque

par

R. WOLLAST

Introduction

L'estuaire de l'Escaut a fait l'objet, au cours de l'année 1973, d'une série de campagnes de mesures mensuelles depuis l'embouchure jusqu'à une distance de 100 km vers l'amont. A chaque station de prélèvement distantes de 2 à 5 km , on prélève un échantillon d'eau de surface à un même moment de la marée, soit à marée basse, soit à marée haute.

Ces échantillons font l'objet de nombreuses mesures qu'il serait fastidieux d'énumérer ici. Nous avons choisi de présenter dans ce rapport d'activité, deux sujets qui ont été l'objet au cours de l'année 1973, d'une attention particulière et qui concernent le comportement de certaines substances nutritives dans l'estuaire.

Le premier sujet concerne le comportement de la silice dissoute qui est étudié par O. Beckers. Comme on le verra, ce problème est d'actualité et a conduit à une polémique entre les partisans des processus inorganiques opposés à ceux des processus biologiques pour expliquer la consommation de silice dans les estuaires.

L'apport estuarien de silice au milieu marin mérite une attention particulière, puisqu'il représente la source principale de cet important nutrient qui permet le large développement des diatomées que l'on observe au voisinage des estuaires. Une modification de ces apports est donc de nature à perturber l'équilibre écologique de milieux tels que la mer du Nord.

Le deuxième sujet, étudié par G. Billen, se rapporte au processus de nitrification dans l'estuaire. Nous avons montré dans le rapport précédent, l'importance de la charge organique que doit supporter l'Escaut.

Celle-ci subit une dégradation bactérienne intense qui conduit à la libération d'importantes quantités d'ammoniaque. Le temps de séjour des masses d'eau est suffisamment grand dans l'estuaire pour que le processus de nitrification, qui conduit à l'oxydation de l'ammoniaque, puisse s'y dérouler. S'il existe de nombreuses études *in vitro* de ce processus, on connaît par contre encore mal les conditions qui contrôlent ce phénomène dans les milieux naturels. Les résultats obtenus par G. Billen dans l'estuaire de l'Escaut l'ont conduit à émettre une hypothèse originale qui met en évidence l'importance des conditions physico-chimiques sur les processus biologiques.

1.- Comportement de la silice dissoute

1.1.- Introduction

Les estuaires constituent une source importante de silice dissoute pour le milieu marin et en particulier pour les mers côtières telle que la mer du Nord où la productivité primaire est largement due à l'activité des diatomées.

Le comportement de silice dissoute dans les eaux estuariennes a récemment retenu l'attention des chercheurs et à l'heure actuelle, deux hypothèses s'affrontent pour expliquer la consommation de ce nutrient. Pour Bien *et al.* (1958), la silice dissoute dans le Mississipi réagit chimiquement avec les solides en suspension lorsque la salinité devient suffisante. De manière similaire, Liss et Spencer (1970) estiment que 10 à 20 % de la silice dissoute de la rivière Conaway est éliminée par un phénomène d'adsorption inorganique.

Stefanson et Richards (1963), Banoub et Burton (1968), Burton *et al.* (1970), Wollast et De Broeu (1971), Fanning et Pilson (1973), ont par ailleurs montré que la consommation de silice par des réactions chimiques inorganiques était probablement négligeable et que celle-ci devait plutôt être attribuée à l'activité des diatomées.

Aucune de ces études n'a cependant établi de relations suffisamment quantitatives pour apprécier correctement l'importance relative de ces phénomènes. L'objet de ces recherches est de tenter de préciser la cinétique de consommation de la silice par les diatomées et les conditions qui peuvent éventuellement conduire à la fixation de cette silice par des processus purement inorganiques.

1.2.- Profils longitudinaux de silice dissoute dans l'Escaut

Il est commode de tester la consommation ou la production d'une espèce dissoute dans les estuaires en comparant l'évolution de sa concentration par rapport à la chlorinité. Cette dernière grandeur est conservative et l'évolution de sa concentration est uniquement liée aux paramètres physiques qui contrôlent le mélange des eaux douces à l'eau de mer, dans la région estuarienne. Si l'espèce dissoute est elle-même conservative, l'évolution de sa concentration en fonction de la chlorinité se traduit par une droite, dite droite de dilution. Les écarts positifs ou négatifs à la droite traduisent les phénomènes de production ou de consommation de cette substance. Les figures 4.1 et 4.2 montrent à titre d'exemple l'évolution de la silice dissoute dans l'Escaut au cours des campagnes de mesure de 1973. Si l'on compare les courbes obtenues aux droites de dilution, on constate que la silice est pratiquement conservative en hiver et qu'elle subit une consommation qui s'accentue au cours de l'été pour se résorber à nouveau au cours de l'automne. On notera aussi que la consommation s'accroît lorsque la chlorinité augmente et en particulier lorsque celle-ci est supérieure à 4 ‰ .

Il est intéressant à cet égard de considérer l'évolution de la turbidité des eaux de surface en fonction de la chlorinité représentée dans la figure 4.3. Les solides en suspension dans les eaux douces qui

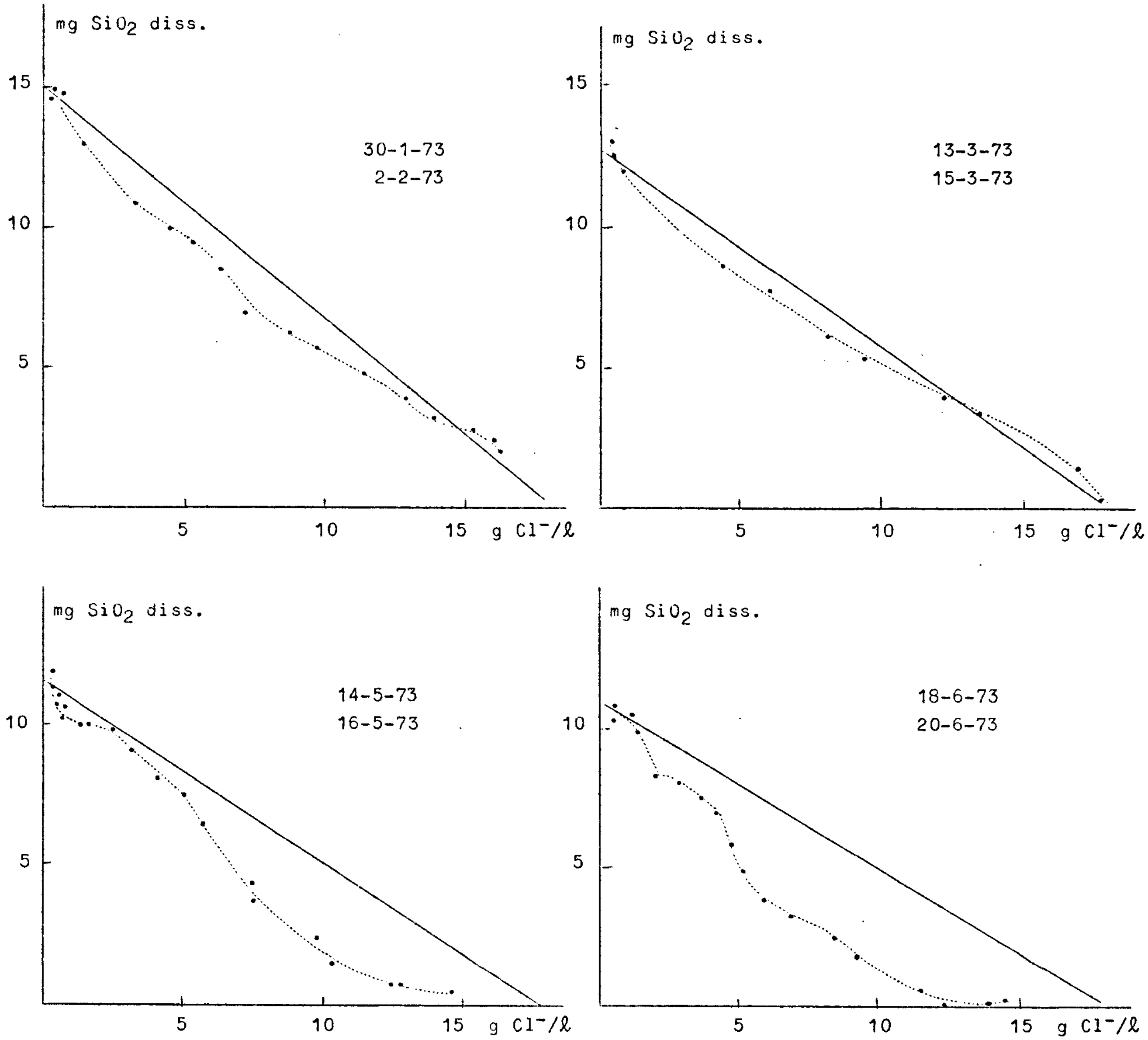

fig. 4.1.- Evolution de la silice dissoute en fonction de la salinité et comparée à la droite de dilution (février, mars, mai, juin).

sont extrêmement turbides subissent rapidement un phénomène de floculation et de sédimentation lorsque ces eaux sont mélangées à des eaux de salinité croissante [Wollast (1973), Peters (1973)].

Ce processus contribue de manière très significative à améliorer la qualité des eaux de l'Escaut. Non seulement la pénétration lumineuse

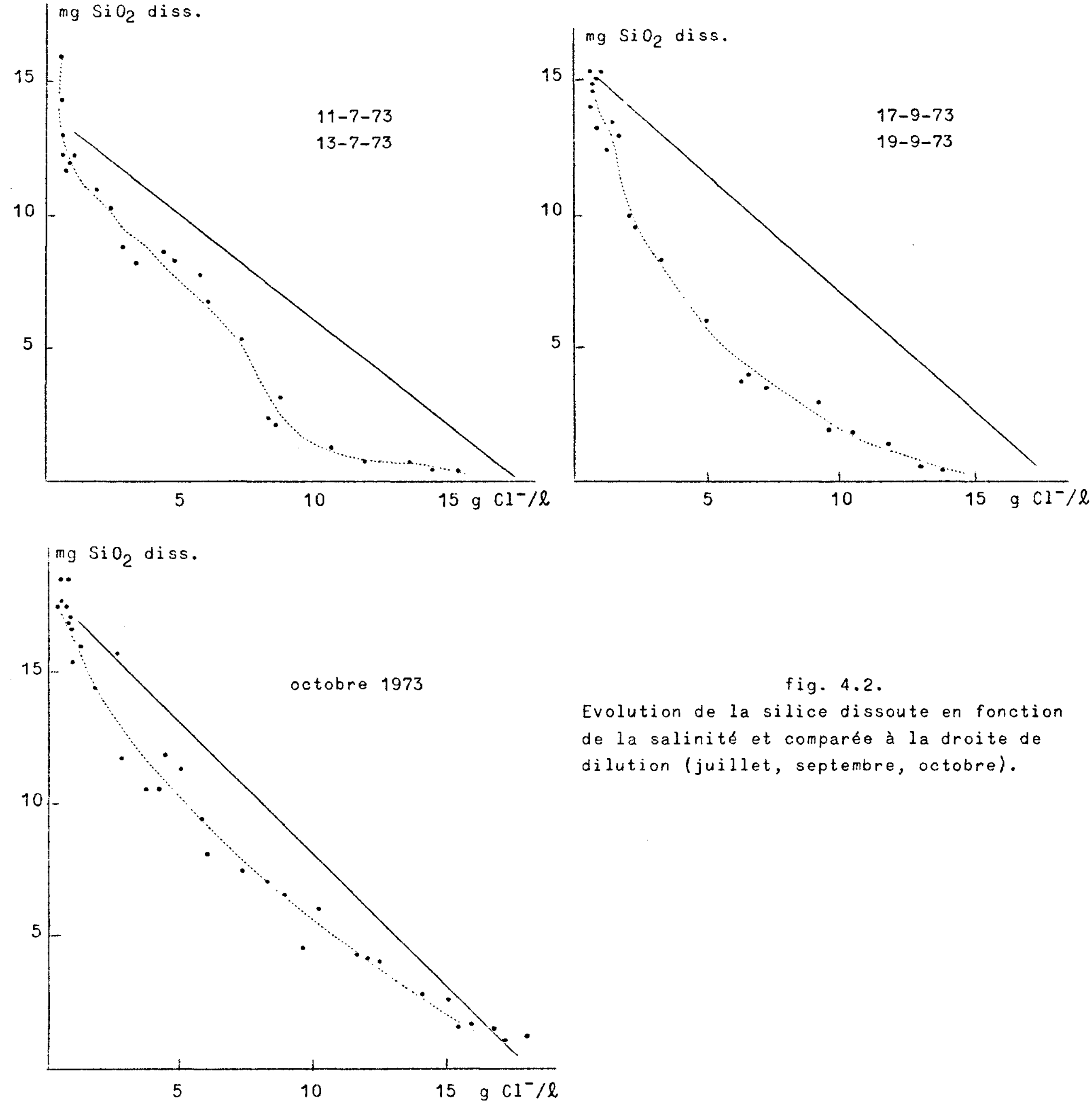

fig. 4.2.
Evolution de la silice dissoute en fonction de la salinité et comparée à la droite de dilution (juillet, septembre, octobre).

s'améliore considérablement, mais encore l'oxygène dissous réapparaît ainsi que le montre la figure 4.4.

Ces conditions sont évidemment favorables au développement des diatomées. L'influence de la saison, de la turbidité et de l'oxygène dissous est de nature à confirmer le rôle prépondérant que jouent les diatomées dans la consommation de silice dans l'estuaire.

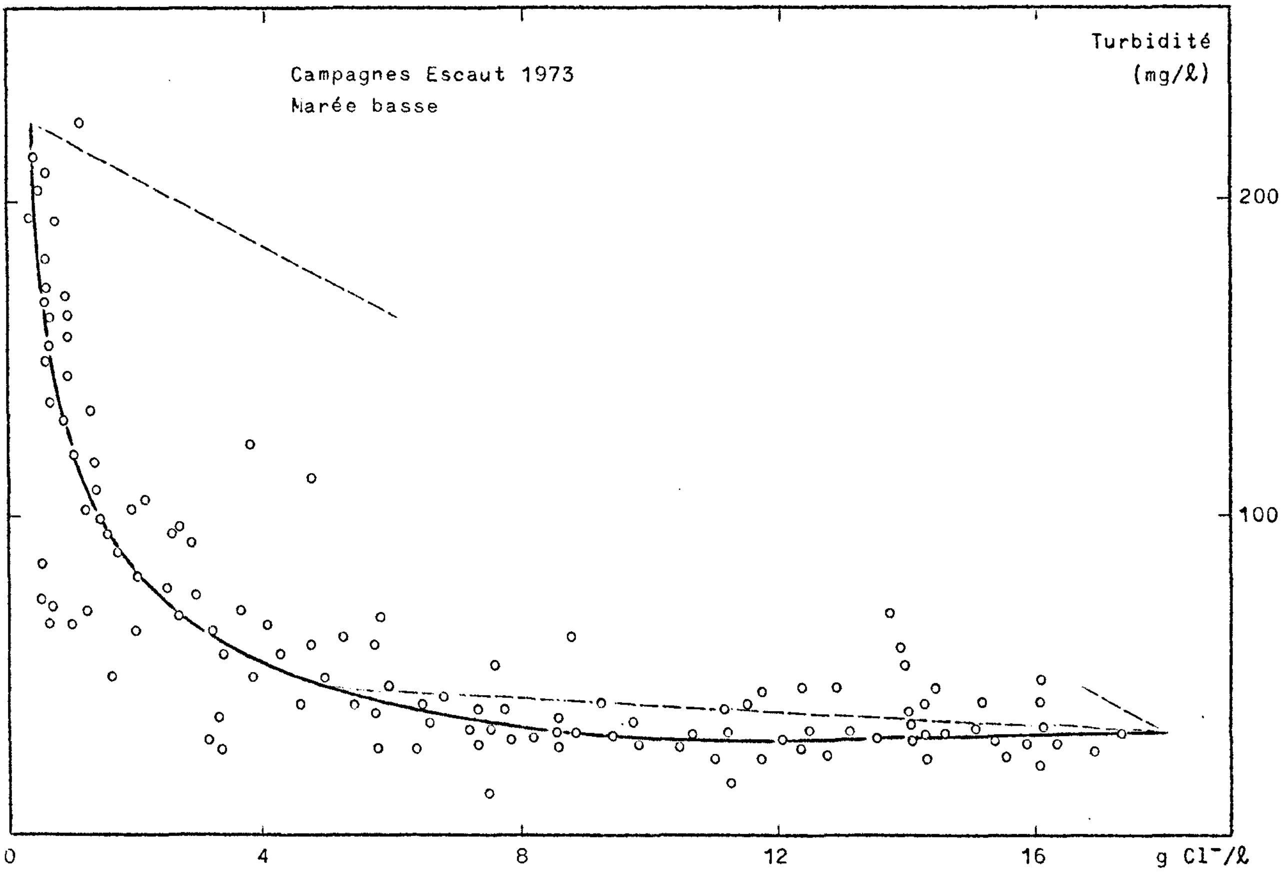

fig. 4.3.- Evolution de la turbidité en fonction de la salinité.

En vue de préciser plus quantitativement l'importance de cette consommation, nous avons utilisé le modèle stationnaire unidimensionnel de l'Escaut représenté précédemment [Wollast (1973)].

A partir des profils de silice dissoute relevés expérimentalement, et en tenant compte des termes d'advection et de convection déduits du profil de salinité, on peut calculer en tout point du profil le terme de production ou de consommation de la silice dissoute.

Les figures 4.5 and 4.6 montrent à titre d'exemple les résultats obtenus au cours des mois de mai et d'octobre. Ces profils sont très significatifs. On constate en effet de manière générale deux zones de consommation de silice : l'une située en amont et relativement faible en importance, l'autre située en aval et dont l'importance croît lorsque les conditions sont favorables au développement des organismes vivants. En dehors de ces zones, on constate une production faible de silice.

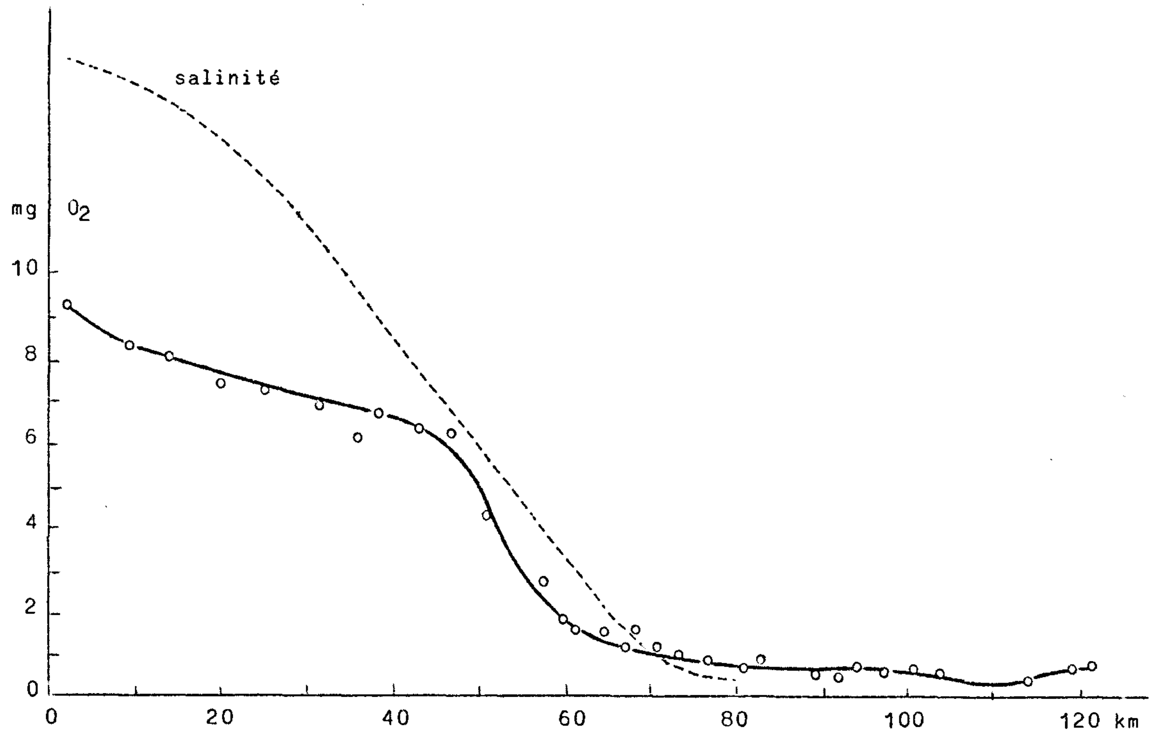

fig. 4.4.- Profil longitudinal de la concentration en oxygène dissous en fonction de la distance à l'embouchure.

Remarquons que les variations de silice qui sont discutées ici représentent des productions ou des consommations nettes et indiquent donc lequel des processus l'emporte sur l'autre.

En ce qui concerne la zone d'amont, il est difficile d'attribuer la consommation de silice à une activité biologique quelconque, compte tenu des conditions extrêmement défavorables qui y règnent (voir fig. 4.3 et 4.5). Par contre, la teneur élevée en silice dissoute et la turbidité importante sont défavorables aux processus de fixation inorganiques. Cette zone est d'ailleurs suivie d'une zone de production nette de silice. Comme il n'existe pas d'apports latéraux importants de silice dissoute dans cette région, il pourrait s'agir d'une libération de la silice fixée précédemment par suite de la diminution de la concentration en silice dissoute. L'origine exacte de ce processus de fixation et de libération n'est pas encore connu dans le cas de l'Escaut, mais on peut imaginer qu'il s'agit d'un simple processus d'adsorption et de désorption

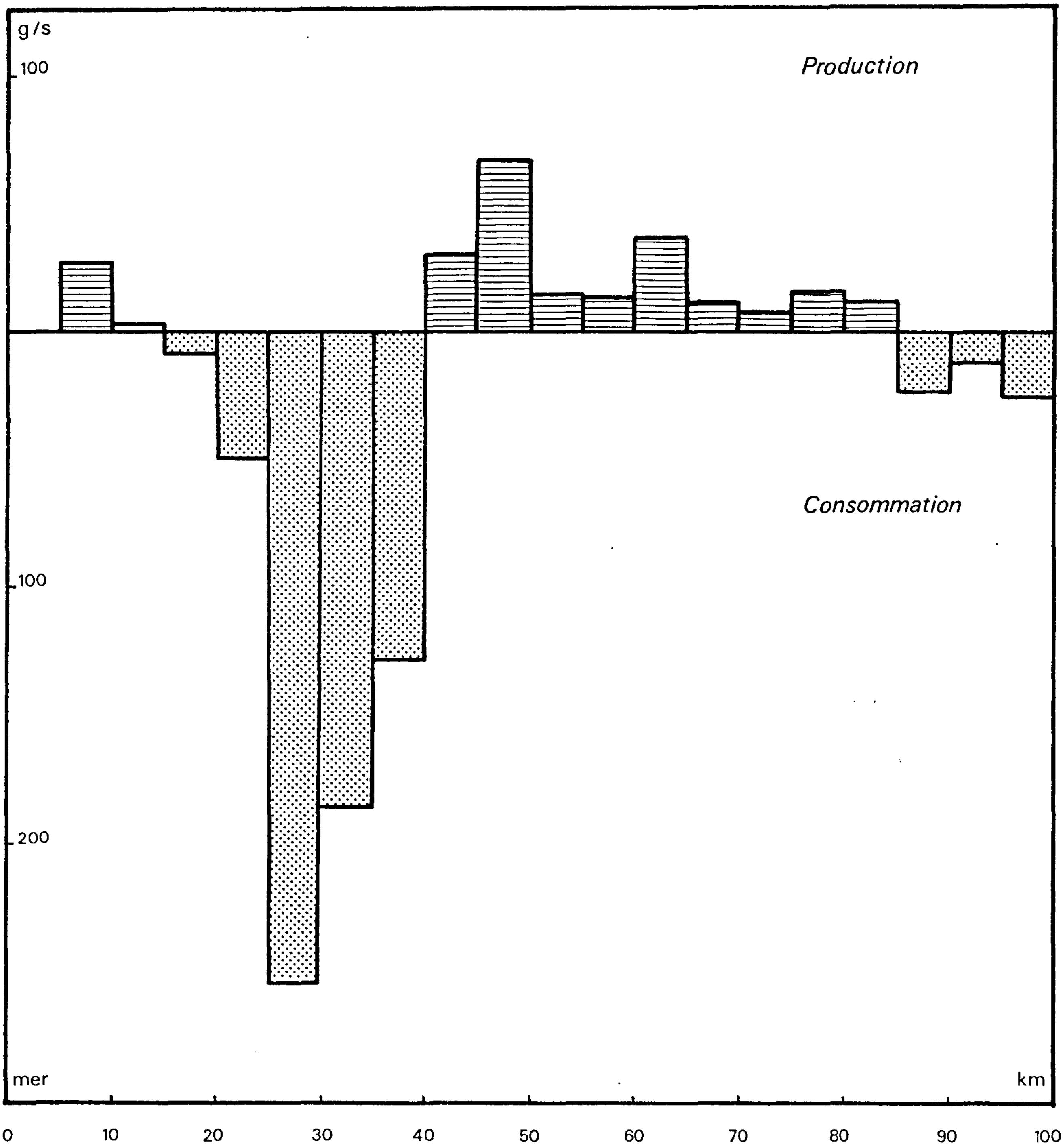

fig. 4.5.- Production et consommation de silice dans l'estuaire au cours du mois de mai 1973.

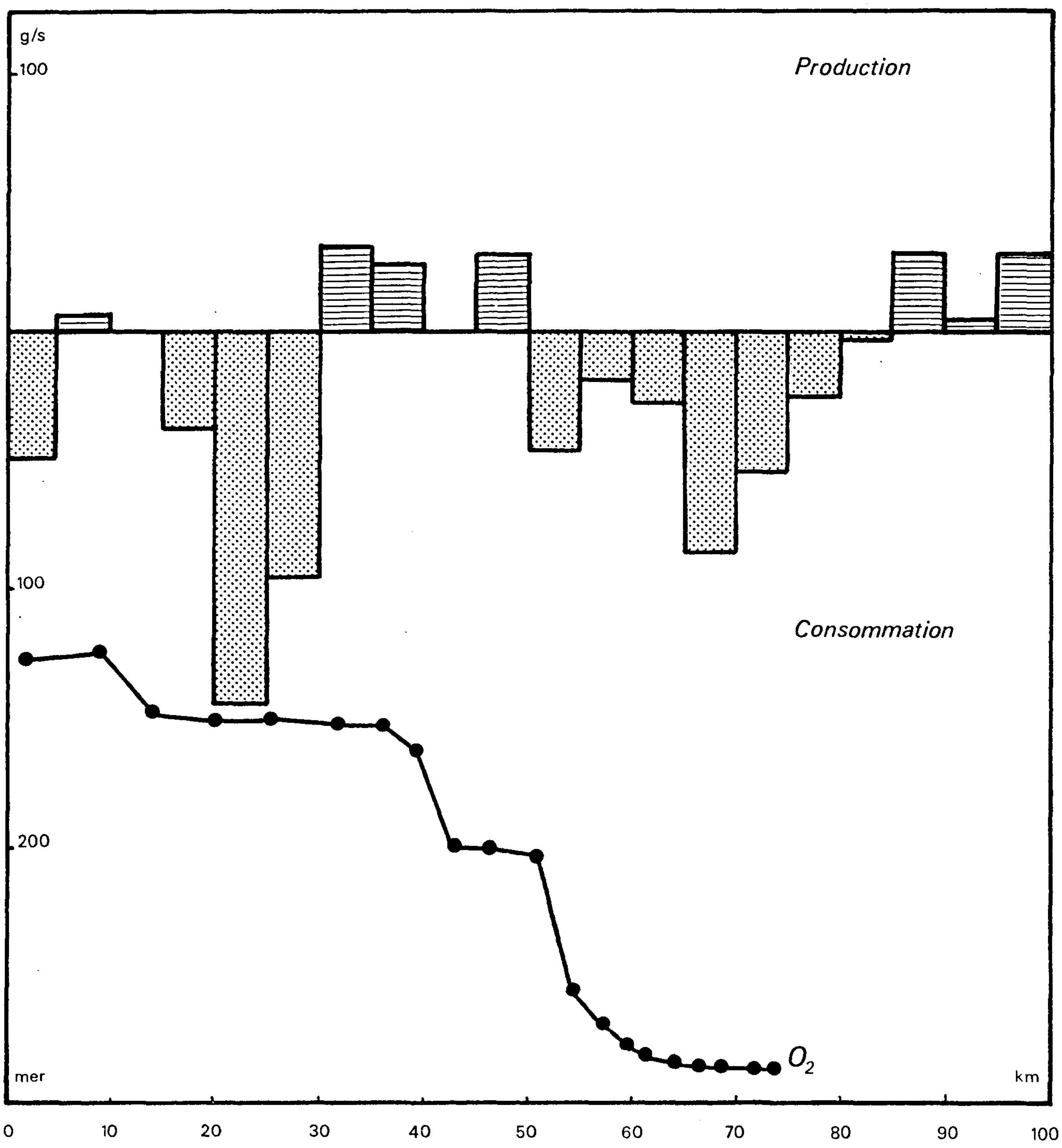

fig. 4.6.- Production et consommation de silice dans l'estuaire au cours du mois d'octobre 1973.

tel que l'ont signalé Liss et Spencer (1970) ou plutôt des réactions de fixation et de relargage de silice dissoute par les argiles en suspension prévus théoriquement et mis en évidence expérimentalement par Mackenzie et Garrels (1967). Il est en effet intéressant de remarquer (fig. 4.7) que les concentrations en silice dissoute que l'on observe dans l'estuaire de l'Escaut se situent dans le domaine où les réactions de fixation ou de libération de silice peuvent se présenter.

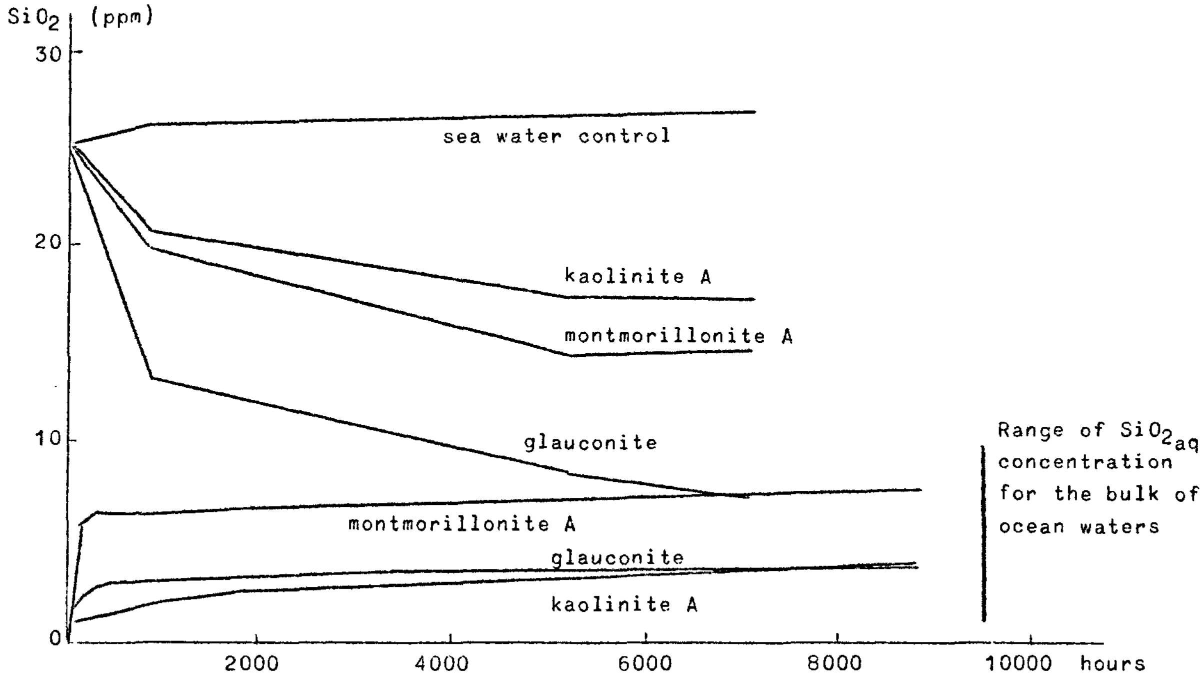

fig. 4.7.- Concentration de silice dissoute en fonction du temps pour diverses suspensions d'argile dans l'eau de mer. Les argiles ont été ajoutées à de l'eau de mer contenant initialement 0,03 ou 25 ppm de SiO_2 [Mackenzie (1967)].

Le bilan global de silice dans l'Escaut est cependant peu affecté par ce processus car les deux phénomènes se compensent assez bien avec un léger avantage en faveur de la fixation de silice dissoute. Il faut encore remarquer qu'au voisinage de l'embouchure, la production de silice redevient prépondérante et spécialement durant les mois de faible activité biologique (février, mars). On peut donc envisager que dans les zones côtières dominées par l'influence des estuaires, l'apport de silice dissoute par les matières en suspension pourrait être significatif. Nous reviendrons ultérieurement sur ce point.

Nous avons vu précédemment les arguments qualitatifs qui plaident en faveur d'une consommation biologique de silice dans la zone aval de l'estuaire. L'examen des chlorophylles confirme cette hypothèse : le coefficient de corrélation entre les chlorophylles-phaeophytines et la consommation de silice est de + 0,87 . Les vitesses de consommation moyenne de la silice dans la région de Doel à Hansweert sont de l'ordre de 1 à 2 mg $SiO_2/m^3/h$. Ces chiffres sont en bon accord avec les valeurs déterminées par Peterson *et al.* (1971) pour la consommation de silice par les diatomées dans la baie de San Francisco.

1.3.- Mesure de la productivité primaire

La mesure de la productivité primaire devrait permettre d'estimer un taux de silice fixé par activité biologique. Nous avons donc tenté de mesurer cette productivité à l'aide de l'incorporation de carbone 14.

En fait, la mesure de la productivité primaire s'est avérée fort compliquée. En effet, Billen (1973) a mis en évidence une consommation importante de $H^{14}CO_3^-$ à l'obscurité dans la zone amont de l'estuaire. Il a montré que cette incorporation était due principalement (80 %) à l'incorporation de CO_2 par les bactéries hétérotrophes qui l'utilisent pour une partie de leur métabolisme carboné total (voies anaplerotiques). L'autre partie est utilisée par les bactéries chemoautotrophes (bactéries nitrifiantes) pour lesquelles le carbonate représente la seule source de carbone. Bien que cette consommation soit moins importante dans la partie aval de l'estuaire, moins chargée en matières organiques, elle est cependant gênante car elle donne un bruit de fond élevé.

D'autre part, nous avons remarqué qu'il existait une activité photosynthétique importante, après filtration de l'eau dans la fraction inférieure à 25 microns. Il est vraisemblable qu'il s'agit d'une activité bactérienne photosynthétique. A nouveau, cette activité doit être soustraite de l'activité totale pour rendre compte de la productivité primaire potentielle liée au phytoplancton. Elle introduit à son tour une incertitude élevée sur la valeur de la production primaire car elle peut représenter plus de 90 % de l'activité totale mesurée.

On peut cependant estimer que la mesure de la productivité primaire se présentera de manière satisfaisante lors des périodes d'intense activité biologique. La figure 4.8 montre à titre d'exemple le relevé obtenu au cours de la campagne du mois de septembre. Bien que l'activité soit déjà réduite, on observe une bonne corrélation entre les mesures de productivité primaire et les concentrations des chlorophylles dans le microplancton.

La corrélation est moins nette dans le cas de la consommation de silice par suite du recouvrement de l'effet de fixation inorganique de la silice de la région d'amont.

1.4.- Apport de silice dissoute par les sédiments

Les estimations de consommation nette de silice nécessitent une bonne connaissance des divers apports possibles. Le relargage de silice dissoute à partir des eaux interstitielles des sédiments peut constituer une source de silice dissoute appréciable.

Le flux de silice dissoute vers les eaux de surface peut être estimé d'après l'équation de diffusion

$$J_{z=0} = D \left. \frac{d\, SiO_2}{dz} \right|_{z=0}$$

si l'on connaît le gradient de concentration $\frac{d\, SiO_2}{dz}$ au voisinage de l'interface eau-sédiment.

La figure 4.9 montre à titre d'exemple le profil de concentration en silice dissoute relevé dans les eaux interstitielles d'une carotte de forage relevée à Zandvliet.

Pour un coefficient de diffusion de la silice égal à 2.10^{-6} cm^2/s [Wollast et Garrels (1971)], on obtient dans ce cas un flux égal à 3.10^{-12} g/cm^2/s . Pour une section de 5 km de long ceci représente un apport de 0,15 g/s . Dans la même section, l'apport latéral de silice par les eaux douces riches en silice dissoute (15 ppm) représente 7,5 g/s . L'apport des sédiments peut donc être considéré comme négligeable dans le cas de l'Escaut.

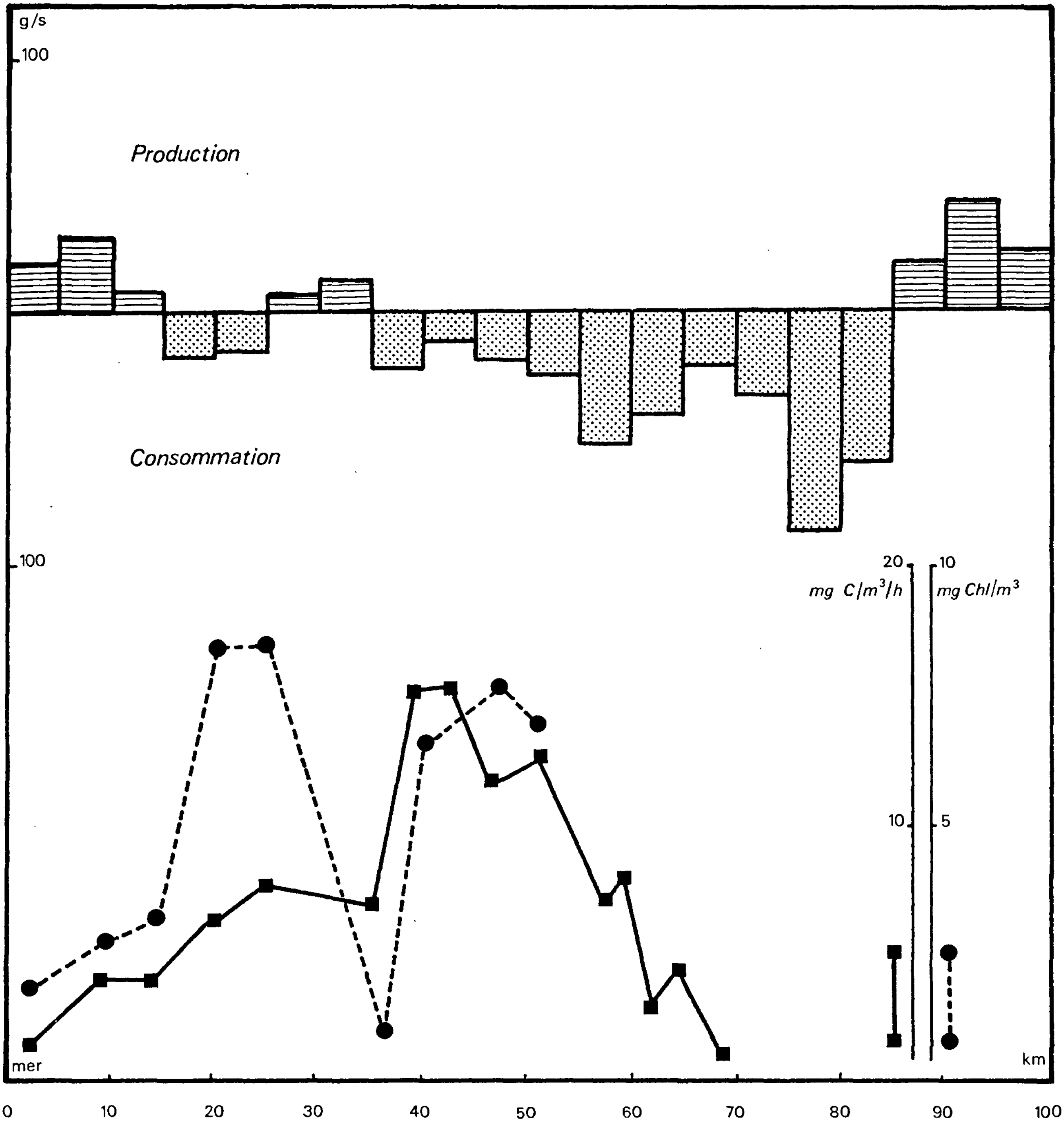

fig. 4.8.- Comparaison entre la production et la consommation de silice dissoute, la productivité primaire et la concentration en chlorophylle.

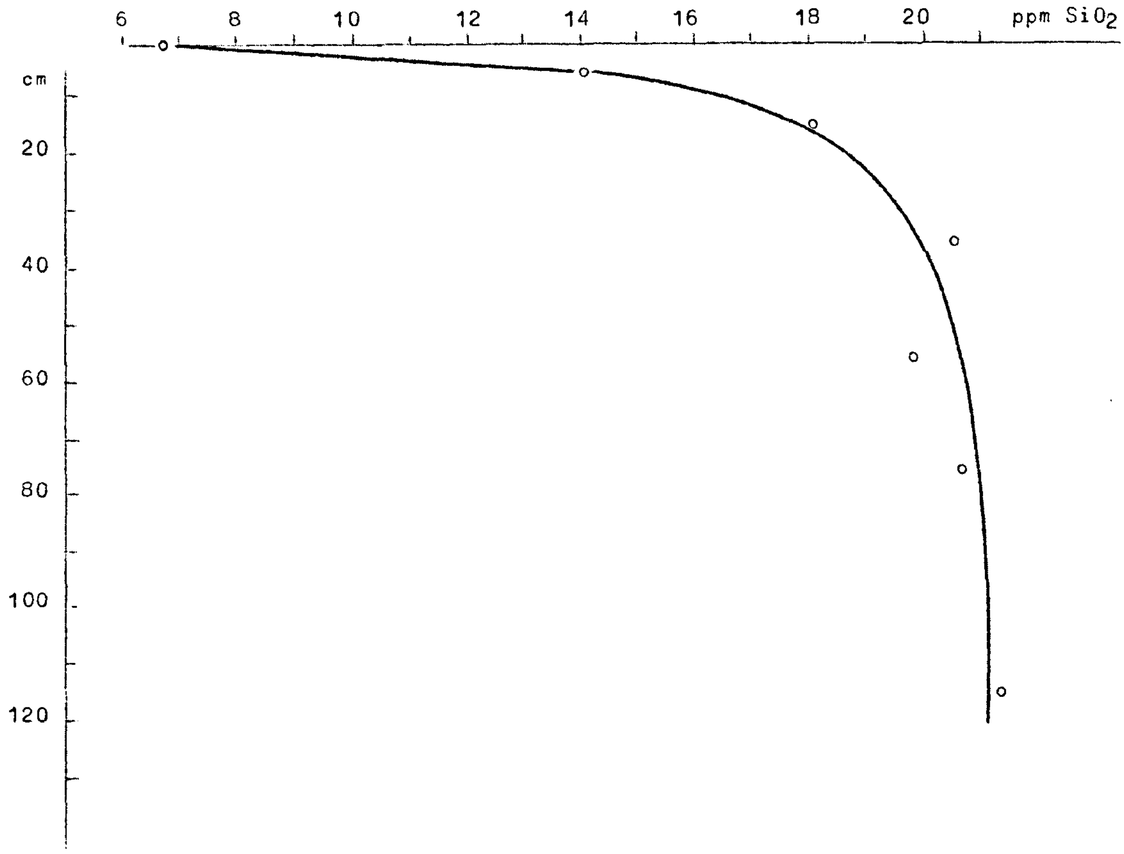

fig. 4.9.- Profil vertical de concentration en silice dissoute dans les eaux interstitielles d'une carotte de sondage prélevée à Zandvliet.

1.5.- Conclusions

Les relevés des profils longitudinaux de la silice dissoute mis en relation avec l'évolution de grandeurs tels que la turbidité, l'oxygène dissous, la concentration en chlorophylles et la productivité primaire montrent l'importance déterminante de l'activité biologique dans le processus de consommation de silice. Si le processus de fixation de la silice par des réactions inorganiques est vraisemblable dans la région amont de l'estuaire, il ne paraît pas que ce processus joue un rôle important puisque cette réaction semble réversible et que de la silice dissoute est libérée à nouveau dans la région aval du fleuve.

La consommation de silice dans l'estuaire par les diatomées est considérable pendant les mois d'intense activité biologique. La figure

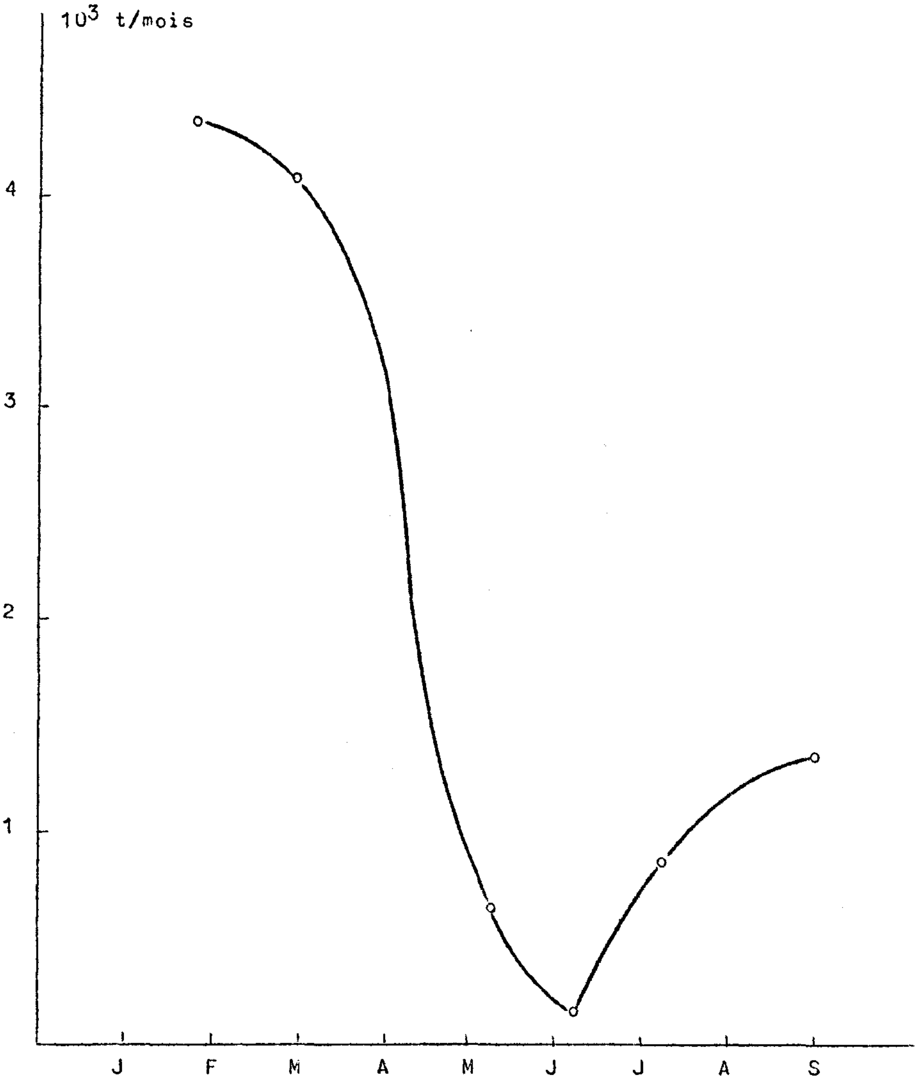

fig. 4.10.
Apport de silice en mer du Nord par l'estuaire de l'Escaut au cours de l'année 1973.

4.10 montre que l'apport de silice en mer du Nord par l'estuaire de l'Escaut devient pratiquement nul au cours de l'été. Plus de 95 % de la silice dissoute apportée par les eaux douces d'amont est consommé dans l'estuaire lui-même. Si, comme nous le pensons, cette consommation de silice résulte d'une eutrophysation et est relativement récente, on prive actuellement la mer du Nord d'une source importante de silice dissoute. Ceci pourrait y modifier l'équilibre écologique, la silice devenant limitante par rapport au phosphore ou l'azote.

2.- La nitrification

2.1.- Introduction

Le processus de nitrification représente la dernière étape de la dégradation de la matière organique dans le phénomène d'auto-épuration des rivières. Au cours de ce processus, l'ammoniaque provenant de la décomposition de la matière organique est transformé en nitrites et en nitrates et cette oxydation peut affecter de manière sensible l'oxygène dissous [Courchaine (1968)]. Il est donc important de préciser les conditions de nitrification et la cinétique de ces phénomènes dans les milieux naturels si l'on désire réaliser un modèle de gestion de la rivière.

L'oxydation de l'ammoniaque en nitrate est essentiellement liée à l'activité de bactéries autotrophes bien spécifiques (*Nitrosomanas* et *Nitrobacter*) [Painter (1970)] et le problème de la nitrification dans les rivières est donc un exemple particulièrement judicieux pour étudier l'activité des micro-organismes dans un milieu naturel en utilisant diverses approches.

Une première approche consiste à envisager un modèle thermodynamique tel que celui développé par Stumm (1966). Dans un tel modèle, purement théorique, on considère que les espèces dissoutes sont en équilibre thermodynamique entre-elles et que les bactéries agissent en quelque sorte comme catalyseur pour maintenir l'équilibre chimique.

De tels modèles peuvent être utiles pour décrire des systèmes qui évoluent très lentement comme les sédiments ou les eaux profondes, par exemple [Thorstenson (1970)].

L'hypothèse d'un équilibre interne est cependant peu probable dans le cas des cours d'eau. Les biologistes attachent généralement peu d'importance à de tels modèles car ceux-ci ne tiennent pas compte de la cinétique de l'action bactérienne.

Les modèles biologiques tentent en effet de décrire l'activité bactérienne en fonction du nombre de bactéries et de la concentration du substrat. Il existe de nombreux travaux de laboratoire sur l'activité des bactéries nitrifiantes [Painter (1970), Wild (1971)] qui ont conduit à la détermination de paramètres intéressants, tels que la vitesse de croissance, la constante de Michaelis, etc.

Les modèles mathématiques basés sur une vitesse constante de croissance ont été appliqués avec succès à des portions isolées de cours d'eau [Wezernak et Gannon (1968)], mais ils sont peu satisfaisants lorsqu'on considère l'ensemble du processus de dégradation de la matière organique dans un cours d'eau, et en particulier dans ceux qui sont fortement pollués. On observe en effet, au cours de l'auto-épuration, que la nitrification ne se produit qu'après un temps de latence plus ou moins long. Pour certains auteurs, la nitrification ne commence que lorsque l'oxygène dissous a atteint une valeur minimum [Weatland *et al.* (1959)], mais ce critère est mis en doute par d'autres auteurs qui se réfèrent plutôt à un paramètre empirique lié au degré de dégradation de la matière organique [Eekenfelder (1967), Edeline (1973)].

L'Escaut se prête remarquablement à ce type d'étude étant donné la charge polluante élevée et les temps de séjour considérables des masses d'eau dans la partie estuarienne.

La figure 4.11 montre trois profils longitudinaux de nitrate, nitrite et ammoniaque effectués à trois époques différentes. On observe distinctement deux zones : celle d'amont où l'ammoniaque est la seule forme présente et celle d'aval où les formes oxydées d'azote apparaissent. Le début de la nitrification se marque de manière nette et peut être fixé avec une précision de plus ou moins trois kilomètres.

L'étude des conditions régissant cette limite a été abordée à la fois sur la base des modèles thermodynamiques et biologiques en vue de préciser l'importance des conditions physico-chimiques sur l'activité des bactéries nitrifiantes.

2.2.- Influence du Eh sur la nitrification

L'Escaut dont la charge polluante atteint un maximum dans la région d'Anvers (km 78) subit une auto-épuration remarquablement rapide par suite d'une sédimentation importante de la matière organique en suspension et du processus de dilution par l'eau de mer bien aérée. Le potentiel d'oxydo-réduction, tel qu'il est mesuré à l'électrode de

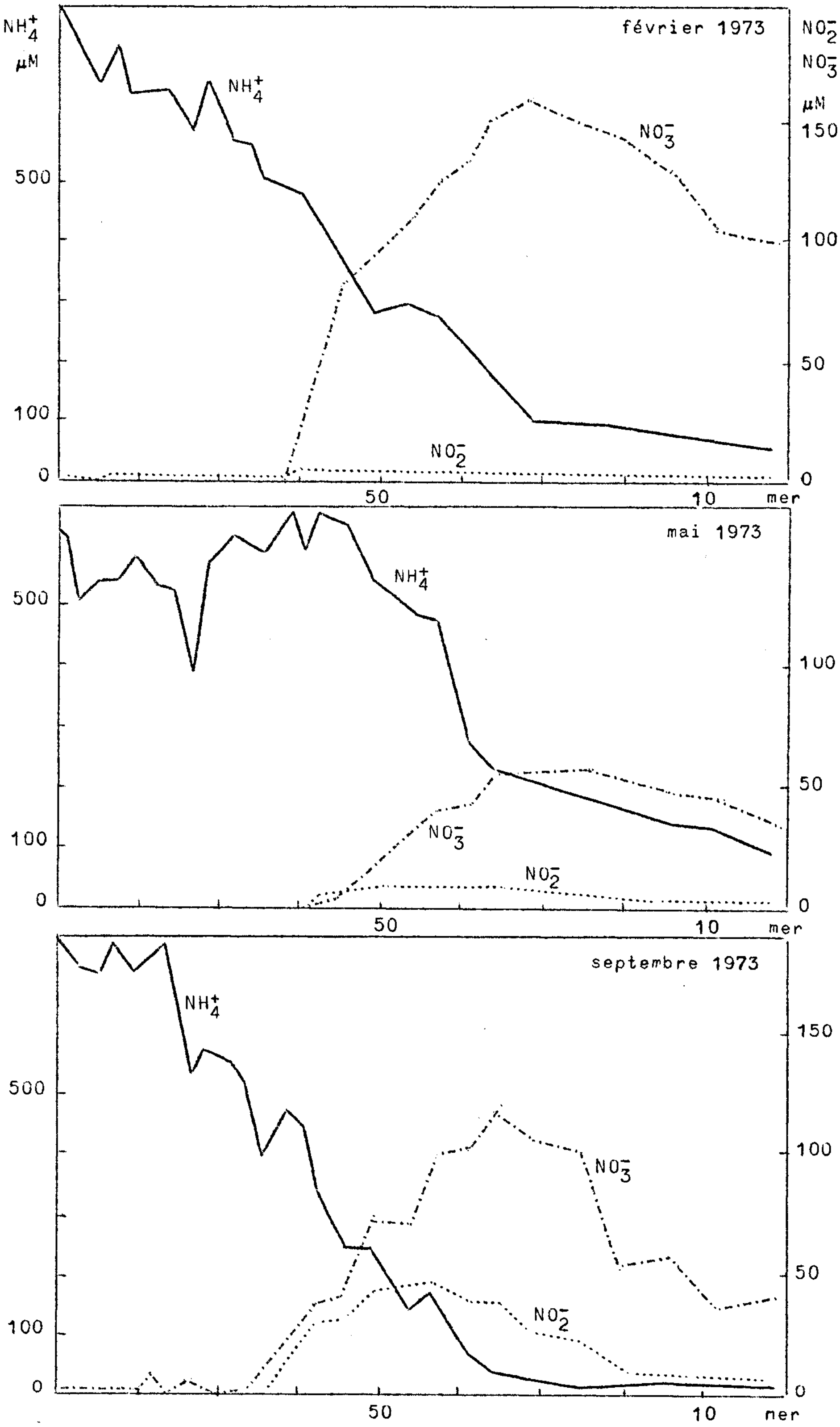

fig. 4.11.- Profil longitudinal des concentrations de NH_4^+ , NO_2^- et NO_3^- en fonction de la distance à l'embouchure.

platine, peut atteindre à Anvers des valeurs aussi basses que - 100 mV au cours de l'été, lorsque la dégradation bactérienne est la plus intense. En hiver, la dégradation est très faible et le potentiel d'oxydo-réduction remonte à + 200 mV . Quelles que soient les conditions règnant à Anvers, le potentiel d'oxydo-réduction augmente progressivement vers l'aval et atteint dans tous les cas + 350 mV à quelques kilomètres de l'embouchure.

Nous avons reporté dans un diagramme Eh-pH les valeurs de ces paramètres pour les zones où les nitrates et les nitrites étaient présents ou absents (fig. 4.12).

Il apparaît immédiatement qu'il existe dans ce diagramme une séparation nette entre ces deux zones qui peut être décrite par l'équation empirique

$$Eh = 0{,}820 - 0{,}08\ pH .$$

Ces données expérimentales ont été comparées aux prédictions d'un modèle thermodynamique d'équilibre entre les espèces NH_4^+ , NO_2^- et NO_3^- basé sur les énergies libres de formation de ces espèces citées par Garrels et Christ (1965). Les résultats de ces calculs sont représentés dans la figure 4.13. Dans le diagramme théorique, la limite de stabilité de l'ammoniaque par rapport aux nitrites et nitrates est représentée par une droite dont l'équation est

$$Eh = 0{,}897 - 0{,}079\ pH .$$

Le parallélisme entre la limite expérimentale de la zone de nitrification et la prévision thermodynamique de stabilité des espèces dissoutes est remarquable. La différence de 77 mV entre les deux limites de stabilité se prête mal à une discussion plus détaillée. On sait en effet que les mesures de Eh à l'aide d'une électrode de platine ne représentent pas nécessairement la grandeur thermodynamique réelle par suite de l'irréversibilité des réactions à la surface de l'électrode [Sato (1960), Stumm (1966), Morris et Stumm (1967), Breck (1972)]. Ceci n'empêche toutefois pas que les mesures de potentiel d'oxydo-réduction à l'aide des électrodes de platine peuvent être utilisées de manière fructueuse comme paramètre semi-empirique pour caractériser l'activité biochimique [Baas-Becking (1960), Whitfield (1969), Borchardt (1966)].

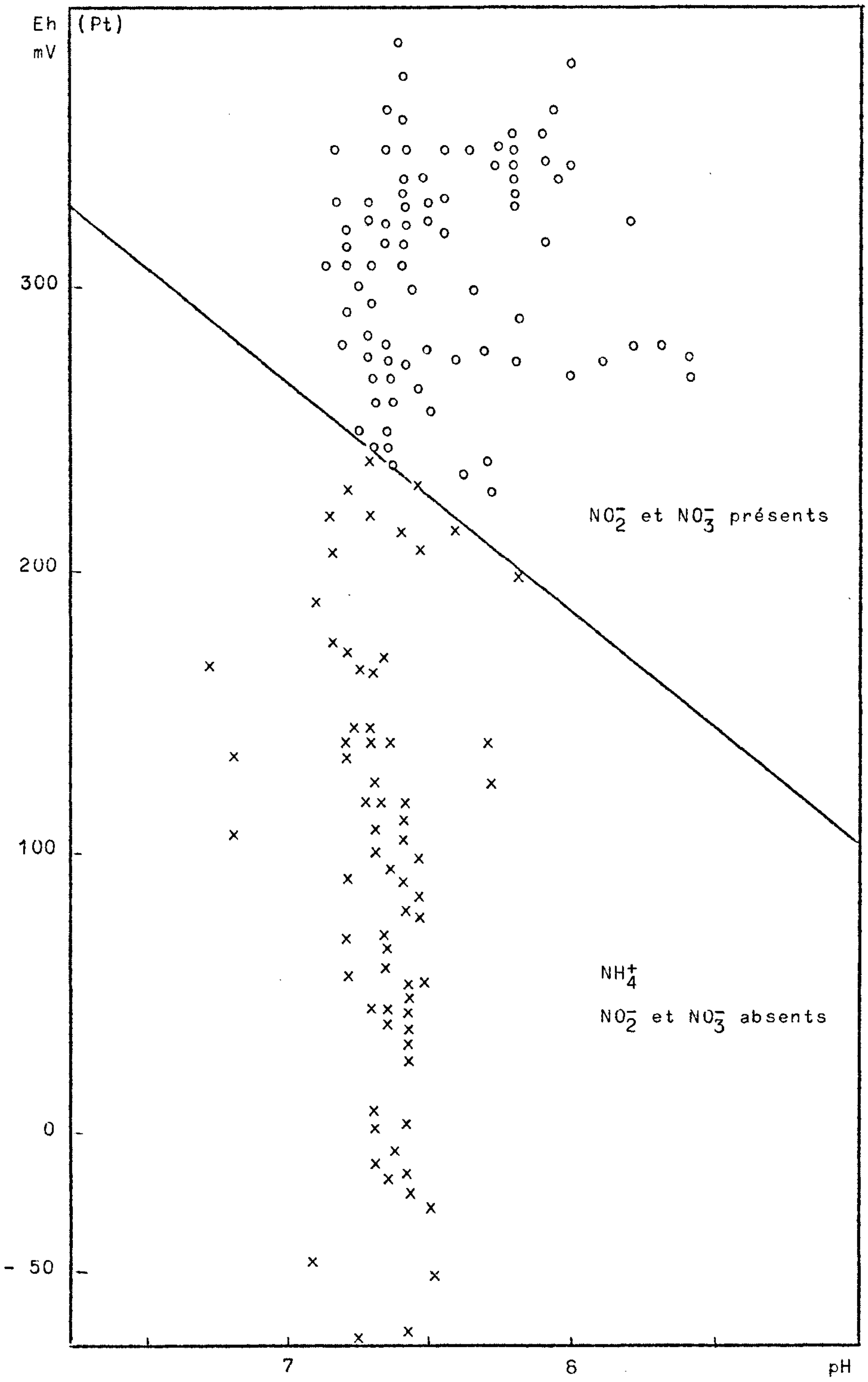

fig. 4.12.- Influence du potentiel d'oxydo-réduction sur le processus de nitrification. Les croix correspondent à des eaux qui contiennent uniquement de l'ammoniaque et les ronds à des eaux où une forme oxydée de l'azote est présente.

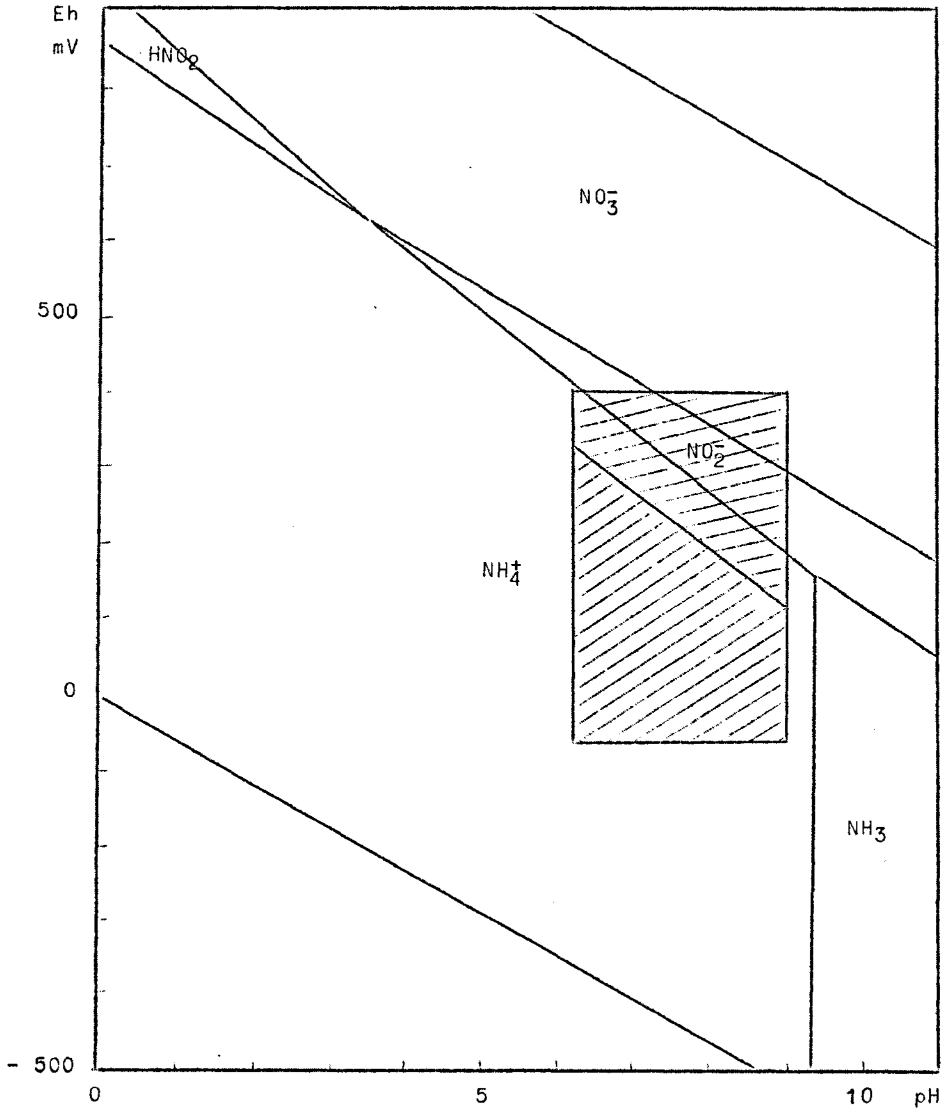

fig. 4.13.- Diagramme de stabilité du système NH_4^+ , NO_2^- , NO_3^- , dans lequel on a reporté (rectangle hachuré) le diagramme de la figure 4.12.

Le parallélisme entre les observations expérimentales et l'équilibre thermodynamique n'implique toutefois pas que celui-ci soit réalisé dans les eaux de l'Escaut. Il indique plutôt que la nitrification ne se produit que lorsque les conditions d'oxydo-réduction sont thermodynamiquement favorables pour les bactéries nitrifiantes. Ceci n'est pas surprenant d'ailleurs puisque ces bactéries utilisent l'oxydation de l'ammoniaque comme seule source d'énergie.

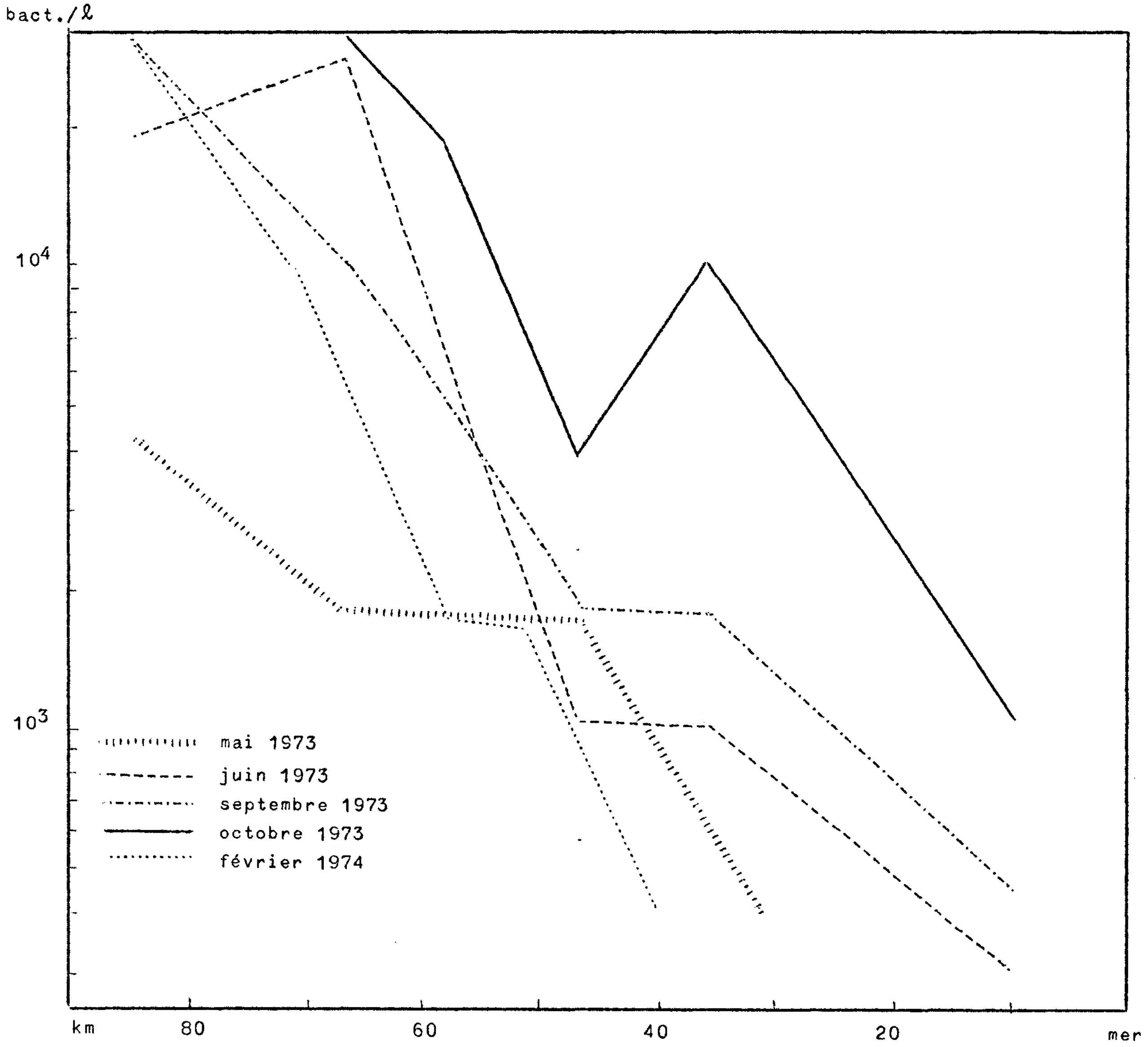

fig. 4.14.- Profils longitudinaux du nombre de bactéries nitrifiantes en fonction de la distance à l'embouchure.

2.3.- Numération des bactéries nitrifiantes

Le nombre de bactéries nitrifiantes a été compté sur des milieux enrichis soit salins, soit d'eau douce. Les résultats obtenus pour un milieu d'eau douce sont représentés dans la figure 4.14. Tous les profils indiquent une diminution rapide des bactéries vers l'aval. En les comparant avec les profils des nitrites et des nitrates de la figure 4.11, il est évident que la zone de nitrification ne correspond nullement

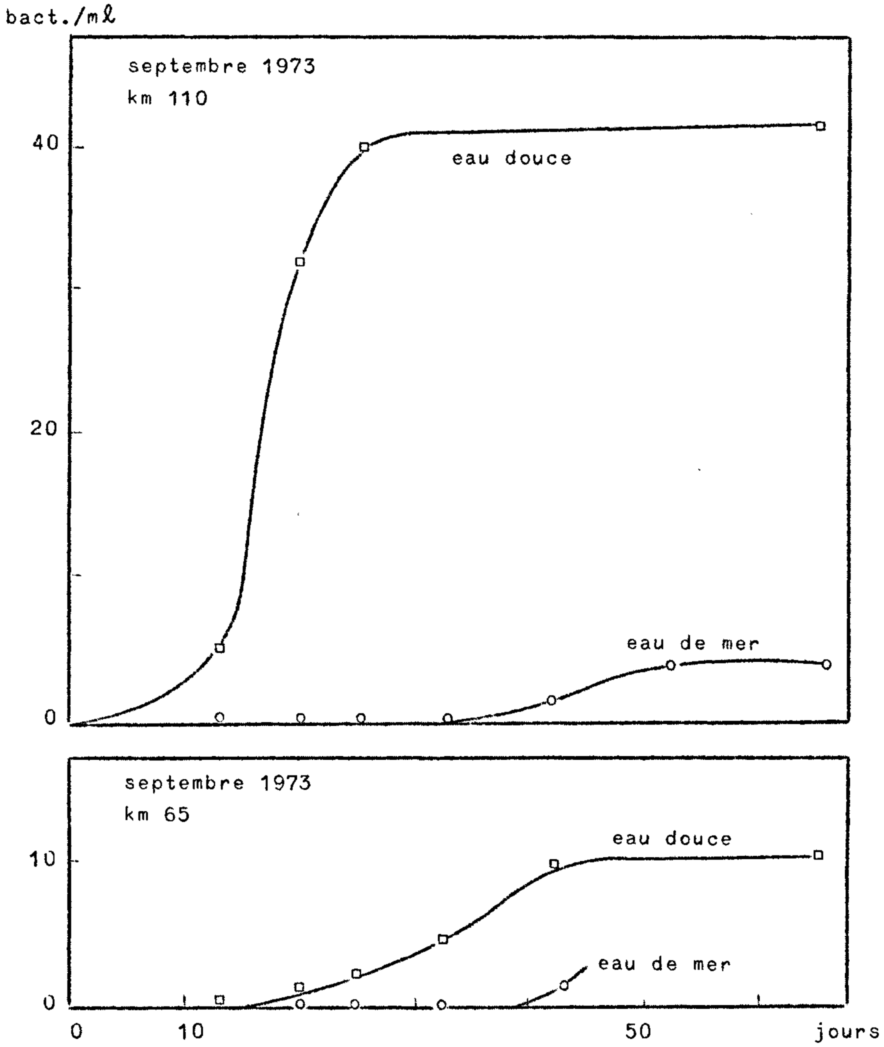

fig. 4.15.- Cinétique de croissance des bactéries nitrifiantes en milieu d'eau douce (salinité 2 °/₀₀ NaCl) et d'eau de mer (33 ‰ NaCl).

avec le maximum du nombre de bactéries nitrifiantes. Les comptages effectués en milieu salin fournissent toujours des valeurs nettement plus faible et la croissance des bactéries y est plus lente (fig. 4.15). Il semble donc que la nitrification doive être attribuée principalement à la présence de bactéries d'eau douce, bien que leur nombre diminue vers l'aval à la suite de la dilution par l'eau de mer et de leur mortalité. Ces conclusions méritent toutefois d'être approfondies.

2.4.- Production de nitrate par les sédiments

En vue d'estimer le rôle des sédiments dans la production de nitrates, Billen a analysé les eaux interstitielles d'une carotte prélevée à marée haute dans la zone de nitrification et les résultats sont présentés dans la figure 4.16. Le fait que les nitrites et les nitrates disparaissent en dessous d'une profondeur de 3 cm indique que la dénitrification prédomine en dessous de ce niveau. Dans les deux premiers centimètres, la concentration de ces composés est toutefois supérieure à celle qui règne dans les eaux de surface. Il n'est toutefois pas évident que cette augmentation soit due au seul processus de nitrification puisque la couche superficielle des sédiments peut être influencée par les variations de composition de l'eau surnageante liées à la marée.

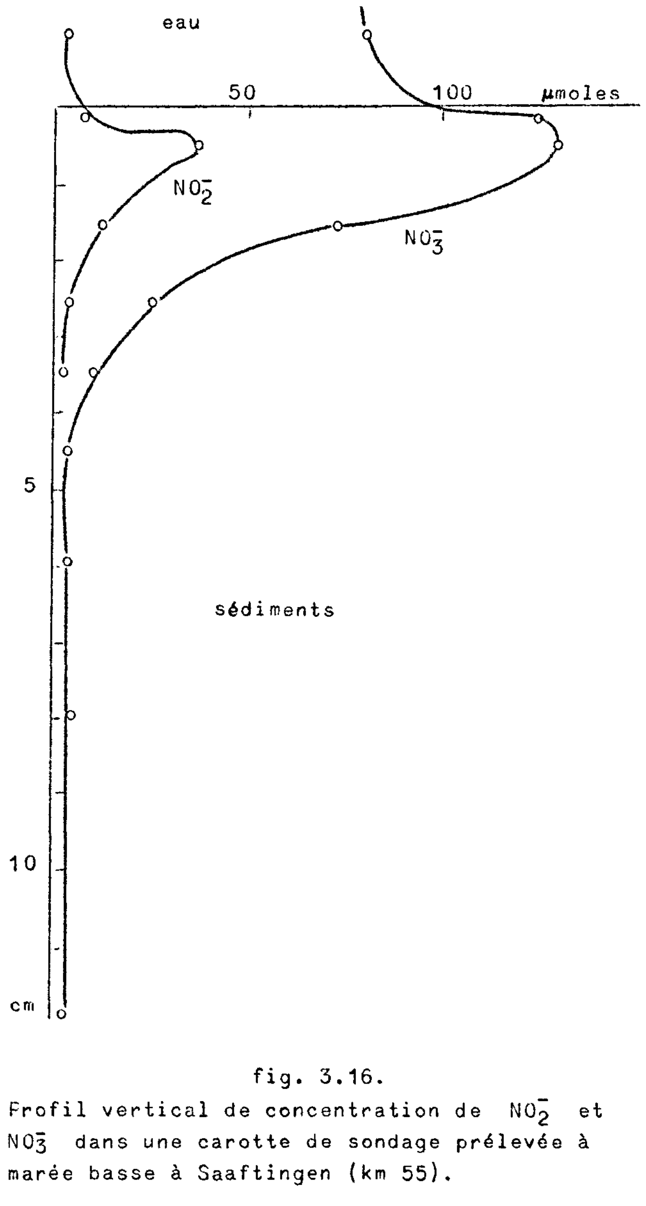

fig. 3.16.
Profil vertical de concentration de NO_2^- et NO_3^- dans une carotte de sondage prélevée à marée basse à Saaftingen (km 55).

A marée haute, ce sédiment est en effet en contact avec une eau plus riche en nitrites et nitrates et l'on peut supposer que l'excès de concentration de ces composés observé dans les eaux interstitielles correspond à un effet de mémoire de la situation antérieure. Ce phénomène fait actuellement l'objet de recherches plus approfondies.

En tout état de cause, le gradient observé à marée basse représente certainement un gradient maximum et correspond donc à un flux maximum de 0,01 µ mole/m^2 s . Cette valeur est d'un ordre de grandeur inférieur à l'augmentation en nitrate et nitrite que l'on observe dans les eaux de surface et l'on peut en conclure que la nitrification s'opère essentiellement dans les eaux de surface.

2.5.- Conclusions

Les diverses observations que nous avons décrites ci-dessus peuvent s'expliquer par le modèle suivant. La rivière transporte des germes nitrifiants d'origine terrigène vers l'estuaire. Aucune croissance de ces germes ne s'opère avant qu'ils n'atteignent la zone de nitrification où les conditions de potentiel d'oxydo-réduction sont énergétiquement favorables à leur activité métabolique. Dès que ces conditions sont réalisées, leur activité se déclenche immédiatement ainsi que le montre l'augmentation brutale de la concentration en nitrate. Cependant, la vitesse de croissance des bactéries est fortement inhibée par l'augmentation croissante de la salinité et, en conséquence, la population des bactéries nitrifiantes diminue plus rapidement par dilution à l'eau de mer qu'elle n'augmente par division. Ceci explique que la production de nitrate diminue vers l'embouchure bien que l'ammoniaque soit encore présent en quantités appréciables.

Le processus de nitrification dans l'Escaut constitue un bel exemple de situation où il n'y a pas de lien apparent entre l'activité d'une population et la densité d'un groupe de bactéries. Une telle situation est possible par suite de la facilité des micro-organismes à subsister longuement sans manifester aucune activité métabolique. Il est évident qu'il n'est pas possible dans ces conditions, de déduire l'activité d'une telle population en considérant simplement un comptage de bactéries et une mesure de concentration du substrat.

D'autre part, cette étude suggère que les modèles thermodynamiques des systèmes naturels peuvent être extrêmement utiles, non pas pour décrire l'état d'un système, mais pour prévoir la direction de l'évolution du système soumis à une influence biologique.

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Chapter V

Inventory of Water-Pollutions

by

P. HERMAN and J. BOUQUIAUX

Introduction

C.I.P.S. Inventory Group

The general inventory of the pollutions of water and sediments of the coastal area of the sea and waterways in Belgium started two years ago. The activity of the two institutions (I.H.E. and I.R.C.) entrusted with this task is carried out in the frame of the conventions established between the Ministry of Scientific politics, and the Ministry of Public Health and Environment (M22) on the one hand, and the Ministry of Agriculture (M15) on the other hand. These works are noted in the National R-D Programme on the pollution of waters organised by the C.I.P.S. : the general coordination is assumed by Professor Nihoul.

Programmes

a) Optional Subjects

First, the results have to be put in correlation with those obtained by the teams, entrusted with the elaboration of the Mathematical Model of the Sea.

Afterwards, the inventory must take into consideration the whole of the surface waters in Belgium. In this respect, the inventory has been conceived independently of the existing data, those data being generally incomplete. The samplings are made on significant locations after an identical analytical scheme on the physical, chemical, bacteriological and hydrobiological points of view. The sampling net is gradually completed together with the progress of the work.

Finally, the global studies by regions or by sector activity are carried out on the basis of the results of the inventory and other data.

b) Proceedings

The proceedings are function of the available means. The number of inventoriated locations is especially limited as the determination of about 50 parameters is bound to each of them; some of those parameters asking for very delicate analysis. Perfection of the methods and presentation of the results must equally be assumed.

About 12 locations situated along the Belgian coast and at about a few hundred meters in the sea are inventoriated several times a year. The same thing is done for coastal wastes to this area, that is : 11 channels and some sewers.

About one hundred locations of the drainage basin of the Scheldt, Meuse and Yser have been sampled twice. They are distributed in a geographical point of view and according to the sector activities : big industries, bio-industries, agriculture. Use of water is also taken into consideration if it has to be used as drinking water.

Presentation of the results

a) In general

All the results are noted on record-cards so that the data specific to the sampling of one inventoriated location are easy to find again. One double of the record-cards is left at the documentation center of the C.I.P.S. This center and the Institutions collaborating to the inventory are able to supply a copy of each card to the persons concerned.

Half-yearly and annual activity reports are established. The first synthesis report was presented at the end of 1972 during "Days of the Sea" and during the "Days of the Sambre".

b) Synthesis report of 1973

The following synthesis report refers to the state of the inventory at the end of 1973; the results obtained in 1973 are put together with those of 1972. Nevertheless, the conclusions only are printed if no new determinations have been done in 1973, and the reader is sent back to the synthesis report of 1972 for detailed results.

The presentation of the results has been altered : for each of the chapters (I, Sea and II, Rivers) gathered this time in one volume, the I.H.E. results are assembled on one side (part A — water) and the I.R.C. ones on the other side (part B — sediments).

A short and global synthesis is shown as a conclusion hereafter.

c) Study of the drainage basin of the Yser

It has been foreseen that the results should be gathered and coordinated for a well defined sectorial activity or hydrographical drainage basin. A regional study on the drainage basin of the Yser is being published.

Different reasons justify the choice of this region for carrying out a first comprehensive study :

- the case of the Yser is relatively simple. It concerns a farming area of middle importance with cattle breedings but with little industrial activities;
- the drainage basin is not much extended;
- many analytical results were known before the inventory.

PARTICIPATIONS

Institute for Hygiene and Epidemiology (study of the water)
Have participed to the study under the direction of Mr. J. Bouquiaux and Mr. De Brabander :
- physical chemistry and nutrients : Mr. J. Van Dijck and Mr. H. Vandeputte
- special determinations : Miss Ch. Boelen and Mr. E. De Wulf
- heavy metals : Mr. R. De Boeck and Mrs. J. Verhoeven
- toxicology, hydrobiology : Mrs. C. Van der Wielen, Mr. G. Vanhooren

Under the direction of Mrs. S. De Maeyer and Mr. J. Barbette

- bacteriology : Mr. J.P. Dauby and Mr. M. Duboquet

Under the direction of Mr. L. Gordts
- pesticides : Mr. A. Vandezande

Institute for Chemical Researches (study of the sediments)
Have participed to the study under the direction of Mr. P. Herman
and of Mr. R. Vanderstappen
- physic and chemistry : Mrs. K. Meeus-Verdinne and Messrs. P. Haniset, G. Istas
- spectrochemistry : Mr. J. Cornil, Mr. G. Ledent, Mr. R. Vanderzeyp

and of Mr. G. Neirinckx
- hydrocarbons : Mr. P. Heimes, Mr. H. Stuelens

and of Mr. Th. Jacobs
- physical chemistry : Mr. R. Van Cauter.

Mr. M. Bultinck, manager Engineer (T.M.Z.A.K.) has been kind enough to assume the sampling of the Blankenberge sewers. The sampling of the sea has been carried out thanks to the collaboration of Mr. Van Cauwenberghe (manager Hydrographical service of the belgian coast). We thank them deeply.

Redaction of the present report :
- waters : Miss Ch. Boelen, Mr. J. Barbette and Mr. G. Vanhooren
- sediments : Mrs. K. Meeus-Verdinne.

RECORD CARDS

List of the numbers of cards for each watercourse - C1 to C305 (beginning of the inventory - end 1973)

Berwinne	C158	Mer	C11 to 22, 28 to 39, 54 to 65, 119 to 130, 169 to 180, 208 to 211
Bocq	C91		
Brugge-Zeebrugge kanaal	C81,221		
Dender	C43		
Dijle	C270 to 288	Marche-en-Famenne (ruisseau de -)	C303 to 305
Egouts de Blankenberge	C66 to 72, 110 to 116, 200 to 207, 262 to 268	Meuse	A to H, C8 to 10, 84 to 109, 153 to 159, 212 to 224, 260, 261, 289, 290
Egouts de Nieuwpoort	C40		
Espierres	C51, 233, 234		
Grote Gete	C23 to 27	Molignée	C89
Hand samenvaart	C150	Noortdevaart	C78, 218
Haringebeek	C143	Oostende-Brugge kanaal	C79, 219
Heidebeek	C139, 140	Ourthe	C106, 107, 167, 168, 232
Hoëgne	C164, 229		
Hoyoux	C101	Plassendaalkanaal	C73, 213
Ieperlee	C147	Port de Nieuwpoort	C76, 216
Julienne	C157	Port d'Oostende	C77, 217
Laclaireau	C257	Rebais	C132
Leie	C47	Rulles	C254 to 256
Lesse	C86	Rupel	C45
Lovaart	C146	Sambre	C94
Membrette	C137	Samson	C96
Mehaigne	C99, 235 to 240	Schelde	C41 to 53, 291 to 302

Schipdonkkanaal	C82, 222
Semois	C1 to 7, 131 to 138
Spuikom de Blankenberge	C117, 118, 269
Ton	C258, 259
Vaart de Blankenberge	C80, 220
Vesdre	C105, 160 to 166, 225 to 231
Veurnekanaal	C75, 215
Vierre	C5
Vresse (ruisseau de -)	C135
Yser	C74, 141 to 152, 181 to 199, 214, 241 to 253
Zelzatekanaal	C83, 223

1.- Sea results

1.1.- Waters (I.H.E.)

The coastal zone has been inventoriated from the point of view "emission of the pollutants to the sea" as well as "pollution of the sea itself".

Where emissions are concerned, our analysis refers to samples taken in different coastal fairways as well as in the Blankenberge sewers. The fairways (11 samples) have been inventoriated in 1972 and 1973. The results of the chemical analysis agree remarkably; the bacteriological ones vary a little more from one year to another. Nevertheless, the chemical, bacteriological and hydrobiological analysis have given the same picture of these fairways, that is, a high grade of pollution at Oostende in front of the station, in the Noortedevaart channel, the Blankenberge channel and the Schipdonk channel; a situation of a scarcely less pollution in the Oostende-Brugge channel and a middle pollution level in the Zelzate channel and the three Nieuwpoort channels : Yser, Veurne and Plassendael channels.

Our analysis of the sewers are divided into four sampling campaigns which took place during 1972 and 1973; twice in winter, in February and twice in summer, in July. As could be expected for sewage water, the level of organic and faecal pollution is very high. A slight increase of pollution during the summer can be detected, but, the sewer flow being twice as high during this period, the situation is clearly less favorable where emission to the sea is concerned.

We have arranged five sampling campaigns of seawater samples situated 200 m in front of the line of low tide all along the coast.

Table 5.1

WATERS

Sewers of Blankenberge

		Winter						Summer					
		1972			1973			1972			1973		
		Min	Max	$\overline{X}$	Min	Max	$\overline{X}$	Min	Max	$\overline{X}$	Min	Max	$\overline{X}$
BOD	mg/ℓ	125	250	199	28	49	37	250	500	426	47.5	412	252
COD	mg/ℓ	140	296	230	310	473	368	500	896	758	444	940	548
MS	mg/ℓ	-	-	-	110	190	153	180	300	256	20	430	187
N_{tot}	mg/ℓ	43.1	54.6	50.2	14.2	14.6	14.5	80	112	103	14.8	17.6	17.1
N_{amm}	mg/ℓ	27.7	38.6	32.4	14.2	14.6	14.5	51	85	73	14.8	17.6	17.1
NO_2^-	mg/ℓ	-	-	-	-	-	-	-	-	-	0	0	0
NO_3^-	mg/ℓ	4.7	10.4	7.4	0	0	0	0	24	7.3	0.02	0.13	0.07
PO_4^{---}	mg/ℓ	3.55	4.2	3.8	12.7	15.3	14.1	61.8	117.4	91.8	17.2	17.5	17.4
F^-	mg/ℓ	0.31	0.61	0.41	0.55	0.66	0.59	0.48	0.75	0.53	0.39	0.84	0.55
Cl^-	mg/ℓ	1760	2160	2020	2500	3100		1060	1270	1110	1030	1210	1092
SO_4^{--}	mg/ℓ	326	396	372	302	458	410	205	298	232	195	323	272
Dét.	mg/ℓ	11.2	28.7	18.6	32.5	55	46.7	33	68	50	7.4	20.0	13.1
EH	mV	+ 24	+ 194	+ 90	- 36	+ 74	+ 12	- 56	- 20	- 38	- 111	- 61	- 89
Ag	ppb	-	-	-	-	-	-	< 5	< 5	< 5	< 0.8	12.5	< 4.5
Cd	ppb	-	-	-	< 2	< 2	< 2	< 10	< 10	< 10	< 1	1.4	< 1
Co	ppb	< 5	< 5	< 5	< 10	< 10	< 10	< 5	< 5	< 5	< 2	< 2	< 2
Cr	ppb	< 5	< 5	< 5	18	105	80	< 5	< 5	< 5	< 4	< 4	< 4
Cu	ppb	8	22	17	21	35	26	26	36	30	2	17	7.1
Fe	ppb	135	190	146	28	196	109	210	380	290	680	1210	927
Hg	ppb	0.59	7.8	1.87	0.15	0.29		0.23	13.5	2.58	-	-	-
Mn	ppb	102	155	129	< 10	443	132	30	92	61	80	100	85
Ni	ppb	< 5	< 5	< 5	4.1	7.5	5.7	16	32	22	< 2	< 2	< 2
Pb	ppb	13	20	17	43	163	105	58	100	80	9.3	14	11.5
Zn	ppb	-	-	-	38	1925	472	48	80	73	111	195	146
Output	m^3/h	116.5	133.3	121.7	126.4	149.5	135.2	196.2	211.5	202.3	181.5	226.3	211.4

Table 5.2

WATERS

Sea

		Number	Min	Max	$\overline{X}$
O_2	%	52	57.5	95.8	76.9
BOD	mg/ℓ	60	0.9	8.7	3.3
COD	mg/ℓ	60	1.6	9.5	4.7
MS	mg/ℓ	60	75	980	40.6
N_{tot}	mg/ℓ	60	0	4.15	1.65
NO_2^-	mg/ℓ	56	0	0.096	0.036
NO_3^-	mg/ℓ	56	0	11.9	3.59
PO_4^{---}	mg/ℓ	58	0	5.1	0.383
F^-	mg/ℓ	60	1.2	5.0	2.28
Cd	ppb	24	1	6	3.2
Co	ppb	60	inferior to the detection limit		
Cr	ppb	60	inferior to the detection limit		
Cu	ppb	59	4	32	14
Fe	ppb	60	8.5	360	149.7
Hg	ppb	46	0.03	0.76	0.16
Mn	ppb	60	5	270	73
Ni	ppb	60	inferior to the detection limit		
Pb	ppb	59	5	58	19
Zn	ppb	56	5	88	36

The twelve sampling stations are disposed from Oostduinkerke to Knokke. The pollution level doesn't change much from one month to another.

The last series of analysis have been set up for TOC determination. The results of the latter confirm our previous belief; that is : the pollution level is higher North-East from Oostende than on the South-West coast and shows a slight increase from Heist onward.

Table 5.3

WATERS

The fairways and the channels

	O_2 %	COD mg/ℓ	BOD mg/ℓ	MS mg/ℓ	N_{tot} mg/ℓ	N_{amm} mg/ℓ	NO_2^- mg/ℓ	NO_3^- mg/ℓ	PO_4^{---} mg/ℓ	F^- mg/ℓ	Cl^- mg/ℓ	SO_4^{--} mg/ℓ
Plassendael	97	86	7.8	40	1.0	0	+	4.7	0.4	1.12	3800	554
	107	35	6.9	40	2.62	0	32.1	0.32	0.56		9800	260
Yser	46.7	59	5.2	35	6.4	2.4	+	3.6	1.1	0.47	152	158
	98.3	39	12.5	80	6.4	1.56	192	1.47	0.47		784	250
Veurne	77.8	86	5.5	40	0.83	0	+	1.94	0.95	1.11	4300	636
	167	86	12.6	110	3.62	0	2.8	0.48	0.19		3680	581
Nieuwpoort-Haven	63.4	129	1.8	220	1.4	0	+	0	0.25	1.33	16500	1902
	94	490	4.0	150	2.76	0.6	1.22	0.19	0.59		15600	972
Oostende	25.9	122	6.8	130	10.8	6.5	0	0	6.25	1.17	9800	1210
	60	796	10.5	380	12.2	3.4	0.05	5.41	10.56		13200	795
Noortede vaart	75.9	141	15.2	85	5.9	2.0	+	0	7.50	1.47	9600	408
	68.3	169	12.3	40	9.04	3.29	0.5	5.12	11.80		5300	758
Brugge kanaal	5.0	67	7.6	30	12.4	8.7	0	0	8.50	0.76	700	196
	14.1	63	0.3	130	12.1	8.1	2.35	8.96	15.84		1520	324
Blankenberge vaart	54.6	133	10	80	4.5	1.0	+	0	4.20	1.66	5550	718
	113.1	204	21.4	200	9.3	3.01	1.43	0.45	6.56		5700	744
Zeebrugge kanaal	138.2	204	7.6	180	1.5	0.0	+	0	0.40	2.50	14300	1846
	75.8	611	8.7	250	4.4	1.63	5.41	0.80	0.61		14800	981
Schipdonk	11.7	67	6	35	14.2	9.7	0	1.8	8.50	0.78	216	146
	60	86	9.7	40	10.7	5.6	0.10	1.18	5.76		800	214
Zelzate	101.2	141	16.2	45	8.2	4.6	+	0	7.00	1.37	4300	472
	66.6	584	10.3	340	11.06	7.5	1.33	0.42	1.41		11900	974

These conclusions can be drawn from all our chemical and bacteriological results.

As a conclusion, it can be said that many discharge outlets with a high level in pollutants can be found on the Belgian coast, the action of those pollutants on the pollution state of the coastal waters, being clearly marked.

Table 5.3

(continuation)

WATERS

The fairways and the channels

	Det. mg/ℓ	CN^- mg/ℓ	Ø OH* mg/ℓ	Ag ppb	Cd ppb	Co ppb	Cr ppb	Cu ppb	Fe ppb	Hg ppb	Mn ppb	Pb ppb	Zn ppb
Plassendael	0	0	0	-	-	< 5	< 5	9	69	0.5	40	10	50
	0	0	0.02	< 5	< 1	< 5	< 5	10	25	0.13	80	9	22
Yser	0	0	0	-	-	< 5	< 5	< 5	76	0.2	158	< 5	44
	8	0	0	< 5	< 1	< 5	< 5	8	37	0.3	245	6	21
Veurne	0	0	0	-	-	< 5	< 5	< 5	30	0.65	62	7	41
	2.2	0	0	< 5	< 1	< 5	< 5	8	45	0.15	200	9	23
Nieuwpoort-Haven	0	0	0	-	-	< 5	< 5	6	200	0.45	59	10	44
	0	0	0	< 5	< 1	< 5	< 5	10	46	0.05	95	9	29
Oostende	0	0	0.01	-	-	< 5	< 5	7	193	0.1	135	8	46
	0.9	0	0	< 5	< 1	< 5	< 5	115	37	0.05	125	11	32
Noortede vaart	0	0	0	-	-	< 5	< 6	< 5	55	0.15	145	7	35
	0	0	0	< 5	< 1	< 5	< 5	21	22	< 0.05	155	15	24
Brugge kanaal	0	0	0.095	-	-	< 5	< 5	< 5	160	0.05	206	12	39
	0	0	0	< 5	< 1	< 5	< 5	41	50	< 0.05	280	15	34
Blankenberge vaart	0	0	0	-	-	< 5	< 5	7	69	0.3	118	8	40
	0.5	0	0	< 5	< 1	< 5	< 5	11	25	< 0.05	190	9	32
Zeebrugge kanaal	0	0	0	-	-	< 5	< 5	5	132	0.5	113	10	39
	0	0	0	< 5	< 1	< 5	< 5	8	175	< 0.05	220	9	37
Schipdonk	0	0	0.40	-	-	< 5	< 5	6	102	9.4	255	7	42
	0	0	0.02	< 5	< 1	< 5	< 5	10	58	0.07	345	11	39
Zelzate	0	0	0	-	-	< 5	< 5	6	71	0.1	174	8	38
	0.5	0	0	< 5	< 1	< 5	< 5	8	45	0.62	1050	6	35

* Ø OH = phenols.

1.2.- Sediments - Suspended matters (I.R.C.)

1.2.1.- Emission

Suspended matters and sewer sludges can be considered as being particularly polluted, in Blankenberge and in Nieuwpoort, regarding Ag, Ba and Bi as well as Cu, Zn, Pb and Sn. The pollution of water seems to be especially important. Pollution due to fairways and channels discharging into the sea, may seem of little importance compared to the

Table 5.4

SUSPENDED MATTERS

Sewers

Chemistry		Blankenberge			Nieuwpoort
		Winter 1972 $\bar{X}$ 7 samples	Summer 1972 $\bar{X}$ 7 samples	Winter 1973 $\bar{X}$ 7 samples	Winter 1972 1 sample
P/F 110-550 °C	%	40.3	-	-	77.9
P_2O_5	%	0.7	8.3	-	1.8
Ag	ppm	> 175	> 32	> 26	24
Ba	ppm	2150	920	840	1300
Bi	ppm	610	790	150	40
Cr	ppm	68	30	16	24
Cu	ppm	150	> 65	> 120	308
Ga	ppm	1	0.5	< limit	0.6
Mn	ppm	82	160	6	168
Mo	ppm	< limit	7	5	2
Ni	ppm	9	15	4	10
Pb	ppm	800	770	37	136
Sn	ppm	66	96	36	75
Sr	ppm	-	490	103	110
V	ppm	12	12	5	9
Zn	ppm	4860	4120	132	2500
Zr	ppm	35	34	15	< limit

Be, Cd, Co, Ge, In, Li, Sb, Tl : < detection limit.

Table 5.5

Sludges of the sewers of Blankenberge

Chemistry		Pumping station				Spuikom			Sea Sed.[1]
		Winter 72	Summer 72	Winter 73		Summer 72		Winter 73	5 samples
					[2]	[3]	[4]	[4]	
< 37 μ	%	-	18.7	17	11.2	55.6	91.8	74.5	83.8
P/F 110 - 550 °C	%	-	0.43	0.48	1.52	6.04	8.1	0.7	8.5
P/F 550-1000 °C	%	-	3.22	2.6	2.14	8.2	9.43	4.2	9.3
Org. M.	%	5.5	2.2	6.03	3.14	5.3	6	6	3.56
Al_2O_3	%	3	2.3	3.05	2.48	5.37	10.5	7.87	8
Fe_2O_3	%	1.45	0.86	0.95	1.1	1.83	4.53	2.57	3.13
TiO_2	%	0.2	0.12	0.14	0.12	0.25	0.61	0.4	0.46
P_2O_5	%	0.8	0.91	-	-	-	-	-	-
CaO	%	5.4	1.82	4.62	2.47	6.4	13.51	10	14.2
MgO	%	0.25	0.17	-	-	1.16	1.76	-	1.52
K_2O	%	0.8	0.81	0.77	0.74	1.32	2.25	1.6	1.68
S_{tot}	%	1.16	1.01	1.7	1.3	0.92	1.53	1	0.64
Cl	%	< 0.01	< 0.01	0.03	< 0.01	0.25	0.25	0.14	0.19
Ag	ppm	> 40	> 10	> 16	> 12	20	2	0.5	2
Ba	ppm	1430	410	560	430	170	< limit	70	130
Bi	ppm	48	8	33	32	5	< limit	< limit	< limit
Co	ppm	3	1	1	1	15	4	3	5
Cr	ppm	41	11	11	8	34	130	36	77
Cu	ppm	79	> 22	> 64	> 50	48	35	14	31
Ga	ppm	1.5	0.5	3	3	2	4	7	8
Hg	ppm	0.13	0.02	0.42	0.12	0.33	0.71	0.73	0.52
Mn	ppm	230	110	160	120	210	660	430	860
Ni	ppm	27	7	5	12	11	28	12	20
Pb	ppm	320	87	56	110	55	76	35	125
Sn	ppm	50	16	31	36	7	8	1	12
Si	ppm	130	60	118	18	175	300	260	380
V	ppm	14	6	8	6	32	100	49	58
Zn	ppm	6000	1465	1285	1310	475	265	110	190
Zr	ppm	90	58	60	38	120	110	250	230

Be , Cd , Ge , In , Li , Mo , Tl , W : < detection limit.

[1] off Blankenberge.

[2] after grinding the waste.

[3] at the overflowing mouth of the sewer.

[4] the opposite side of this mouth.

Table 5.6

SEDIMENTS

Fairways (1972 and 1973)

First part

Chemistry		Nieuwpoort				Oostende		
		Channel Plassendael 1 s.	Channel Yser 1 s.	Channel Veurne 1 s.	Fairway 2 s.	Channel Noord Ede 1 s.	Ch. Brugge-Oostende 2 s.	Fairway 2 s.
Al_2O_3	%	5.87	5.9	5.07	6.05	9.5	7	9.25
Fe_2O_3	%	1.62	1.95	1.48	2.2	4.25	3.72	3.48
TiO_2	%	0.25	0.28	0.26	0.30	0.5	0.4	0.47
CaO	%	7.2	9.55	10.75	7.62	11.6	4.8	16
MgO	%	-	-	-	-	-	1.21	1.4
K_2O	%	1.25	1.56	1.35	1.33	1.67	1.40	1.51
S_{tot}	%	0.06	0.1	0.44	0.52	3.49	2.22	0.68
Cl	%	< 0.01	< 0.01	< 0.01	0.15	0.22	< 0.01	0.21
Ag	ppm	1	0.5	< limit	< limit	103	1	< limit
Ba	ppm	< limit	< limit	< limit	< limit	< limit	340	< limit
Co	ppm	3	10	3	4	4	8	4
Cr	ppm	50	54	23	43	31	90	66
Cu	ppm	130	190	6	26	66	130	36
Ga	ppm	3	2	3	4	2	4	4
Hg	ppm	0.02	0.08	0.01	0.55	0.35	0.05	0.31
Mn	ppm	150	700	300	410	320	390	455
Ni	ppm	14	43	12	18	16	28	19
Pb	ppm	100	200	17	46	90	100	53
Sn	ppm	7	12	< limit	< limit	8	7	3
Sr	ppm	140	185	295	380	220	110	335
V	ppm	43	72	56	47	47	53	69
Zn	ppm	45	86	60	105	614	650	195
Zr	ppm	48	150	199	180	150	140	250
Crude	$\frac{m\ell}{100g}$	0.003	0.004	0.002	0.06	0.074	0.25	0.01

Be , Bi , Cd , Ge , In , Mo , Sb , Tl : < detection limit.

Table 5.6

SEDIMENTS

Fairways (1972 and 1973)

Second part

Chemistry		Blankenberge	Zeebrugge	Heist	Locations of the maxima
		2 s.	1 s.	Channel Schipdonk 2 s.	
Al_2O_3	%	10.6	4.66	7.98	Ch. Blankenberge
Fe_2O_3	%	3.8	1.6	3.7	Ch. Noord Ede
TiO_2	%	0.63	0.24	0.55	Ch. Blankenberge
CaO	%	4.3	3.72	4.53	Ch. Noord Ede
MgO	%	1.65	-	0.8	-
K_2O	%	1.97	1.05	1.72	Ch. Blankenberge
S_{tot}	%	0.19	0.65	0.7	Ch. Noord Ede
Cl	%	0.03	0.1	0.01	Ch. Noord Ede
Ag	ppm	< limit	< limit	1	Ch. Noord Ede
Ba	ppm	250	< limit	270	Ch. Brugge-Oost.
Co	ppm	8	4	6	Ch. Yser
Cr	ppm	85	45	130	Ch. Schipdonk
Cu	ppm	12	150	87	Ch. Yser
Ga	ppm	12	3	3	Ch. Blankenberge
Hg	ppm	0.17	0.2	0.43	F. Nieuwpoort
Mn	ppm	285	240	300	Ch. Yser
Ni	ppm	31	12	32	Ch. Yser
Pb	ppm	53	160	140	Ch. Yser
Sn	ppm	< limit	9	10	Ch. Yser
Sr	ppm	115	75	100	F. Nieuwpoort
V	ppm	76	34	32	Ch. Blankenberge
Zn	ppm	95	275	960	Ch. Schipdonk
Zr	ppm	305	260	430	Ch. Schipdonk
Crude	$\frac{m\ell}{100g}$	0.007	0.028	0.27	Ch. Schipdonk

Table 5.7

SEDIMENTS

Coastal zone (immixtion)

(5 campaigns 1971 to 1973)

Chemistry		Number	Min	Max	$\bar{X}$	Observations
< 37 μ	%	54	0	92	48.8	
P/F 110 - 550 °C	%	54	0.21	15.41	4.81	
P/F 550-1000 °C	%	54	1.44	16.95	7.61	
Org.M.($K_2Cr_2O_7$)	%	54	0.04	5.8	2.37	
Al_2O_3	%	54	2.28	10.83	6.03	
Fe_2O_3	%	54	0.53	3.96	2.16	
TiO_2	%	54	0.05	0.55	0.30	
P_2O_5	%	3	0.07	0.30	0.17	
CaO	%	54	3.61	16.41	10.60	
MgO	%	54	0.14	2.15	0.97	
K_2O	%	54	0.85	1.97	1.40	
Na_2O	%	3	1.03	2.24	1.51	
S_{tot}	%	54	0.02	1.27	0.5	
Cl^-	%	54	0.01	0.25	0.14	
Ag	ppm	54	< limit	2	0.7	$\bar{X}$ on 17 samples, 37 samples < limit
Ba	ppm	7	56	140	110	$\bar{X}$ on 7 samples (aug. 1972)
Bi	ppm	54	< limit	16	10	$\bar{X}$ on 2 samples, 52 samples < limit
Co	ppm	54	0.3	14	3	
Cr	ppm	54	4	120	47	
Cu	ppm	54	0.6	58	16	
Ga	ppm	54	0.8	22	7	
Ge	ppm	54	0.7 !	8	3 !!	$\bar{X}$ on 20 samples, 34 samples < limit
Hg	ppm	54	0.01	1.24	0.31	
Mn	ppm	54	70	1488	556	
Ni	ppm	54	0.4	27	12	
Pb	ppm	54	10	280	88	
Sn	ppm	54	0.3	18	8	
Sr	ppm	54	115	660	301	
V	ppm	54	0.8	105	32	
Zn	ppm	54	15	271	120	
Zr	ppm	54	33	370	180	
Crude	$\frac{m\ell}{100g}$	30	< limit	0.22	0.10	$\bar{X}$ on 9 samples, 13 samples < limit

pollution of waterways, but when compared to the amounts of marine sediments, very high figures can be observed in S_{tot} , Ag , Cu as well as important amounts in Hg , Pb , Zn and hydrocarbons in some of these emettors. Other channels are less polluted, like the Blankenberge, Veurne and Plassendael channels.

1.2.2.- Immixtion

Sediments sampled in the sea offer a very interesting characteristic : their amounts of elements, pollutants or not, are very closely bound to their content in fine particles. By analysis of the granulometry of the samples, it has been possible to classify them in sands and clays by means of a triangular diagram, ordinarily used for soils.

Each of these categories contains well distinct amounts from those of the other category, for all determined elements : in sands, low amounts; in clays : more important amounts. On about 1000 analysis, only 1 % of the amounts has been recorded as being either too high in sands, or too low in clays. Once this distinction established, a mere graphic, giving in ordinate the contents in fine particles of the 54 samples taken in the sea, and in abcissa, the locations of the samples, has been enough to obtain a localization of the sludges and of the pollution. Working that way, it has been possible to notice that all samples taken in Blankenberge, Wenduine, Knokke and particularly in Oostende have a fine granulometry and that these places are consequently more polluted. On the other hand, all the samples taken in Oostduinkerke are of coarse granulometry and the pollution of this place is very low.

If a sub-marine map of the sludges could be established, we should have a better idea of the belgian coast pollution.

Sand samples have also been taken on beaches at low tide, their amounts agree very well with those of the sediments taken in open sea : they are very coarse sands with no pollution.

The pollution degree of sediments of the coastal zone is higher than that of sediments taken in open sea (*cf. Rapport de synthèse, II)* about twice for Hg , five times for Mn , six times for Zn and eight times for Pb as an average. For copper and chromium, the opposite can be observed, there is twice more copper and chromium in open sea.

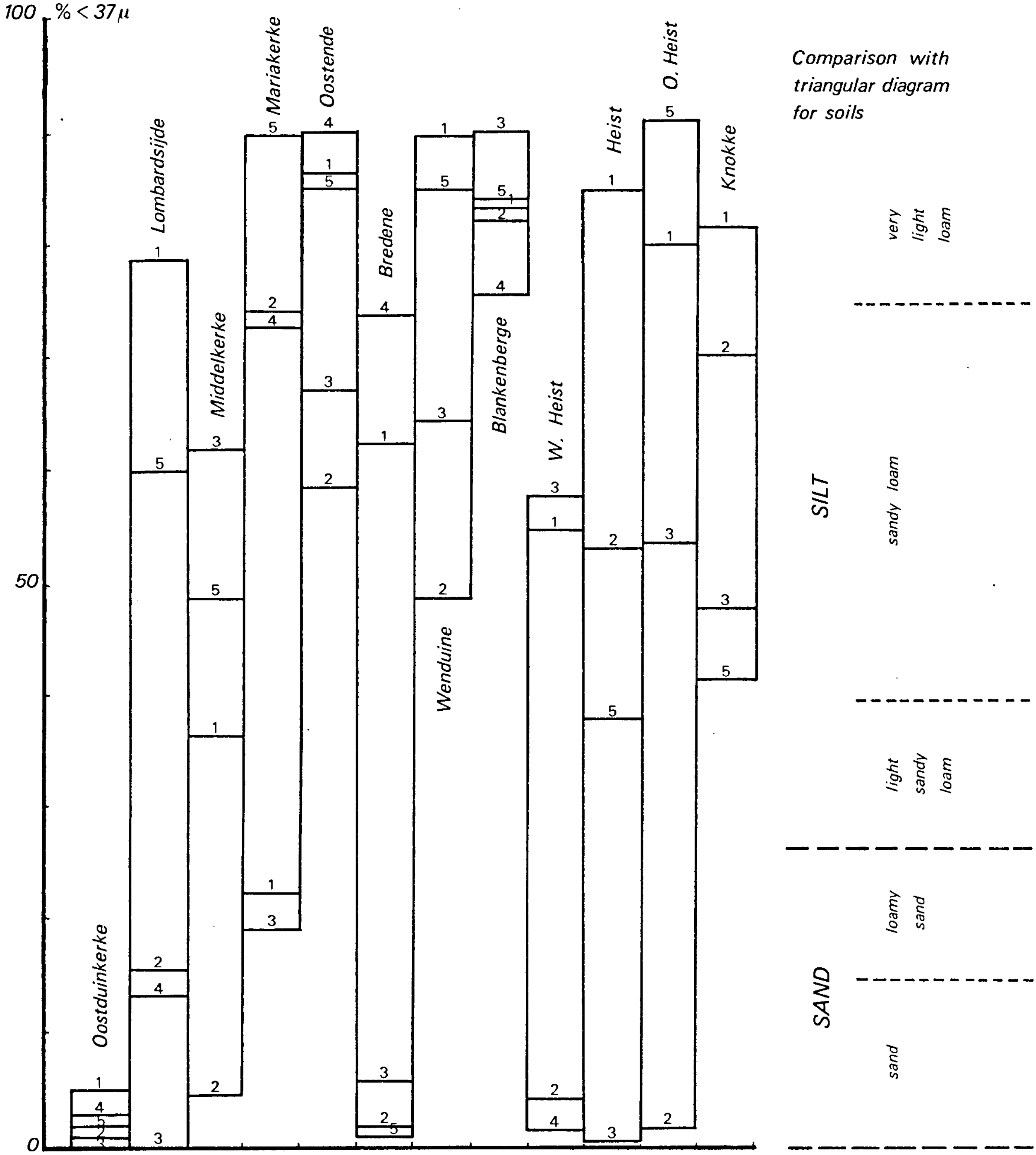

fig. 5.1.- Proportion of fine particles (< 37 μ) in sea sediments. Dates of the campaigns : 1 , 29-9-71 ; 2 , 30-11-71 ; 3 , 3-2-72 ; 4 , 1-8-72 ; 5 , 11-1-73 .

Table 5.8

SEDIMENTS

Coastal area of the sea
Comparison of the sediments classified according to their granulometry
(5 campaigns, 1971 to 1973)

		Sand				Silt				Observations
		n	Min	Max	$\bar{X}$	n	Min	Max	$\bar{X}$	
Al_2O_3	%	18	2.3	4.5	1.2	34	5.7	10.8	7.73	2 samples silt : 3.16 and 3.9
Fe_2O_3	%	18	0.53	1.35	0.74	36	1.45	3.96	2.85	
TiO_2	%	18	0.05	0.22	0.11	36	0.25	0.55	0.4	
CaO	%	18	3.61	8.96	5.53	36	9	16.41	12.74	
MgO	%	18	0.14	0.65	0.29	36	0.8	2.14	1.32	
K_2O	%	18	0.85	1.25	1.04	36	1.02	2	1.59	
	%	17	0.02	0.32	0.11	36	0.38	1.27	0.89	1 sample sand : 0.48
Co	ppm	18	0.3	2	1	36	2	14	4	
Cr	ppm	18	4	23	13	36	32	120	58	
Cu	ppm	18	0.6	10	3	36	4	58	23	
Ga	ppm	17	0.8	3	2	36	3	22	9	1 sample sand : 12
Hg	ppm	16	0.01	0.2	0.08	36	0.1	1.24	0.52	2 samples sand 0.38 and 0.44
Mn	ppm	18	70	330	136	36	340	1500	747	
Ni	ppm	17	0.4	7	4	36	8	27	17	1 sample sand : 15
Pb	ppm	17	10	39	24	36	40	280	122	1 sample sand : 59
Sn	ppm	16	0.3	4	2	36	4	18	10	2 samples sand : 16 and 7
Sr	ppm	17	115	220	147	36	223	660	382	1 sample sand : 240
V	ppm	18	0.8	17	7	36	17	105	44	
Zn	ppm	16	15	61	38	35	60	271	166	2 samples sand : 178 and 217 1 sample silt : 36
Zr	ppm	18	33	270	135	36	88	370	203	

On the other hand, no development of sea sediments pollution has been observed since 1971.

2.- River results

2.1.- Basin of the Meuse

Table 5.9

WATERS

Meuse - French border

		5-6-72	6-4-73	17-7-73	26-9-73
O_2	%	99.8	105.3	102.3	97.6
COD	mg/ℓ	15	12	8	16
BOD	mg/ℓ	5.1	7.5	2.5	2.5
MS	mg/ℓ	10	10	10	10
N_{tot}	mg/ℓ	2.46	2.76	1.76	4.6
N_{amm}	mg/ℓ	0	0.05	0.05	0.06
NO_2^-	mg/ℓ	neg.	0.06	0.03	0.014
NO_3^-	mg/ℓ	6.24	6.93	2.8	1.29
PO_4^{---}	mg/ℓ	0.27	0.33	0.42	0.39
F^-	mg/ℓ	0.36	0.039	0.063	0.45
Cl^-	mg/ℓ	14	16	18	20
SO_4^{--}	mg/ℓ	36	38	38	44
Det.	mg/ℓ	0	0	0.3	0
CN^-	mg/ℓ	0	0	0	0
Ø OH	mg/ℓ	0	0	0	0
Ag	ppb	< 0.05	< 0.8	< 0.8	
Cd	ppb	5.5	± 1	< 1	
Co	ppb	3	< 2	< 2	
Cr	ppb	2.6	< 4	< 4	
Cu	ppb	13	9	9.5	
Fe	ppb	112	360	150	
Hg	ppb	0.09	0.18	0.32	
Mn	ppb	34	117	90	
Ni	ppb	25	< 2	< 2	
Pb	ppb	7	13.5	4.5	
Zn	ppb	170	165	50	

Table 5.10

WATERS

Meuse - Liège

		Flémalle-Haute		Liège		Herstal	
		27-4-72	19-9-72	24-4-72	19-9-72	24-4-72	19-9-72
O_2	%	94.3	84.4	88.1	71.9	87.0	68.0
COD	mg/ℓ	8	4	8	8	4	8
BOD	mg/ℓ	4.8	2.7	4.5	6.8	6.4	9.2
MS	mg/ℓ	15	15	55	40	25	25
N_{tot}	mg/ℓ	1.62	1.23	2.14	1.65	3.14	0.2
N_{amm}	mg/ℓ	0	0	0.22	0	0	0.06
NO_2^-	mg/ℓ	neg.	0.09	neg.	0.09	neg.	0
NO_3^-	mg/ℓ	8.40	1.17	4.80	1.17	9.48	3.46
PO_4^{---}	mg/ℓ	0.28	5.02	0.46	4.5	0.54	1.0
F^-	mg/ℓ	1.43	1.42	1.37	1.53	0.99	1.66
Cl^-	mg/ℓ	3.6	46	34	36	36	32
SO_4^{--}	mg/ℓ	59	72	46	68	47	64
Det.	mg/ℓ	0	0.7	0	0.7	0	0.7
CN^-	mg/ℓ	0	0	0	0	0	0
Ø OH	mg/ℓ	0	0	0	0.1	0.03	0
Cd	ppb	11.0	9	11.1	12.1	8.7	10
Co	ppb	< 2	-	4	-	< 2	-
Cr	ppb	3.6	< 2	2	6	6	11
Cu	ppb	25	7	25	8	28	11
Fe	ppb	158	255	312	875	752	552
Hg	ppb	0.14	0.65	0.13	0.53	0.12	0.35
Mn	ppb	74	136	123	223	136	223
Ni	ppb	43	10	17	8	± 10	8
Pb	ppb	4	20	11	73	5	48
Zn	ppb	210	538	355	469	255	398

2.1.1.- Waters

A detailed study of the Meuse and of each of its affluents at the confluence point has been thoroughly studied by a serie of samplings

Table 5.11

WATERS

Meuse - Netherlands border

		19-9-72	14-3-73	19-7-73	13-9-73
O_2	%	79.7	92.6	65.5	85.7
COD	mg/ℓ	4	7	4	19
BOD	mg/ℓ	12.5	6.8	4.6	7
MS	mg/ℓ	15	10	10	10
N_{tot}	mg/ℓ	0.03	2.89	4.08	
N_{amm}	mg/ℓ	0.03	0.74	1.78	2.5
NO_2^-	mg/ℓ	0	0.14	0.48	0.29
NO_3^-	mg/ℓ	3.9	2.36	7.80	5.1
PO_4^{---}	mg/ℓ	0.7	1.1	5.6	
F^-	mg/ℓ	0.45	1.36	0.012	0.2
Cl^-	mg/ℓ	32	38	74	90
SO_4^{--}	mg/ℓ	32	57	82	90
Det.	mg/ℓ	1.3	1.5	0.4	0.6
CN^-	mg/ℓ	0	0	0	0
Ø OH	mg/ℓ	0	0	0	0
Ag	ppb	-	-	< 0.8	
Cd	ppb	19.2	< 2	1.7	
Co	ppb	-	< 2	< 2	
Cr	ppb	19.2	< 4	< 4	
Cu	ppb	11.7	47	10	
Fe	ppb	617	18	320	400
Hg	ppb	0.29	-	0.41	0.13
Mn	ppb	155	102	100	77
Ni	ppb	< 5	5	< 2	
Pb	ppb	30	90	10	
Zn	ppb	434	501	200	

made on each border and in the area of Liège. The division of the river Meuse in three zones, from the french border to above Liège, Liège, and from Liège to the Netherlands border meets a physical reality.

As a matter of fact, the hydrobiological, bacteriological and chemical studies concur to say that the river Meuse is less polluted above Liège, indicates the presence of a big agglomeration and an important industrial zone in Liège, and develops towards a less pollution degree from Liège to the Netherlands border.

We have completed the study of the affluents by a serie of samplings in the Mehaigne, an agricultural river with a low chemical and bacteriological pollution level, the latter being remarkably constant along its whole course. But, as could be expected for an agricultural river, very high concentrations of pesticides are to be found, more specially lindane and its α-isomere.

The Vesdre, an other affluent has been inventoriated systematically twice. The results of the two series agree, and a positive correlation can be observed between the organic and microbiological levels, with a maximum below Verviers, a decrease as far as above the agglomeration of Liège and finally an increase in the agglomeration. On the other hand, if the hydrobiological investigation confirms an increase of pollution below Verviers, no regeneration but on the contrary a constant degradation is to be found up to Chênée. Finally, a high contamination due to lindane has been found all along the Vesdre and a contamination due to heavy metals, especially Cd and Pb , at Chênée.

The pollution of the Meuse at the exit of Belgium is always higher that the level at the entrance in our territory. Its affluents have usually the same pollution level as the Meuse, or at least, they have no influence on it except the Sambre and the Vesdre.

2.1.2.- Sediments

Sediments of the basin of the Meuse cannot be classified according to their granulometric characteristics, as it has been done for sediments taken in the sea in order to give an idea of their concentration in polluting or non polluting elements.

A relationship can be seen between their amount in particles $< 37\ \mu$ and the amounts in different elements in the least polluted area of the Meuse, that is above Tihange, but elsewhere a far more important accumulation of pollutants even in samples containing less fine particles can be noticed in certain points.

Table 5.12

WATERS

Laclaireau, Ton - Rulles

		Laclaireau, Ton			Rulles		
		Ethe	Dampicourt	Harnoncourt	Habay-la-Neuve	Downstream Mellier (distillery)	Upstream Semois
O_2	%	102.8	11.3	63.5	109.8	109.5	117.0
COD	mg/ℓ	4	7	42	4	11	14
BOD	mg/ℓ	5	6.1	7.2	9.4	9.9	7.9
MS	mg/ℓ	10	10	30	10	10	10
N_{tot}	mg/ℓ	0.94	1.76	4.08	1.21	1.87	1.47
N_{amm}	mg/ℓ	0.02	0.38	1.29	0.1	0.12	0.77
NO_2^-	mg/ℓ	0	0.45	0.13	0	0.06	0.06
NO_3^-	mg/ℓ	3.37	5.86	8.00	0.87	2.55	2.40
PO_4^{---}	mg/ℓ	0.14	0.85	2.58	0.74	0.51	0.41
F^-	mg/ℓ	0.06	0.76	0.10	0.09	0.11	0.07
Cl^-	mg/ℓ	6	10	170	6	8	10
SO_4^{--}	mg/ℓ	14	28	165	4	8	9
Det.	mg/ℓ	0	0.3	0	0	0	0
CN^-	mg/ℓ	0	0	0	0	0	0
Ø OH	mg/ℓ	0	0	0	0	0	0
Cd	ppb	± 1	± 1	< 1	< 1	± 1	< 1
Co	ppb	< 2	< 2	< 2	< 2	< 2	< 2
Cr	ppb	< 4	< 4	< 4	< 4	< 4	< 4
Cu	ppb	12	3	17	10	9	6
Fe	ppb	130	290	1900	360	680	560
Hg	ppb	0.16	< 0.02	0.29	0.09	0.15	0.15
Mn	ppb	20	90	620	40	110	60
Ni	ppb	< 2	< 2	4	< 2	< 2	< 2
Pb	ppb	38	12	9	11.5	15.5	8
Zn	ppb	55	17	83	± 20	± 25	± 10
Ag	ppb	± 0.8	± 0.8	< 0.8	< 0.8	< 0.8	± 0.8

Table 5.13

WATERS

Mehaigne

		Dhuy	Mehaigne	Branchon	Ambresin	Huccorgne	Wanze
O_2	%	129.7	84.6	99.0	106.9	90.0	95.0
COD	mg/ℓ	7	4	7	11	11	7
BOD	mg/ℓ	10.2	4.8	7.0	6.7	6.3	6.1
MS	mg/ℓ	10	10	10	10	10	10
N_{tot}	mg/ℓ	3.09	3.93	2.54	2.01	2.95	-
N_{amm}	mg/ℓ	0	0.07	0	0.13	0	0.06
NO_2^-	mg/ℓ	0.04	0.02	0.06	0.04	0.01	0.03
NO_3^-	mg/ℓ	1.23	1.85	2.48	2.48	3.21	12.6
PO_4^{---}	mg/ℓ	0.66	0.73	1.06	0.96	0.96	1.12
F^-	mg/ℓ	0.83	0.50	0.62	0.50	0.80	0.43
Cl^-	mg/ℓ	56	56	54	58	26	54
SO_4^{--}	mg/ℓ	70	64	66	62	63	65
Det.	mg/ℓ	0	1.07	0.2	0.2	0.7	0.4
CN^-	mg/ℓ	0	0	0	0	0	0
Ø OH	mg/ℓ	0.01	0.01	0.01	0.01	0	0
Ag	ppb	< 2	< 2	< 2	< 2	< 2	< 2
Cd	ppb	1.2	± 0.5	± 0.6	< 1	< 0.5	± 1
Co	ppb	< 2	< 2	< 2	< 2	< 2	< 2
Cr	ppb	<10	<10	<10	< 10	< 10	< 10
Cu	ppb	7.5	3.7	8	3	4.5	6
Fe	ppb	57	63	43	< 20	33	30
Hg	ppb	0.11	< 0.05	0.12	0.12	< 0.05	0.08
Mn	ppb	64	124	28	± 10	16	12
Ni	ppb	± 3	± 3.6	3.5	< 2	4	6
Pb	ppb	< 6	8	< 5	8	< 5	± 5
Zn	ppb	37	50	<10	15	± 21	± 20

Table 5.14

WATERS

Vesdre, Hoëgne

		Membach		Surdents		Ensival		Pepinster		Hoëgne	
		9-72	5-73	9-72	5-73	9-72	5-73	9-72	5-73	9-72	5-73
O_2	%	95.2	95.9	89.7	98.3	85.4	87.0	64.5	81.4	96.3	96.4
COD	mg/ℓ	2	7	64	4	15	53	98	122	4	4
BOD	mg/ℓ	4	3	9	3	11	10	10	9	4	5
MS	mg/ℓ	5	20	10	20	10	30	40	30	5	20
N_{tot}	mg/ℓ	0.25	0.56	0.27	0.58	1.55	7.11	0.2	8.2	0.09	2.8
N_{amm}	mg/ℓ	0.25	0.40	0.27	0.53	1.55	2.27	0.2	3.36	0.09	0
NO_2^-	mg/ℓ	0	0.06	0.04	0.01	0.18	0.21	0.66	0.002	0	0.01
NO_3^-	mg/ℓ	0.96	3.82	1.68	1.15	2.05	0.42	1.51	0	1.88	1.39
PO_4^{---}	mg/ℓ	0.3	0.08	0.4	0.07	0.7	0.96	2.3	0.53	0.2	0.2
F^-	mg/ℓ	0.29	0.83	0.22	0.23	0.25	0.25	0.2	0.18	0.16	0.18
Cl^-	mg/ℓ	16	10	16	10	20	16	22	18	12	10
SO_4^{--}	mg/ℓ	26	27	32	48	44	28	58	103	20	26
Cd	ppb	4.2	4	2.9	3	7.5	4	7.1	29	6.8	± 1
Co	ppb	-	6	-	2	-	2	-	6	-	3
Cr	ppb	10.1	<10	20	<10	47.9	<10	49.8	<10	<2	<10
Cu	ppb	112	47	9	15	11	31	20	37	4	6
Fe	ppb	650	90	306	138	445	260	495	420	327	74
Hg	ppb	0.13	< 0.05	0.18	< 0.05	0.07	< 0.05	0.7	< 0.05	1.55	< 0.05
Mn	ppb	223	104	177	184	200	480	218	805	82	60
Ni	ppb	12	15	18	4.5	12	6.5	15	15.5	< 5	4
Pb	ppb	15	20	16	22	30	101	27	104	10	8
Zn	ppb	264	38	192	46	150	65	165	105	110	21

Table 5.15

WATERS

Vesdre, Ourthe

		Forêt		Chênée			Ourthe Chênée		Ourthe Angleur		
		9-72	5-73	4-72	9-72	5-73	4-72	9-72	4-72	9-72	5-73
O_2	%	84.3	93.8	71.4	66.4	94.5	96.9	97.6	97.6	96.7	99.0
COD	mg/ℓ	26	4	37	30	15	4	8	8	19	7
BOD	mg/ℓ	14	6	0.4	5	6	3	2	4	6	5
MS	mg/ℓ	120	40	45	60	30	5	15	20	25	10
N_{tot}	mg/ℓ	1.03	2.8	4.2	0.42	4.2	1.12	0.21	2.74	0.19	-
N_{amm}	mg/ℓ	0.67	0.6	0.34	0.42	1.21	0	0.15	0	0.19	-
NO_2^-	mg/ℓ	0.1	0.02	-	0.15	0.01	neg.	0.02	-	0.04	0.02
NO_3^-	mg/ℓ	1.91	2.1	4.32	1.87	1.95	1.80	1.71	1.08	1.68	1.95
PO_4^{---}	mg/ℓ	0.4	0.23	0.38	0.9	0.34	0.01	0.3	0.54	0.5	1.22
F^-	mg/ℓ	0.21	0.18	0.22	0.21	0.44	0.12	0.14	0.01	0.19	0.16
Cl^-	mg/ℓ	16	18	26	14	14	16	14	22	18	16
SO_4^{--}	mg/ℓ	40	38	74	58	46	16	14	23	24	28
Cd	ppb	3.7	10	106	40	140	4.1	10.6	29	57.2	-
Co	ppb	-	4	7	-	4	< 2	-	3	-	-
Cr	ppb	21.5	<10	40	13.2	<10	8.4	9.4	20	9.8	-
Cu	ppb	10	9	36	23	49	45	3	65	17	-
Fe	ppb	650	160	528	638	178	832	312	902	460	-
Hg	ppb	1.4	< 0.05	1.00	0.86	0.07	0.15	0.6	0.14	1.04	-
Mn	ppb	282	510	450	305	310	83	86	160	141	-
Ni	ppb	8	4	22	15	5	± 10	± 5	14	10	-
Pb	ppb	21	8	32	100	96	6	9	15	31	-
Zn	ppb	165	31	513	1545	102	213	50	290	398	-

Table 5.16

WATERS

Julienne, Berwinne

		Julienne	Berwinne
O_2	%	88.3	97.9
COD	mg/ℓ	8	8
BOD	mg/ℓ	17	19
MS	mg/ℓ	15	25
N_{tot}	mg/ℓ	1.4	0.03
N_{amm}	mg/ℓ	0	0
NO_2^-	mg/ℓ	1.36	0
NO_3^-	mg/ℓ	3.08	6.16
PO_4^{---}	mg/ℓ	3.0	6.0
F^-	mg/ℓ	0.51	0.43
Cl^-	mg/ℓ	30	20
SO_4^{--}	mg/ℓ	125	74
Det.	mg/ℓ	0.7	3.3
CN^-	mg/ℓ	0	0
Ø OH	mg/ℓ	0	0
Cd	ppb	2.3	7.1
Cr	ppb	< 2	< 2
Cu	ppb	7.3	5.6
Fe	ppb	334	740
Hg	ppb	0.22	0.14
Mn	ppb	373	123
Ni	ppb	12	10
Pb	ppb	49	11
Zn	ppb	125	110

For instance, the river Ourthe at Angleur, a very polluted river, where sediments are relatively coarse, shows higher amounts in many polluting elements than the fine sediments from Liège where the Meuse is most polluted and higher amounts than the fine sediments from the Mehaigne, a non polluted river.

Nevertheless for a same place, a better idea of the pollution state can be given with a fine sample than with a coarse one. Besides we must remember that some samples are taken from embankments and are essentially very fine sedimentation sludges (for instance in Liège) while in some other cases (for example the Ourthe at Angleur) the sediment is probably mixed with earth coming from the erosion of the banks.

So, a relationship between pollution and presence of fine sludges cannot be established, as it has been done for the sea sediments because in rivers, the texture of a sample depends on different influences. When possible, we are trying to take fine sludges, real sedimentation sludges, these being more representative.

In this study, the basin of the Meuse has been divided into three parts : (i) from Heer to Tihange, (ii) from Flémalle-Haute to Herstal, (iii) below Herstal, according to the observed state of pollution. In the first section, low amounts of pollutants are observed especially above Namur. The amounts are much higher in the second section and they decrease in the third section without equalling those of the first section. The pollution in the region of Liège is clearly different from that of the other parts of the Meuse.

A study of the sediments of all the affluents of the Meuse just before their confluence point has also been done.

Among the affluents of the first section, the Molignée, the Samson can be considered as being non polluted.

The sediments of the Lesse, the Bocq and the Mehaigne are usually non polluted, but high amounts of Sn and Co can be found in the Lesse, and some bismuth, which is usually below the detection limit, can be traced in the Bocq and the Mehaigne.

The Hoyoux has high amounts of in Fe_2O_3 , Ba , Sn as well as Mo , and high amounts in Zn and Pb .

Table 5.17

SEDIMENTS

Meuse : from Heer to Tihange

Chemistry		Number	Min	Max	$\overline{X}$	Locations of the maxima
< 37 µ	%	14	12.8	61.5	40.3	Heer
P/F 110 - 550 °C	%	18	3.77	9.41	6.5	Namèche
P/F 550-1000 °C	%	18	5.8	10.9	9.1	Namèche
Org.M.($K_2Cr_2O_7$)	%	18	2.44	9.33	5.48	Tihange
Al_2O_3	%	18	5.2	8.9	7.18	Yvoir
Fe_2O_3	%	18	2.77	4.23	3.7	Heer
TiO_2	%	18	0.37	0.65	0.52	Poilvache
CaO	%	18	7.27	16.52	10	Namèche
MgO	%	18	0.57	6.72	1.69	Namèche
K_2O	%	18	1	1.84	1.4	Poilvache
S_{tot}	%	18	0.06	0.38	0.22	Namèche
Ba	ppm	18	< limit	360	234	Andenne, $\overline{X}$ on 5 samples
Co	ppm	18	6	11	9	Heer
Cr	ppm	18	34	120	61	Andenne
Cu	ppm	18	35	134	82	Poilvache
Ga	ppm	18	3	12	6	Andenne, Tihange
Ge	ppm	18	< limit	4	2	Anseremme, $\overline{X}$ on 7 samp.
Hg	ppm	18	0.06	0.68	0.3	Namèche
Mn	ppm	18	503	2000	1011	Annevoie
Ni	ppm	18	23	44	33	Yvoir
Pb	ppm	18	67	240	128	Andenne
Sn	ppm	18	7	22	14	Tihange
Sr	ppm	18	5	45	28	Heer
V	ppm	18	30	56	40	Namèche, Tihange
Zn	ppm	18	346	1500	833	Tihange
Zr	ppm	18	200	610	402	Namèche
Crude	$\frac{m\ell}{100g}$	17	0	0.533	0.11	Namèche

Cl, Ag, Be, Bi, Cd, Li, Mo, Sb, Tl : < detection limit.

Table 5.18

SEDIMENTS

Meuse : from Flémalle-Haute to Herstal

Chemistry		Number	Min	Max	$\overline{X}$	Locations of the maxima
< 37 µ	%	6	87	90.2	88.5	Ougrée
P/F 110 - 550 °C	%	6	8.5	10.3	9.34	Ougrée
P/F 550-1000 °C	%	6	10.77	14.56	13	Liège
Org.M.($K_2Cr_2O_7$)	%	6	10.33	15.64	14.1	Ougrée
Al_2O_3	%	6	9.73	13.24	11.08	Herstal
Fe_2O_3	%	6	5	10.2	7.63	Ougrée
TiO_2	%	6	0.48	0.72	0.6	Herstal
CaO	%	6	9.11	15.81	13.4	Liège
MgO	%	4	1.53	1.84	1.69	Ougrée
K_2O	%	6	1.44	1.92	1.7	Herstal
S_{tot}	%	6	0.45	1.03	0.71	Herstal
Ag	ppm	6	2	5	3	Herstal
Ba	ppm	6	365	620	459	Herstal
Bi	ppm	6	18	83	40	Herstal
Cd	ppm	6	< limit	240	233	Herstal, $\overline{X}$ on 4 samples
Co	ppm	6	9	24	15	Herstal
Cr	ppm	6	98	560	260	Herstal
Cu	ppm	6	> 90	>110	-	high everywhere
Ga	ppm	6	7	13	11	Herstal
Hg	ppm	6	1.02	1.69	1.35	Liège
Mn	ppm	6	985	1950	1522	Liège
Mo	ppm	6	3	7	6	Ougrée
Ni	ppm	6	49	110	79	Herstal
Pb	ppm	6	285	380	328	Herstal
Sn	ppm	6	32	270	187	Herstal
Si	ppm	6	115	325	185	Flémalle-Haute
V	ppm	6	71	180	122	Herstal
Zn	ppm	6	2500	4470	3575	Liège
Zr	ppm	6	220	372	282	Flémalle-Haute
Crude	$\frac{m\ell}{100g}$	6	0.12	0.45	0.24	Herstal

Cl, Be, Ge, In, Li, Sb, Tl : < detection limit.

Table 5.19

SEDIMENTS

Meuse : below Herstal

Chemistry		Number	Min	Max	$\bar{X}$	Locations of the maxima
< 37 µ	%	2	57.5	76	67	Visé
P/F 110 - 550 °C	%	2	5.21	14.70	10	Visé
P/F 550-1000 °C	%	2	8.45	10.75	9.6	Lanaye
Org.M.($K_2Cr_2O_7$)	%	2	12.33	17.45	14.9	Visé
Al_2O_3	%	2	6.8	9.76	8.3	Visé
Fe_2O_3	%	2	4.85	5.51	5.18	Visé
TiO_2	%	2	0.43	0.7	0.56	Visé
CaO	%	2	9.76	13.50	11.63	Lanaye
MgO	%	1	-	-	1.22	
K_2O	%	2	1.23	1.51	1.37	Visé
S_{tot}	%	2	0.48	0.53	0.5	Visé
Ba	ppm	1	-	-	320	
Bi	ppm	1	-	-	24	
Co	ppm	2	10	12	11	Lanaye
Cr	ppm	2	100	175	137	Visé
Cu	ppm	2	82	170	126	Lanaye
Ga	ppm	2	4	11	7	Visé
Hg	ppm	2	1.1	1.73	1.43	Lanaye
Mn	ppm	2	970	1150	1060	Lanaye
Ni	ppm	2	50	55	53	Lanaye
Pb	ppm	2	180	260	220	Lanaye
Sn	ppm	2	37	53	45	Visé
Sr	ppm	2	40	50	45	Lanaye
V	ppm	2	59	64	62	Visé
Zn	ppm	2	1530	1580	1555	Lanaye
Zr	ppm	2	310	450	380	Visé
Crude	$\frac{m\ell}{100g}$	2	0.085	0.45	0.26	Visé

Cl, Ag, Be, Cd, Ge, In, Li, Mo, Sb, Tl : < detection limit.

The Sambre can be considered as being very polluted in many elements.

In the second section the only affluent is the Ourthe shortly after the junction with the Vesdre. The confluence of these two rivers forms at

Table 5.20

SEDIMENTS

Mehaigne

Chemistry		Number	Min	Max	$\overline{X}$	Locations of the maxima
P/F 110 - 550 °C	%	7	2.7	8	4.8	Dhuy
P/F 550-1000 °C	%	7	0.9	5.1	2.72	Wanze
Org.M.($K_2Cr_2O_7$)	%	7	3.2	8.7	5.38	Dhuy
Al_2O_3	%	7	6.64	8.46	7.71	Dhuy
Fe_2O_3	%	7	2.43	3.26	2.97	Branchon
CaO	%	7	1.01	6	2.60	Wanze
K_2O	%	7	1.23	1.73	1.57	Huccorgne
S_{tot}	%	7	0.08	0.62	0.29	Dhuy
Ag	ppm	7	< limit	3	0.8	Mehaigne, $\overline{X}$ on 6 samples
Ba	ppm	7	135	277	173	Wanze
Co	ppm	7	3	8	6	Huccorgne
Cr	ppm	7	42	110	78	Mehaigne
Cu	ppm	7	18	36	25	Wanze
Ga	ppm	7	7	18	14	Mehaigne, Huccorgne
Hg	ppm	7	< 0.01	0.6	0.21	Wanze, $\overline{X}$ on 4 samples
Mn	ppm	7	430	1500	778	Wanze, $\overline{X}$ on 4 samples
Ni	ppm	7	16	41	27	Huccorgne
Pb	ppm	7	110	170	140	Ambresin
Sn	ppm	7	< limit	9	8	Wanze, $\overline{X}$ on 5 samples
Sr	ppm	7	35	65	50	Dhuy
V	ppm	7	24	78	56	Huccorgne
Zn	ppm	7	121	350	176	Wanze
Zr	ppm	7	530	1010	888	Ambresin
Crude	$\frac{m\ell}{100g}$	7	0.01	0.08	0.04	Wanze

Cl, Be, Bi, Cd, Ge, Mo, Sb, Tl : < detection limit.

Angleur a very polluted river which certainly contributes to the increase of pollution of the Meuse as can be seen in Liège and below this town. The Hoëgne which joins the Vesdre is also polluted (Pb and Zn).

In the third section, the affluents Julienne and Berwinne are not polluted (except for high amounts in Sb in the Berwinne).

Table 5.21

SEDIMENTS

Vesdre (3 campaigns 1972-1973)

Chemistry		Number	Min	Max	$\overline{X}$	Locations of the maxima
< 37 µ	%	13	9	53	42	Ensival
P/F 110 - 550 °C	%	13	1.85	14.34	7.21	Ensival
P/F 550-1000 °C	%	13	3.3	7.6	5.13	Forêt-Trooz
Org.M.($K_2Cr_2O_7$)	%	13	2.5	23	11.2	Ensival
Al_2O_3	%	13	9.6	13.52	11.8	Forêt-Trooz
Fe_2O_3	%	13	4.2	4.86	4.47	Surdents
TiO_2	%	13	0.6	0.77	0.67	Chênée
CaO	%	13	1.42	4.65	3.07	Forêt-Trooz
K_2O	%	13	1.36	3.74	2.21	Forêt-Trooz
S_{tot}	%	13	0.22	2.2	0.85	Surdents
Ba	ppm	13	190	420		Pepinster
Bi	ppm	13	< limit	100	50	Ensival, $\overline{X}$ on 8 samples
Cd	ppm	13	< limit	650	-	2 samples at Chênée
Co	ppm	13	15	25	18	Ensival
Cr	ppm	13	85	520	250	Ensival
Cu	ppm	13	> 70	>230	-	Chênée
Ga	ppm	13	8	23	15	Chênée
Ge	ppm	13	< limit	3	2	Membach, Surdents, $\overline{X}$ on 6 s.
Hg	ppm	13	0.08	3	0.64	Chênée
In	ppm	13	< limit	8	-	2 samples at Chênée
Mn	ppm	13	450	1200	695	Membach
Ni	ppm	13	66	115	94	Ensival
Pb	ppm	13	250	670	430	Chênée
Sb	ppm	13	-	50	-	Membach 1 sample
Sn	ppm	13	17	725	161	Surdents
Sr	ppm	13	20	55	39	Ensival
V	ppm	13	55	110	91	Forêt-Trooz
Zn	ppm	13	515	2780	1531	Chênée
Zr	ppm	13	350	760	537	Chênée
Crude	$\frac{m\ell}{100g}$	13	0.03	1.35	0.47	Ensival

Cl, Ag, Be, Li, Mo, Tl : < detection limit.

Two affluents, the Sambre and the Ourthe are therefore very polluted, the Hoyoux is polluted.

We have specially turned our attention to the river Ourthe so that sediments have been taken twice in the Ourthe above the confluence point with the Vesdre and along the whole course of the Vesdre. This has enabled us to confirm a very high pollution state in the sediments of the Vesdre in several places of its course, and to a lesser degree in those of the Ourthe.

Besides a study of the whole course of the Mehaigne, from source to mouth, has enabled us to confirm the very low amounts in all the pollutants found previously just before the confluence point with the Meuse.

Other sediments studies of rivers converging towards the basin of the Meuse are in progress. It concerns the Rulles, Ton, Laclaireau and the brook of Marche en Famenne.

2.2.- Basin of the Scheldt

2.2.1.- Waters

The course of the Scheldt has been inventoriated twice during the past three years, at an interval of one year and a half. Our bacteriological, chemical and hydrobiological studies show clearly that the organic and faecal pollution is already very important in the Scheldt when entering Belgium.

This pollution increases and reaches a maximum below the confluence with the Espierres which has higher concentrations in many parameters than those found in sewers. The Espierres has a very important effect on the pollution level of the Scheldt downstream; besides, the Espierres throws large quantities of chromium and lindane on the Scheldt.

The Leie is a second and indubitable source of organic and faecal pollution of the Scheldt.

On the other hand the Dender, which has a pollution level equal to that of the Scheldt, seems to have but a limited or almost limited part on the pollution level of the Scheldt. The same thing can be said again for the Rupel.

Table 5.22

WATERS

Scheldt

		Vaulx		Warcoing		Helkeijn		Kerkhove		Zwijnaarde	
		1-72	5-73	1-72	5-73	1-72	5-73	1-72	5-73	1-72	5-73
O_2	%	55.2	41	54.0	40.1	49.6	28.8	29.8	3.8	32.3	0
COD	mg/ℓ	70	54	70	47	154	101	168	216	108	91
BOD	mg/ℓ	9	43	9.5	72	26	13	72	30	5	10
MS	mg/ℓ	30	200	20	150	60	160	120	580	530	80
N_{tot}	mg/ℓ	9.5	15.3	10.1	23.7	12.9	25.7	13.8	26.2	13.2	22.7
N_{amm}	mg/ℓ	5.2	15.3	5.7	20.2	6.7	21.5	7.8	23.2	5.9	16.5
NO_2^-	mg/ℓ	neg.	0.50	neg.	0.44	neg.	0.38	neg.	0.14	neg.	0.02
NO_3^-	mg/ℓ	9.5	2.9	9.8	2.4	4.8	1.5	2.4	0.1	9.2	0.02
PO_4^{---}	mg/ℓ	2.0	1.82	2.3	3.49	1.9	14.14	12.0	19.3	7.6	22.3
F^-	mg/ℓ	0.03	0.81	0.05	0.9	0.25	10	0.25	6.6	0.10	5.0
Cl^-	mg/ℓ	90	102	88	96	96	112	104	132	78	132
SO_4^{--}	mg/ℓ	185	196	188	191	183	244	215	281	175	197
Det.	mg/ℓ	0	0.14	0	0.24	0	1.7	1.3	2.5	0.35	1.32
CN^-	mg/ℓ	0	0	0	0	0	0	0	0	0	0
Ø OH	mg/ℓ	0	0	0.01	0	0.2	0	0.06	0	0.04	0
Cd	ppb	-	15	-	23	-	12	-	8	-	6
Co	ppb	< 5	< 5	< 5	13	< 5	< 5	< 5	7	< 5	7
Cr	ppb	< 5	<100	< 5	<100	400	645	920	387	< 5	225
Cu	ppb	11	24	24	84	14	16	63	12	9	12
Fe	ppb	90	80	100	360	150	183	150	206	250	120
Hg	ppb	0.31	-	0.25	-	0.31	-	0.8	-	0.16	-
Mn	ppb	485	176	470	364	520	285	500	309	650	255
Ni	ppb	13	58	11	91	17	146	21	102	12	120
Pb	ppb	34	23	26	60	28	40	20	37	10	30
Zn	ppb	392	265	80	333	80	130	82	46	63	56

Table 5.23

WATERS

Scheldt

		Wetteren		Dender-monde	Temse		Hoboken		Doel	
		1-72	5-73	5-73	1-72	5-73	1-72	5-73	1-72	5-73
O_2	%	46.0	0	0	24.4	0	40.8	0	54.7	8.5
COD	mg/ℓ	30	80	110	92	133	114	179	144	376
BOD	mg/ℓ	9.6	60	84	16	6	8.8	40	4.0	7.6
MS	mg/ℓ	80	90	230	370	65	490	170	230	245
N_{tot}	mg/ℓ	62.7	23.7	20.5	54.0	15.6	49.3	15.7	56.0	7.2
N_{amm}	mg/ℓ	48.5	18.8	16.5	32.5	12.2	29.1	11.2	28.0	6.8
NO_2^-	mg/ℓ	neg.	0.02	0.02	neg.	0.02	neg.	0.01	neg.	0.12
NO_3^-	mg/ℓ	0	0.08	0.01	1.8	0.01	5.4	0.005	3.0	0.09
PO_4^{---}	mg/ℓ	6.0	17.2	13.3	7.3	12.2	2.8	10.8	1.9	3.7
F^-	mg/ℓ	4.3	5.5	6.2	3.12	3.5	2.9	4.0	3.4	3.1
Cl^-	mg/ℓ	200	194	236	300	608	110	1030	4900	7700
SO_4^{--}	mg/ℓ	285	309	266	164	253	280	300	774	118
Det.	mg/ℓ	0.3	1.48	1.08	0	1.38	0	1.40	0	0.62
CN^-	mg/ℓ	0	0	0	0	0	0	0	0	0
Ø OH	mg/ℓ	0.09	0	0	0.19	0	0.05	0	0	0
Cd	ppb	-	6	15	-	20	-	40	-	23
Co	ppb	< 5	20	10	< 5	17	< 5	13	< 5	10
Cr	ppb	< 5	<100	<100	< 5	<100	< 5	<100	< 5	290
Cu	ppb	< 5	< 10	92	< 5	76	6	84	5	108
Fe	ppb	285	131	228	188	423	88	411	40	234
Hg	ppb	0.09	-	-	0.02	-	0.07	-	0.11	-
Mn	ppb	480	345	394	414	267	400	315	358	345
Ni	ppb	8	98	120	17	120	14	142	8	120
Pb	ppb	10	30	25	5	20	10	35	5	45
Zn	ppb	38	106	219	29	104	47	150	50	140

Table 5.24

WATERS

Dyle

		Houtain le mont (source)	Loupoigne	Ways	Thy	Court-St-Etienne	Limal	Gastuche ab. papermill	Gastuche bel. papermill	Florival
km		0	3.6	6.8	9.4	13.9	22.0		30.1	
O_2	%	86.6	88.6	69.8	80.6	88.3	18.9	16.8	42.3	59.4
COD	mg/ℓ	4	12	15	15	23	35	38	58	31
BOD	mg/ℓ	2.2	4.5	8	5.2	3.6	7.8	6	4.2	4.6
TOC	mg/ℓ	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	2	4	12	9
MS	mg/ℓ	8	16	36	36	28	20	16	60	68
N_{tot}	mg/ℓ	0.63	2.33	2.19	0.86	2.11	2.33	1.80	4.03	2.72
N_{amm}	mg/ℓ	0.1	0.24	1.7	0.86	0.40	0.81	0.98	4.03	1.22
NO_2^-	mg/ℓ	0.16	1.25	1.70	2.43	1.53	0.98	2.69	3.07	1.73
NO_3^-	mg/ℓ	29.4	25.17	20.64	21.27	17.42	21.9	13.0	11.8	10.0
PO_4^{---}	mg/ℓ	0.53	1.42	2.38	1.50	1.58	0.99	1.58	2.84	0.86
F^-	mg/ℓ	0.2	0.22	0.22	0.18	0.16	0.18	0.28	0.22	0.18
Cl^-	mg/ℓ	52	54	52	56	54	56	54	50	44
SO_4^{--}	mg/ℓ	56	62	64	62	57	131	113	113	188
Det.	mg/ℓ	0.8	1.7	2.1	0.3	0.5	1.2	0.3	6.3	1.9
CN^-	mg/ℓ	0	0	0.003	0	0	0.002	0	0	0
Cd	ppb	2.5	0.8	1.2	0.8	1	0.6	0.6	1	1.6
Co	ppb	1.2	± 1	2.8	< 1	1.5	2.5	4	2	4
Cr	ppb	< 3	< 3	< 3	< 3	< 3	6	< 3	3.3	< 3
Cu	ppb	4	< 1	4.5	2.6	6.5	5	4	4	12.5
Fe	ppb	41	44	74.5	142	83.5	48	122.5	107	2000
Hg	ppb	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Mn	ppb	<20	< 20	<20	31	< 20	38.5	< 20	< 20	177
Ni	ppb	3	2	3.5	3.5	7	50	140	95	103.5
Pb	ppb	26	6	10	16	12	6	18	10	600
Zn	ppb	20	45	70	90	60	75	95	105	75
Index		0.9	1.4	2.4	1.8	1.5	2.8	2.6	3.8	3.3

Table 5.25

WATERS

Dyle

		Korbeek Dyle	Heverlee	Leuven Stella	Leuven exit	Wijgmaal	bel. Demer	Muizen	Mechelen	Mechelen	Sennegat
km		44.9	49	53.7	56.5	57.4	65.9	82.4	85.5	85.4	92.3
O_2	%	23.2	15.1	7.2	19.6	19.6	0	0	0	0	0
COD	mg/ℓ	65	65	35	35	50	96	69	108	69	127
BOD	mg/ℓ	8	6	6.4	6	6	9	9	24	19.2	27.2
TOC	mg/ℓ	14	11	9	11	11	18	15	25	22	26
MS	mg/ℓ	44	40	12	24	32	44	8	72	24	28
N_{tot}	mg/ℓ	4.66	3.78	1.74	3.90	0.99	4.79	6.27	6.63	3.62	7.49
N_{amm}	mg/ℓ	1.29	1.05	1.23	1.07	0.99	2.72	3.21	3.29	3.62	7.49
NO_2^-	mg/ℓ	2.62	0.64	1.4	1.12	1.12	0.61	0	0	0	0
NO_3^-	mg/ℓ	11.13	21.16	6.3	5.04	3.9	1.6	0.21	0.47	0.21	0.88
PO_4^{---}	mg/ℓ	4.77	4.22	3.27	2.94	3.45	3.76	4.31	4.12	5.02	5.87
F^-	mg/ℓ	0.40	0.66	0.22	0.25	0.33	0.66	0.44	0.79	0.66	0.66
Cl^-	mg/ℓ	58	66	46	48	48	560	568	522	576	360
SO_4^{--}	mg/ℓ	98	98	90	94	94	97	101	98	105	120
Det.	mg/ℓ	3.4	0.3	0	0	0.4	0	0	0	1.1	1.9
CN^-	mg/ℓ	0.001	0.003	0	0	0	0	0.001	0	0.001	0
Cd	ppb	18.4	0.8	7	6.2	5.4	1.6	4.5	6	2	1
Co	ppb	2.5	2.8	1.2	± 1	2	1.2	< 1	1.5	1.5	2
Cr	ppb	15	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3	< 3
Cu	ppb	9	7	9	6.5	34	2	2	17	6.5	2.5
Fe	ppb	600	700	550	350	470	2500	2170	2230	2000	2000
Hg	ppb	± 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	± 0.01	< 0.01	0.05	0.06
Mn	ppb	< 20	27	< 20	< 20	< 20	31	115	238	54	285
Ni	ppb	50	75	38	30	34	63.5	75	120	25	26
Pb	ppb	44	44	36	20	38	14	26	26	36	18
Zn	ppb	70	70	50	70	45	70	70	70	50	60
Index		3.7	3.5	2.8	2.5	2.8	4.7	4.5	6.1	5.6	6.9

Table 5.26

WATERS

Espierres

		Estaimpuis		Espierres		
		5-73	10-73	1-72	5-73	10-73
O_2	%	23.2	0	-	2.1	2
COD	mg/ℓ	1410	1740	2980	500	1552
BOD	mg/ℓ	680	475	680	400	340
MS	mg/ℓ	1260	1500	1340	630	1320
N_{tot}	mg/ℓ	8.7	52.3	23.5	8.6	32.6
N_{amm}	mg/ℓ	5.8	25.7	4.2	5.6	13.8
NO_2^-	mg/ℓ	10.1	0.14	-	0.08	0.16
NO_3^-	mg/ℓ	4.08	0.18	4.9	0	0.24
PO_4^{---}	mg/ℓ	22.2	103	13.8	0.4	114
F^-	mg/ℓ	8.3	125	0.1	1.8	125
Cl^-	mg/ℓ	180	314	424	176	232
SO_4^{--}	mg/ℓ	810	349	440	668	488
Det.	mg/ℓ	6.8	5.6	4.3	5.1	3.9
CN^-	mg/ℓ	0	0	0	0	0
Ø OH	mg/ℓ	0.65	pos.	0.41	1.5	pos.
Ag	ppb	< 2	-	-	< 2	-
Cd	ppb	40	6	-	8.7	11
Co	ppb	6	22	10	5	117
Cr	ppb	8300	1161	12000	2060	2096
Cu	ppb	84	92	150	53	212
Fe	ppb	500	3770	270	172	8580
Hg	ppb	< 0.05	-	0.33	< 0.05	-
Mn	ppb	380	218	615	490	424
Ni	ppb	58	107	47	15	427
Pb	ppb	4	55	66	24	40
Zn	ppb	81	84	80	59	187

We have sampled the whole course of the Dyle in a very detailed manner.

That river has a low pollution level at its source, but it increases quickly after passing through industrial areas especially in Ways, Gastuche and Florival. Besides a toxic effect on aquatic life can be detected in those places. A second pollution area starts in Leuven and goes on till the entrance of Mechelen where a clear degradation of the situation can be observed. This degradation increases in a continuous way from below the Demer up to the confluence with the Senne.

The outlines of the organic and microbiological pollution are remarkably parallel on the whole course of the Dyle.

Finally a linear increase of the pollution due to pesticides can be observed up to Leuven with a stabilization downstream. A battery works situated in Florival is responsible for the high concentrations of Pb that are found downstream.

Finally the situation in the Scheldt seems to deteriorate again with time as a decrease was noted in 1973 compared to the situation observed in 1971.

2.2.2.- Sediments

The study of the sediments of the Scheldt (from the French border to Zwijnaarde) and of the suspended matters (from Wetteren to Doel) has enabled us to determine the development of the pollution all along the river, as well as the pollution of some affluents. Low amounts in pollutants are observed at the French border and at Warcoing and they increase below the confluence with the Espierres, an indubitably polluted river, and particularly at Kerkhove. The amounts decrease at Zwijnaarde.

The study of the suspended matters, below Gent, shows that the amounts of pollutants increase after the confluence point with the Dender at Temse. At Hoboken, a slight decrease of the pollution can be noted in spite of the industrialisation of the river banks and of the contribution of the Rupel waters. The amounts in pollutants decrease very strongly at Doel.

A sampling campaign of sediments has been carried out all along the Scheldt; it will give a better idea of the river pollution, especially below Gent.

Table 5.27

SEDIMENTS

Scheldt (Vaulx to Zwijnaarde)

Chemistry		Number	Min	Max	$\bar{X}$	Locations of the maxima
< 37 µ	%	4	24	66	52.5	Warcoing
P/F 110 - 550 °C	%	4	1.8	9.9	4.45	Kerkhove
P/F 550-1000 °C	%	4	3	8.5	5.4	Kerkhove
Org.M.($K_2Cr_2O_7$)	%	4	2.5	11	5.3	Kerkhove
Al_2O_3	%	5	3.7	8.9	6.9	Warcoing
Fe_2O_3	%	5	1.6	3.3	2.7	Vaulx
TiO_2	%	5	0.2	0.6	0.47	Warcoing
P_2O_5	%	2	0.5	0.66	0.59	Kerkhove
CaO	%	5	2.6	11.2	6.95	Helkijn
MgO	%	5	0.3	0.9	0.58	Warcoing
K_2O	%	5	1.1	1.8	1.47	Kerkhove
S_{tot}	%	4	0.1	0.54	0.38	Vaulx, Zwijnaarde
Co	ppm	5	2	8	5	Kerkhove
Cr	ppm	5	54	> 1000	332	Kerkhove, $\bar{X}$ on 4 samples 1 sample > 1000
Cu	ppm	5	54	> 80	35	Kerkhove, $\bar{X}$ on 4 samples 1 sample > 80
Ga	ppm	5	4	9	6	Kerkhove
Hg	ppm	4	0.09	1.28	0.4	Kerkhove
Mn	ppm	5	230	414	342	Kerkhove
Ni	ppm	5	12	37	25	Kerkhove
Pb	ppm	5	24	571	187	Kerkhove
Sn	ppm	5	5	25	14	Helkijn
Sr	ppm	5	54	679	208	Kerkhove
V	ppm	5	14	40	31	Kerkhove
Zn	ppm	5	61	1750	501	Kerkhove
Zr	ppm	5	250	490	421	Helkijn
Crude	$\frac{m\ell}{100g}$	5	0	0.376	0.09	Helkijn

Cl, Ag, Be, Bi, Cd, Ge, Li, Mo, Sb, Tl : < detection limit.

Table 5.28

SUSPENDED MATTERS

Scheldt (Wetteren to Doel)

Chemistry		Number	Min	Max	$\overline{X}$	Location of the maxima
P/F 110-550°C	%	4	7.5	15.3	11	Wetteren
Al_2O_3	%	3	1.2	14.5	9.04	Hoboken
Fe_2O_3	%	3	1.1	7.5	5.27	Temse
TiO_2	%	3	0.1	0.8	0.56	Temse
P_2O_5	%	4	< limit	1.5	1.23	Wetteren, $\overline{X}$ on 3 samples
CaO	%	3	0.5	4.2	2.26	Hoboken
MgO	%	3	0.7	1.7	1.2	Hoboken
K_2O	%	3	0.3	2.3	1.6	Hoboken
Ag	ppm	4	0.3	7.3	3.3	Temse
Co	ppm	4	< 0.4	14	10	Temse, $\overline{X}$ on 3 samples
Cr	ppm	4	25	1185	470	Wetteren
Cu	ppm	4	6	> 190	-	Hoboken, 3 samples > 60
Ga	ppm	4	1	14	7	Temse
Mo	ppm	4	< limit	10	6	Temse, $\overline{X}$ on 3 samples
Mn	ppm	4	36	448	291	Temse
Ni	ppm	4	4	109	52	Temse
Pb	ppm	4	30	385	189	Temse
Sb	ppm	4	< limit	48	48	Hoboken, $\overline{X}$ on 2 samples
Sn	ppm	4	3	25	16	Hoboken
Si	ppm	3	50	125	95	Hoboken
V	ppm	4	7	177	76	Temse
Zn	ppm	3	125	1600	947	Temse
Zr	ppm	4	12	176	120	Temse

Be, Bi, Cd, Ge, Ni, Tl : < detection limit.

Where affluents are concerned, the Espierres has particularly drawn our attention. Sediments have been sampled just before the confluence with the Scheldt, and they confirm the results of the first sampling : the Espierres is highly polluted especially in Cr .

Table 5.29

SEDIMENTS

Espierres

Chemistry		January 72	June 73
< 37 μ	%	30.5	42.3
P/F 110 - 550 °C	%	11.06	10.7
P/F 550-1000 °C	%	6.42	6.6
Org.M.($K_2Cr_2O_7$)	%	14.43	14.5
Al_2O_3	%	7.21	7.82
Fe_2O_3	%	2.88	4.16
CaO	%	7.9	8.19
K_2O	%	1.16	1.08
S_{tot}	%	1.75	2.56
Ag	ppm	2	4
Ba	ppm	-	233
Bi	ppm	< 20	8
Co	ppm	13	25
Cr	ppm	> 2000	> 2000
Cu	ppm	> 85	> 120
Ga	ppm	4	10
Hg	ppm	0.37	0.19
Mn	ppm	410	230
Ni	ppm	28	52
Pb	ppm	149	220
Sn	ppm	46	20
Sr	ppm	140	-
V	ppm	30	48
Zn	ppm	1500	985
Zr	ppm	420	310
Crude	$\frac{m\ell}{100g}$	-	0.32

Cl, Be, Cd, Ge, Mo, Sb, Tl : < detection limit.

The suspended matters of the Dender are also polluted, especially in Co and Cr ; much Mo and some Sb can be found in them.

The suspended matters from the Rupel are less charged in pollutants; nevertheless the amounts in Ni , Cu , Pb , Zn and Sb are high.

The Grande Gete and the Dyle, affluents of the Rupel, have also been selected for sampling of sediments. Sediments of the Grande Gete taken above and below sugar-works have not shown any possible influence due to these industries.

The study of the Dyle is in progress.

2.3.- Basin of the Yser

The research works that have been performed have been published : *De Yser, Inventaris van de waterverontreiniging in het stroomgebied van de Yser* (IHE-IRC), pp. 1-105, November 1973.

The situation in the Yser basin has been established by means of the following data :

1) the hydrographical situation;

2) the sources of pollution in the catchment area of the Yser and its affluents;

3) the study of the river water itself. The following parameters have been determined :

a) physical and chemical determinations : the parameters indicating organic waste charge, toxic substances and heavy metals;

b) pesticides : organochlorine, organophosphorus- and carbamate compounds;

c) hydrobiological determinations : the plankton, organism-development on glass microscope slides, toxicity tests;

d) bacteriological indicators of faecal pollution;

4) the study of sediments and suspended matter :

a) physico-chemical analysis : granulometry, macroscopic observations, ignition losses, mineralogy;

b) chemical analysis : organic substances, hydrocarbons and trace elements.

From the data of this inventory study on the pollution of the Yser some obvious conclusions can be made :

1) In the Yser itself no significant indication can be found about a true pollution by toxic substances, neither in the water nor in the sediments. However pesticide contents are higher than in most surface waters, they never exceed a "tolerance limit", whatever criterium is used from the literature for evaluating this.

At their confluence, the affluents of the Yser do not show any indication of possible sources of toxic substances upstream that would be able to exert a negative influence on the situation in the Yser itself.

2) Some important sources of organic pollution were clearly revealed : the sewage of Roesbrugge, the Eurofreez factory (discharging until 1970 in Roesbrugge's sewage and from 1970 through the Haringebeek), the city of Diksmuide via the "Handzamevaart" channel. As a consequence of the very minor currents their influence is very local, but nevertheless very pronounced, going as far as the development of an anaerobic situation at these sites.

3) The nutrient content of the Yser along its whole traject is extremely high, with phosphate values between 10 and 20 mg/ℓ .

From a review of the domestic, industrial and animal waste in the whole Yser basin in our country a relative importance of 1.4 and 20 respectively can be derived for the number of equivalents per inhabitant for these three sectors.

Knowing that the mineralisation of animal waste leads to important quantities of nitrate and phosphate, this could already be a first explanation for the high figures found for these nutrients in the Yser.

Moreover, the Heidebeek tributary has a very high charge in phosphates coming from France (up to 50 mg/ℓ).

A third reason for the very high "input" of nutrients in the Yser should be found in the high agricultural development of this region.

In order to be able to make an evaluation of the possible drainage of nitrogen and phosphorus from the land, data of an OECD paper giving the run-off as a function of the different cultures and surface conditions have been used.

4) The hydrobiological research data clearly reveal a eutrophication in the whole Yser, which is related with these high nutrient levels. Actually the trophic level is already beyond the eutrophication stage ("hypertrophy") and typical phenomena of autogeneous pollution occur, *i.e.* algal blooms, anaeroby, decomposition gases. In this the true reason for the deterioration of the Yser must be found. As it is a biological phenomenon showing cyclic characteristics depending on temperature, solar radiation, flow, salt content and other ecological factors this is undoubtedly the reason for the cases of massive fish-dying occuring regularly in this river.

5) From these previous conclusions it can be derived that the curing of the Yser is a question of combating the eutrophication phenomenon. This implicates :

a) a solution for the nutrient-inflow from France through the Heidebeek;

b) that the treatment process for domestic sewage in this region should include a so-called third step purification stage in order to obtain a maximum removal of the nutrients;

c) that the sewage waters from the cattle breeding especially those from the bio-industry should not be discharged without prior reduction of the nitrogen and phosphorus contents to an acceptable level;

d) an adaptation of the irrigation system when these curing measures do not lead to the desired results.

Indeed it is not impossible that from the use of fertilisers in periods of high rainfall the run-off of phosphorus and principally nitrogen compounds is too important for the low flow rate that is characteristic to the Yser. The water from the most important irrigation channels and brooks should then be collected to allow an efficient removal of these fertilisers.

3.- General synthesis

A short global synthesis is done here and some anomalies are mentioned. Other more complete synthesis are put ahead of the results.

3.1.- Sea

The results of the complementory campaign performed in 1973 confirm those obtained in 1972. The coastal sea zone, an immixtion zone, has a higher pollution state than the open sea, this pollution being far more marked eastwards, from and including Oostende. Where bacterial pollution is concerned, the influence of discharge outlets seems obvious.

For other pollution forms, it is not possible to specify the influence of the emittors on waters of the coastal area although these are usually far more polluted.

To estimate this influence is specially difficult, as the fairways' flow rates cannot be determined practically. In that field, it seems that the qualitative aspect only has to be considered. Some correlations have also been confirmed, for example those that have been noticed between the proportion of fine particles of a sediment and its pollution degree.

3.2.- Rivers — Complementory campaigns

As a whole, the results of complementory campaigns performed in 1973 lead to an increase of the number of data, to a better specification of the pollution state as described in 1972 and confirm the first results as well.

Are considered here : the very important pollution of the Scheldt, the Espierres pollution where amounts of Cr reach 3000 ppm , the presence of high amounts of Cd in the Vesdre and in sediments taken from some places of the Meuse (one of them being Chênée). The Yser case is fully developped in a study that has been published since; this river shows an advanced state of eutrophication.

3.3.- Rivers — New campaigns

The Mehaigne flows in a farming area and has a very low pollution in heavy metals. The pesticides content might be a bit higher than the usual average without being too high. This typical case of agricultural area will be better specified with a new campaign and with particular and more frequent samplings for Hg and the pesticides.

High amounts in Pb have been found in the Rulles (wood distillery); an increase of organic pollution (although it remains a low one) has been observed in the Ton (paper mills) but no anomaly in Hg could be detected.

High organic pollutions as well as pesticides such as lindane, heptachlore, DDVP, are found in the Dyle in the vicinity of Leuven. These pollutions change all along the river but they increase markedly towards the confluence point with the Demer, a particularly charged river. A local increase of the organic pollution is observed upstream at Gastuche (paper mills).

Irregularities in Pb and Fe can be detected in Florival (battery works); aquatic life does not exist anymore there but can be seen again a few kilometers downstream.

Those are very significant anomalies; expected or unexpected, it was necessary to specify their importance, in the frame of the general inventory.

The global view on the present pollution state of surface waters is therefore gradually completed.

4.- Conclusions

One hundred and fifty-nine significant locations have been studied for two years.

The ten thousand corresponding analytical data are easily available starting from the alphabetical list of waterways where the numbers of the result cards are noted for each river.

All the coordinates of time and space related to location and sampling are also noted on those cards (652 cards for water and 269 cards for sediments); they can be obtained by addressing either to the center for collecting data or to one of the participating Institutes. The interest of this inventory is obvious, not only on national but also on international ground.

For example, whenever an investigation has been made by the EEC or the OECD, we have always been able to give reference data for Belgium very quickly.

Other countries have undertaken similar studies. A first inventory called 'thousand points inventory' has just been performed in France; it has to be repeated during three consecutive years. This inventory is centered on the way of working of basin societies; flow rates are taken into consideration but fewer parameters are determined.

As the surfaces and the water volumes that are to be determined are relatively high, and the number of instantaneous samplings is rather low, a lack of representativity ensues, this being the main defect of the method.

Nevertheless, this way of proceeding seems to be the only one that leads to the knowledge of the pollution state of waters on the scale of the country, in a reasonable delay and with relatively modest means.

For this reason, the leaders of the project decided not to alter the chosen options as long as the inventory was not developped enough. Under some circumstances, the soundness of this choice may seem somewhat uncertain.

Actually, accurate steps in protection or in water treatment will never be based on the results of the inventory only.

In each separate case, more frequent and better locally distributed measurements will have to be repeated again. It will not be necessary to determine every parameter but we must be able to establish a correlation between analytical data and flow rates.

In the same line of idea, further measurements in the frame of this inventory should not perhaps be necessary if automated measurements networks were set up.

However, as a maximum of physical, chemical, bacteriological and hydrobiological parameters is measured and as the studies of sediments and water are done concurrently by means of the same methods for each significant location, together with great adaptability of the works organisation, the results have a particular scientific quality and an exceptional comparative value which is the very characteristic of this inventory.

The choice of many locations and the arrangement of results by regions are particularly easy for a better determination of the pollution state of the whole hydrographical network and of the sectorial influences as integrated in each river.

Even if the knowledge of pollution states involves political and economical implications, or if arrangements are to be taken practically, the main thing remains scientific information.

The Inventory Group endeavours to the performance of this task.

Chapter VI

I. Aspects of dynamic biology in the Southern Bight of the North Sea and the Sluice Dock at Ostend

by

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General introduction

As an ecosystem is a dynamic entity, it is impossible to understand its functioning by a structural description of static parameters such as concentrations, biomasses, etc. It is necessary to estimate the *activities* of the different organisms (primary and secondary production, respiration rates, heterotrophic activity, etc.). Only the quantitative and qualitative description of interactions and transfers, temporally and spatially integrated, gives us a dynamic picture of the working of the ecosystem.

In our opinion, only this fundamental knowledge of the interactions in the ecosystem will allow us to understand pollution problems, such as eutrophication, or heavy metals contamination. This knowledge will also be very useful for applied biology, as in fisheries or marine organisms farming.

The following report is a first step in this direction of dynamic description of the biology of the marine ecosystem, in the Sluice dock at Ostend and the Southern Bight of the North Sea.

1.- Primary production

1.1.- Methods

1.1.1.- Primary production (photosynthesis measurements)

The $^{14}CO_2$ technique [Steemann Nielsen (1952)] has been used for photosynthesis measurements in the pelagic environment. *In vitro* incubations (potential production) have been performed at sea on each cruise and all sampling stations. Several *in situ* and *semi situ* incubations (integrated production) have also been performed [Mommaerts (1973a,b)]. Results are given separately for nannoplankton and netplankton after fractional filtration on 45 µm or 25 µm meshes [Mommaerts (1973a, b,f)].

Similarly, *in vitro* and *in situ* incubations were performed weekly in the Sluice Dock at Ostend [Podamo Jo (1973a), (1974)].

A prototype for the automatization of sampling and *in vitro* incubation has been built and used in the Sluice Dock. This device allows the collection of records for 24 h periods (experiments actually performed) or longer times (several days) [Podamo Jo (1973b), Cromboom and Mommaerts (1973)].

The phytobenthos production in the Sluice Dock has also been investigated. Some *in situ* oxygen production determinations (Winkler method) have been made. Clear and dark plexiglass incubation chambers were designed for such experiments [Podamo Jo (1973a)].

1.1.2.- Photosynthetically available radiation (P.A.R.)

Use was made of global solar radiation data known for the area from the continuous records made at De Haan, near Ostend, and calculated in Joules/cm^2/30 min at the Royal Meteorological Institute. We have measured the absorption of available radiation in the water column (range 400 - 700 mμ) . This was done at sea and in the Sluice Dock with an immersible photometer fitted with green, red and blue filters (Chance Pilkington O Gr 1, BG 7, RG 630). Calculations of energy fluxes are made as suggested in Vollenweider (1969).

1.1.3.- Phytoplankton standing crop

Chlorophyll and phaeophytin a have been determined weekly in the Sluice Dock at Ostend as described in Strickland and Parsons (1968). In the North Sea, this work is done and discussed by Steyaert and Lancelot-Van Beveren (1973).

The Utermöhl technique [Utermöhl (1936)] has been used for the nannoplankton numerations in the Sluice Dock [Podamo Jo (1974)].

The improving of autoradiographic procedures for phytoplankton numeration is going on [Mommaerts (1972d), Cromboom et Mommaerts (1974)].

1.1.4.- Precision of the measurements

a) $^{14}CO_2$ incubations

At the 30 mg C/m^3/h level, the standard deviation represents 8 % of the average [Mommaerts (1973d)]. At the 2 mg C/m^3/h level, it amounts to 23 % [Mommaerts (1973e)]. In both cases this was determined experimentally by incubating 10 subsamples under the usual working conditions.

b) Pigments

The precision of the measurements has been estimated in the same way for the Sluice Dock at Ostend : 10 subsamples : standard deviation 2 % of the average, at the 10 mg chlor a/m^3 level.

1.2.- Results

1.2.1.- Spatial and temporal variations of phytoplankton

a) North Sea

A synthetic approach to the spatial distribution patterns of phytoplankton in the area studied is attempted with the potential production results collected from 1971 to 1973 [Mommaerts (1972a), (1972b), (1972c), (1973c)].

From the average depth profile (fig. 6.1) it appears that the water is thoroughly mixed in the water column (the mouth of the estuaries excepted) [Mommaerts (1973b)].

An average horizontal distribution profile (from coast to open sea) has also been computed for each cruise. The existence of an important nannoplanktonic fraction (escaping meshes of 45 µm and even 25 µm) has been emphasized [Mommaerts (1973a), (1973f)]. It seems to be chiefly composed of flagellates as shown in Mommaerts (1973g) and also Steyaert et Van Beveren (1972). When nannoplankton and netplankton are considered separately, typical patterns are demonstrated for each period of the year (figs. 6.2 and 6.3) : winter, spring bloom, summer, automnal bloom. All these profiles can in turn be synthetized in one figure (fig. 6.4). One sees that the high standing crop fringe extends to 50 km off the coast.

From 30 km , the nannoplanktonic potential production becomes proportionally more important than that of netplankton. It is possible that this pattern is related to the nutrients profile [Elskens (1972)] in connection with the lower specific half-saturation constants for limiting nutrient uptake that are exhibited by nannoplanktonic phytoplankton [Parsons and Takahashi (1973)].

Our records, however limited in number, show that the amplitude of seasonal variations of netplanktonic production can be important in the coastal area in contrast with those of nannoplanktonic production. However, in the open sea both categories exhibit variations of very low amplitude. Such patterns have led to the concept of zones [Elskens (1972)] *i.e.* a coastal fringe (zone 1), relatively important for the area

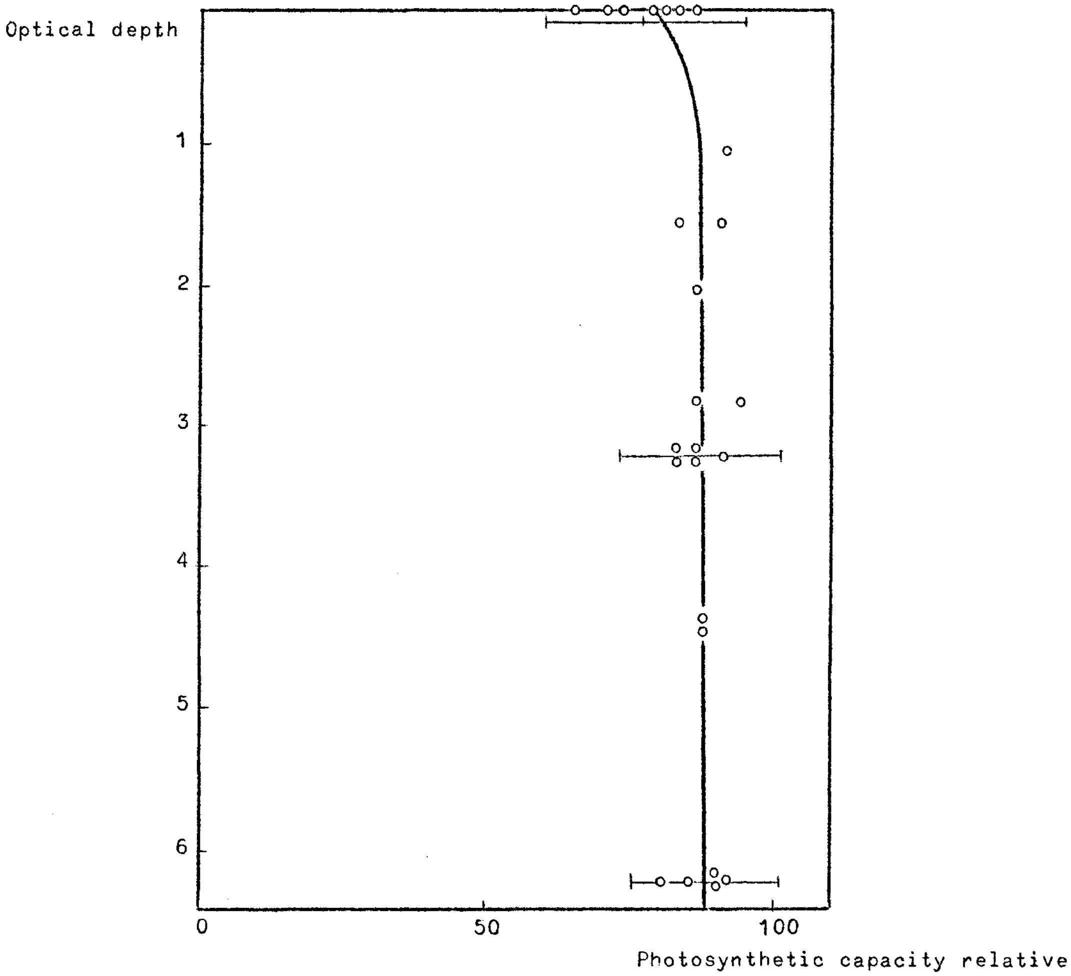
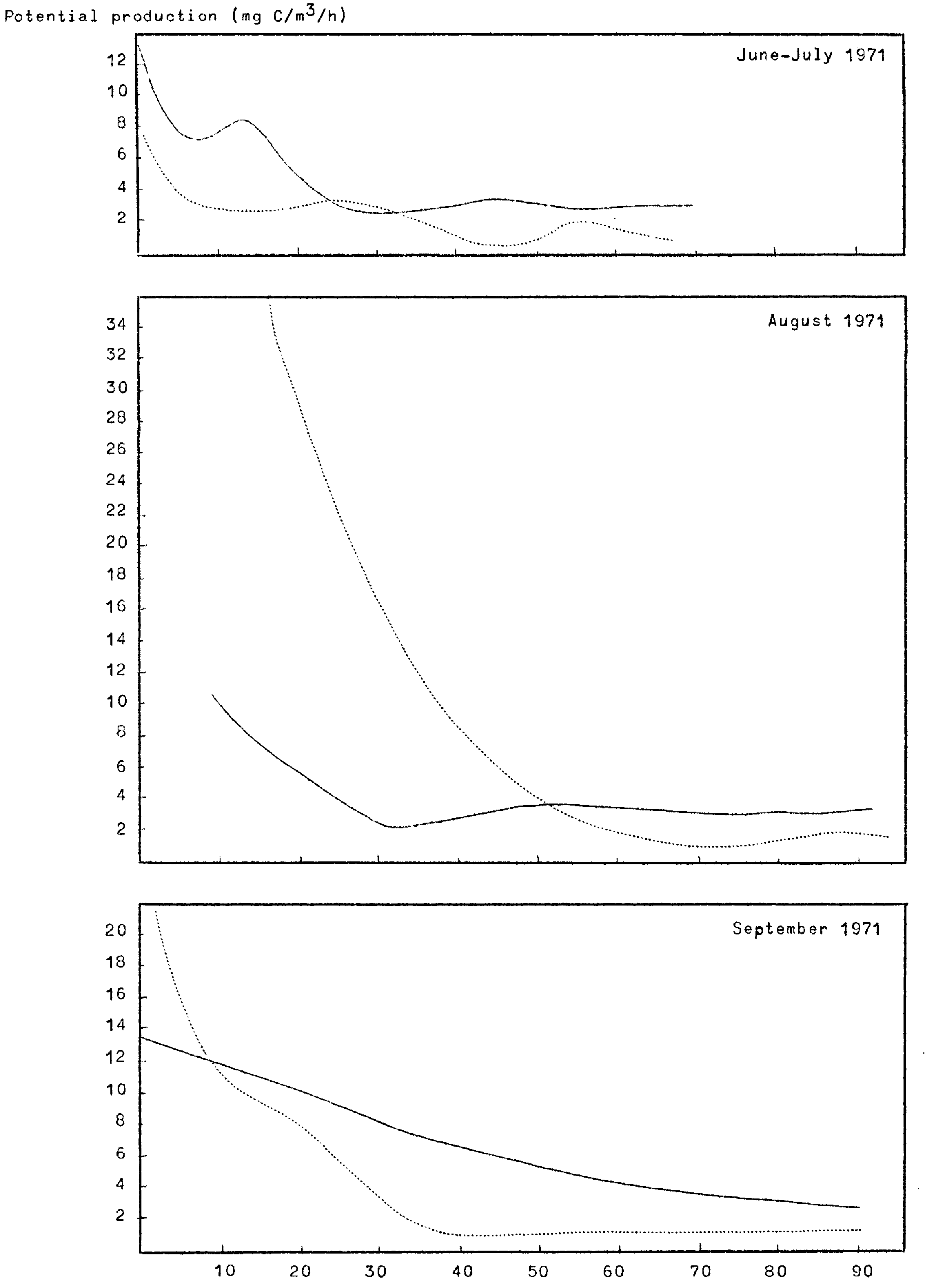


fig. 6.1.
Average depth profile of potential production. Each potential production result has been expressed as a percentage of the maximum figure recorded in the water column; then the figures are averaged for every cruise and relative irradiance level. The optical depth scale is such that each unit causes a halving of irradiance.

studied, and the beginning of a vast area (zone 2) more exactly representative of the Southern Bight of the North Sea. One has also considered a division in zone 1 (fig. 6.38 and table 8.1), as figures differ frequently in the northern (1N) and in the southern parts (1S). Seasonal variations recorded in the North Sea (fig. 6.5) conform to patterns known from the literature for temperate coastal seas [*e.g.* in Raymont (1963)]. In the course of a week however, the potential production variations seem to be negligible. The study of the nycthemeral cycle of production might help in the understanding of this slow variation pattern. Such cycles


Potential production (mg C/m³/h)
June-July 1971
12
10
8
6
4
2
August 1971
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
September 1971
20
18
16
14
12
10
8
6
4
2
10
20
30
40
50
60
70
80
90
Distance to the coast (km)

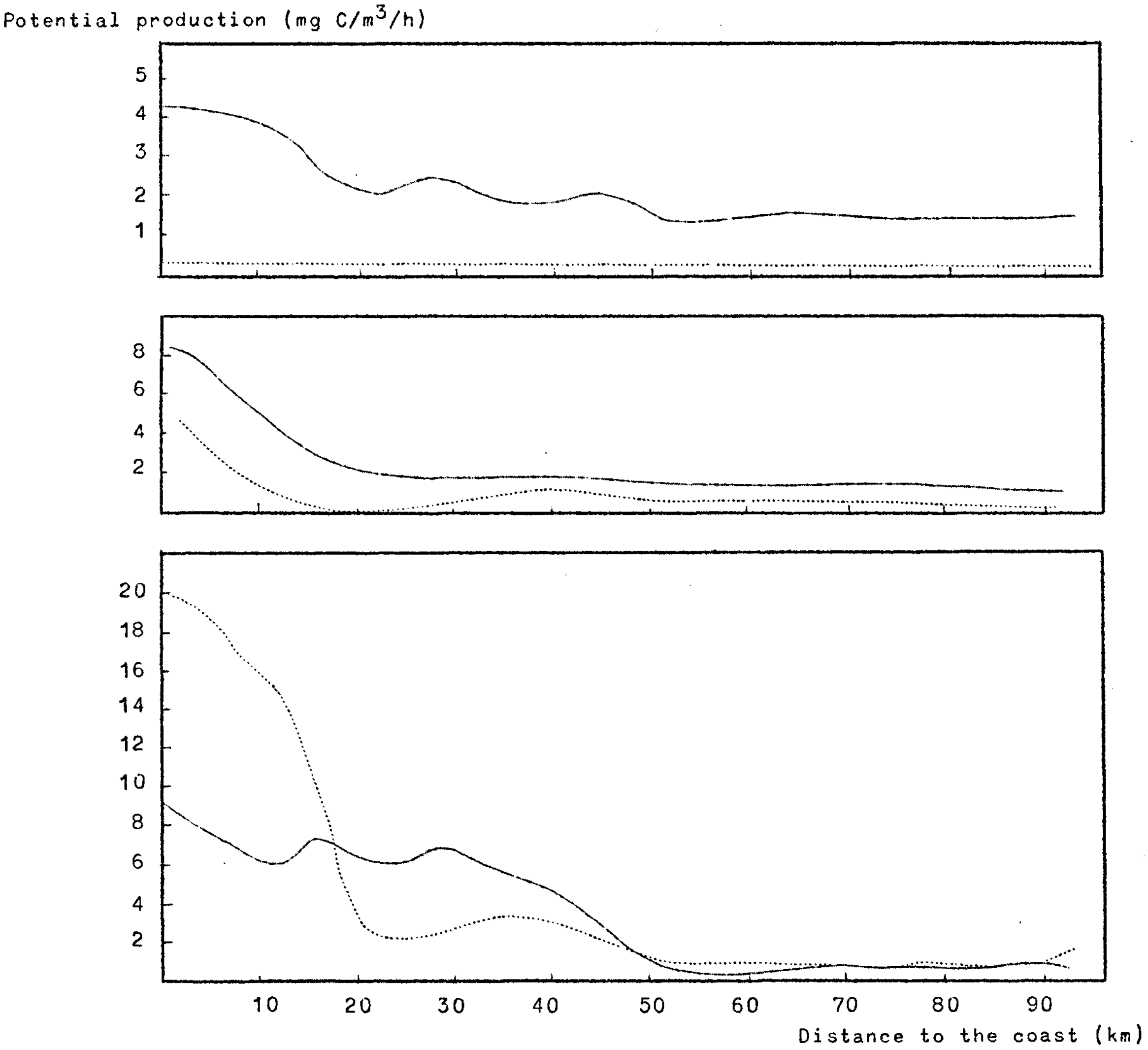


fig. 6.2. and 6.3.

Average horizontal distribution patterns of potential production at different times of the year. (Stippled line : netplankton; solid line : nannoplankton.)

have been studied at sea with variable results [Mommaerts (1973g)]. Indeed, water motions interfere on such experiments. However, experiments made in the Sluice Dock either with automatization device [Cromboom et Mommaerts (1973)] or in the usual way (see below) give consistent results.

b) Sluice Dock

The water is fairly homogeneously distributed in the Sluice Dock. Phytoplankton stratification is negligible in most cases. Where the horizontal distribution pattern is concerned, a narrow littoral fringe shows

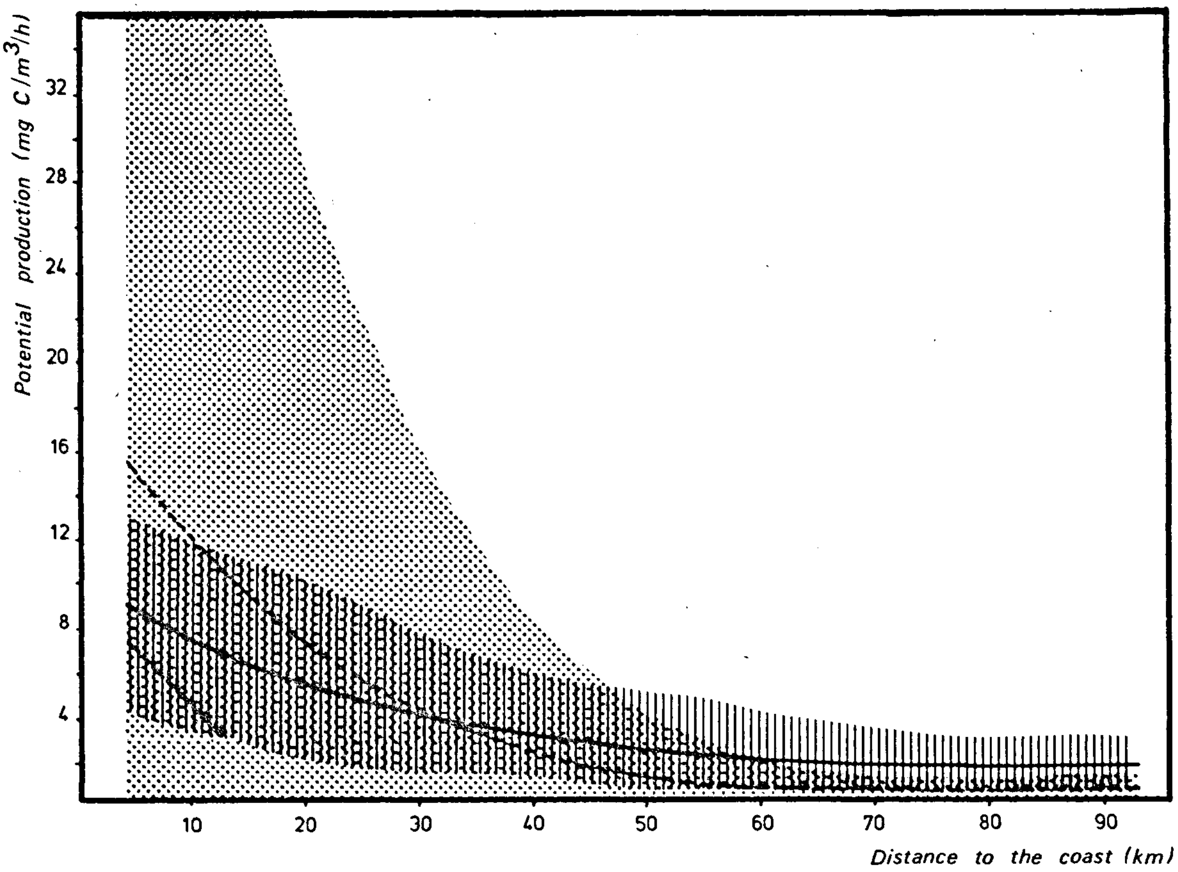


fig. 6.4.
Average horizontal distribution pattern of potential production, averaged for the year (stippled line : netplankton; solid line : nannoplankton). The dotted area shows the range of variations for netplankton. The hatched area shows the range of nannoplankton variations.

higher production figures. However, results collected from a single central sampling station are very representative for most of the area.

An important phytobenthic community of macrophytic seaweeds can develop in the Sluice Dock as relatively high irradiance levels (commonly 25 % of surface irradiance) are recorded on the bottom. The seaweeds grow mainly at the periphery. Biomasses are very important. As much as 2 to 3 kg wet weight/m^2 have been recorded in July. At this time of the year the total Sluice Dock phytobenthic production amounts to about one third of that of the phytoplankton [Podamo Jo (1973a)].

Seasonal variations recorded in the Sluice Dock [Podamo Jo (1974)] are very different from those observed in the North Sea. In this

Table 6.1

Period	Zone	Production/ m^2/d	Total biomass/ m^2	Implied biomass/ m^2	Available radiation/ m^2/d	Efficiency/kcal	
						(1)	(2)
January 71	1S	960	13500	2250	52000	0.82	0.13
June-July 71	1S	6420	37530	5000	440000	0.29	0.03
	2	7220	37170	15930	440000	0.10	0.04
August 71	1N	18420	46620	15150	349000	0.35	0.11
	2	9530	28660	18830	349000	0.14	0.09
September 71	1S	7000	53520	10700	289000	0.22	0.04
	1N	15000	107190	32150	289000	0.16	0.04
	2	7320	28350	15390	289000	0.16	0.08
January 72	1S	520	9040	1500	52000	0.66	0.11
	1N	1550	4500	3370	52000	0.88	0.66
	2	1290	9450	3510	52000	0.70	0.26
April 72	1S	3150	24570	6550	302000	0.15	0.04
	1N	3440	19440	5340	302000	0.20	0.05
	2	3320	11180	6070	302000	0.18	0.09
June-July 72	1S	7160	13770	10100	440000	0.16	0.11
	1N	7300	9450	9450	440000	0.17	0.17
	2	5670	13230	13230	440000	0.10	0.09
September 72	1S	3800	20110	6030	289000	0.21	0.06
	1N	5750	48150	14440	289000	0.13	0.04
	2	5080	10710	5200	289000	0.34	0.16
October 72	1S	4880	17680	6480	176000	0.42	0.15
	2	4390	4450	4390	176000	0.56	0.55
January 73	1S	1180	4110	1370	52000	1.65	0.55
	2	1200	3920	1570	52000	1.47	0.58
April 73	1S	4950	81670	13610	302000	0.10	0.01
	1N	6260	49220	17220	302000	0.12	0.04
	2	2470	15570	4000	302000	0.20	0.05
June 73	1S	3400	13420	2230	435000	0.35	0.05
	1N	13250	30140	24110	435000	0.12	0.10
	2	1090	5350	3520	435000	0.07	0.04

All parameters in gcal.

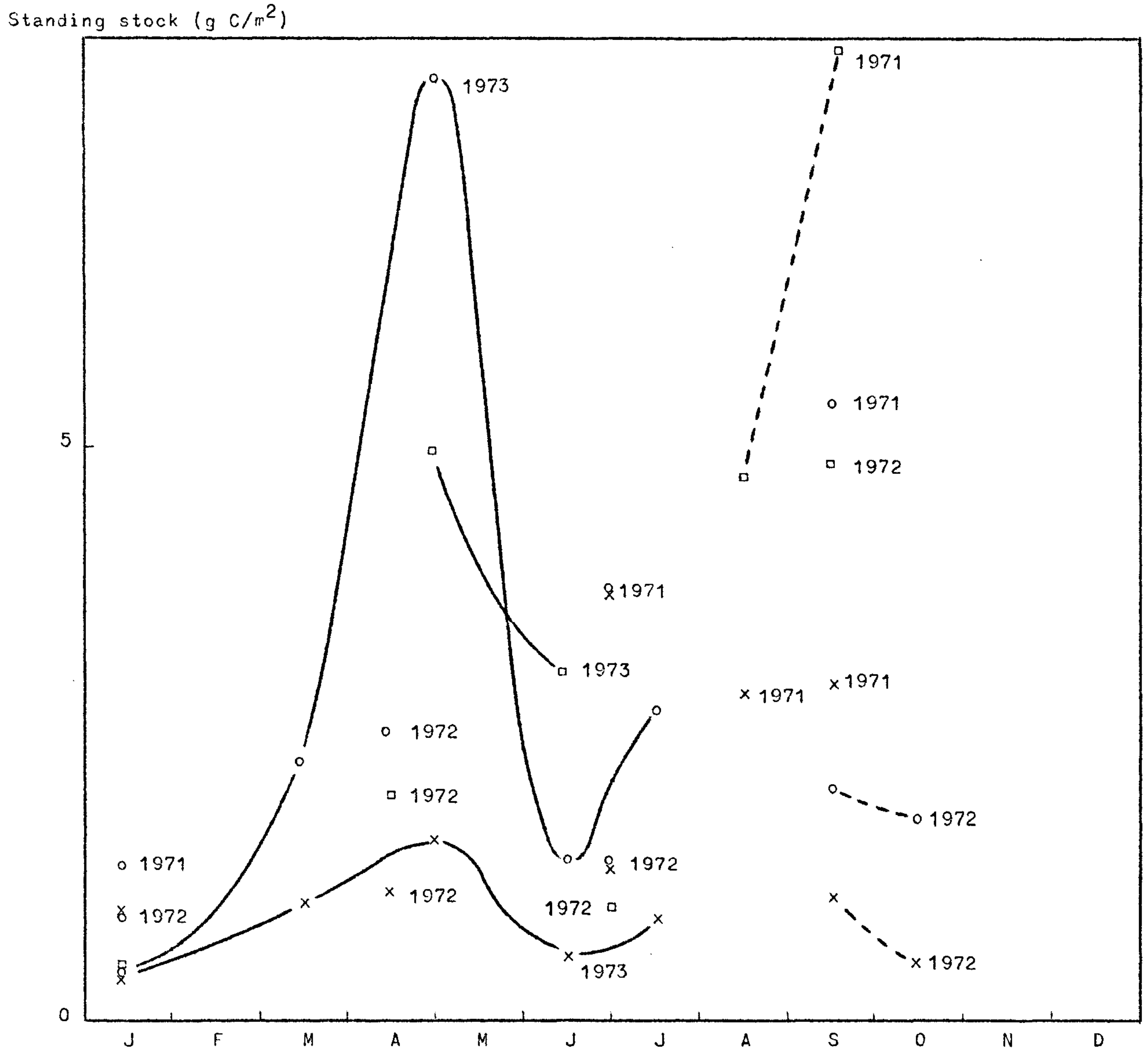


fig. 6.5.
Annual variation of phytoplankton standing stock in the Southern Bight of the North Sea known from the different cruises. A sufficient frequency of samplings allows the 1973 results to be linked (circles : zone 1S ; crosses : zone 2 ; squares : zone 1N).

particular environment, low production levels are observed until the end of May. Grazing is the main limiting factor in May. From June to the end of August, production is very important (fig. 6.6). This is only possible with a very efficient recycling of the nutrients.

Nycthemeral cycles of production observed at various times of the year show typical features. One of those cycles has been particularly

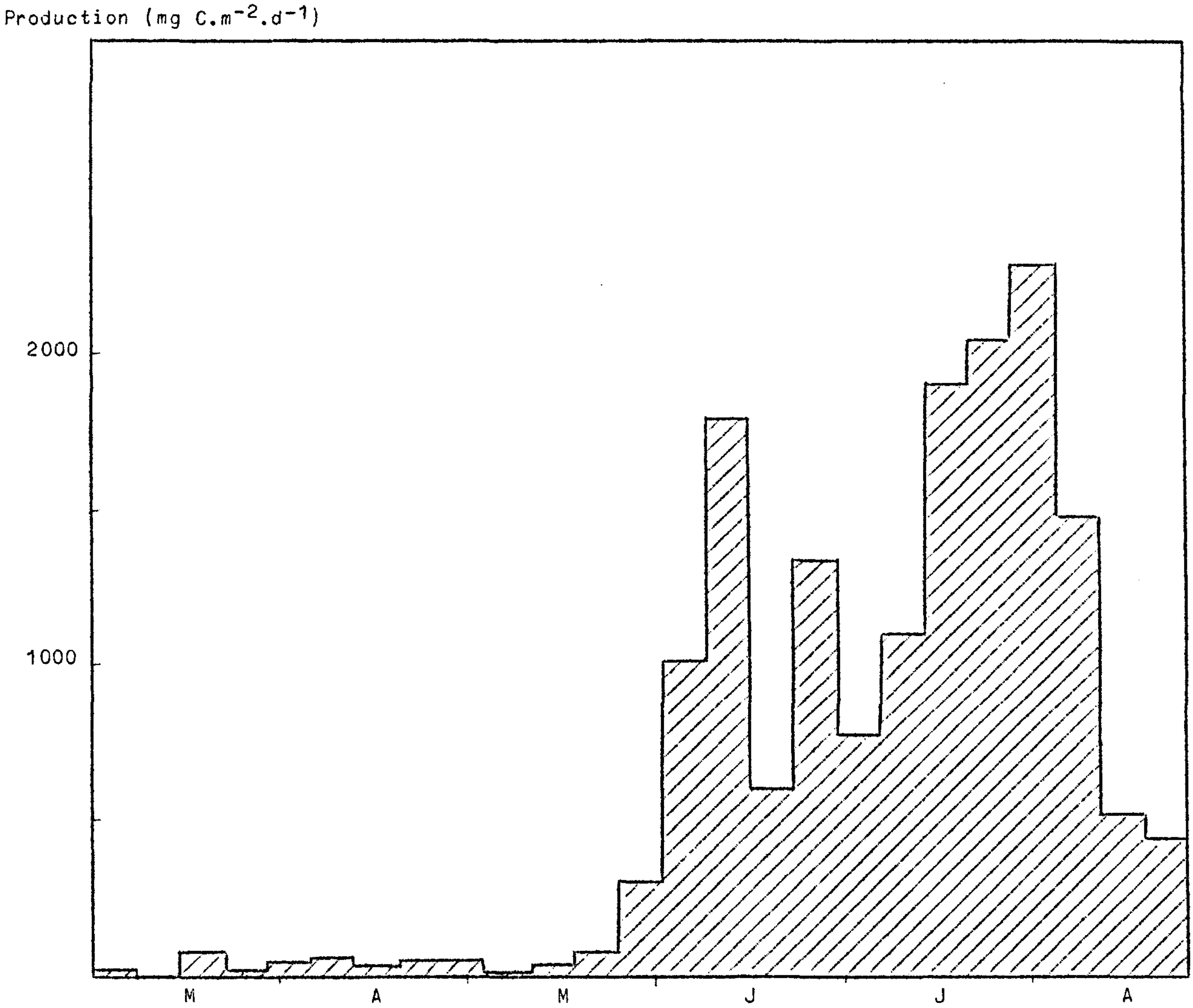


fig. 6.6.
Annual variation of phytoplankton production in the Sluice Dock at Ostend, in 1972.

studied in a slow variation period (May) [Mommaerts (1973g)]. Fig. 6.7 shows the evolution of potential production, chlorophyll a and phaeophytin a on 28.5.1973.

As a result of primary production, the phytoplanktonic biomass increases in the day time (as shown in the simultaneous fluctuations of chlorophyll a and potential production) until a peak is reached at the end of the afternoon. Phaeophytin a peaks seem to correspond to decay periods (especially at night). Figure 6.8 shows the production-mortality balance computed for 30 min intervals. The mortality factor operates

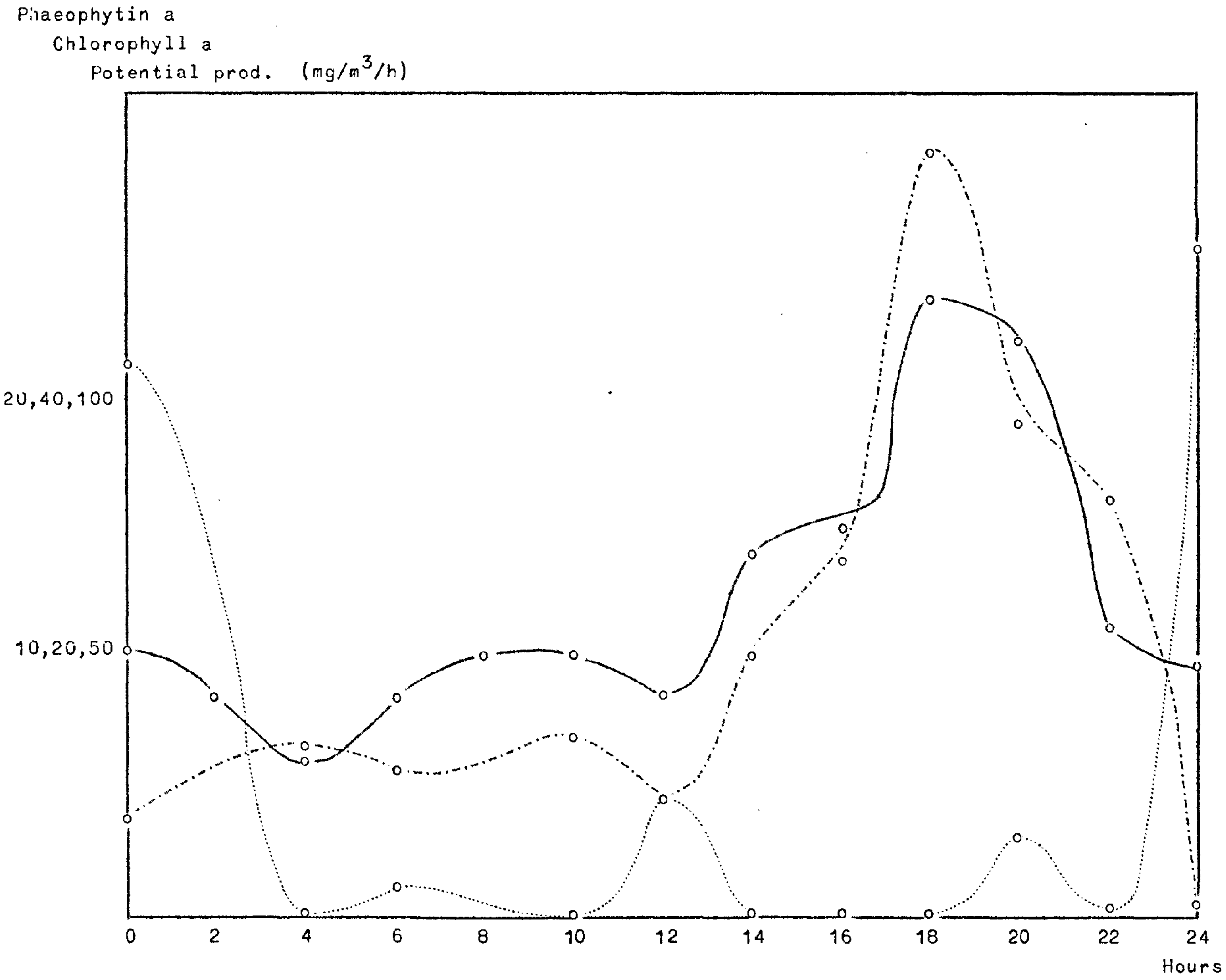


fig. 6.7.
Nycthemeral variation of potential production (solid line), chlorophyll a (dots and dashes) and phaeophytin a (dotted line) in the Sluice Dock at Ostend on 29th May 1973.

at day but is most important at night. Correspondingly, biomass increases are limited and ultimately annulled. The relative importance of grazing in the mortality measured on this particular day could not be determined. We think that such a cycle could explain the slow variation pattern demonstrated in May and perhaps also those observed at sea.

1.2.2.- Productivity

The ratio $\frac{\text{potential production}}{\text{biomass}}$ (productivity) reflects the physiological condition of the phytoplankton community at the sampling station as well as its specific composition.

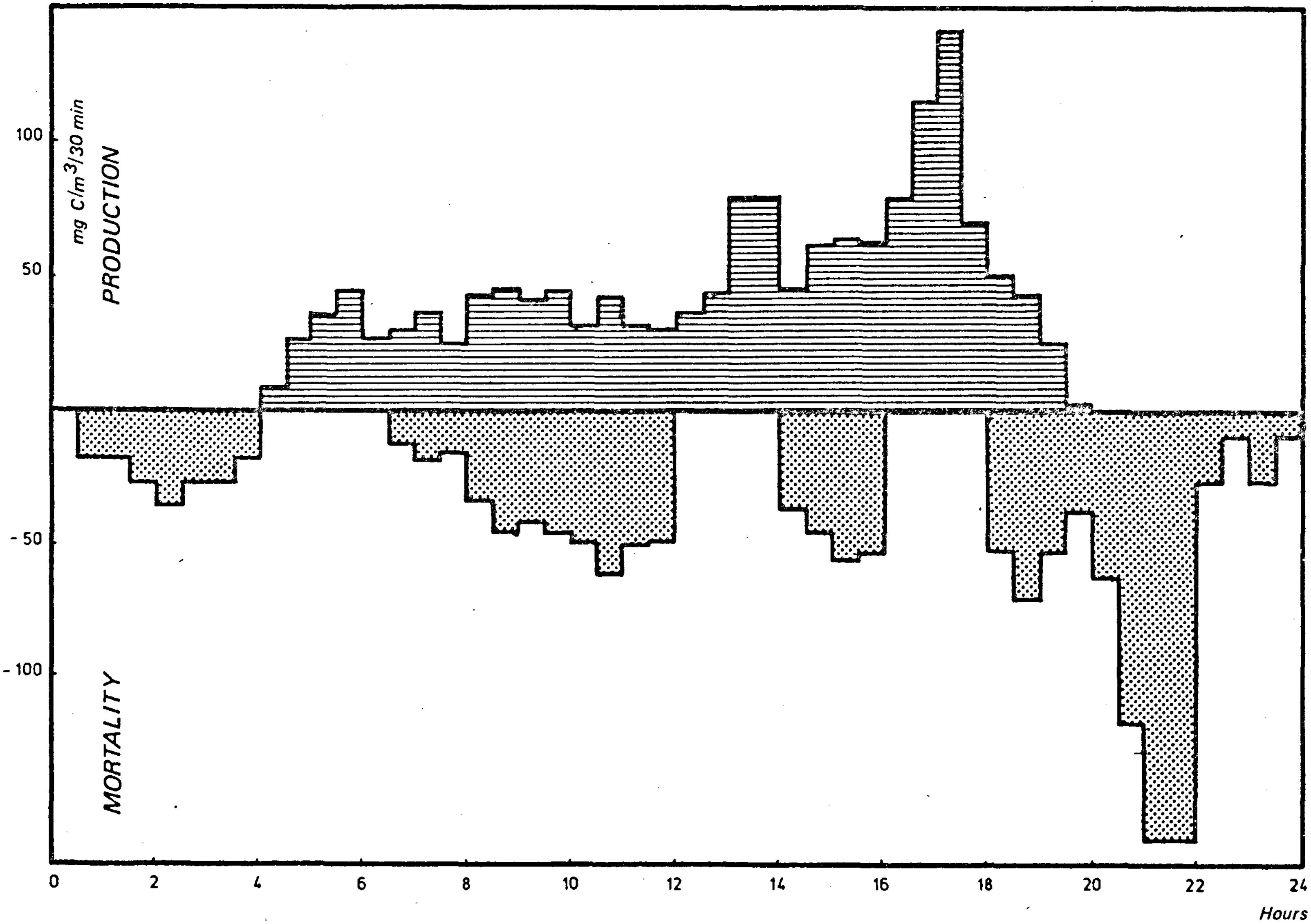


fig. 6.8.

Production-mortality balance computed for the 29th May 1973 cycle. The actual production increment for each 30 min block is the sum of mortality (-) and production (+) figures.

In the first case it can reflect the effect of environmental modifications. Population ageing or internal rhythms are corollary effects. Examples are provided by the lower winter figures (temperature effect), the abnormal figures recorded at sampling stations 6 and 7, July 1971 (environmental disturbance) [Mommaerts (1973b)]. An example of seasonal transition is observed in the Sluice Dock at Ostend when productivity is in full augmentation however nothing of this appears from production measurements [Podamo Jo (1974)]. Indeed, at this time of the year (May), the phytoplanktonic biomass remains low as zooplankton is actively grazing on it.

Nycthemeral variations of productivity reflect also physiological modifications. Such variations have been demonstrated in the North Sea [Mommaerts (1973g)]. One has recorded a peak of maximal endogenous activity at the time of optimal daylight intensity (noon in the winter and . later in the afternoon at the end of spring) (fig. 6.9).

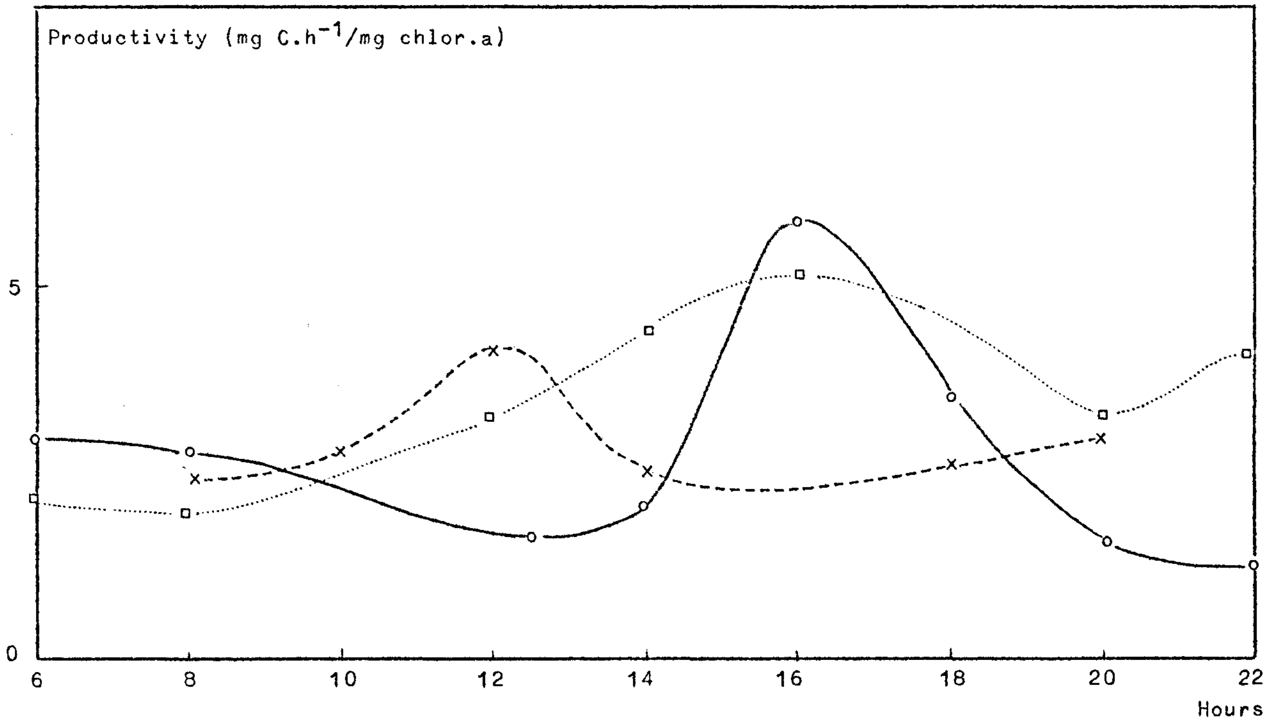


fig. 6.9.

Nycthemeral variation of productivity (P/B ratio) in the Southern Bight, at sampling station 16, 8th May 1973 (solid line); sampling station 1, 24th January 1973 (stippled line) and sampling station 6, 7th June 1973 (dotted line).

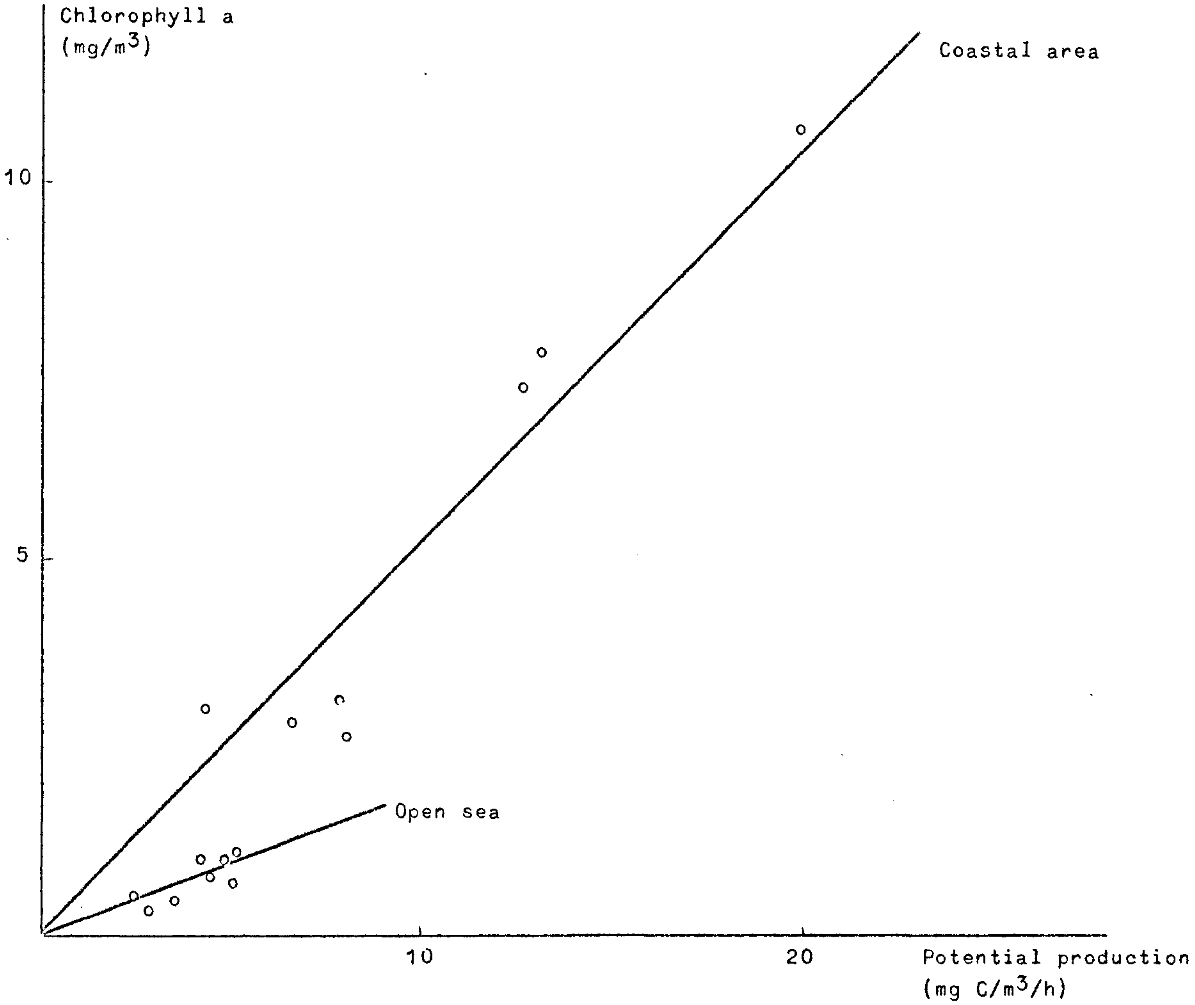


fig. 6.10.
Potential production - chlorophyll a relationship in the Southern Bight of the North Sea, in September 1972.

Where the specific composition is concerned, an example is found in the differences recorded between open sea and coastal water productivity figures [Mommaerts (1973g)]. Productivity is higher in the open sea, where nannoplankton is dominant. On the contrary, figures recorded for coastal waters where netplankton is dominant are lower (fig. 6.10).

1.2.3.- Light-temperature adaptation properties

With production measurements made simultaneously *in situ* and *in vitro*, one has computed photosynthesis-light diagrams for many sampling stations and cruises (fig. 6.11) [Mommaerts (1973g)]. From each diagram

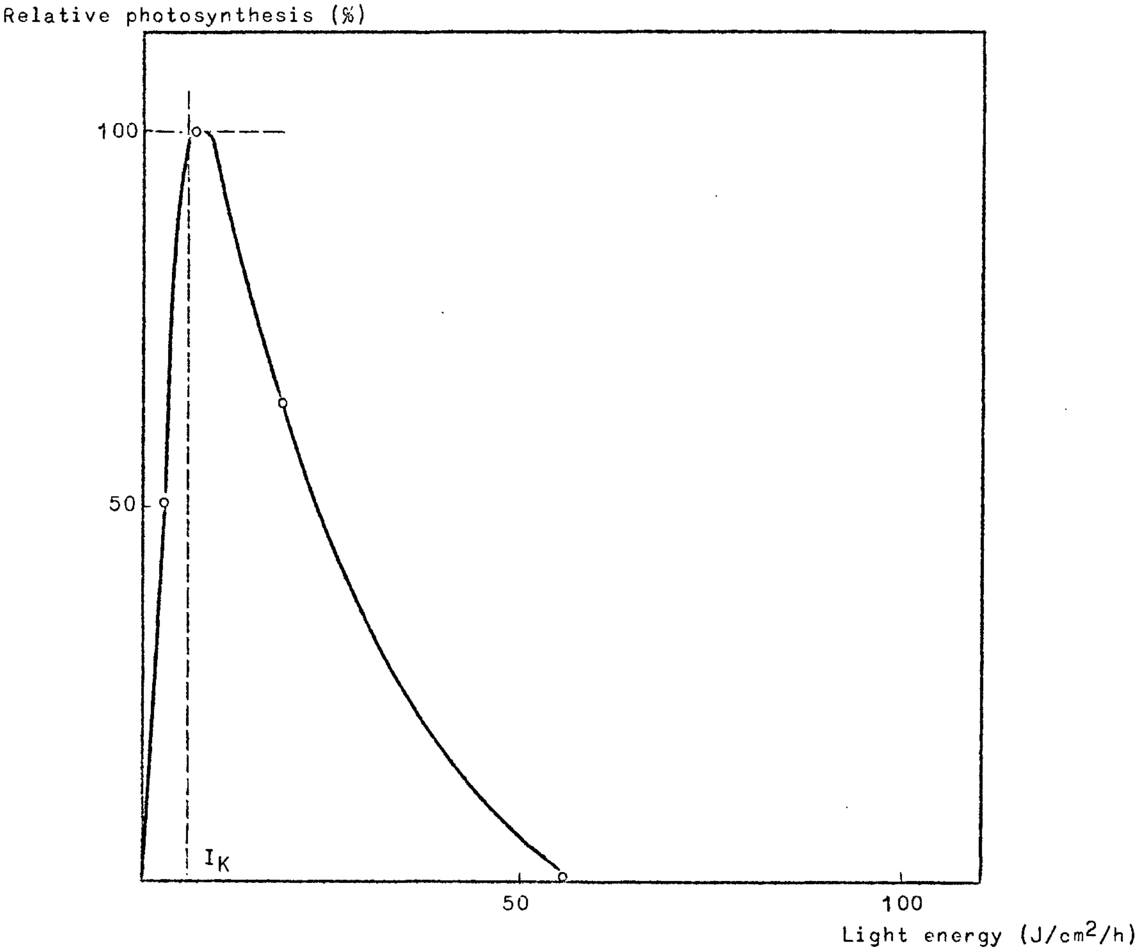


fig. 6.11.

Photosynthesis-light diagram for phytoplankton collected at sampling station 61, 17th April 1972, in the Southern Bight of the North Sea.

one can calculate a light intensity I_K (defined as the intensity at which the onset of photosynthesis saturation is recorded) which measures the light-adaptation property of the phytoplankton community at sampling time. A small I_K corresponds to a better efficiency of light energy utilization. In the North Sea, figures ranging between 2 and 34 J/cm^2/h (P.A.R.) have been recorded. In the Sluice Dock (fig. 6.12) at Ostend however, I_K figures are always higher (about 50 J/cm^2/h). Another difference is the strong photoinhibition pattern that is exhibited immediately after saturation (no real plateau) for North Sea phytoplankton while the Sluice Dock phytoplankton shows almost no photoinhibition in the range of light intensities recorded (up to 200 J/cm^2/h). These

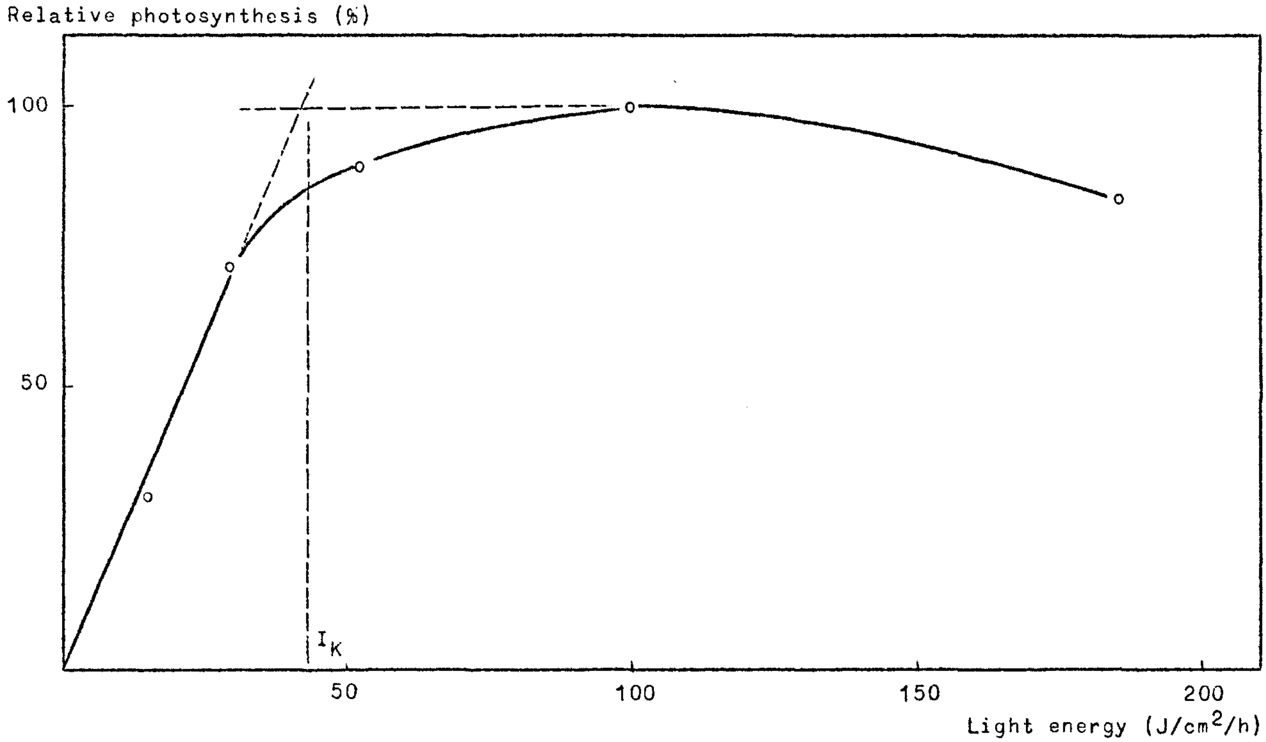


fig. 6.12.
Photosynthesis-light diagram for phytoplankton collected on 2d May 1973 in the Sluice Dock at Ostend.

differences probably reflect the adaptation of the North Sea phytoplankton to the lower average illumination conditions that prevail in this environment.

I_K is also temperature-sensitive. Lower winter figures have an ecological importance as saturation of photosynthesis is reached at deeper levels. Hence, the effect of poor illumination conditions is partially compensated by an improved utilization of light energy in the water column.

Finally, diurnal variations of I_K have been observed in the Sluice Dock and are at study.

1.2.4.- Integrated production

The spatial distribution of phytoplankton in the North Sea being known, and having determined :

1) the variation mechanisms of productivity [Production = f (Biomass) with light energy kept constant].

2) the variation mechanisms of light adaptation [Production = f (Light energy) with biomass kept constant],

one can feed these parameters in an integrated production model. The absorption coefficient of the water for photosynthetically available radiation η and the incident radiation I_0 are also used in such a model [*e.g.* Vollenweider (1965), Mommaerts (1973g)].

Hence, spatial distribution of potential production (as well as pigments) does not strictly reflect that of real *in situ* primary production. It was demonstrated that the low transparency of coastal waters limits the primary production in such a way that only a fraction (upper layer) of the phytoplanktonic biomass is implied in photosynthesis. This has a considerable levelling effect on differences between zones (fig. 6.13).

But this also means a difference in yields [Mommaerts (1973g)]. Expressed as efficiency percentage of energy transfer per Kcal of total biomass under a m^2 , one finds on an average 0.11 % in zone 1-South, 0.15 % in zone 1-N and 0.18 % in zone 2. Hence the flux of organic matter through the phytoplankton is about 1.5 times greater in the open sea than that measured in the coastal fringe (Table 6.1).

1.3.- Conclusion

The Southern Bight of the North Sea and the Sluice Dock at Ostend have been surveyed intensively so that we have a fairly good picture of spatial and temporal variations of phytoplankton activity, by now. A further insight on production mechanisms was given by the study of productivity ($\frac{P}{B}$ ratio) and light adaptation variations. Still there is much left to do in this respect especially in connection with the nutrients availability. In the same connection, the study of specific nutrient uptake abilities could help in the understanding of the succession or the spatial distribution of phytoplanktonic populations. The differences observed between netplankton and nannoplankton are probably relevant to this problem.

The study of the effect of zooplankton grazing on phytoplankton production is also scheduled. Studies on phytoplankton mortality have already been started in 24 h observation cycles. On the other hand

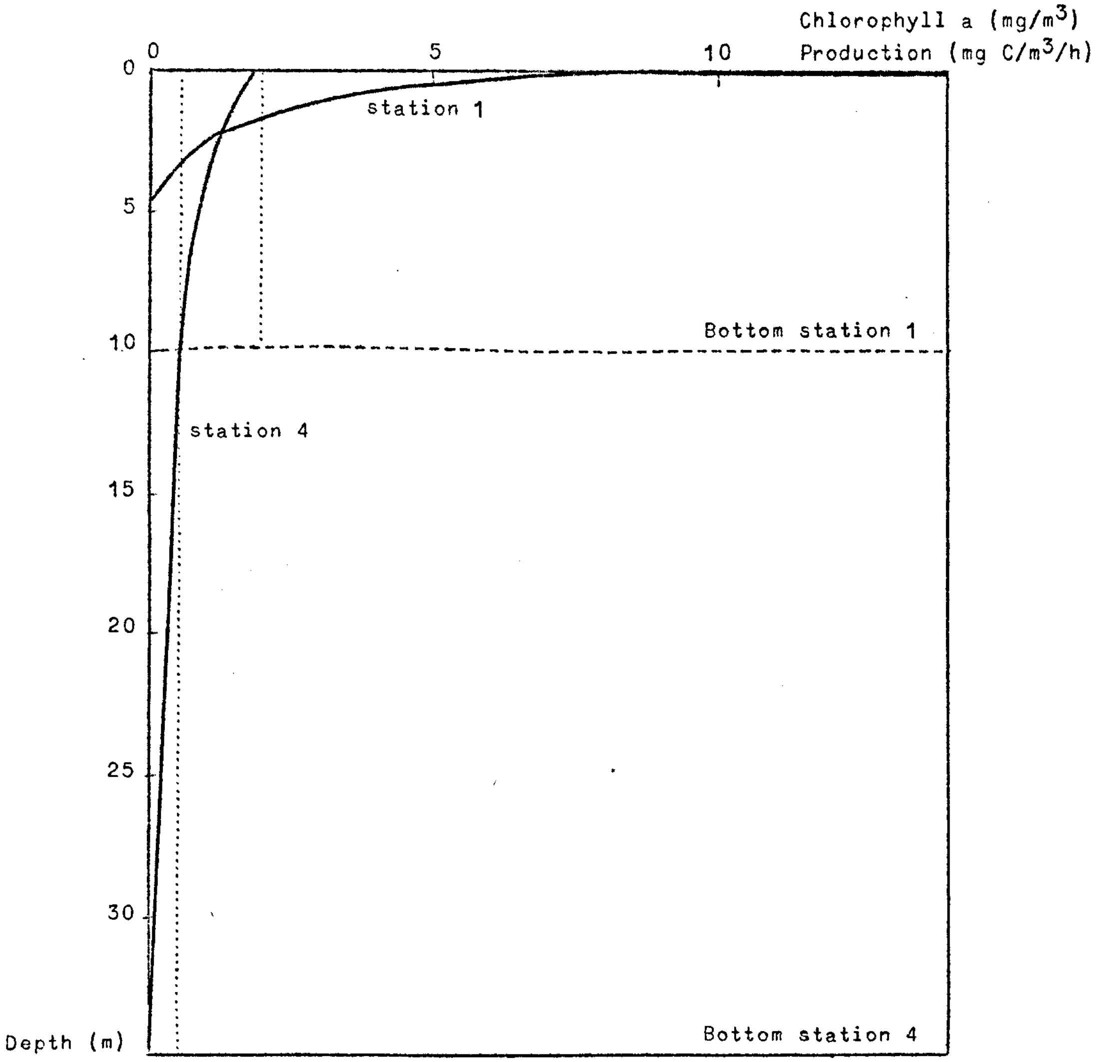


fig. 6.13.
Production (solid line) and chlorophyll a (dotted line) vertical profiles at sampling stations 1, 11th October 1972, and 4, 12th October 1972, in the Southern Bight of the North Sea.

some *in situ* experiments (unpublished) have shown an enhancement of primary production when the phytoplankton was exposed to the influence of zooplankton. Grazing effect and enhancement set an interesting interaction problem.

The problem of production modelling remains. First attempts concern only static solutions. One hopes to feed more interaction parameters and variation laws in successively improved models.

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2.- Zooplankton

2.1.- Introduction

The quantitative and qualitative evolution of zooplankton has been studied for several years at the Sluice Dock at Ostend [Leloup and Polk (1967), Daro and Soroa (1970), Daro (in preparation)], in 1970, 1971 and 1972 in the North Sea in a zone of 20 km^2 near the shore (zone 1S) by monthly sampling and in the Southern Bight of the North Sea (Mathematical model of the North Sea network) during the cruises in 1971, 1972 and 1973.

The description of the spatial and temporal distribution of the zooplankton different species in the North Sea [Polk (1971), Bossicart, Hecq, Heyden, Houvenaghel and Polk (1972)] is followed by a description of their metabolic activity and their role in the ecosystem.

An approach for the calculation of the secondary production is proposed.

2.2.- Methods

2.2.1.- In the Sluice Dock at Ostend

Weekly sampling by filtering 50 ℓ water through a 48 μ mesh net gives us the year cycli on a quantitative and qualitative basis. A composed net was designed to study the nycthemeral vertical migrations [Daro (1974)] and observations by a binocular was done on living material in the field laboratory to study the ethology and autoecology of the dominant species [Daro (1973)].

2.2.2.- Lombardzijde

Monthly quantitative sampling was obtained by filtering 50 ℓ water in a plankton net of 48 μ meshes; 9 points were sampled in a 20 km^2 zone.

2.2.3.- Southern Bight of the North Sea

Sampling of zooplankton was done during the cruises at each point of the network as in §2.2.2 (Qualitative sampling was done with a

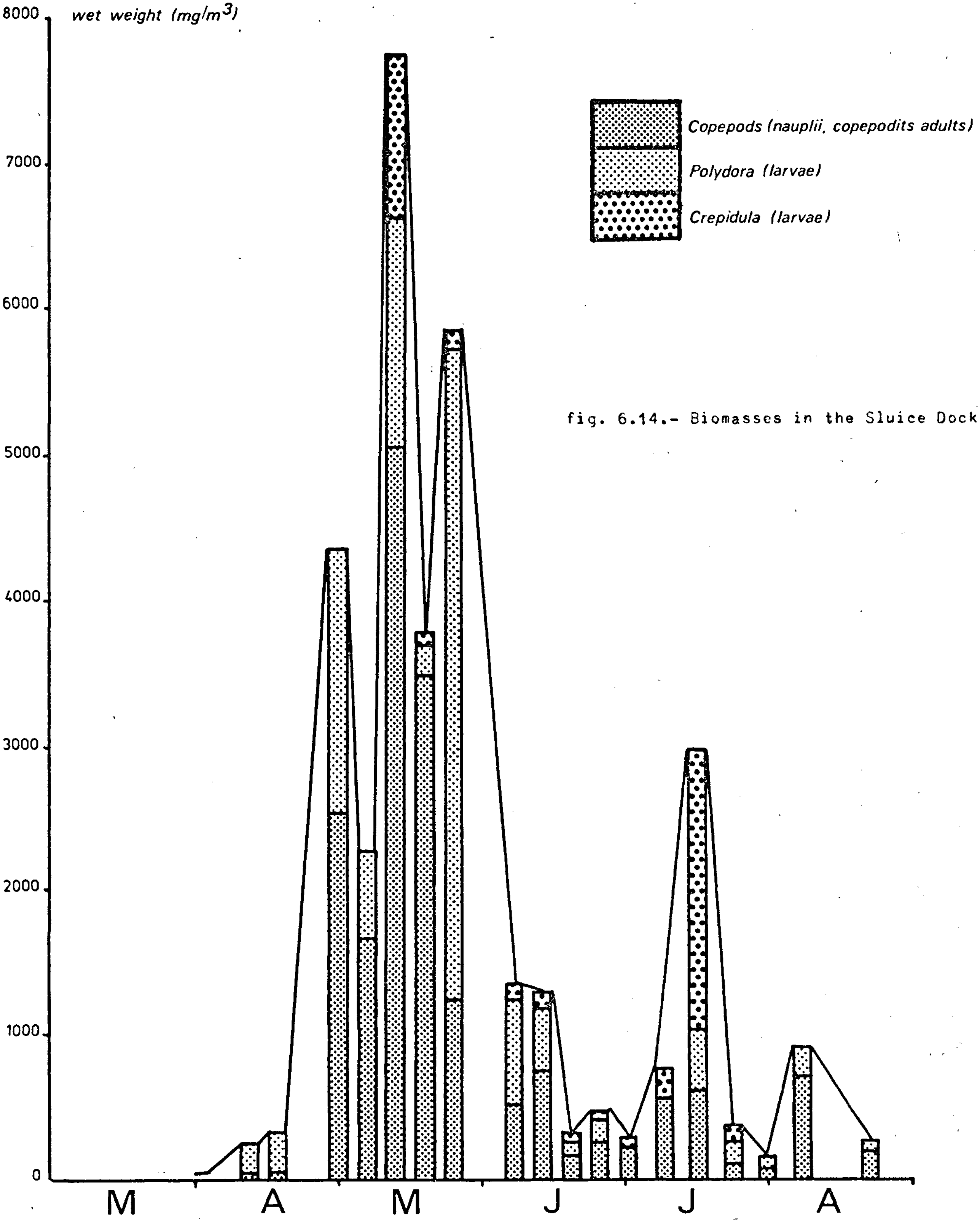


fig. 6.14.- Biomasses in the Sluice Dock.

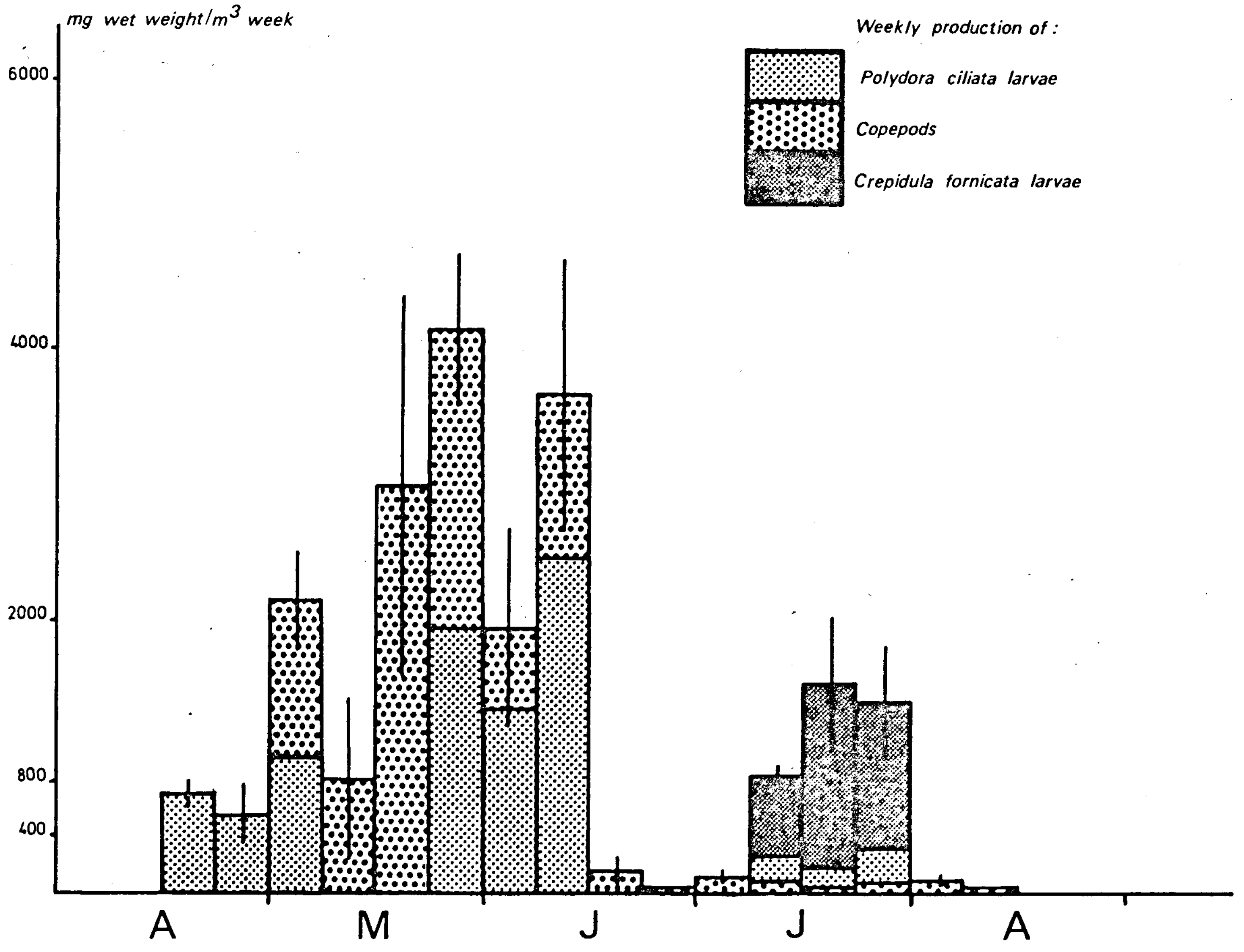


fig. 6.15.- Secondary production in the Sluice Dock.

zooplankton net of 200 µ meshes by hauls of ± 15 min). Respiration rates were carried out on the ship by incubation of zooplankton in dark bottles Winkler of 300 mℓ , at the temperature of the sea water during 9 h time. Oxygen was determined by the Winkler method (see Hecq).

2.3.- Results

2.3.1.- Sluice Dock

a) Distribution

The horizontal distribution in the Sluice Dock is homogeneous; vertical nycthemeral migrations were studied. Specific migrations patterns are established for the dominant species and their age classes [Daro (1973), Daro (1974)].

b) Secondary production

The evolution of the biomass during the year shows the dominancy of 4 species all herbivorous (fig. 6.14). To calculate the secondary production, we used the method of Winberg [Winberg (1970)]. Full details are found in Podamo Jo (1974).

The weekly production of each species is calculated for a 6 month period (fig. 6.15).

2.3.2.- North Sea

a) Distribution

The vertical distribution is homogeneous [Bossicart (1973)]. The horizontal distribution, correlated with hydrodynamics of the North Sea and under the influence of the estuaries [Polk (1972), Bossicart and Daro (1973)] permits us, using the dominant group of Copepoda (biomasses in wet weight) to distinguish three zones (see paragraph 1, Primary production) (figs. 6.16, 6.17, 6.18 and Table 6.2).

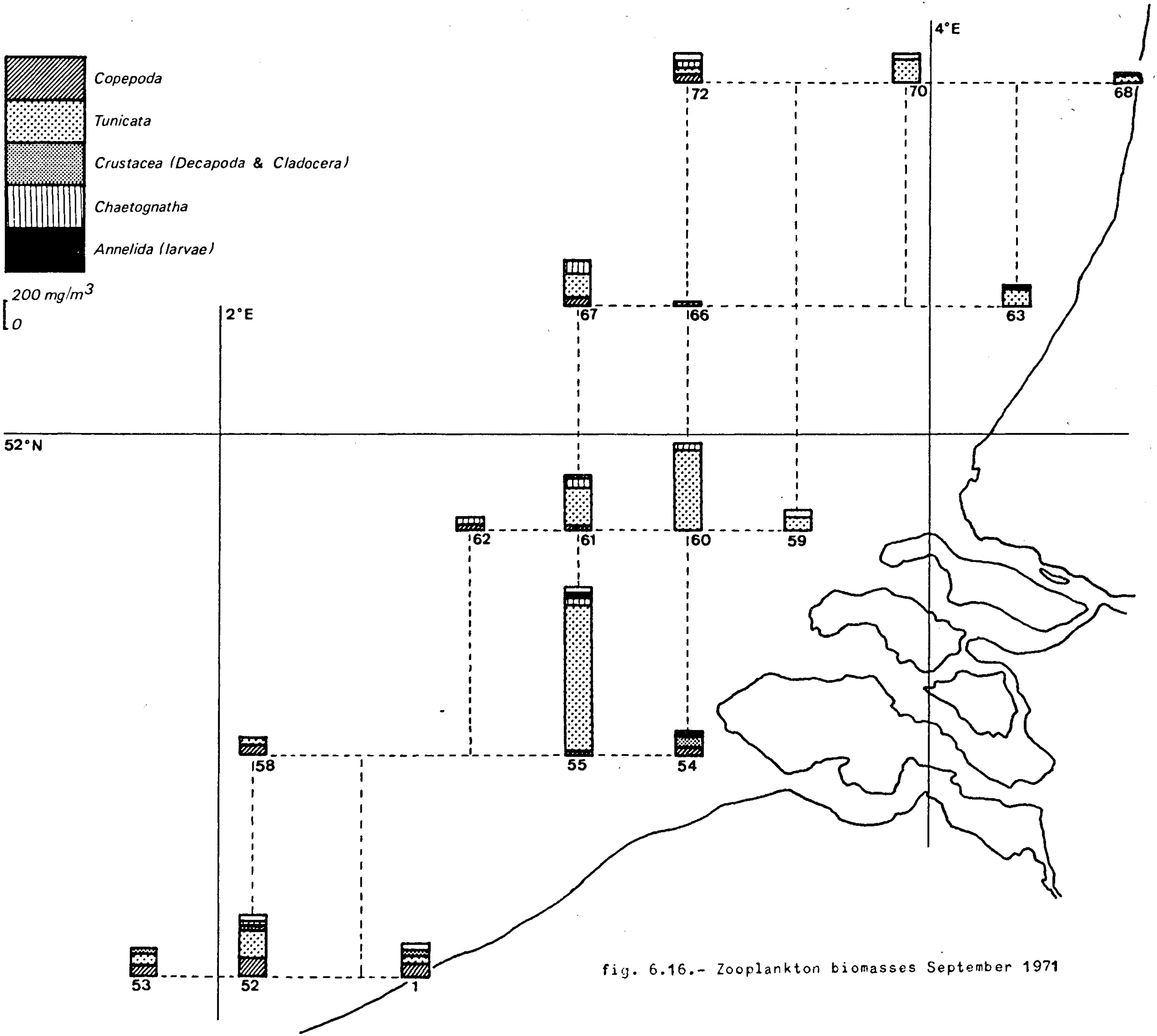


fig. 6.16.- Zooplankton biomasses September 1971

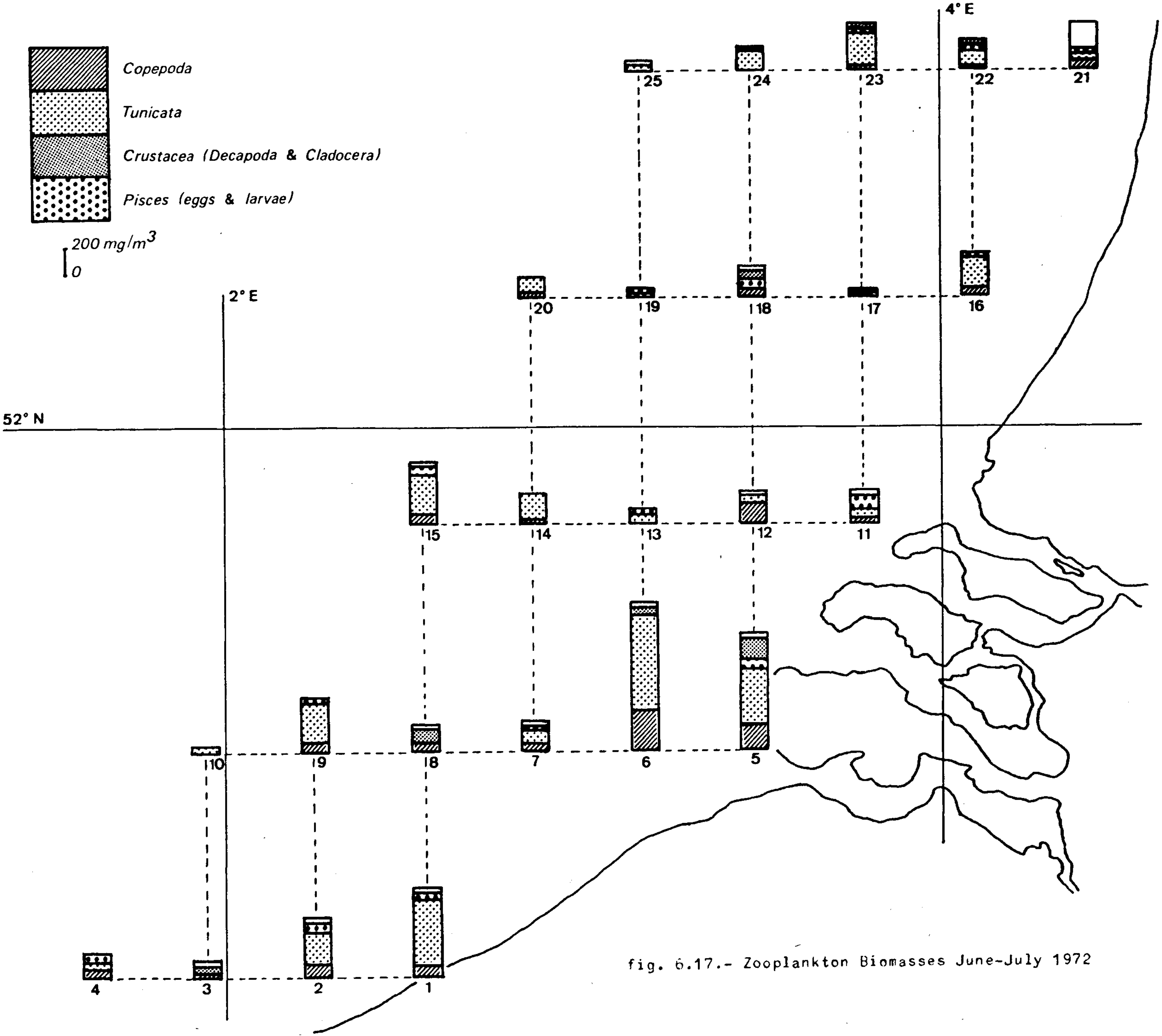


fig. 6.17.- Zooplankton Biomasses June-July 1972

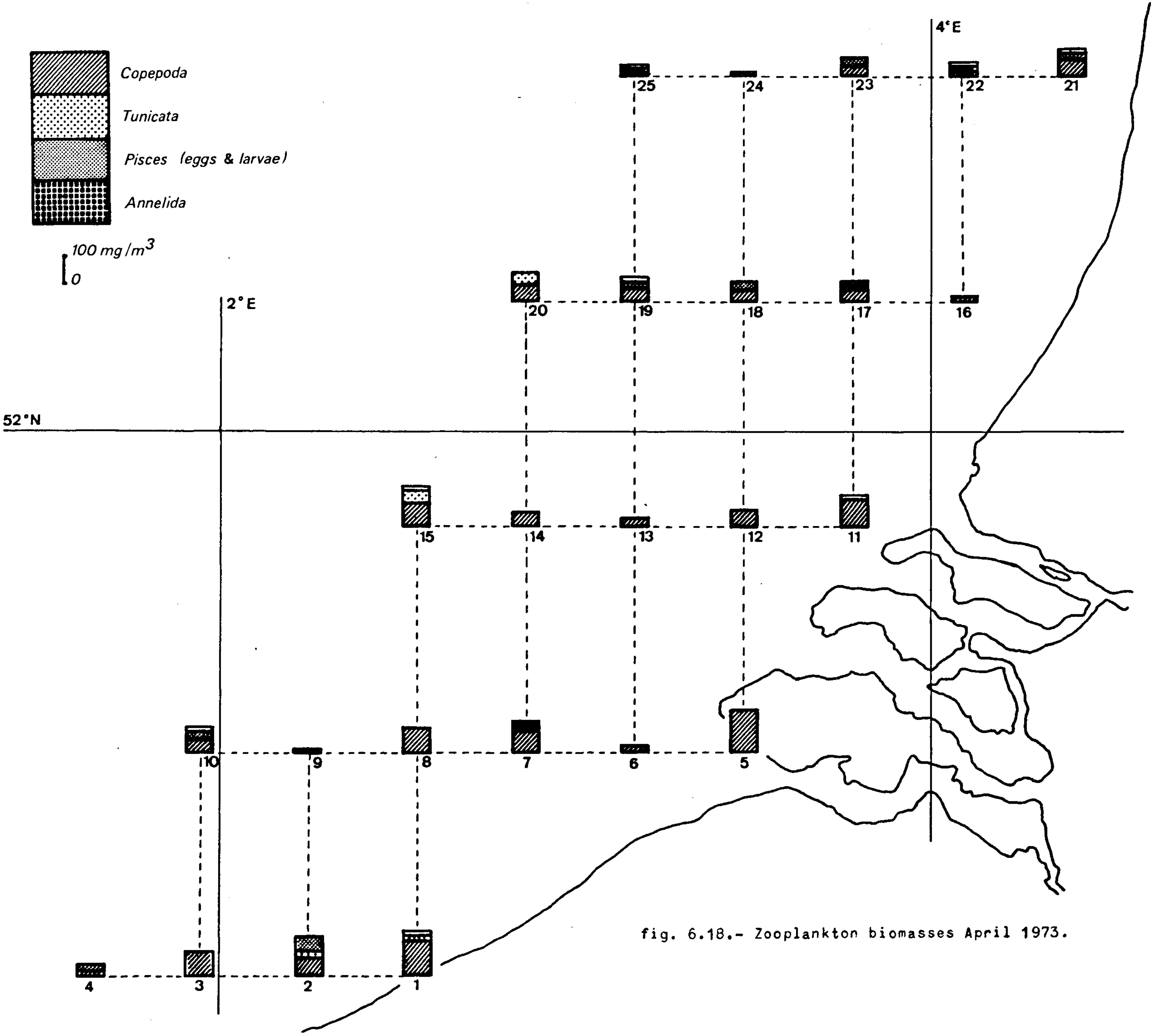


fig. 6.18.- Zooplankton biomasses April 1973.

Table 6.2

Mean values of biomasses of Copepodes per zone / per cruise (net weight/m^3)

Cruise	Zone 1 South	Zone 1 North	Zone 2
April-May 1973	84	31	27
September 1971	75	4	42
September 1972	205	41	80

b) Dominancy

Three groups are dominant : the herbivorous group of Copepods and Tunicates (*Oikopleura*), the carnivorous Chaetognathes [Bossicart and Daro (1973), see figs. 16, 17, 18]. The activities and food ingestion, linked with the biomasses of these groups are retained to calculate the transfers of matter.

c) Food chains

1° Lombardzijde

As the sampling was at regular monthly intervals at Lombardzijde (§ 2.2.2), we used these data to calculate the food chain.

The mean value of the 9 points was used. Using the biomasses (figs. 6.19, 6.20) and the daily food rations [Petipa (1970)] the grazing or predation are calculated (Tables 6.3, 6.4, 6.5 and fig. 6.21).

Table 6.3

Predation of Chaetognatha in 1971 expressed in mg/m^3/month (wet weight)

Month	Predation
June	51
July	331
August	612
September	637
October	153
November	25
Total	1809

Table 6.4

Grazing of Copepods in 1971 expressed in mg/m^3/month (wet weight)

Month	Nauplii	Copepodites	Adults	Total
January	102.3	111.6	65.1	279
February	102.3	111.6	65.1	279
March	174.3	231	101.2	506.5
April	553	385	63	1001
May	503.5	849.4	194.1	1547
June	999.8	1633.6	591.5	3225
July	802.2	1578.5	1657.6	4038.3
August	685	1719.3	1504	3908.3
September	356.5	1417	476.8	2250.3
October	882	1617	850.5	3359.5
November	651	859	945	2454
December	198	216	315	729
Total	5010	10729	6828.9	23576.9

Table 6.5

Grazing of Oikopleura in 1971 expressed in mg/m^3/month (wet weight)

Month	Grazing
January	78
February	78
March	9.9
April	39
May	156
June	487
July	702
August	877
September	1251
October	731
November	263
December	39
Total	4710.9

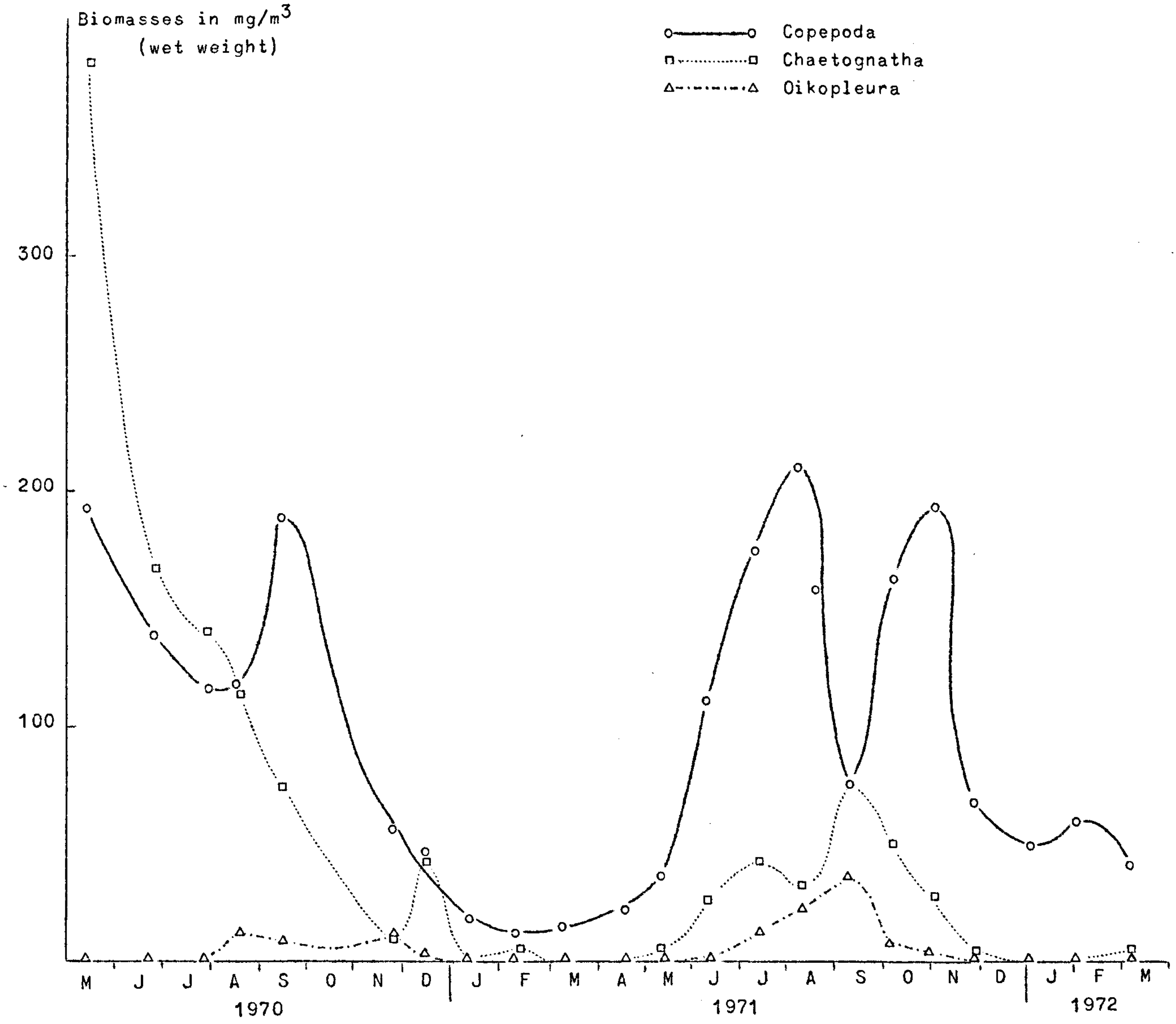
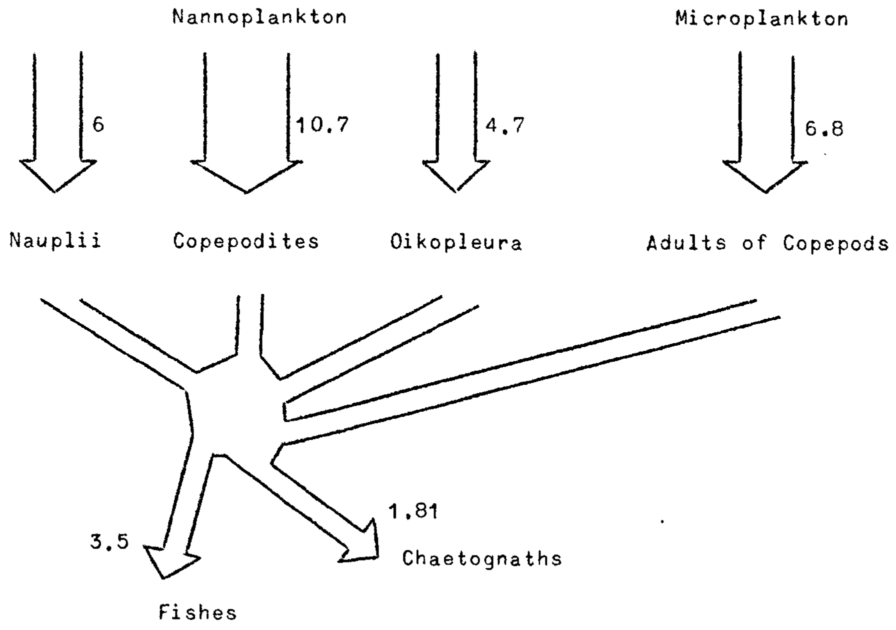


fig. 6.19.- Lombardzijde biomasses Copepoda - Tunicata.

Complete food chain

The results of Gulland (1970) permit us to estimate the predation of fishes on herbivores : the fishes use 12.5 % of the total food intake of the herbivores on an annual basis. Total annula is 28,288 mg/m^3 of which predation is 3,536 mg/m^3 by fishes.

The food chain expressed as g wet weight/m^3/year is :



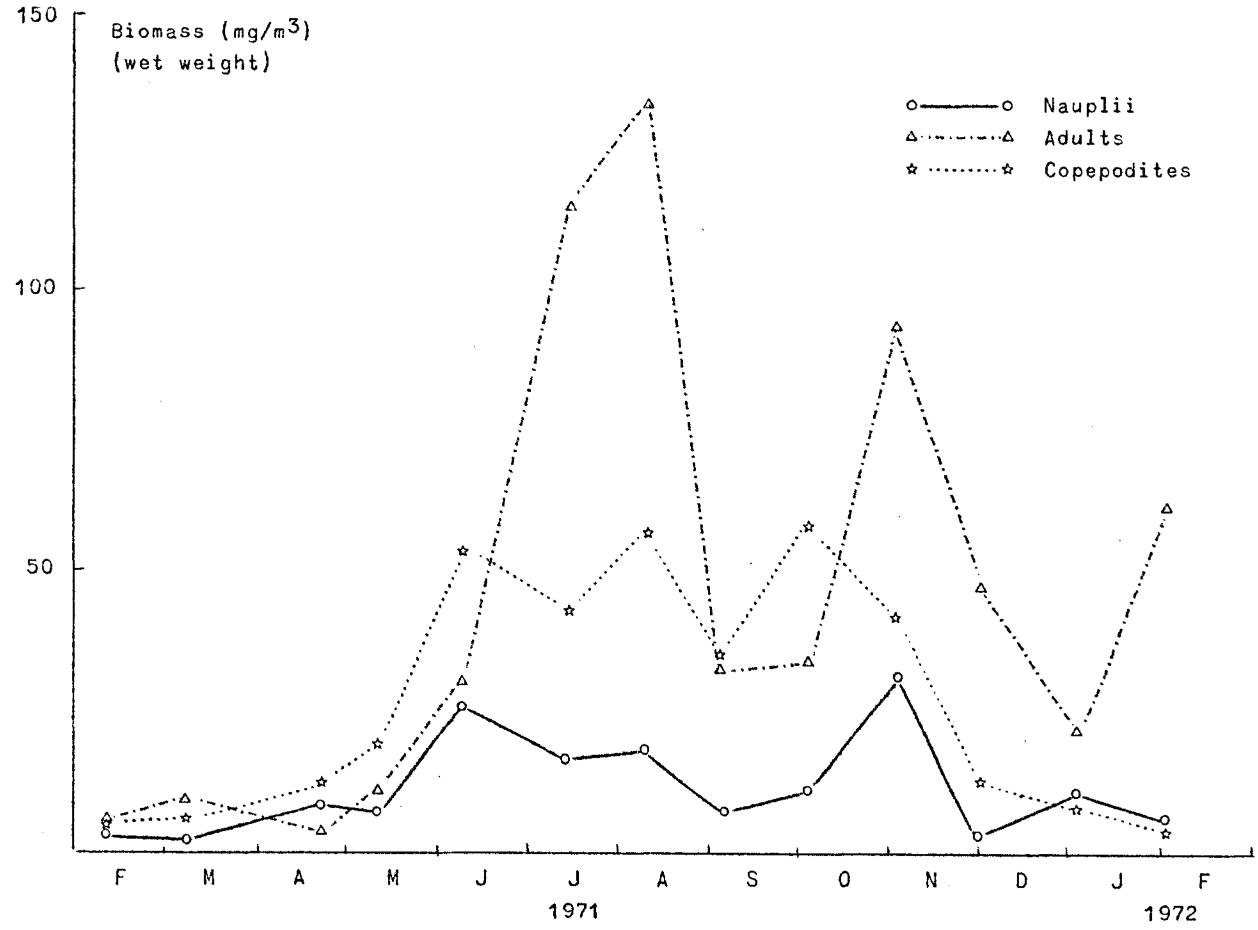


fig. 6.20.- Lombardzijde : biomasses at different stages Copepoda.

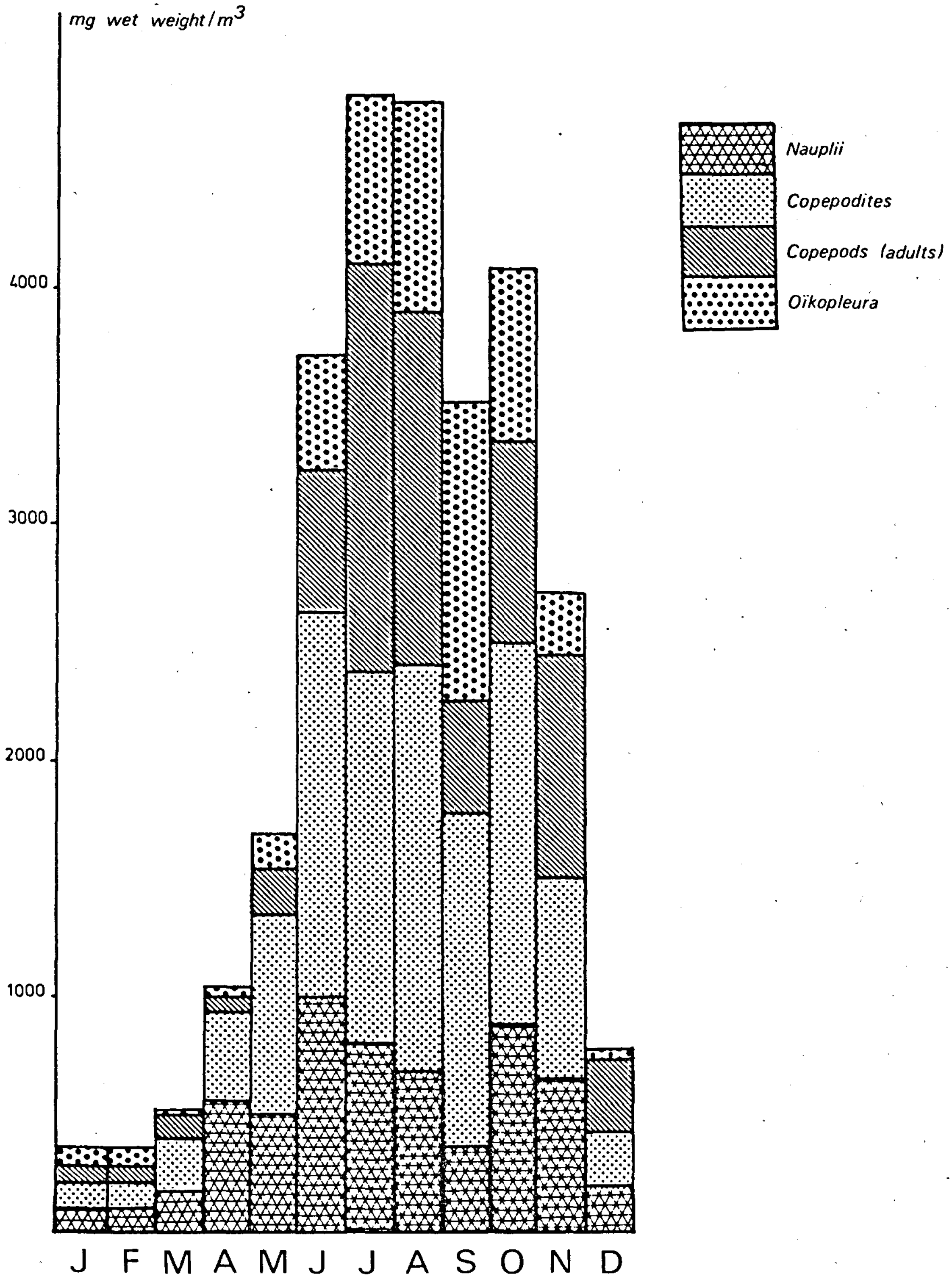


fig. 6.21.- Grazing Copepoda and Oikopleura, Lombardzijde 1971.

2° Grazing in the North Sea

To evaluate the biomasses of the three dominant groups, the mean values of biomasses have been calculated for each zone and cruise (see Table 6.6) and the evolution of the biomasses evaluated (see figs. 6.22, 6.23, 6.24).

Table 6.6

Mean values of biomasses of Copepods, Oikopleura and Chaetognatha expressed in mg/m^3 (wet weight)

Month	Zone 1 South			Zone 1 North			Zone 2		
	Cop.	Oik.	Chaet.	Cop.	Oik.	Chaet.	Cop.	Oik.	Chaet.
July 1971	231	104	0	-	-	-	86	0	0
August 1971	-	-	-	29	225	45	109	62	60
September 1971	75	334	16	4	334	16	42	95	39
January 1972	36	0	0	41	0	0	40	0	0
April 1972	87	185	0	30	2	0	106	174	0
June-July 1972	140	384	0	45	82	0	37	105	0
September 1972	205	50	13	41	224	34	80	28	12
October 1972	182	27	3	-	-	-	82	9	1
April-May 1973	84	9	0	31	3	0	27	10	0

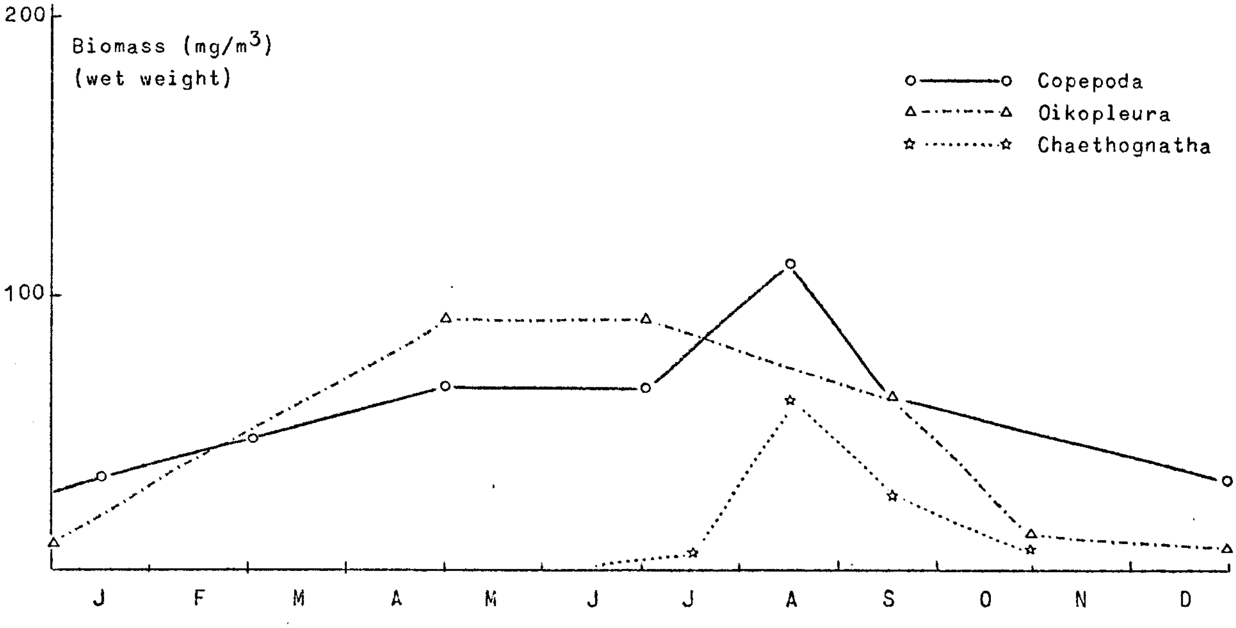


fig. 6.22.- Biomasses zone 2.

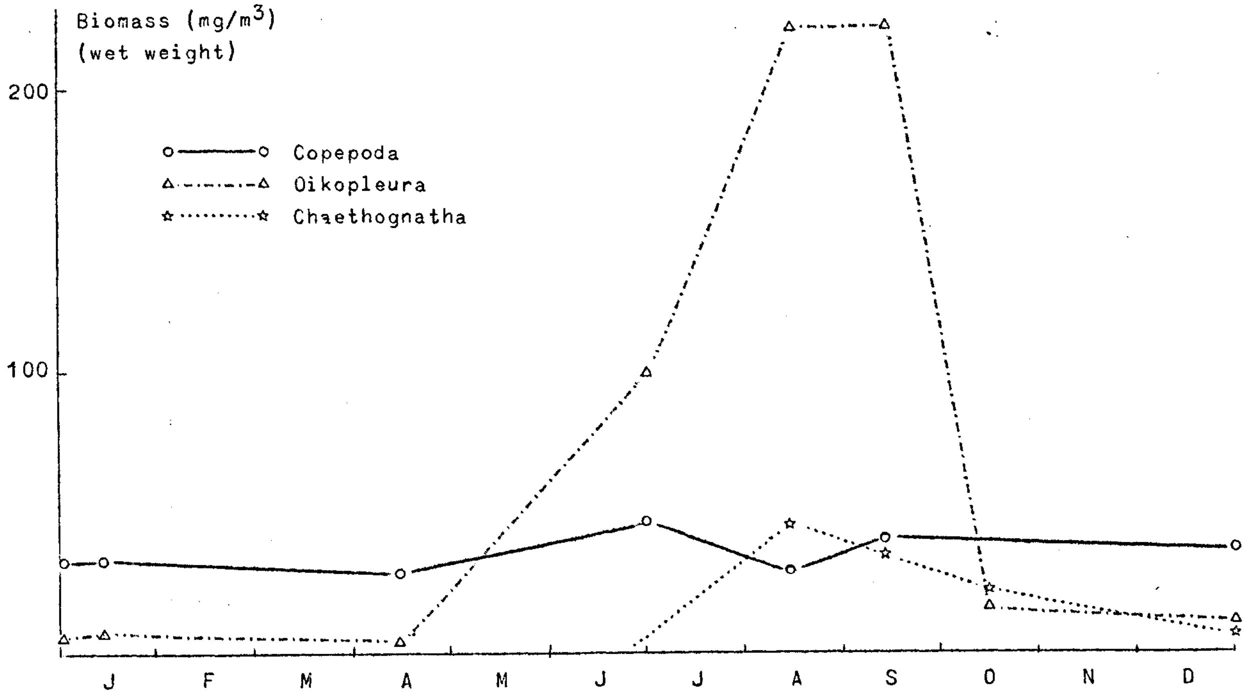


fig. 6.23.- Biomasses zone 1 North.

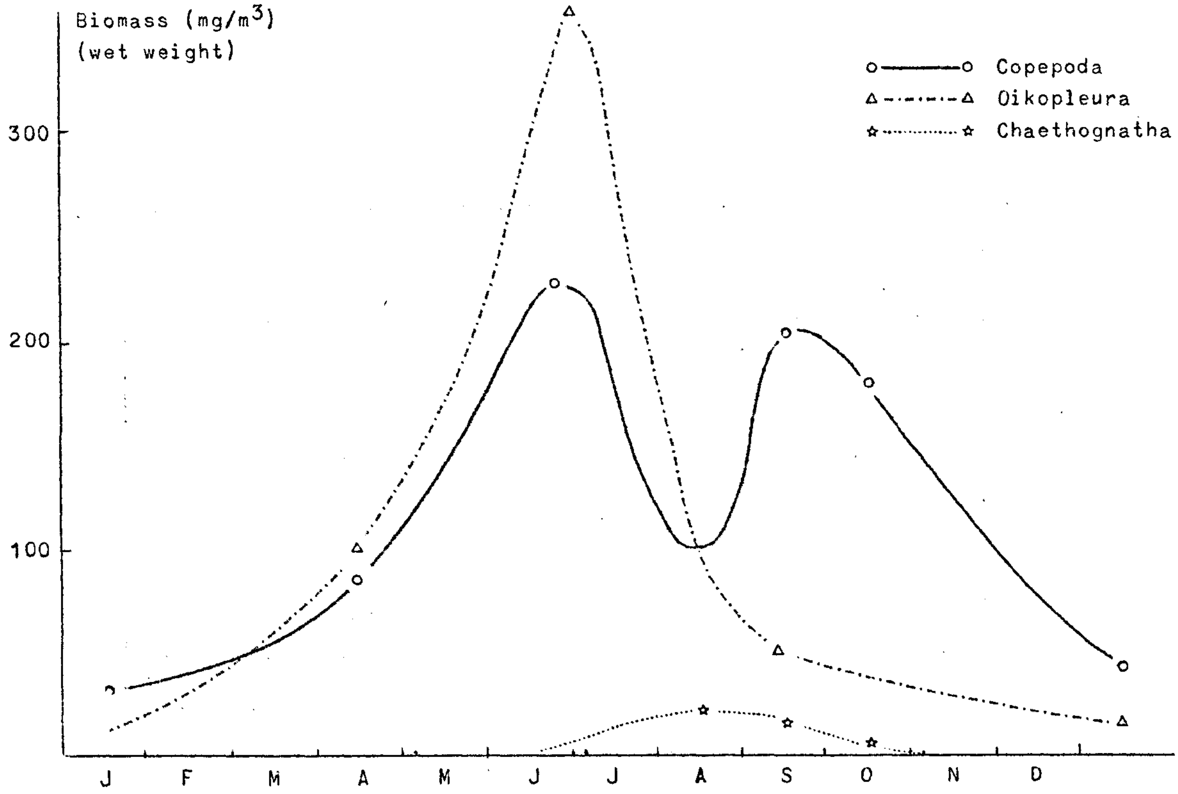


fig. 6.24.- Biomasses zone 1 South.

The grazing values are estimated in the same way as presented in 1° and are represented in Tables 6.7, 6.8, 6.9.

Table 6.7

Zone 1 South

Month	Grazing Copepoda (all stages) mg/m^3/month	Grazing Oikopleura mg/m^3/month	Total
January-February	1530	975	2505
March	1800	1267	3067
April	2700	2086	4786
May	4350	3510	7850
June	6150	5557	11707
July	3765	4192	7957
August	3375	2194	5569
September	5475	1072	6547
October	5250	682	5932
November	2625	487	3112
December	1200	390	1590

Table 6.8

Zone 1 North

Month	Grazing Copepoda (all stages) mg/m^3/month	Grazing Oikopleura mg/m^3/month	Total
January-February	1267	195	1462
March-April	1920	195	2115
May-June	2250	2047	4297
July	1200	2730	3930
August	960	5250	6210
September	1140	3802	4942
October	1170	1170	2340
November	1170	195	1365
December	540	156	696

Table 6.9

Zone 2

Month	Grazing Copepoda (all stages) mg/m^3/month	Grazing Oikopleura mg/m^3/month	Total
January-February	1584	1170	2754
March-April	3450	2730	6180
May-June	5400	2535	7935
July	2400	1657	4057
August	3000	1462	4462
September	1949	1101	3050
October	1800	536	2336
November	1275	195	1470
December	570	175	745

On an annual basis we can express the grazing in the three zones

- Zone 1 South 60,632 mg/m^3 (wet weight) or expressed in m^2 (as the zooplankton is homogeneously distributed over the depth). Mean depth in zone 1 South is 15 m ; grazing is 909,480 mg/m^2/year , or in carbon 36,379 mg C/m^2/year .
- Zone 1 North, Total grazing is 27,357 mg/m^3/year with a mean depth of 20 m , 547,140 mg/m^2/year , or in carbon 21,885 mg C/m^2/year .
- Zone 2, total yearly grazing is 32,989 mg/m^3 , with a depth of 35 m , 1,154,615 mg/m^2 , or in carbon 46,185 mg/m^2/year .

We calculated the ratio of grazing to primary production (Table 6.10).

As the biomasses of zooplankton are not significantly changing, during a week [Bossicart (1973)], these values are significant for the time of a week.

Maximal grazing takes place in zone 1S; minimal in zone 1N. Comparing the grazing with the primary production, only once (April 1972) the grazing is 100 % of the production. The same phenomenon is stated in the Sluice Dock : only one month the grazing is equal to, or a little more than the primary production (see fig. 6.25).

Most of the time in both cases (North Sea and Sluice Dock) grazing is a little part of primary production. This should mean that only exceptionally the phytoplankton growth is hindered by grazing.

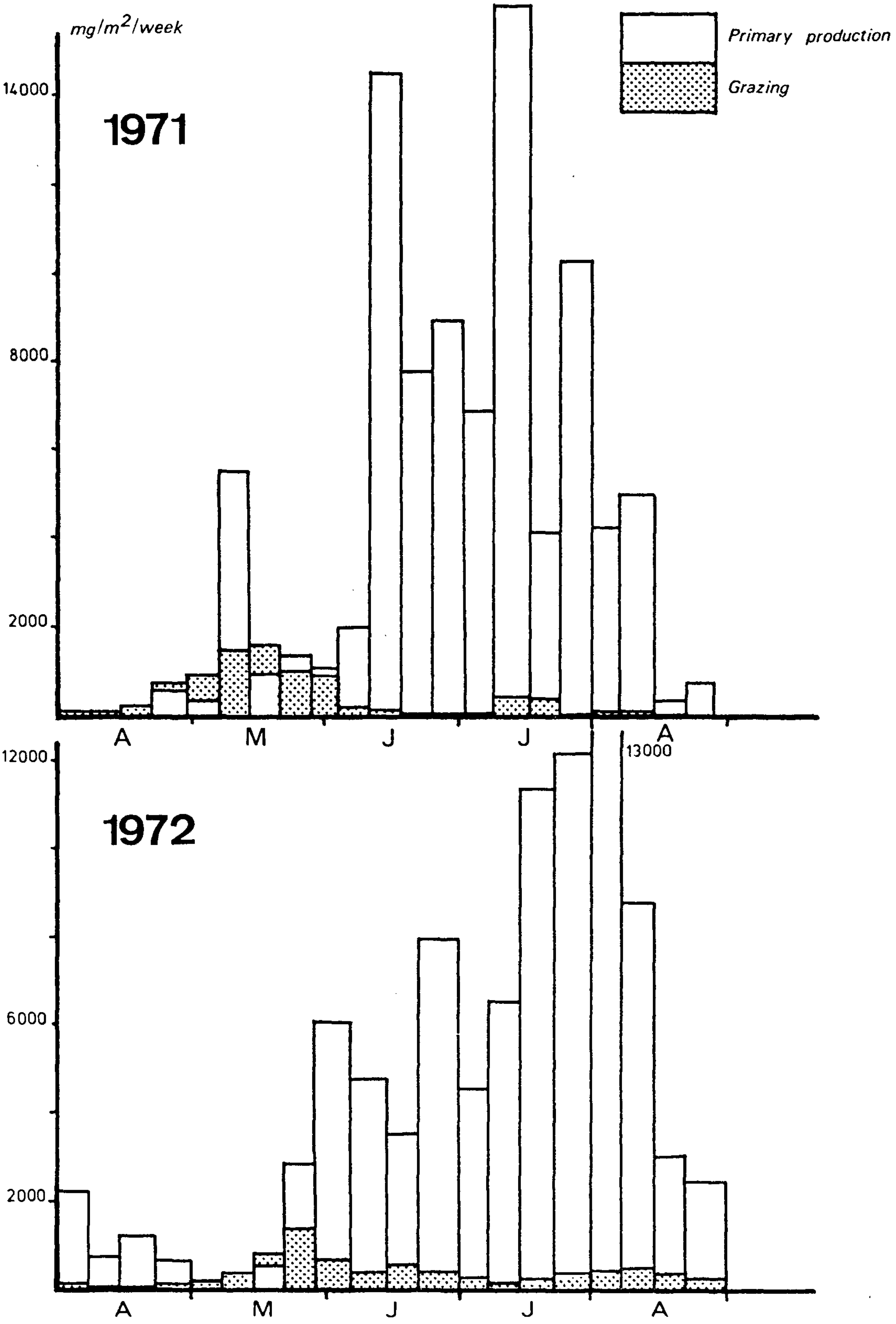


fig. 6.25.- Comparison grazing/primary production at the Sluice Dock.

Table 6.10

Cruise	Grazing expressed in mg C/m^2/day			Grazing expressed % of primary production		
	Zone 1S	Zone 1N	Zone 2	Zone 1S	Zone 1N	Zone 2
June-July 1971	205	-	221	39.7	-	26.5
August 1971	-	135.4	127.4	-	8.7	14.7
September 1971	157.8	95.4	116	5.3	7.8	17.6
January 1972	8	24.3	25	5.4	15.2	19.2
April 1972	222.5	24	312	105.5	6.7	77.7
June-July 1972	182	80	132.5	42	9.3	21.2
September 1972	241	139.8	147.3	74	22.7	54.3
October 1972	152.6	-	88.7	38.5	-	36.5
April 1973	48.5	33.7	38.1	18.6	8	25.4

3° The respiration of zooplankton

The respiration is a good indication of activity of zooplankton. The obtained results are to be taken with caution as the results of these experiments indicate not only the respiration of concentrated zooplankton but include phytoplankton and zooplankton respiration.

The results of the cruise in April 1973 [Hecq (1973)] show a difference in respiration between zone 1N-1S and zone 2.

In the samples where Copepods are dominant, we can express the results in carbon respired/animal/day.

Zone 1 N-S : 1.29 ± 0.59 µg C/animal/day

Zone 2 N : 19.71 ± 8.71 µg C/animal/day

S : 3.19 ± 0.38 µg C/animal/day

The results of respiration were compared with the results of calculated grazing.

After Petipa (1970) the respiration is 80 % of the assimilation for the herbivorous Copepods.

The regression line shows a good correlation (0.91 with confidence < 0.001) between our results of respiration and our estimations of grazing; with an excess of 40 % for the values of respiration : the values of the respiration are 120 % of the values of the grazing.

The measurement of the respiration rates, worked out in the future can be an indicator of the physiological condition of the population and his activity.

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3.- Bacteriology : Heterotrophic Bacteria

3.1.- Methods : counting techniques

The *Institut d'Hygiène et d'Epidémiologie* (Barbette *et al.*) used the pour plate method. Colonies were counted after a maximum incubation period of seven days.

The *Laboratorium voor Ekologie en Systematiek, Vrije Universiteit Brussel* (Joiris *et al.*) used the spread plate method. Counting happened after an incubation period of twelve days at 18 °C .

The latter method gives systematically higher results : shorter incubation time or/and use of too hot smelted agar could give less colonies.

As the reproductibility of the second method is good [Podamo Jo (1972)], standardization is proposed : Marine Agar 2216 (Difco), spread-plate method and incubation at 18 °C for twelve days.

3.2.- Results

3.2.1.- Year cycle of the bacterial concentration

The cycle of the planktonic marine heterotrophic bacteria is known in the Sluice Dock at Ostend [Podamo Jo (1972), Joiris (1973a)]. After closing the sluices, the bacteria disappear (t_{50} = 4 to 5 days) ,

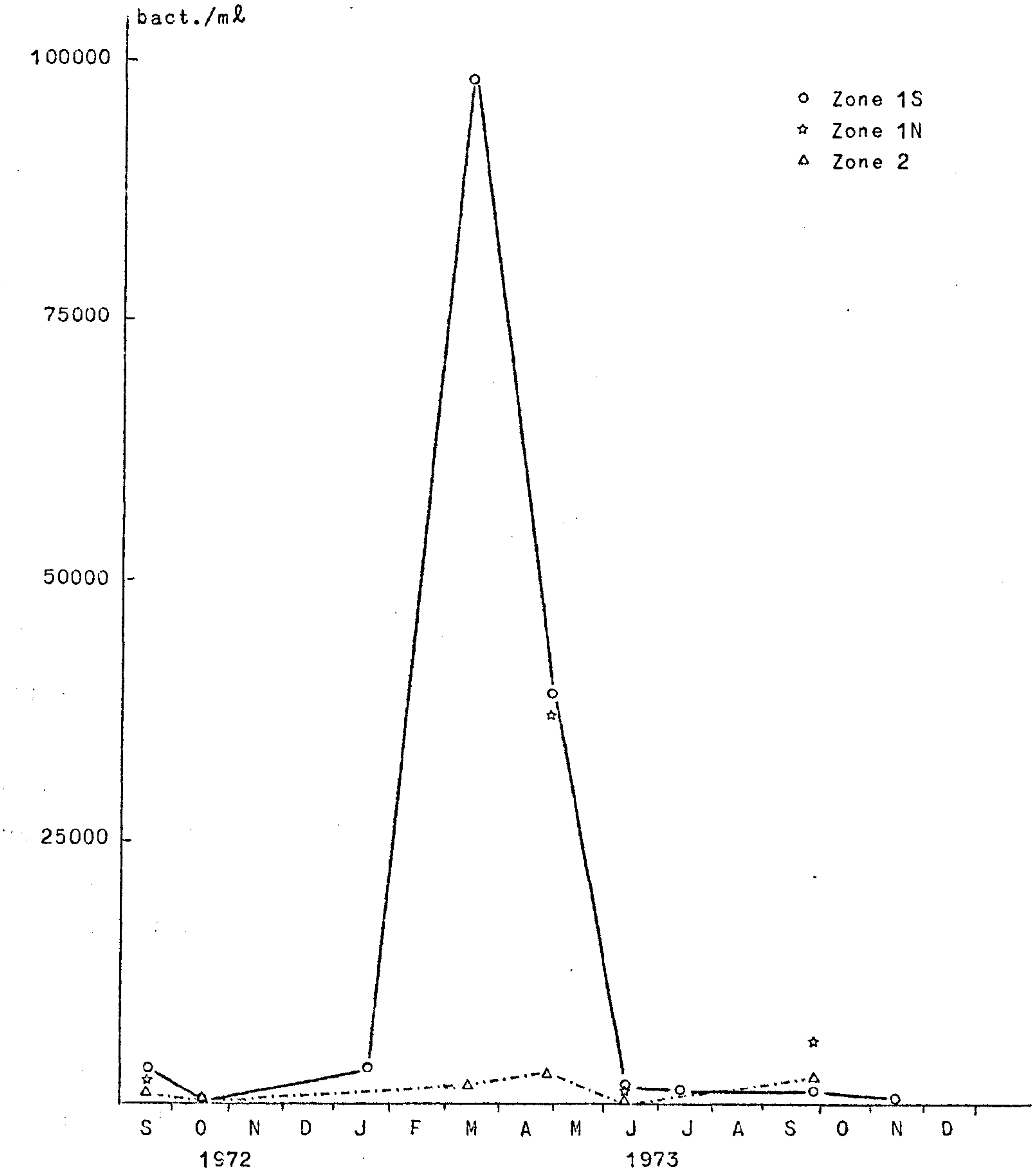

fig. 6.26.

Seasonal variation of the marine heterotrophic bacteria in the Southern Bight of the North Sea (Average number of bacteria/mℓ of water). From Joiris (1974).

probably by consuming the organic matter they are depending on. In the next phase their numbers follow the different peaks of phytoplankton : they depend probably on the dead phytoplankton cells, perhaps the main source of organic matter in seawater.

In the Southern Bight of the North Sea, a summer peak, especially in the coastal zone, is found (fig. 6.26). This peak corresponds also to the spring bloom of phytoplankton (see also §1, Primary production). As in the Sluice Dock, dead phytoplankton is thus probably the most important source of organic matter to be utilized by the heterotrophic bacteria. Indeed, the spring bloom of phytoplankton is responsible for a peak of organic material in sea at the Dutch coast [Duursma (1962), (1963)] and in the Channel [Banoub and Williams (1973)].

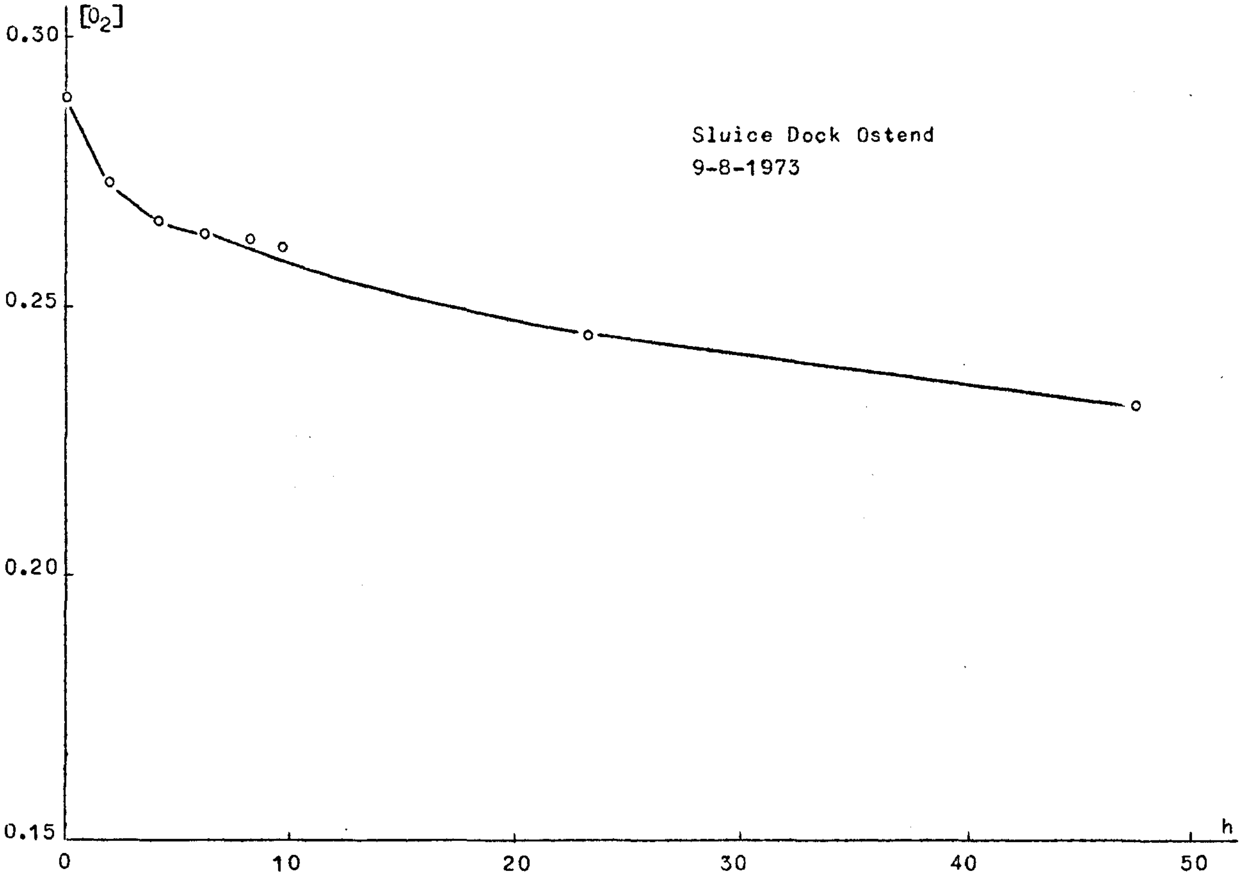

fig. 6.27.
Oxygen consumption in fresh sea water. Incubation : 18 °C , darkness. Oxygen concentration in mM. From Joiris (1973).

Our hypothesis on the relation bacteria-organic matter (spring peak of the phytoplankton) seems to be confirmed by these data [see discussion in Joiris (1974)].

3.2.2.- Relation between bacterial concentration and activity

As the knowledge of activity is more important than that of biomass (see General Introduction), we tried to develop a method of determination of aerobic heterotrophic activity by measuring the initial rate of oxygen consumption in fresh sea water (Winkler method). As seen in figure 7.27, the oxygen consumption rate is decreasing rapidly : the fast evolution of the water and of the bacterial population in time makes it necessary to use only the initial consumption rate as an index of activity. No immediate correlation exists between bacterial concentration and activity : the biomass of bacterial populations cannot be used as an index for their activity (Table 6.11) [Joiris (1973b,c)].

Table 6.11

Measure of activity (oxygen consumption rate), heterotrophic bacteria and organic matter

Sluice Dock Ostend

Date	Initial O_2 consumption rate ($\mu M\ O_2/h$)	BOD_5 ($\mu M\ O_2$)	Heterotrophic bacteria (b/mℓ)
09-08-1973	8.3	107	2.37×10^5
20-08-1973	1.2	83	0.34×10^5
29-08-1973	1.8	119	0.85×10^5
21-10-1973	2.0	74	3.56×10^5
13-11-1973	2.6	160	1.5×10^5
22-11-1973	1.5	63	2.44×10^5
12-12-1973	8.3	44	-

North Sea

Date	Initial O_2 consumption rate ($\mu M\ O_2/h$)	BOD_5 ($\mu M\ O_2$)	Heterotrophic bacteria (b/mℓ)
25-09-1973	2.2	138	2.04×10^3
02-10-1973	2.5	131	-
28-11-1973	15.5	> 300	600

The same conclusions are apparent for the nitrifying bacteria in the Scheldt Estuary (see also the Estuary report) : a decrease in the numbers of nitrifying bacteria is observed from the Rupel on downstream, probably due to dilution and mortality in sea water (as they are mostly of terrigenous origin).

But nitrification occurs only several kilometers downstream Antwerp, where numbers of bacteria are strongly reduced. No correlation is thus found between activity and numbers of the responsible organism, because the latter can be present in high concentration in an environment where they are completely inactive [Billen (1973)].

4.- Bacteriology : Bacterial activity in bottom sediments

4.1.- Global heterotrophic activity

For evaluating the global heterotrophic activity in bottom sediments, two types of methods could be used : on the one hand, a direct *in situ* or near *in situ* measure of bacterial activity. Dark $H^{14}CO_3^-$ incorporation [Romanenko (1964)] can be used, but caution is to be made because of the possible interference with chemoautotrophic metabolisms and the possible variations of the ratio CO_2 incorporated — total C metabolized (Overbeck). Another technique often used is to measure O_2 uptake by a sediment core [Hargrave (1973)]; this technique unfortunately neglects the maybe important anaerobic heterotrophic activity.

On the other hand, if stationary conditions are assumed, heterotrophic activity can be evaluated by differentiating an experimental organic matter-depth curve. This method also needs an evaluation of sedimentation rate.

These two methods ($H^{14}CO_3^-$ incorporation and differentiating of organic N profil) have been used in the Sluice Dock at Ostend [Podamo Jo (1974)], and the obtained results are of the same order of magnitude (96 to 560 g C/m^2 year and 135 g C/m^2 year respectively).

No such measure has been done in the North Sea. However a gross estimation of the order of magnitude of bottom respiration can be deducted from the work of Hargrave (1973) who studied correlations between sediment oxygen uptake, primary production and depth for various aquatic ecosystems. According to this model, bottom respiration respectively in the three zones of the network, would correspond approximately to 25 % of the primary production in zone 1N, 40 % in zone 1S and 35 % in zone 2.

4.2.- Microbial activity involved in the recycling of nitrogen

Profiles of the concentration of ammonium, nitrates and nitrites in the interstitial water of sediments have been measured in the Sluice Dock at Ostend [Podamo JO (1974)]. These data allow us to evaluate the rate of diffusion of nutrients from the bottom, by measuring the concentration gradient at the water-sediments interface. For ammonium, this transfer is approximately constant during the whole season, because of the huge reserve of organic nitrogen and ammonium in the sediments.

In contrast, for nitrates, the transfer rate varies with the concentration in the water. Moreover, the sediments behave as nitrate consumers in the sludgy zone (where only denitrification occurs) and sometimes as consumer, sometimes as producer according to the concentration in the water in the sandy zone (where both nitrification and denitrification occur).

Table 6.12

	Sludgy zone	Sandy zone	Reference
Ammonification	8.4 g N/m^2. 6 months	-	Podamo (1974)
Nitrification	0	0.3 to 0.7 g N/m^2.6 months (only above 5 to 1 cm depth)	Billen et Vanderborght (1974)
Denitrification	0.3 to 0.9 g N/m^2.6 months	0.3 g N/m^2 . 6 months (only under 5 to 1 cm depth)	idem

The mathematical analysis of these profiles by means of a small stationary model has allowed us to relate them with the intensity of bacterial activity in the sediments [Podamo Jo (1974c), Billen and Vanderborght (1974)].

Table 6.12 gives the figures which have been found for the order of magnitude of bacterial activity.

5.- Bacteriology : Pollution indicators and antibacterial properties of sea water

5.1.- Methods

See Technical Reports : Barbette *et al.*(1971-1973), Joiris (1972), (1973).

5.2.- Results

5.2.1.- *In situ* observations

The coliform bacteria [for *E. coli*, faecal *Streptococcus*, see Barbette *et al.* (1971-1973)] have maximal concentrations near the coast (zone 1N and 1S), low concentrations offshore (zone 2) (fig. 6.28).

The year cycle shows seasonal variations with maximal numbers in winter, minimal during summer. The input rates have maximal quantities in summer, minimal in winter (*Rapport Inventaire Pollution*). This indicates that fecal bacteria have a greater survival time in winter than in summer.

5.2.2.- *In vitro* study [Joiris (1973d)]

The antibacterial properties of sea water are studied by inoculating *Escherichia coli* from a culture in sea water. The evolution is studied by counting the colonies twice a day (Petri-dishes, spread-plate method on MacConkey Agar and, except when stated, the experiments are done in the dark at 18 °).

a) Figure 6.29 shows a typical kinetic of disappearance of *E. coli*, with three successive phases : the latency phase, the phase of exponential decrease and eventually a phase of survival of a small percentage of the

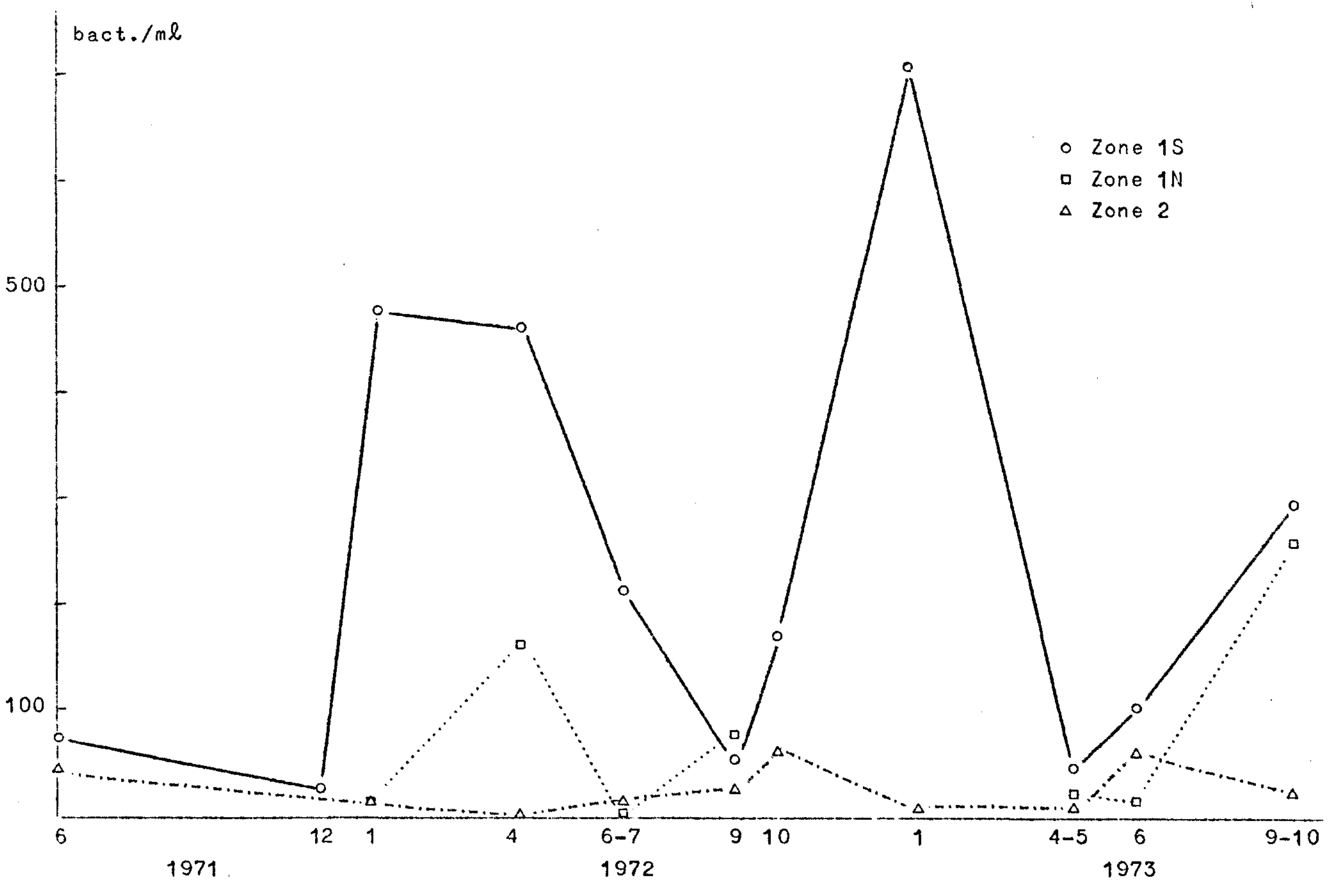

fig. 6.28.
Seasonal variation of the coliform bacteria in the Southern Bight of the North Sea. From the countings of Barbette et al. (1971-1973).

initial inoculum : it is necessary to measure each phase. Counting only the colonies after 2 or 3 days does not give the necessary information.

Control experiment shows that sea water sterilized by autoclave or by filtration on millipore filter (0.45 µ) loses its antibacterial properties and *E. coli* survives for several weeks (fig. 6.30).

b) The results obtained with sterilized sea water are sometimes light-dependent : sterilized sea water has sometimes no antibacterial activity when exposed to constant light intensities, but in other periods, it has.

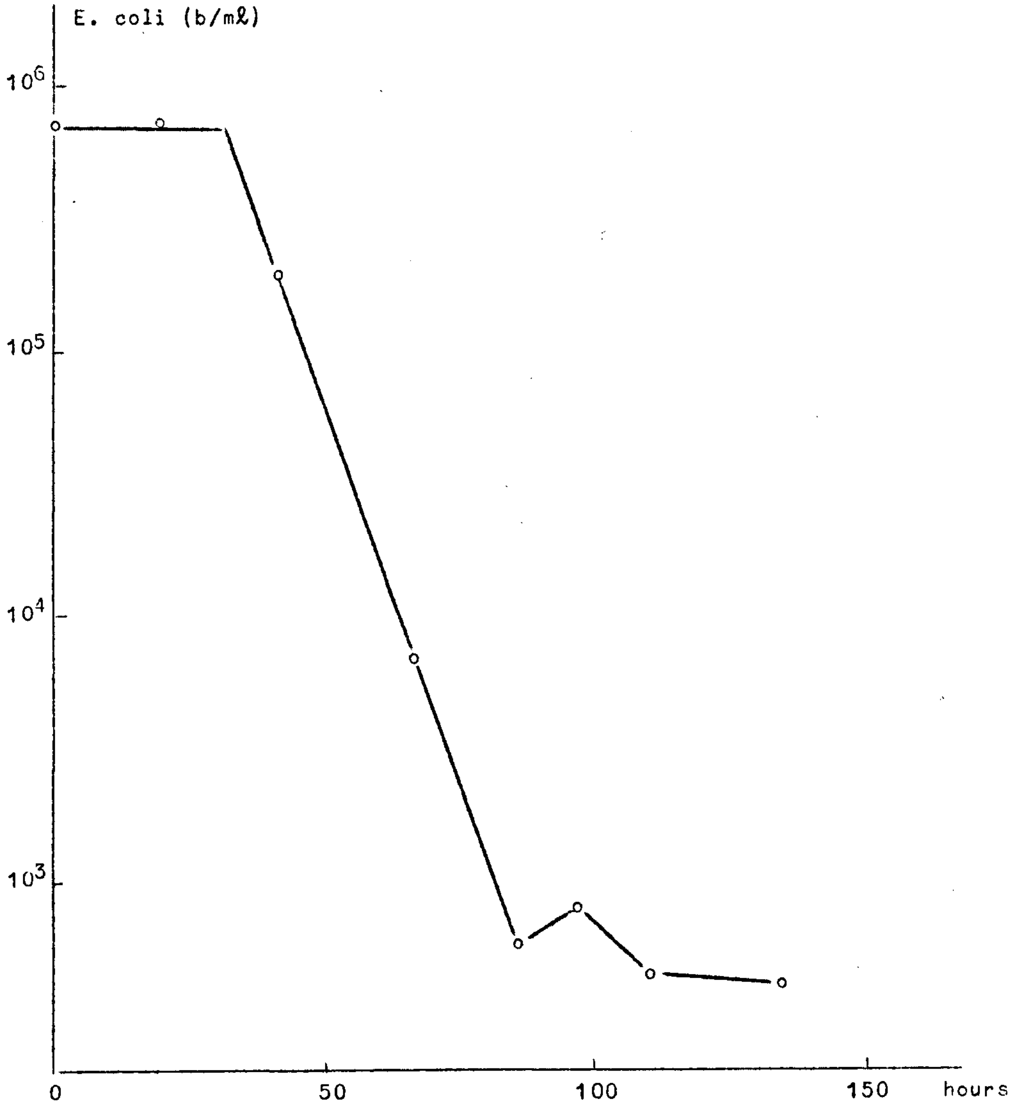

fig. 6.29.
Evolution of the Escherichia coli concentration, when inoculated from a culture in fresh sea water.

c) The antibacterial properties also depend on the temperature : the latency periods are longer when the temperature is lower (Table 6.13).

d) It is possible to re-inoculate sterile sea water for anti-bacterial properties with fresh sea water; the results obtained show that the latency period is longer when less fresh sea water is added. The t_{50} of the exponential decrease remains unchanged (fig. 6.31).

e) When organic matter only is added to fresh sea water, and the *E. coli* inoculum later, the latency period after adding *E. coli* becomes

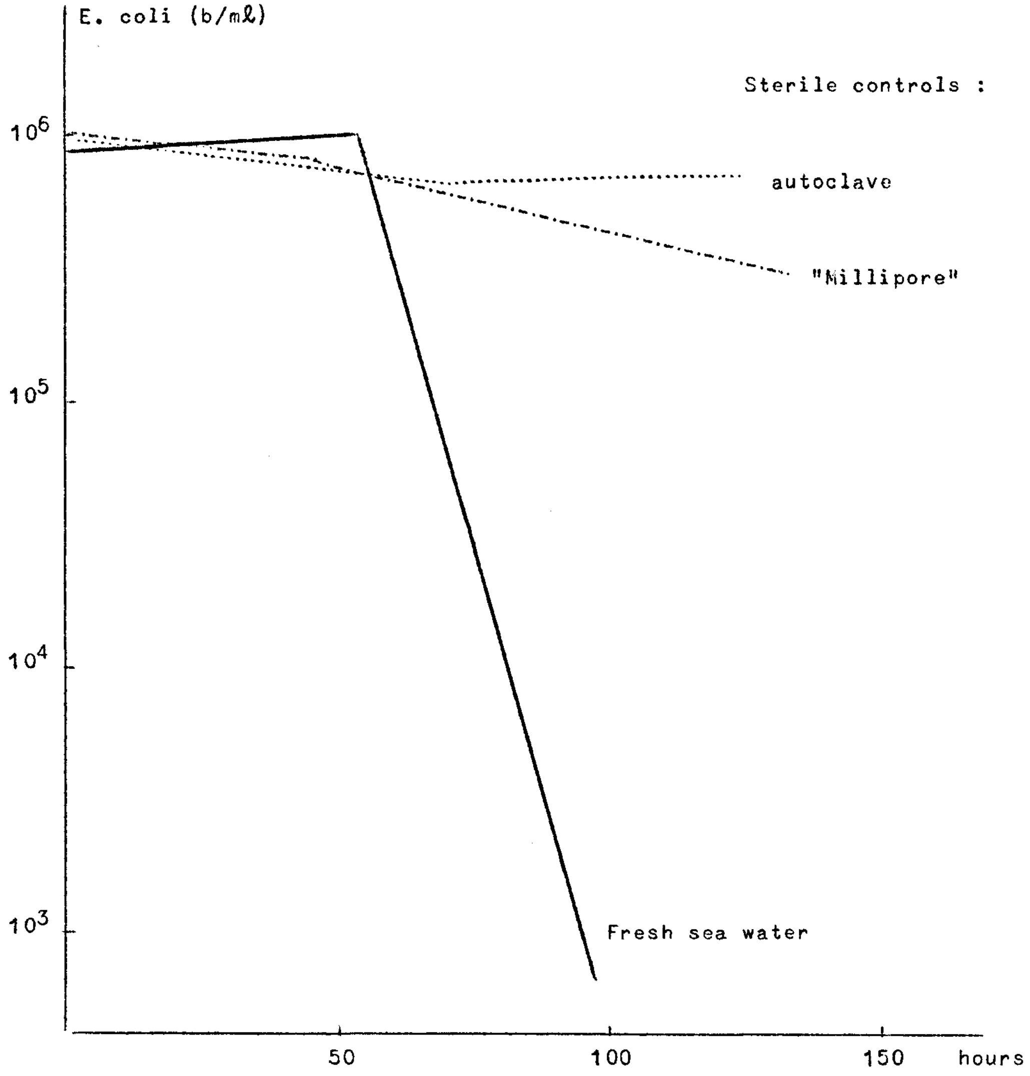

fig. 6.30.
Evolution of the E. coli concentration in fresh sea water and different controls.

Table 6.13

Disappearance of E. coli inoculated in fresh sea water :
Influence of the incubation temperature

Date	Temperature	Latency (h)	t_{50} (h)
09-10-1972	18 °C	22	2.45
	4 °C	200	4.0
12-02-1973	18 °C	48	3.30
	30 °C	26	3.0
	4 °C	> 175	-

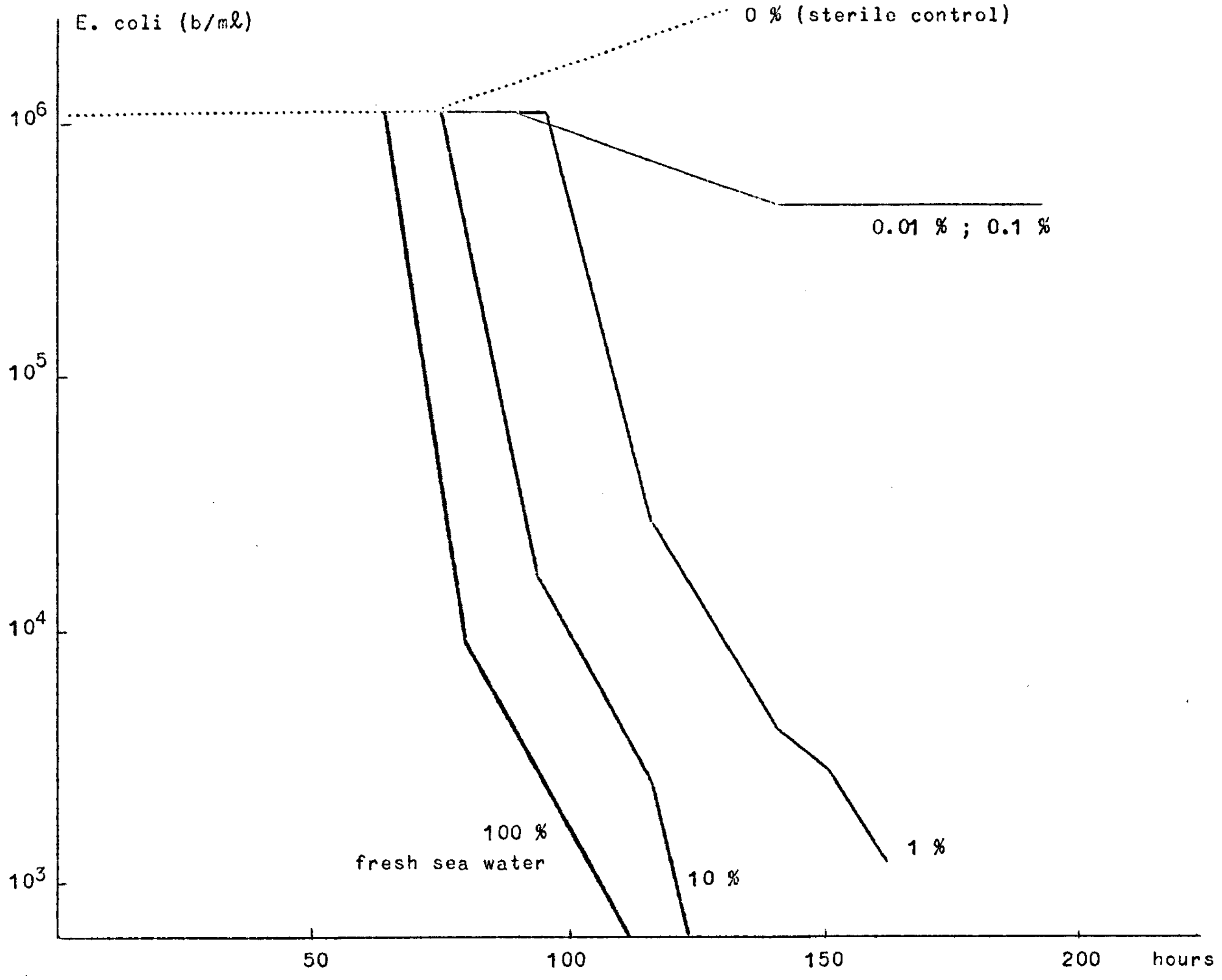

fig. 6.31.
Evolution of the E. coli concentration in sterilized sea water re-inoculated with different doses of fresh sea water.

shorter, but the "total" latency period remains constant (fig. 6.32). So, the addition of organic material can foster the development of phenomenons leading to the disappearance of *E. coli*. An hypothesis is that, at certain periods, some organisms responsible for the antibacterial effect are heterotrophs, and their growth is determined by the addition of organic matter.

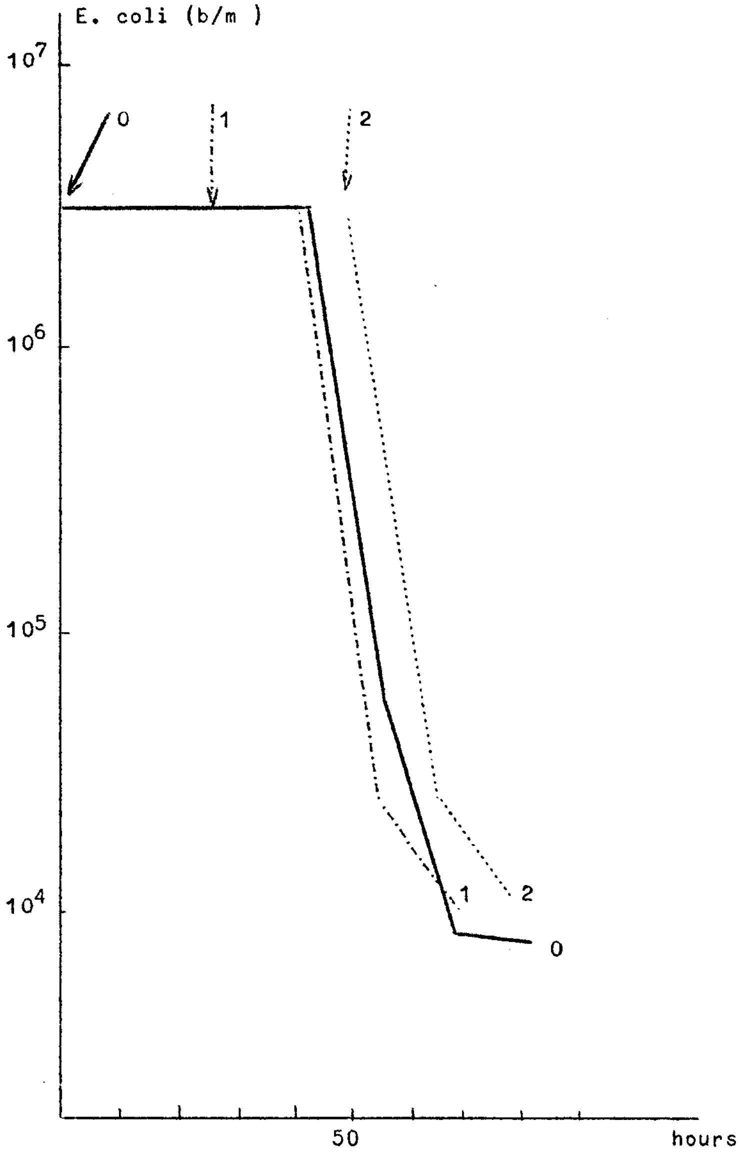

fig. 6.32.
Evolution of the E. coli concentration in fresh sea water, with addition of organic matter at time zero, and inoculation of E. coli at different times indicated by the arrows.

5.3.- Conclusions

The *in situ* observations and *in vitro* experiences demonstrate a strong antibacterial effect of the water of the North Sea against the bacteria of the pollution. The *in vitro* study clearly concerns a potential antibacterial process, because of the suppression of the temperature effects (all tests made at 18 °) and of the processes taking place during the latency phase.

The parallelism of the variations of antibacterial activity and of phytoplankton production [Polk (1972)], together with the effect of adding organic matter in the sea water, suggest that at least two types of organisms could be the main sources for antibacterial activity : phytoplankton and heterotrophs.

Their relative importance can vary spatially and temporally.

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6.- Synthetical approach – Quantitative estimation of nitrogen transfers in the Sluice Dock at Ostend and in the Southern Bight of the North Sea

As an example of dynamical approach to the ecological working of ecosystems, we present here a quantitative description of the nitrogen cycle in the Sluice Dock at Ostend and a first step towards the establishment of a nitrogen budget in the North Sea.

Nitrogen was chosen firstly because it is a general constituent of the living matter so that its circulation illustrates the general pattern of the circulation of biogenous elements, secondly because nitrogen is often the limiting factor in marine ecosystems.

6.1.- Nitrogen cycle in the Sluice Dock at Ostend

6.1.1.- Evaluation of nitrogen transfers

The obtained data (phytoplankton, zooplankton, bacteria) (fig. 6.33) allowed us to evaluate the specific contribution of each component to the nitrogen cycle.

a) Phytoplankton

Taking the $\frac{C}{N}$ ratio as 8 [Strikland (1960)], the nitrogen uptake is calculated from the CO_2 uptake data [Mommaerts (1973), Podamo Jo (1974a)].

b) Zooplankton

The uptake was calculated from the data on grazing, using the same $\frac{C}{N}$ ratio. Production, mortality and excretion was calculated as in Podamo Jo (1974b).

c) Bacteria

Values of heterotrophic O_2 consumption [Joiris (1973)] were used to calculate the ammonification by bacteria.

6.1.2.- Animal balance of nitrogen transfers

The integrated picture of the "ecometabolism" of N in the Sluice Dock is represented in figure 6.34 (period from March to September). Calculated nitrogen transfers are represented by arrows; mean values of statical masses by circles.

The high turnover of dissolved nitrogen in this ecosystem is apparent from this representation. The total mass of nitrogen initially introduced is recycled more than 10 times during the period. The high production of the Sluice Dock is made possible through this high efficiency of the recycling mechanisms. This fact is important when

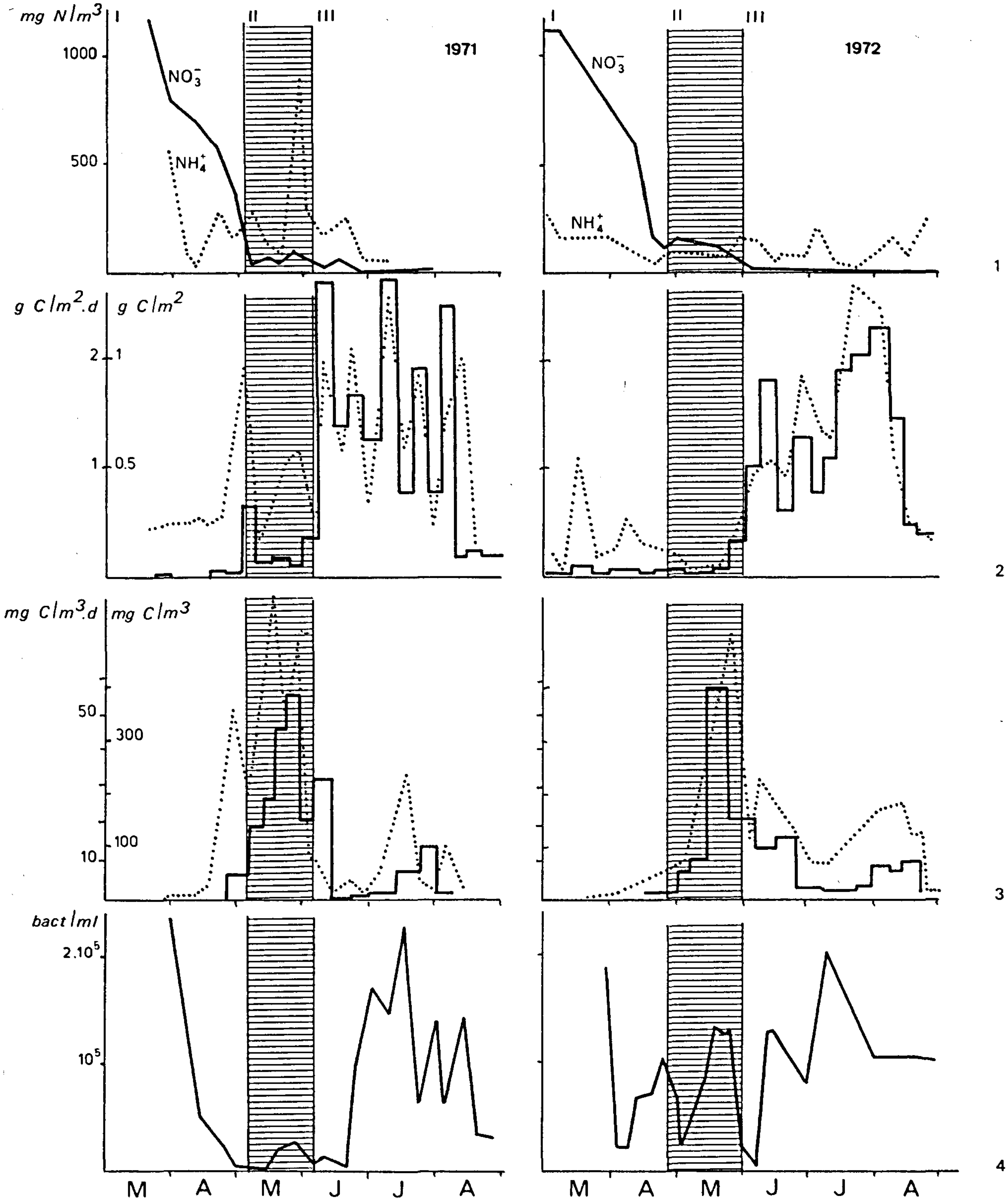


fig. 6.33.

Seasonal evolution of biological parameters in the water of the Sluice Dock at Ostend for the years 1971 and 1972.

1) Nitrate and ammonium concentration.

2) In situ production (histogram) and biomass (broken line) of phytoplankton.

3) Production (histogram) and biomass (broken line) of zooplankton.

4) Biomass of planktonic bacteria.

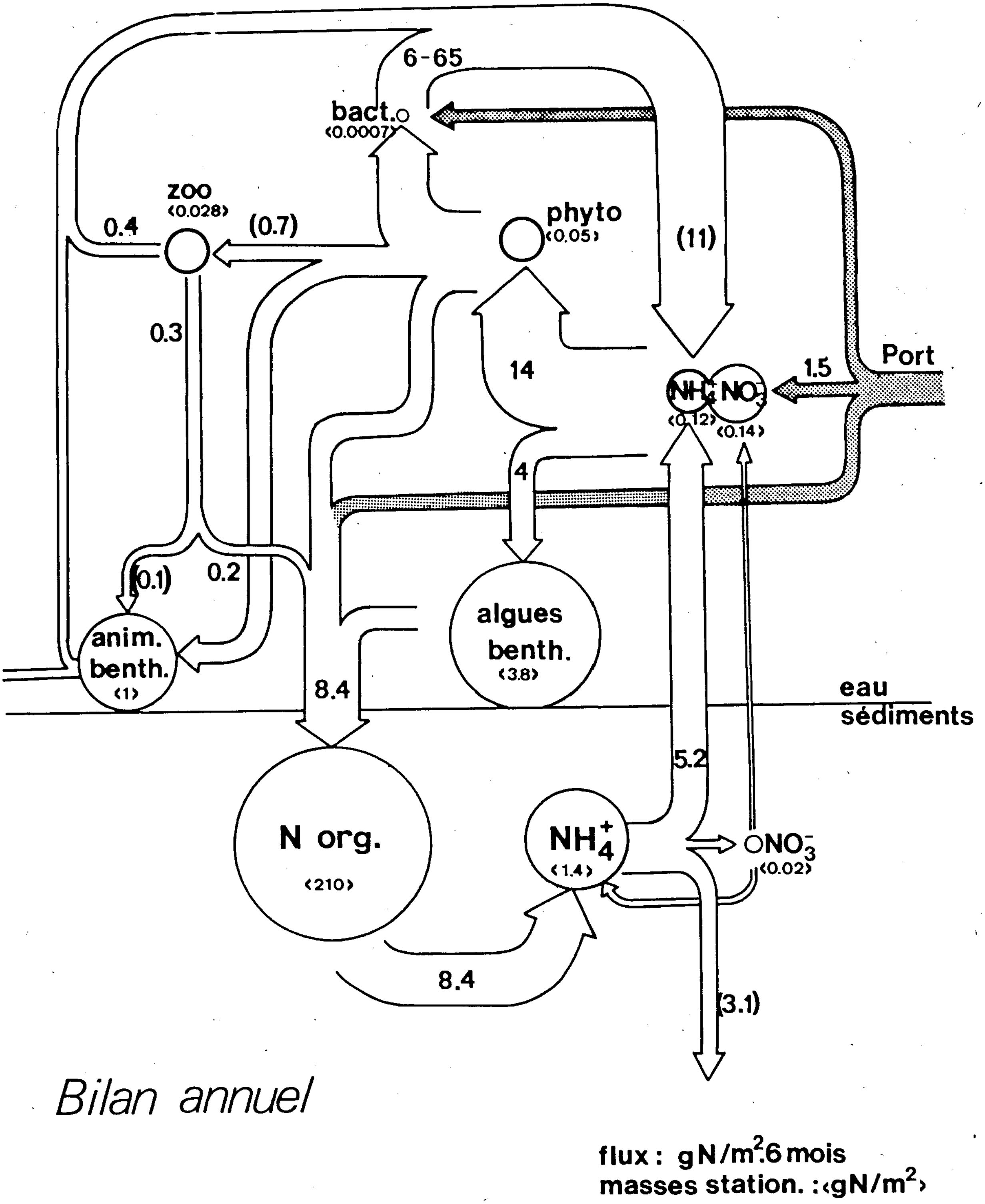


fig. 6.34.- Annual balance of nitrogen transfers between the various compartments in the Sluice Dock at Ostend.

comparing with other eutrophicated ecosystems where organic matter production occurs at the expense of an external source of nutrients without significant recycling. In the recycling mechanisms in the Sluice Dock, benthic and planktonic bacteria appear to play the dominant part.

6.1.3.- Seasonal variations

From the point of view of nitrogen ecometabolism, we distinguished three successive periods (fig. 6.33).

a) From the closing of the sluices to the end of April

The only period of *accumulation* of exogenous nutrients *without* important recycling, partly by the phytoplankton and -benthos, partly by denitrification in the sediments (fig. 6.35).

b) May

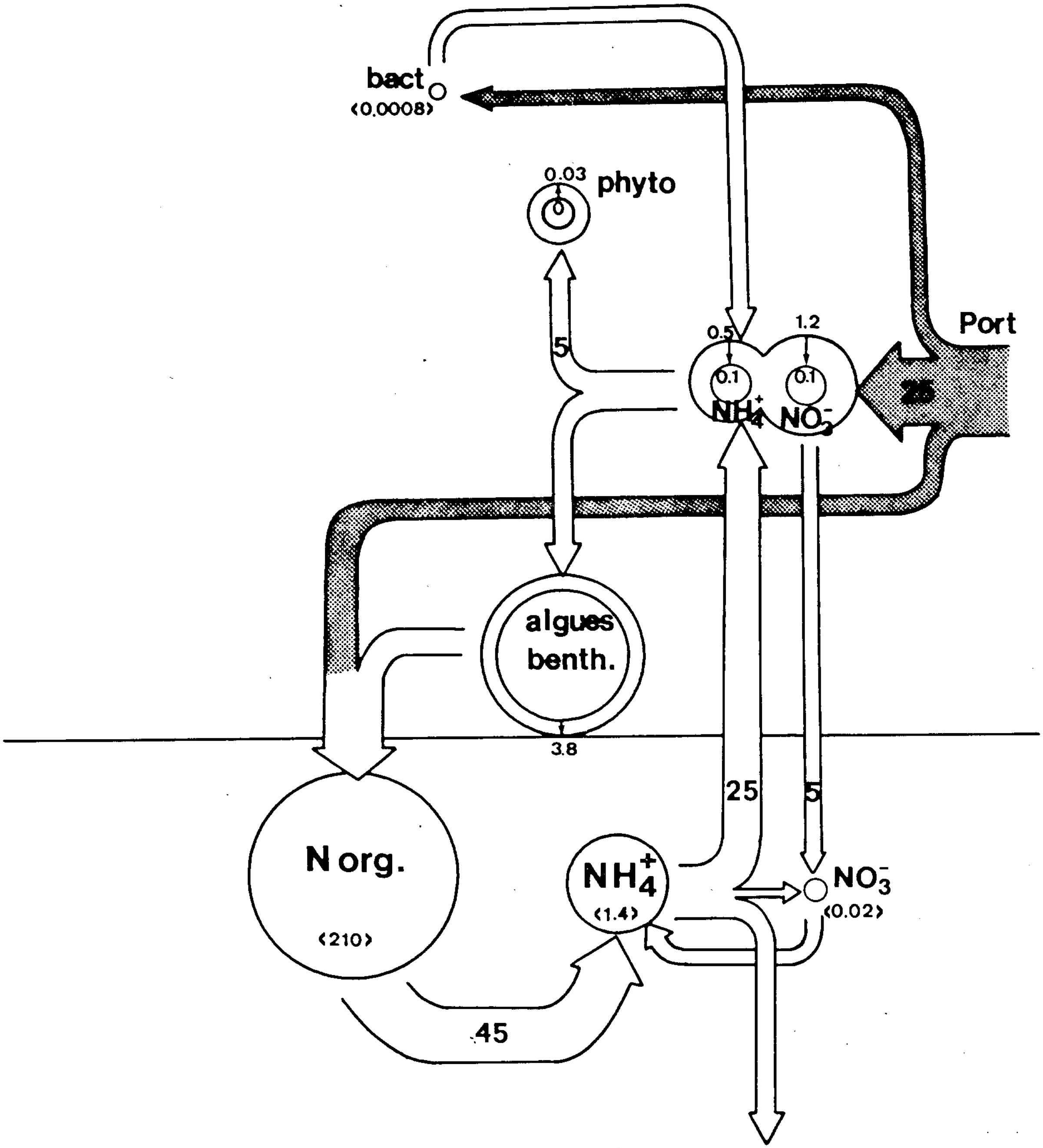
Bloom of zooplankton. Grazing and excretion are the most important factors in the recycling mechanism, together with diffusion from the sediments (fig. 6.36).

c) June-August

Massive development of the phytoplankton. The natural mortality of phytoplankton, followed by its bacterial degradation seems to be responsible for the recycling of biogenous material. The influence of zooplankton is negligible (fig. 6.37). Thus three different types of nitrogen ecometabolism succeed each other in this confined ecosystem.

6.2.- Elements for a nitrogen budget in the North Sea

The following discussion is an attempt in integrating the available biological data in the North Sea. However, time intervals between sampling were often too long for an accurate annual mean to be calculated. For whole compartments relevant data were sometimes lacking (*e.g.* sediments) and were estimated by speculation. Therefore, the present budget must only be regarded as a first working hypothesis and has to be confirmed by more accurate measurements.



Période I (mars,avril)

flux: mgN/m^2.jour
masses: gN/m^2

fig. 6.35.- Mean nitrogen transfers during the two first months after the closing of the sluices in the Sluice Dock at Ostend.

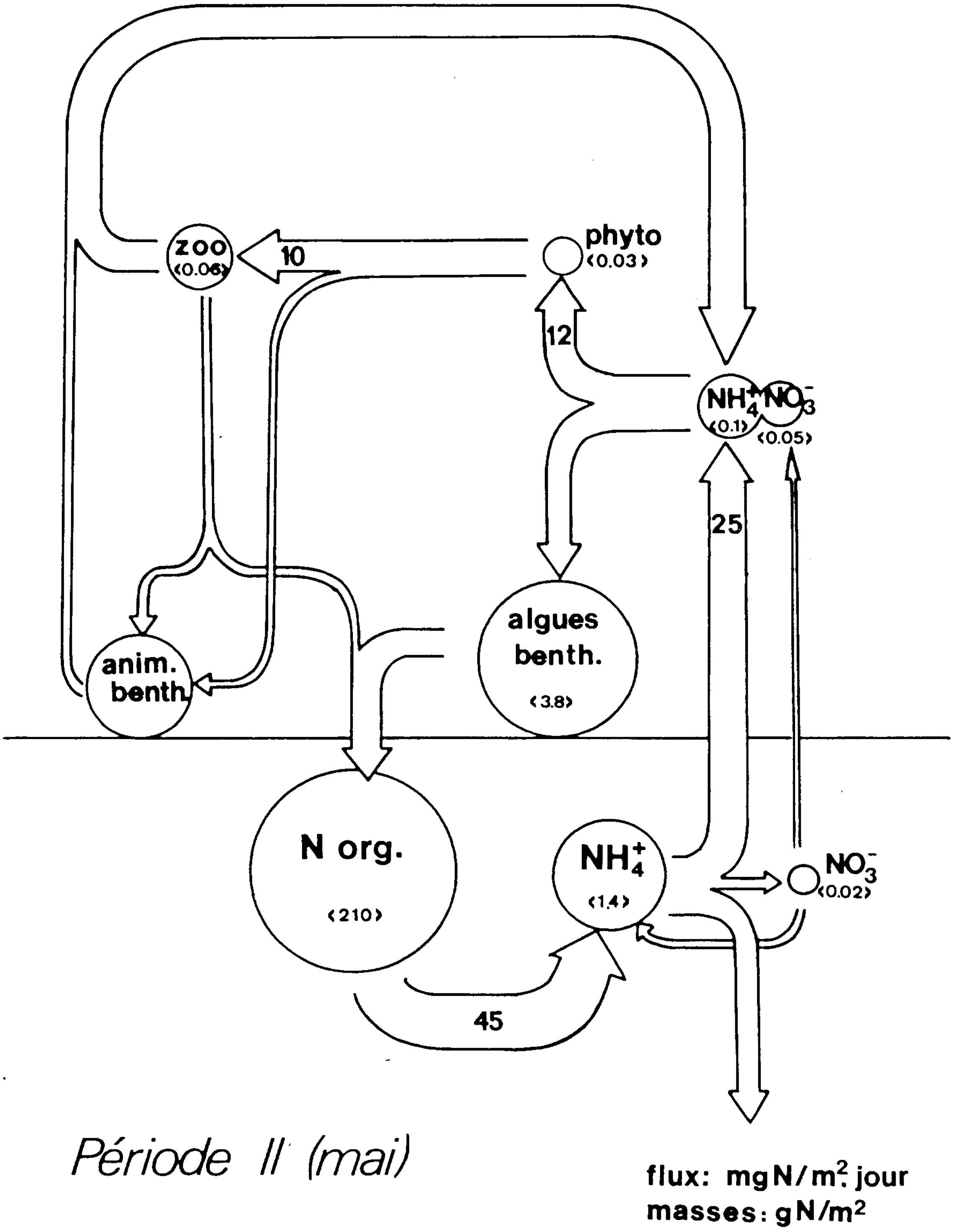


fig. 6.36.- Mean nitrogen transfers during the period of zooplankton bloom (May) in the Sluice Dock at Ostend.

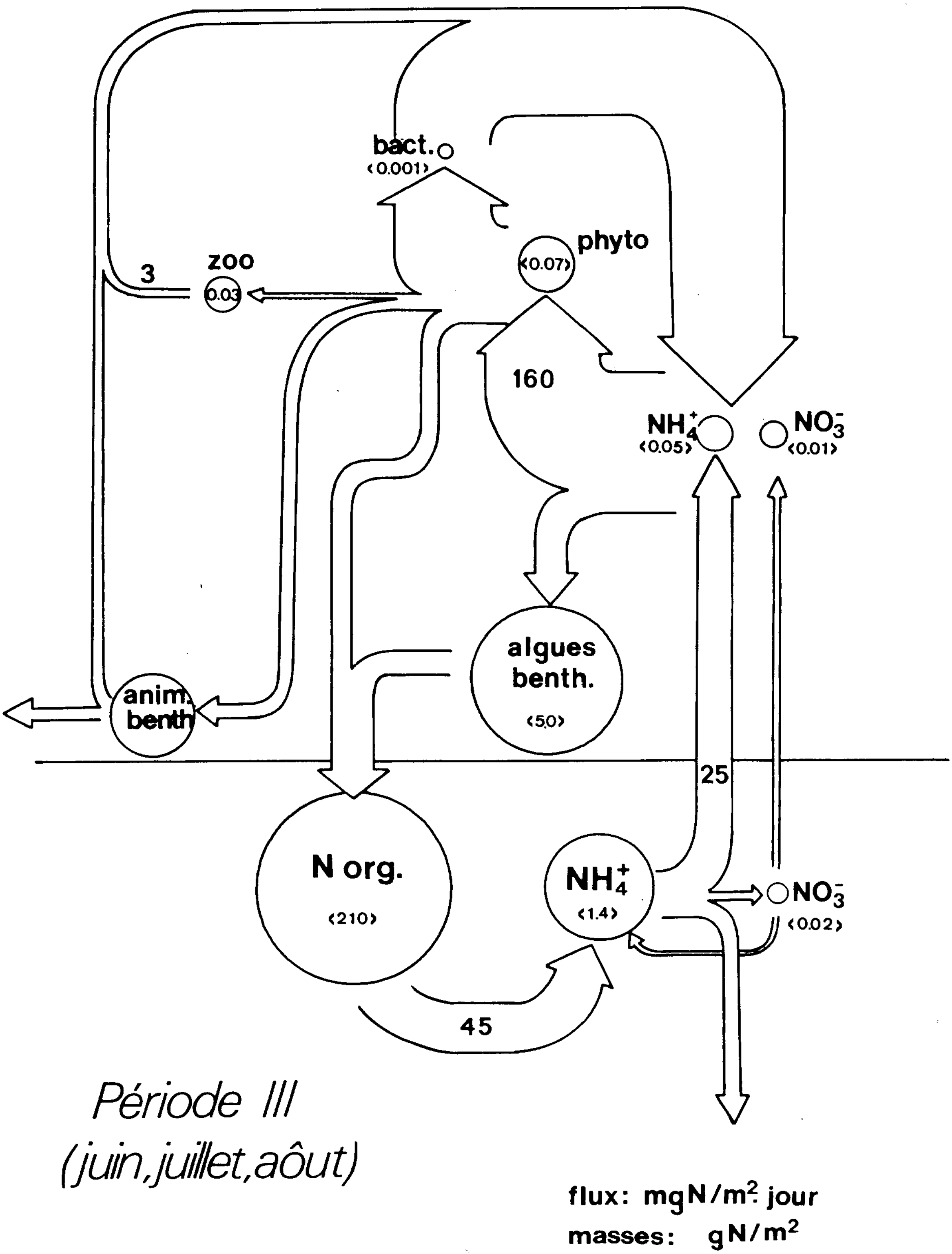


fig. 6.37.- Mean nitrogen transfers during the summer period in the Sluice Dock at Ostend.

6.2.1.- Evaluation of biological nitrogen transfers

Data on the activity of phytoplankton, zooplankton and (pelagic and benthic) bacteria have been given in details in the preceding sections.

Grossly, these data justify *a posteriori* the validity of the division of the network in three zones where significantly different types of biological mechanisms seem to be demonstrated.

In terms of nitrogen transfers, these data can be summarized as follows :

Table 6.14

Zone	Primary production (g N/m^2.y)	Zooplankton grazing (g N/m^2.y)	Planktonic* heterotrophic bacteria (b/m^2)	Benthic** heterotrophic bacteria (g N/m^2.y)
1N	29	2.75	23 x 10^{11}	7.8
1S	19	4.5	25 x 10^{11}	8
2	18	5.75	5 x 10^{11}	6.3

* Too few measurements of planktonic bacterial activity are available to give here a mean value per zone. The figures given are mean numbers of heterotrophic bacteria. It must however be kept in mind that bacterial numbers are a poor index of activity.

** These figures are only orders of magnitude estimated from respiration data of Hargrave (1973).

Thus :

- Zone 1N : characterized by a high primary production with small grazing;
- Zone 2 : lower primary production, high grazing;
- Zone 1S : intermediary characteristics.

6.2.2.- Hydrodynamical nitrogen budget

The area studied, in contrast with the Sluice Dock, is an open system. Thus, an evaluation has to be made of the dissolved nitrogen flows at the frontiers of our three zones. This work is facilitated as the zones have been defined in such a way they correspond accurately to different hydrodynamic regimes [as already pointed out by Elskens (1972) for the distinction between zones 1 and 2] (fig. 6.38).

With the aid of the calculated residual streams in the network [Ronday (1973)], and with the following data on the annual outflow from estuaries and sewage discharges :

Scheldt : 3.3×10^9 m^3/y [Wollast (1972)]
Rhine : 75×10^9 m^3/y [Portman (1969)]
Belgian coast : 0.7×10^9 m^3/y [Portman (1969)]
Dutch coast : 0.7×10^9 m^3/y (by analogy with Belgian coast)

A simplified hydrodynamical budget can be established (fig. 6.38). The mean salinities of the three zones calculated with this simplified model agree satisfactorily with the measured ones, as also indicated in the same figure. The budget of dissolved nitrogen can thus be grossly evaluated from the following data :

- mean NO_3^- concentration [Elskens (Technical Reports)] :

Zone 1N : 175 μg N/ℓ
Zone 1S : 137 μg N/ℓ
Zone 2 : 42 μg N/ℓ
Coastal Channel : 115 μg N/ℓ

(NH_4^+ data are not available : we have chosen the same figures as NO_3^- so that a likely order of magnitude is achieved).

- mean values of concentration gradients :

1N - 2 frontier : 1.5 μg N/ℓ km
1S - 2 frontier : 5 μg N/ℓ km

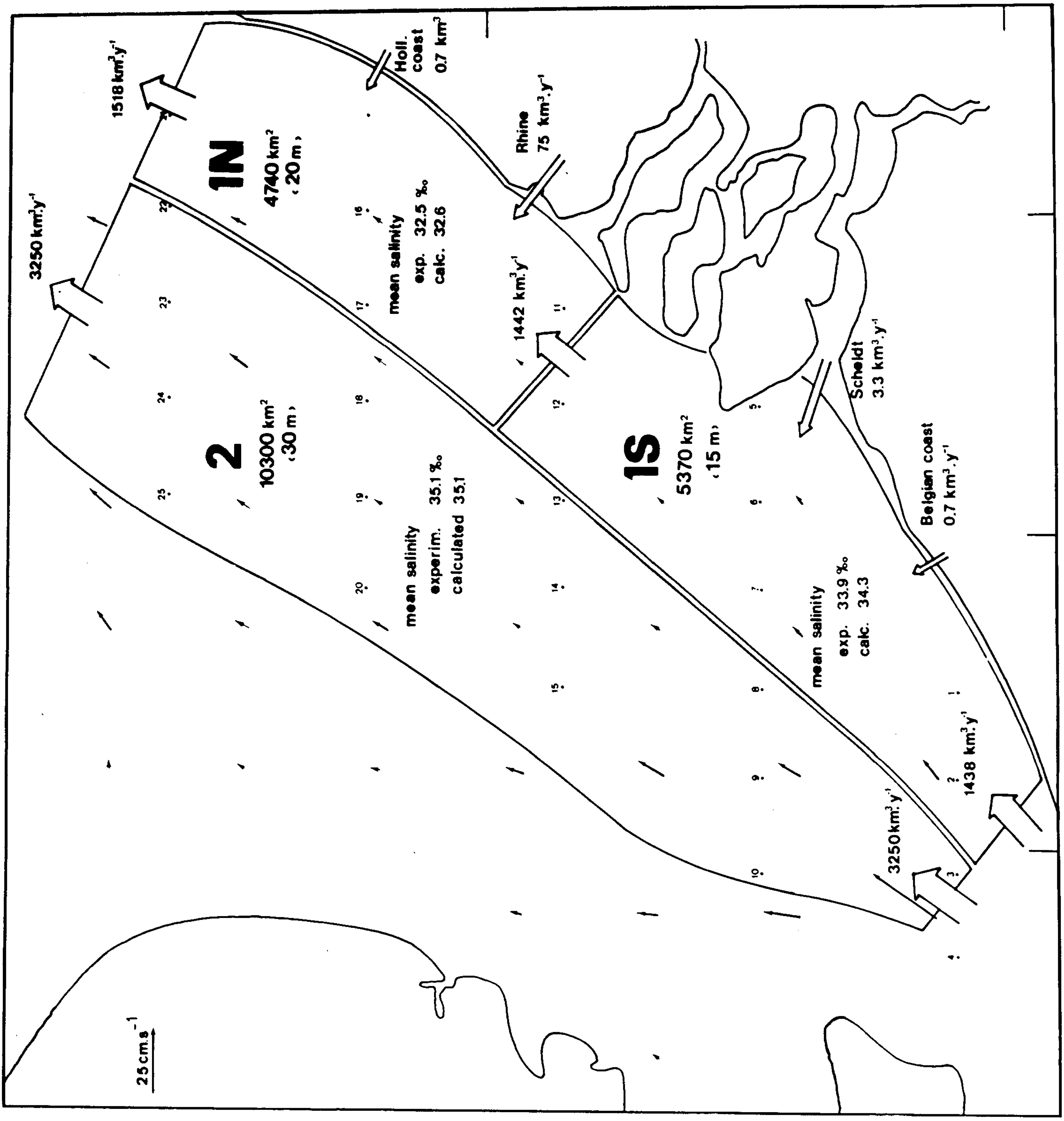


fig. 6.38.

Division of the network in three zones. These three zones, a posteriori characterized by different biological parameters, are defined on basis of hydrodynamical regime. The small arrows indicate the mean residual flows as calculated by Ronday et al. (1973). The great arrows indicate the annual water balance approximately evaluated from mean residual flows and geometric parameters.

- terrigenous imports :

Scheldt	:	46×10^3 TN/y	[calculated from Billen (1973) TR]
Rhine	:	230×10^3 TN/y	[Mead (1970)]
Dutch coast	:	36×10^3 TN/y	[Portman (1969)]
Belgian coast	:	36×10^3 TN/y	(by analogy with Dutch coast)

The circulation of dissolved nitrogen in the three zones of the network is represented in figure 6.39. From this, the net (biological) uptake can be grossly evaluated by difference between imports and exports :

Table 6.15

Zone	Total net uptake (TN/y)	Net uptake/m^2 (g N/m^2.y)
1N	129×10^3	27
1S	16×10^3	3
2	2.3×10^3	0.2

6.2.3.- Annual balance of nitrogen transfers

Figures 6.40, 6.41 and 6.42 present the global ecometabolism of nitrogen in the three zones.

It must be stressed that the given figures are approximative, at this stage of our knowledge, and have to be taken with caution. However some interesting conclusions can already be drawn by only comparing the orders of magnitude of the figures given.

Thus, it is seen that in zone 2 only an insignificant part of the nitrogen taken up by phytoplankton is of exogenous origin. Quantitatively the greatest part of the needs of the primary producers is provided by recycling mechanisms among which zooplankton grazing and excretion play an important role. Although this zone is an open system, its ecological behaviour is perfectly balanced (fig. 6.40).

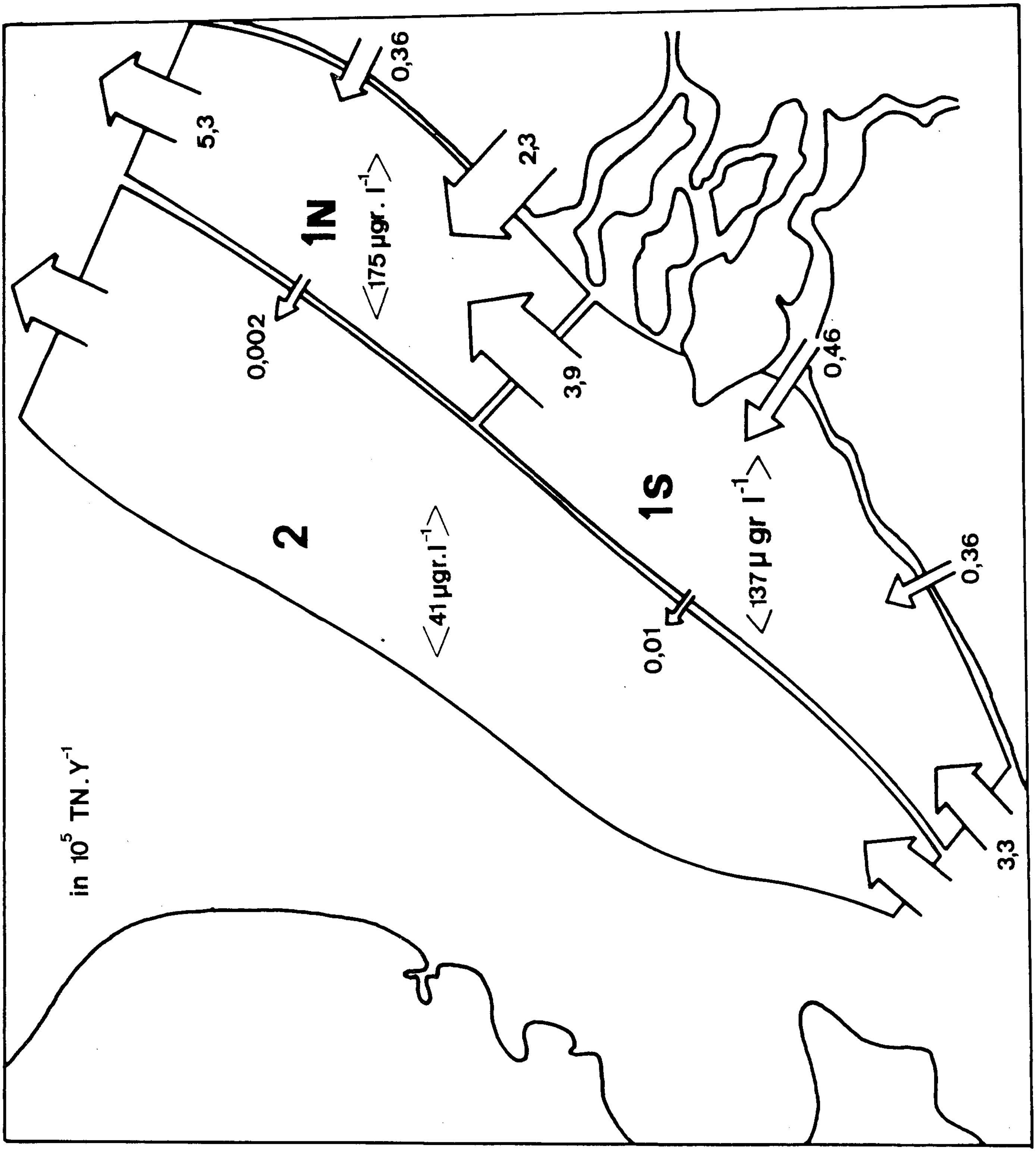
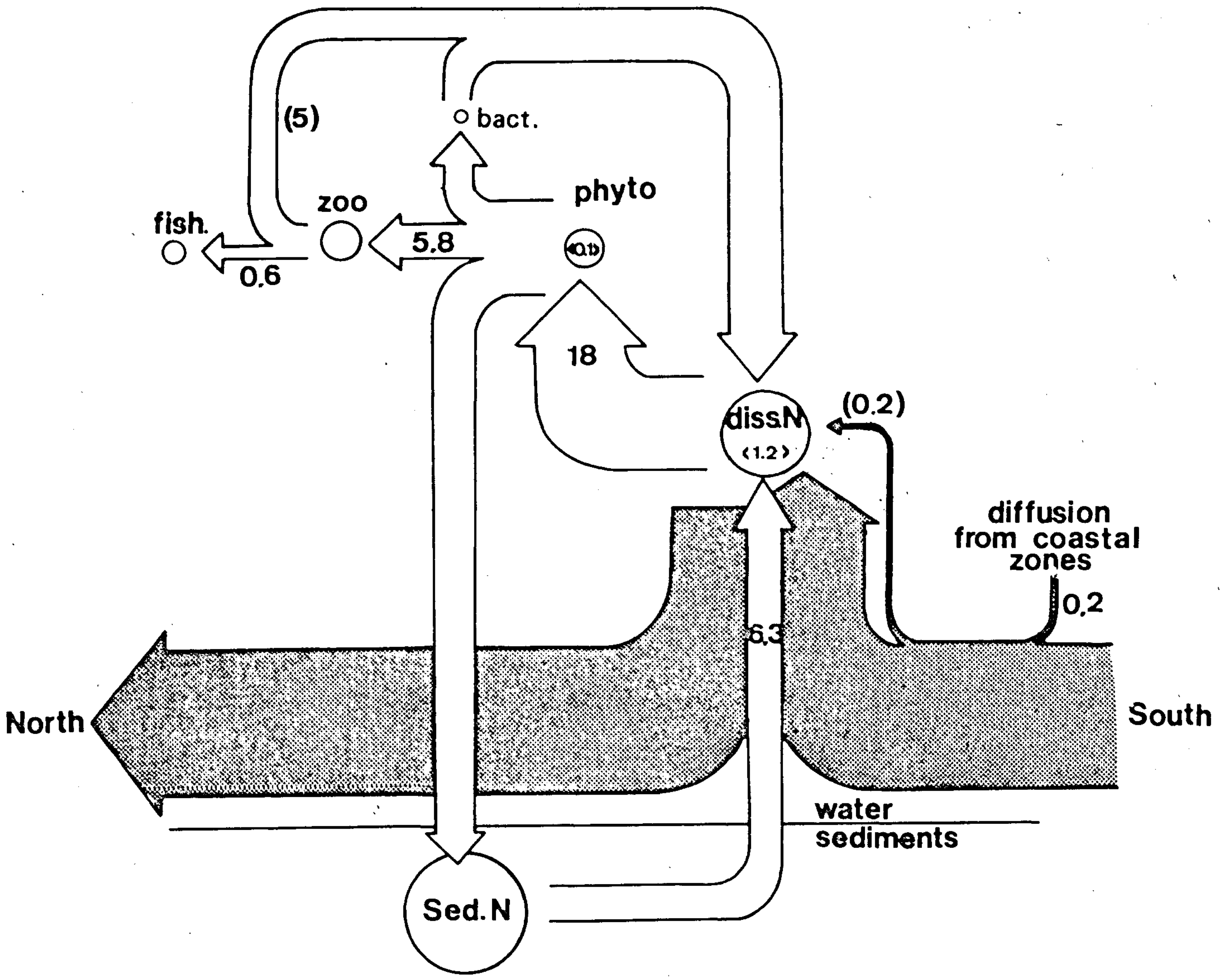


fig. 6.39.
Circulation of dissolved mineral nitrogen in the three zones of the network as calculated from the water balance of fig. 6.38 and the data given in the text.



Zone 2

transferts : gN/m².y
masses: < gN/m² >

fig. 6.40.
Annual balance of nitrogen transfers between the various compartments in the offshore zone of the Southern Bight of the North Sea (zone 2).

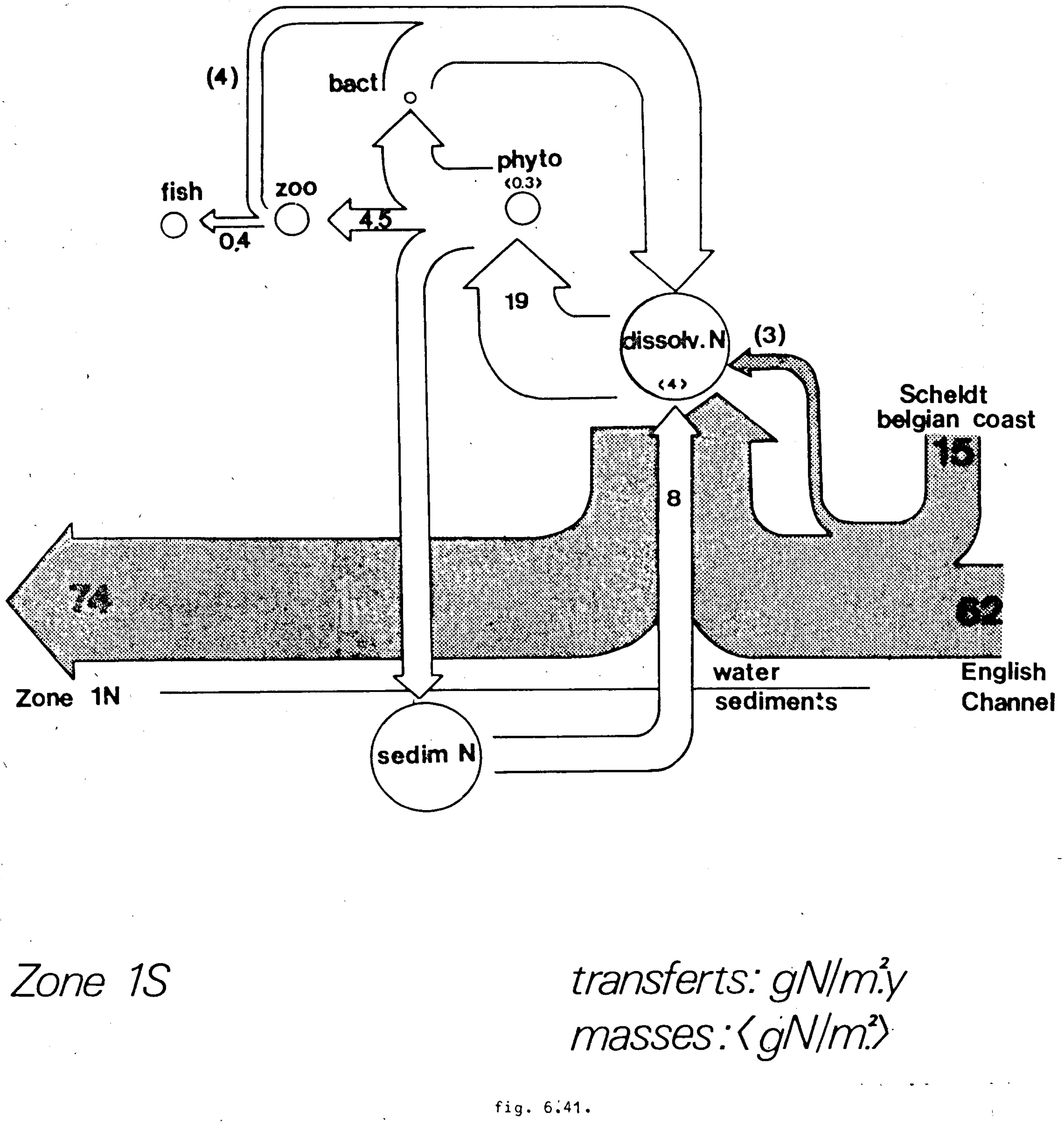


fig. 6.41.
Annual balance of nitrogen transfers between the various compartments in the Belgian coastal zone of the North Sea (zone 1S).

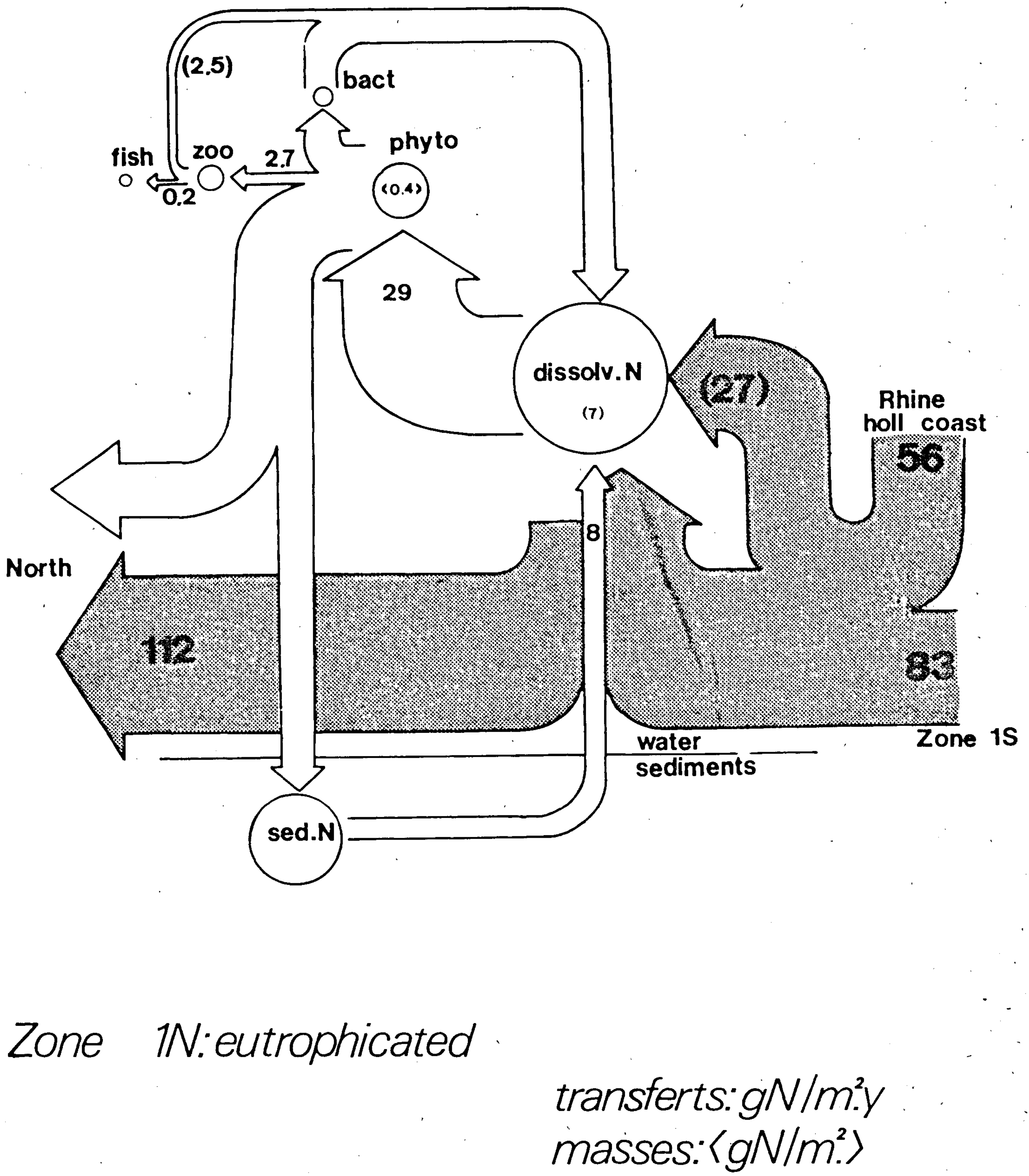


fig. 6.42.

Annual balance of nitrogen transfers between the various compartments in the Dutch coastal zone of the North Sea (zone 1N).

In zone 1 south, the exogenous nutrient utilization is a little more important. The recycling mechanisms are however still efficient. Among these, heterotrophic bacterial activity seems to play a greater role than in zone 2 (fig. 6.41).

In contrast, in zone 1 north, the greatest part of the primary production occurs at the expense of exogenous nutrients without important recycling. Accordingly, most of the biomass produced is probably either exported or sedimented (fig. 6.42). This unbalanced ecological behaviour is of course the consequence of eutrophication of this part of the North Sea.

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II. Role du zooplancton dans le cycle de l'azote.

III. Recyclage de l'azote dans les sédiments.

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II. Building of simulation models of ecosystems : non linear interaction parameters estimation

by

Georges PICHOT and Yves RUNFOLA

Introduction

An ecosystem is evoluting under the influence of a lot of interacting variables. In order to build the *a posteriori* mathematical model simulating its evolution, some of them are chosen and supposed adequate to give a good gross description of this ecosystem. For these ones, the differential evolution equations are written.

The effect and the control of all the other ones have to be introduced in these equations by the numerical values of the interactions coefficients.

If one assumes a spatial homogeneity and neglects the hydrodynamical effects, the box model may be written as :

$$\dot{X} = F(X,\vartheta,t) \qquad (1)$$

with X the state vector and ϑ the parameter vector.

Sometimes, a parameter is expressed by a constant ϑ_i multiplied by a given time fonction $Y_i(t)$. It reproduces the exciting effects of the outside ecosystems from which the considered ecosystem is demarked. So, (1) may be rewritten as

$$\dot{X} = F[X(t),\vartheta,Y(t)] \tag{2}$$

with Y the excitating vector.

The vectors X and Y are known by their values in time series $\tilde{X}(t_k)$ and $\tilde{Y}(t_k)$ at some measure times t_k .

In the building of the model, there are two problems to be considered. It is necessary firstly to fix the analytical forms F of the interactions and secondly to determine the value of the vector ϑ so that at the times t_k the calculated values of X by integrating (2) coincide with the observed values $\tilde{X}$.

1.- Determination of the analytical forms of the interactions

A statistical preprocessing of $\tilde{X}$ and $\tilde{Y}$ may clarify the various interactions. The correlation analysis provides information about series having similar behaviours more than firm relations of causality [Pichot-Hecq (1972)]. The spectral analysis shows up the periodicities of the series and the buffer effects between them [King and Mather (1972)].

It is clear that most of the interactions are non linear. The main semi-empirical laws cited in the litterature are the Verhulst relation (1845) for the logistic growths, the Van 't Hof one (1885) for the activation of metabolic processus by the temperature, the Lotka one (1926) for the prey-predator interaction, the Monod one (1942) for every phenomenon having a level of saturation, etc.

Since then, all the models were built by using more or less sophisticated combinations of these semi-empirical relations. One particularly interesting exception is to be pointed out . Mobley (1973) proposes a systematic way of determing F . He considers that the interactions are linear, bilinear and/or quadratic, tests every hypothesis between H_0 (all the coefficients are zero) and H_N (all the coefficients are different from zero) and retains the hypothesis which minimizes a likelihood ratio statistic expressed as a non-central F-variable. His method has the disadvantage to be restricted at most to the quadratic forms and to require an important CPU time.

2.- Determination of the interactions coefficients

If F is supposed to be known, the parameter vector ϑ must be now determined. As these parameters introduce the mean effect of all the variables that one must (or wants to) ignore, they do not have at all a meaning of universal constants. So, it is sometimes hazardous to put in a model of an ecosystem values of coefficients fitted for another ecosystem or still for an aquarium where one variable is studied in function of two or three other ones, everything else remaining constant.

Thus it is absolutely necessary to estimate ϑ from the information provided by $\tilde{X}$ and $\tilde{Y}$. One may choose as the best estimate ϑ^* of the vector ϑ, the one which minimizes the object function $G_1(\vartheta)$, *i.e.* the error between $X(t_k)$ calculated by integrating (2) and $\tilde{X}(t_k)$ observed.

$$(3) \qquad G_1(\vartheta^*) = \min_{\vartheta} G_1(\vartheta) = \min_{\vartheta} \sum_i \sum_k [X_i(t_k,\vartheta) - \tilde{X}_i(t_k)]^2 .$$

It is a problem of optimization with constraints. These are the system of differential equations (2) and the initial conditions $X_0 = X(t_0)$. This problem may be tackled in two different ways :

2.1.- The gradient method

One may chose the ϑ^* which realizes the minimum of the error of the derivatives. In this case, the object function to be minimized is

$$(4) \qquad G_2(\vartheta^*) = \min_{\vartheta} G_2(\vartheta) = \min_{\vartheta} \sum_i \sum_k \{\tilde{\dot{X}}_i(t_k) - F_i[X(t_k),\vartheta,Y(t_k)]\}^2 .$$

It requires the evaluation of the derivatives by spline functions, the minimization of G_2 and the integration of the differential system for which the procedures are explicited in appendix.

One may modify the object function $G_2(\vartheta)$ to take the possible disparities of the accuracy of the measures into account by balancing every term of the sum with a factor $w_{i,k}$ inversely proportional to the variance of the measure error of $\tilde{X}_i(t_k)$. Moreover, when some variables represent phenomena with very quick variations and other ones with very slow variations, one may also balance the partial sums of $G_2(\vartheta)$ in order to normalize the contribution of every variable to the value of G_2.

This method has the advantage to require as many minimizations and integrations as there are equations in the system (2) and thus to reduce the CPU time. Its main disadvantage is the effect of accumulation — during the integration — of systematic errors of the derivation.

2.2.- The maximum likelihood method

Using the statistical theory of the estimation Bard (1967) built another finer method of evaluating the parameters.

The error

$$u_{i,k}(\vartheta) = X_i(\vartheta,t_k) - \tilde{X}_i(t_k)$$

may be considered as a random variable distributed following a function of probability density $p[u_{i,k}(\vartheta),\varphi]$ with a known form. The statistical parameters φ are fixed from the classical hypothesis of the statistical behaviour of the error : zero mean, no correlation and covariance matrix estimated by

$$V = V(i,j) = \frac{1}{u}\sum_k u_{i,k}u_{j,k}.$$

The maximum likelihood principle is to maximize the object function

$$(5) \qquad G_3(\vartheta,\varphi) = \ln \prod_{i,k} p(u_{i,k},\varphi) .$$

This maximization obtained by the method given in appendix requires the computation of $\frac{\partial G_3}{\partial \vartheta_a}$; thus the one of $\frac{\partial X_i}{\partial \vartheta_a}$.

This one is obtained by integrating the system of the sensitivity equations of the state variables with regard to the parameters :

$$(6) \qquad \frac{\partial}{\partial\vartheta_a}\dot{X}_i = \left(\frac{\partial \dot{X}_i}{\partial\vartheta_a}\right) = \frac{\partial F_i}{\partial\vartheta_a} + \sum_j \frac{\partial F_i}{\partial X_j}\,\frac{\partial X_j}{\partial\vartheta_a}$$

In the maximization processus, the two systems (2) and (6) have to be integrated for every iteration of the ϑ value. The advantage of this method is to make an optimization of a statistically significant function of the state variables themselves (and not of their derivatives). Its disadvantage is obviously an important increase of the CPU time.

So, the adopted strategy is firstly to use the gradient method for a gross estimation of the parameters and then to use these values as the initial values for the maximum likelihood method.

3.- Theoretical application

These two methods were tested with a theoretical model containing the same analytical interaction forms that the previously mentioned ones.

Suppose the system :

$$\dot{X}_1 = \exp(0.1\ Y_1)\ \left[\frac{\vartheta_1 X_3}{\vartheta_2 + X_2} - \frac{\vartheta_1 X_2}{\vartheta_3 + X_1}\right] \tag{7a}$$

$$\dot{X}_2 = \vartheta_4 X_3 + \vartheta_5 \left[\frac{X_1 X_3}{\vartheta_6 + X_3} - X_2 Y_1\right] \tag{7b}$$

$$\dot{X}_3 = \vartheta_7 + \vartheta_8 [X_1 X_2 - \vartheta_9 X_2 X_3]\ Y_2 \tag{7c}$$

with $X = (X_1, X_2, X_3)$ the state vector, $\vartheta = (\vartheta_1, \vartheta_2, \ldots, \vartheta_9)$ the parameter vector, $Y = (Y_1, Y_2)$ the excitating vector and $X(0) = (10\ ,\ 0.5\ ,\ 2.5)$ the initial conditions.

The system (7) is integrated between $t = 0$ et $t = 100$ and sampled at some $t_k (k = 1, \ldots, 15)$. The parameter vector ϑ is then estimated from the information of the "observed" series $\tilde{X}(t_k)$ and $\tilde{Y}(t_k)$ by the first and second methods. The theoretical, initial and estimated values of the components of ϑ are given in Table 6.16.

The agreement between the re-computed with the estimated parameters values of $X(t)$ and the "observed" ones is excellent and the difference between them is of the order of one percent. The agreement between the theoretical and estimated values of ϑ are good, except for its fourth and fifth components.

It is sure that one optimum is reached. But a same optimum can also be found for a set of parameter vectors ϑ of which every component varies inside a wider range as the system sensitivity with regard to it is weaker.

It is probably the case of ϑ_4 and ϑ_5 (paradoxical furthermore for the first one because its initial value is accidentally its

Table 6.16

Parameters	Theoretical values	Initial values	Estimated values
ϑ_1	1.5	1	1.36
ϑ_2	210	1	192
ϑ_3	120	1	122
ϑ_4	1	1	0.248
ϑ_5	3.3	1	0.81
ϑ_6	555	1	566
ϑ_7	10	1	8.9
ϑ_8	0.005	1	0.003
ϑ_9	1.3	1	1.45

theoretical one !) for which the sensitivity of (7) should be weak near the optimum in the accuracy limits of the used methods.

4.- Practical application

For example, a simple model simulating the evolution of the primary production at a quite representative central point of the Ostend Bassin de Chasse between 22nd April and 29th July 1971 is fitted from the data of fifteen observation days well distributed on this period [Podamo Jo (1971), Pichot (1973)].

Suppose x_1 the primary production (mg N/m^2.day) , x_2 the incident light (J/cm^2.day) , x_3 the water temperature (°C) , x_4 the nutrient concentration (mg N/m^3) , x_5 the phytoplankton biomass (mg N/m^3) .

The primary production is measured *in vitro* in mg C/m^2.h . Using a C/N report equal to 8 and a report between the *in situ* primary production per day and the *in vitro* one per hour equal to 12 as noticed by Podamo Jo (1973), one has

$$x_1 \textit{ in situ } (\text{mg N/m}^2\text{.day}) = 1.5\, x_1 \textit{ in vitro } (\text{mg C/m}^2\text{.h}) .$$

The phytoplankton biomass is supposed given by its chlorophyl a concentration which is converted in mg N/m^3 by using a C/chlorophyl a report equal to 45 .

The primary production behaves like the product of functions of the incident light, of the water temperature, of the nutrient concentration and of the phytoplankton biomass, *i.e.*

$$(8) \qquad x_1 = K_1\ f_1(x_2)\ f_2(x_3)\ f_3(x_4)\ f_4(x_5)\ .$$

4.1.- The temperature effect

By extension of the Van 't Hof law, the water temperature is supposed to generate an activity following an exponential relation and to double the production for every 10 °C increase.

So, one chooses :

$$(9) \qquad f_2(x_3) = \exp(\frac{\ln 2}{10}\ x_3) = \exp(0.07\ x_3)\ .$$

4.2.- The incident light effect

Steeman-Nielsen (1960) showed that the primary production depends on the incident light following a Monod relation and the saturation level is usually reached for a lighting of 336 $J/cm^2.d$.

Now the data indicate that the light energy available for the photosynthesis (losses by reflexion and useful fraction of the light spectrum) overtop this level. So it seems that the light does not control the primary production and that (8) becomes :

$$(10) \qquad x_1 = K_2\ \exp(0.07\ x_3)\ f_3(x_4)\ f_4(x_5)\ .$$

4.3.- The nutrient effect

It seems obvious [Sen Gupta (1969)] that the phosphates are in supersaturation and they do not control the phenomenon. Thus one considers as nutrient, the sum of nitrogenous components, *i.e.*

$$x_4 = [NO_2] + [NO_3] + [NH_4]\ .$$

If for a first approximation, the primary production is supposed to depend linearly on x_5 , the productivity defined by

$$x_6 = \frac{x_1}{\exp(0.07\ x_3)\ x_5}$$

only depends on x_4 . The regression between x_6 and x_4 gives

$$x_6 = -\ 0.00027\ x_4 + 0.28655$$

with $r = 0.4322$.

This negative correlation is hardly significant and only shows up the decrease of the mean stock of the nutrients in function of the development of the production.

If one supposes a Monod relation between x_6 and x_4 , one has

$$x_6 = \frac{a\ x_4}{b + x_4}$$

or, in a linear form

$$\frac{x_4}{x_6} = \frac{1}{a}\ x_4 + \frac{b}{a}\ .$$

But the correlation between $\frac{x_4}{x_6}$ and x_4 is not at all significant. It could indicate that this relation is not valid here and that the productivity has well reached its saturation level.

So x_4 does not control the productivity; it is comprehensive because the weakest measured concentration is yet fifteen times higher than a half-saturation constant cited by Eppley (1969b) for the natural marine entrophic communities. Equation (10) becomes :

$$x_1 = K_3\ \exp(0.07\ x_3)\ f_4(x_5)\ . \tag{11}$$

4.4.- The phytoplankton biomass effect

A linear relation between the production and the phytoplankton is the clearest because the photosynthesis is directly proportional to the amount of the chlorophyllian pigments.

Nevertheless various tests showed that a quadratic form of x_5 improves the behaviour and reduces the standard error of the simulation. The form fitted by previously described first method is finally the

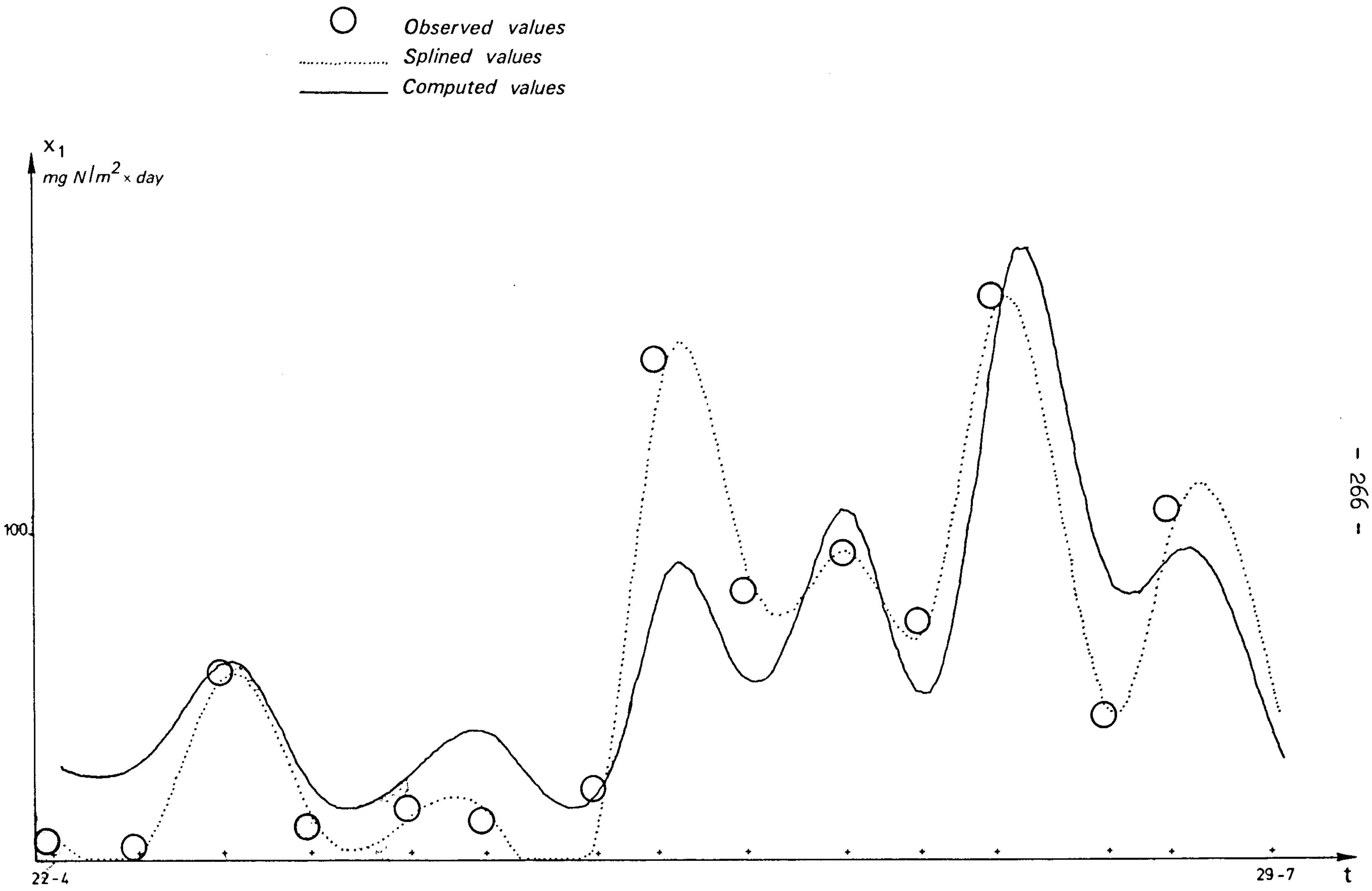

fig. 6.43.- Primary production (Ostend, Bassin de Chasse, 1971).

following one :

$$(12) \qquad x_1 = \exp(0.07\ x_3)\ [0.1028 \times 10^{-2}\ x_5^2 + 0.1338\ x_5]\ .$$

Figure 6.43 gives the curve of the observed (or exactly splined on the observed values) primary production and the one of the computed production. The two curves have the same order of magnitude and present all the same fluctuations.

The proposed model shows that the Bassin de Chasse primary production depends on the water temperature following an exponential law and on the phytoplankton biomass following a quadratic one. In this one, the term x_5^2 non negligeable with regard to the classical linear term perhaps indicates an autocatalytic effect of the primary production. The incident light and the nutrients are indispensable for the primary production, but they are in supersaturation and do not have any influence on this phenomenon.

5.- Conclusions

The present work may be summarized in the following items :

1) It is necessary, in order to build the simulation model of an ecosystem, to find the interactions coefficients from the information provided by the data of that given ecosystem.

2) To this purpose, a gradient method and a maximum likelihood one are proposed. They are connected because the gross parameters given by the first one are used as initial conditions for the second one.

3) A theoretical example shows that these methods properly work but stresses the interest of a sensitivity pre-analysis of the system.

4) The first method is applied for a practical example. In this one, the primary production of the Ostend Bassin de Chasse is given with an exponential function of the water temperature and a quadratic function of the phytoplankton biomass.

6.- Appendix

6.1.- Estimation of the derivatives

The first problem here is to evaluate the derived functions $\dot{\tilde{X}}_i(t_k)$ from $\tilde{X}_i(t_k)$. One cannot use the finite difference formulas because the time intervals between the measures are not generally constant and not small enough to ensure a good accuracy. On the other hand, the spline functions of the interpolation are well adapted to this problem. The spline function of order r which interpolates $\tilde{X}_i(t)$ at the points t_k is the unic function $S_i^r(t)$ defined by :

1) $S_i^r(t)$ is a polynomial of order $2r - 1$ for t between (t_k, t_{k+1}) with $k = 0,\ldots,\ell-1$.

2) $S_i^r(t)$ is a polynomial of order $r - 1$ out of (t_0, t_ℓ) .

3) The derivatives $S_i^{r(s)}(t)$ are continuous for $s = 2r - 2$.

4) $S_i^r(t_k) = \tilde{X}(t_k)$.

The third condition involves that the successive polynomials are connected at t_k and also the derivatives up to the order $2r - 2$. A discontinuity may occur in t_k only for the derivatives of order $2r - 1$.

Another interesting property of the spline function of interpolation is to minimize

$$\ell_r(f) = \int_0^{t_k} [f^{(r)}(t)]^2 \, dt \; .$$

In the case $r = 2$, this will ensure the $S_i^r(t)$ functions to pass through the t_k points and to be as smooth as possible.

For the building of this function, Laurent (1972) proposes the "transport of relations" method which ensures very good results. This general method (for any r and ℓ) avoids the difficulties of the classical method of decomposition in basic polynomials and only requires to solve ℓ linear systems of order $2r$.

6.2.- Minimization

Using the first three terms of the Taylor expression of the function $G_2(\vartheta)$ in a neighbourhood of the minimum ϑ^* , one gets immediately :

(13) $$\vartheta^* = \vartheta - G^{-1}(\vartheta^*)\ g(\vartheta)$$

with G the Hessian of G_2 with regard to ϑ

$$g = \text{grad}_\vartheta\ G_2$$

and the necessary condition that G is positive definite to ensure $G(\vartheta^*)$ minimum. One get the iterative process :

$$\vartheta_{i+1} = \vartheta_i - h_i\ H_i\ g_i$$

with $g_i = g(\vartheta_i)$,

H_i the approximation of $G^{-1}(\vartheta^*)$, h_i the stepsize in the $H_i\ g_i$ direction.

Choice of the direction

In the Newton method $H_i = G^{-1}(\vartheta_i)$. It assures $G(\vartheta_i)$ to be positive definite but it is not always verified, except if ϑ_0 is chosen in a very close neighbourhood of ϑ^* . In the case of problems with which one deals here, the parameters initial guesses may be far from the minimum and this method fails.

In the Davidson Fletcher Powel method (1963), this necessary condition is satisfied by a matrix serie H_i . It is positive definite, computed from any initial H_0 and converging to $G^{-1}(\vartheta^*)$. H_i becomes H_{i+1} by

$$H_{i+1} = H_i + A_i + B_i$$

where A_i and B_i are matrices computed from H_i , g_i , H_i^T and g_i^T such as A_i assures the convergence of H_{i+1} to $G^{-1}(\vartheta^*)$ and B_i makes H_{i+1} definite positive. In the case of a quadratic function G_2 , the convergence occurs in n interactions, n being the dimension of ϑ .

Choice of the stepsize

When the direction $H_i\ g_i$ is chosen, one has to define a distance on this direction where the minimum occurs. The stepsize is roughly evaluated by a finite difference formula :

$$s = 2\,\frac{Y_{est} - Y(0)}{Y'(0)}$$

with $$Y(h) = G_2(\vartheta_i - h\,H_i\,g_i)$$

and Y_{est} a given estimation of the minimum of G_2 .

If $s > 1$, it is set equal to 1 to agree with (13). Y and Y' are computed at points s , $2s$, $4s$, ... , s_1 , s_2 . When $Y'(s_2) = 0$ or $Y(s_2) > Y(s_1)$, the minimum s_3 is found by a cubic interpolation between $[Y(s_1), Y'(s_1)]$ and $[Y(s_2), Y'(s_2)]$. This procedure is repeated until a good accuracy is reached.

One assumes there is no local minimum in the $H_i\,g_i$ direction if

$$s_2\left(\sum_{i=1}^{n} |H_i\,g_i|\right) > 10^{10}\ .$$

6.3.- Integration (Extrapolation method)

In order to integrate a differential system $y' = f(x,y)$ with initial value $y_0 = y(x_0)$, the classical method is to divide $[x_0,x]$ by a stepsize h and to use one of the finite difference formulas (for instance the midpoint rule) to compute the approximation $T(h,x)$ of the integral $y(x)$. The accuracy is a function of h and $T(h,x)$ converges to the solution $y(x)$ when h tends to zero.

In the extrapolation method, some approximations $T(h_i,x)$ are computed and the true solution $T(0,x)$ is extrapolated from these values.

Burlisch and Stoer (1966) proposes a rational extrapolation

$$\hat{T}^i_m(h) = \frac{p^i_0 + p^i_1 h^2 + \dots + p^i_r h^{2r}}{q^i_0 + q^i_1 h^2 + \dots + q^i_v h^{2v}}$$

with $$r = \frac{m}{2}$$

$$v = m - 2$$

$$\hat{T}^i_m(h_k) = T(h_k,x) \qquad k = i, i+1, \dots, i+m$$

$$h_k = \frac{h_0}{2k}\ , \qquad \text{strictly decreasing sequence.}$$

The coefficient p^i is not computed but the extrapolated values $T^i_m = \hat{T}^i_m(0)$ are computed by a recurrent process starting with

$$T^i_{-1} = 0$$

$$T^i_0 = T(h_i, x)$$

$$\vdots$$

$$T^i_k = T^{i+1}_{k-1} + \frac{T^{i+1}_{k-1} - T^i_{k-1}}{\left(\frac{h_i}{h_{i+k}}\right)^2 \left[1 - \frac{T^{i+1}_{k-1} - T^i_{k-1}}{T^{i+1}_{k-1} - T^{i+1}_{k-2}}\right]}$$

This scheme gives a rhombus rule illustrated by the following tableau

$$\begin{tikzcd}
 & T^0_0 \arrow[dr] & & & & \\
T^1_{-1} \arrow[ur] \arrow[dr] & & T^0_1 & & & \\
 & T^1_0 \arrow[ur] & & & & \\
T^2_{-1} \arrow[ur] & & & & T^0_{m-1} & \\
\vdots & & & & & T^0_m \\
T^m_{-1} & & & & T^1_{m-1} & \\
 & T^m_0 & & & &
\end{tikzcd}$$

The initial stepsize and the wanted accuracy EPS are given at the beginning of the computation. This one runs for $m = 1, 2, \dots$ until $|T^0_m - T^0_{m-1}| < \text{EPS}$. m is bounded by 20 to avoid a too large CPU time.

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Chapter VII

I. First trophic level

STUDY OF PHOTOSYNTHETIC PIGMENTS, PARTICULATE ORGANIC MATTER AND PHYTOPLANKTON WITHIN THE AREA DELIMITED BY THE MATHEMATICAL MODEL - NORTH SEA

by

J. STEYAERT-PLANCKE and Ch. LANCELOT-VAN BEVEREN

Introduction

Any biological system evolves with time. The study and understanding of such a system – especially if the interest is focused on the search of anomalies and irregularities – require a preliminary approach including the distribution of its elements and their proper variation. The amplitude and the rate of this variation is depending on the type of organisms, the period of the year and the environmental conditions.

The present quantitative and qualitative study on phytoplankton biomass (first trophic level) and particulate organic matter is based on one hand on the results obtained at four fixed stations and on the other hand on the analysis of all 25 stations of the area. This last study tends to be an approach to the understanding of the seasonal variations in the area under study.

1.- Study of the phytoplankton biomass and particulate organic matter at four fixed stations

1.1.- Methods

The results obtained during the two last years 1972 and 1973 have shown appreciable differences not only between two consecutive cruises but also differences of the same order of magnitude between different stations during a same cruise. In order to interprete the differences in concentrations observed (phytoplankton, chlorophyll, particulate organic matter), it was consequently necessary to reduce the time scale with the aim to get a better knowledge of the variations size proper to those parameters.

Four fixed stations were investigated during January and June each representing a special zone of the model : one offshore station M14 and three coastal stations, M01, M16, M06, respectively in the South, in the North and in front of the estuary. This last one is submitted to the mixing of waters from different origins.

Investigations extended generally on 5 days and included :

- a daily sampling at the depth of 2 m .
- an examination of a 24 h cycle at the depth of 2 m , at the rate of one sample every two hours.
- a study of variations with depth. The three levels — surface, medium and bottom were chosen.

1.2.- Results

The daily variations observed on the samples taken within one week or sometimes two (station M14 in June) are generally not very significant compared to those observed at the same stations but at the different cruises. From figures 7.1 to 7.9 which show daily and seasonal variations for each of the four stations, we may deduce :

a) M14 : offshore station sampled in January and June (figs. 7.1, 7.2)

One observes at this point for all three parameters (phytoplankton cells — chlorophylls — particulate organic matters) disordered daily variations probably more due to the errors on the measure than to an effective variation in concentration. Observed quantities are as a matter

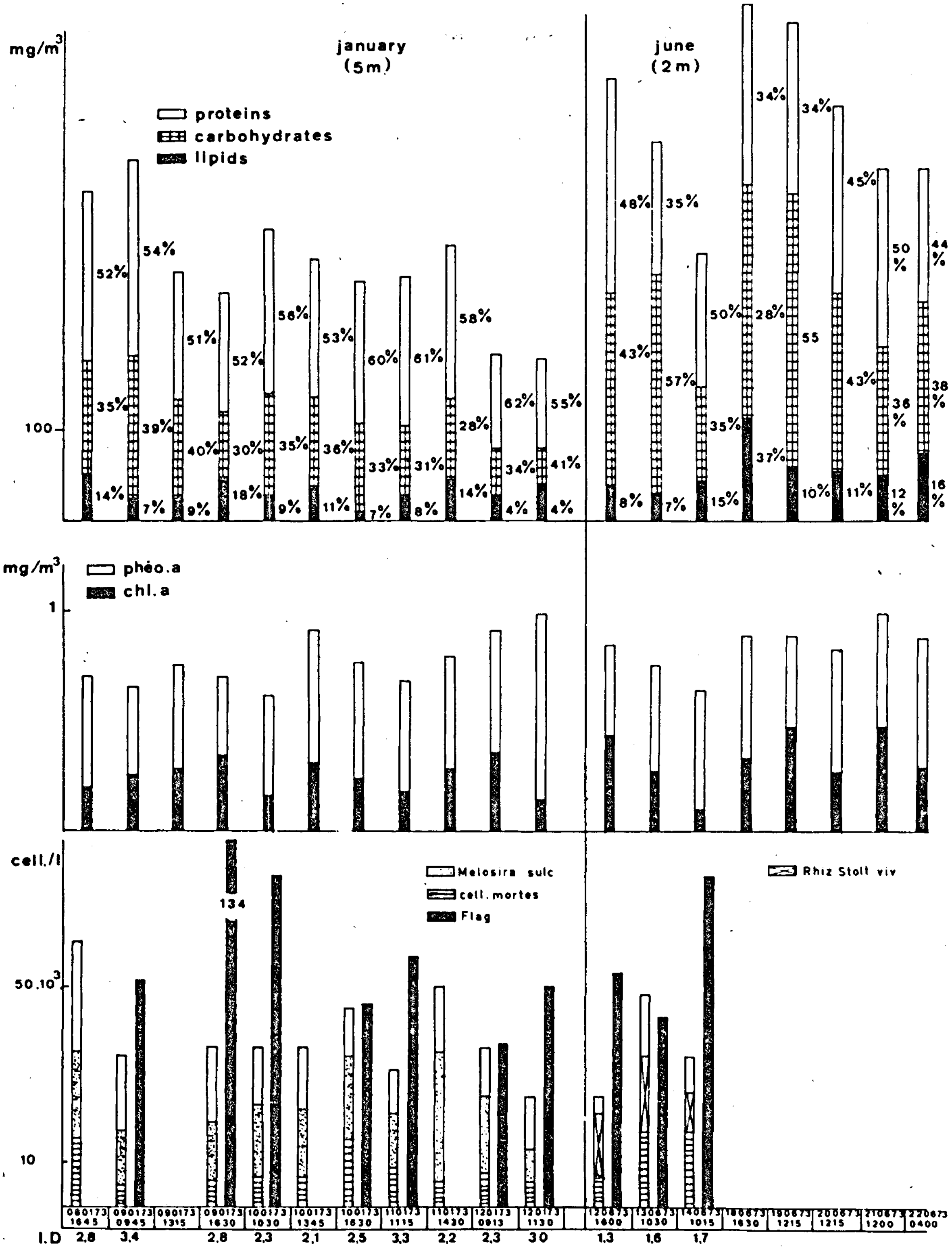


fig. 7.1.- Station M14, daily variations.

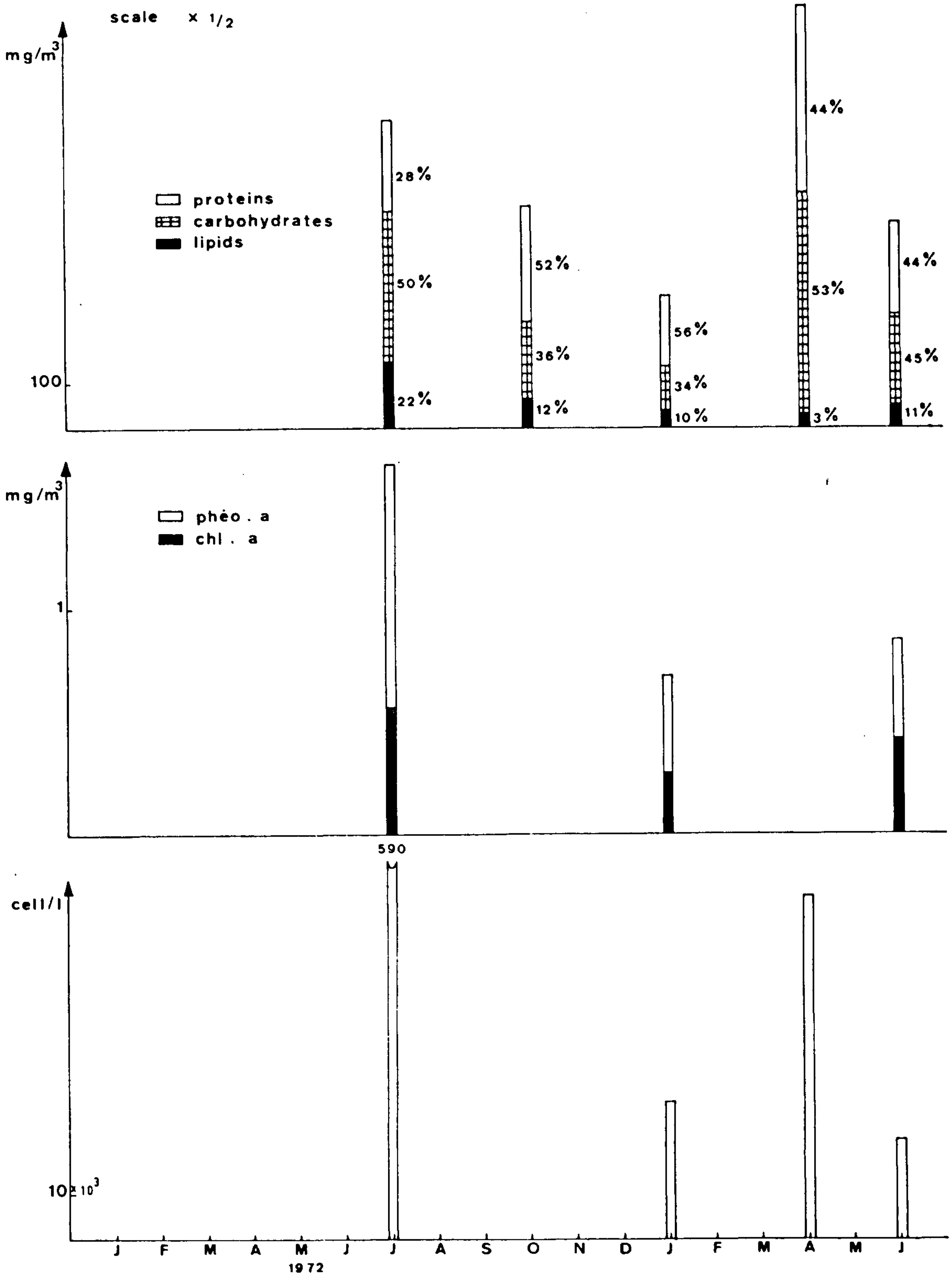


fig. 7.2.- Station M14, seasonal variations.

of fact very weak and lower than the sensitivity of the dosing and counting techniques.

In addition the comparison of the results obtained at this station at different times of the year, emphasizes the importance of detrital organic matter : for an equal quantity of pigments, larger quantities of particulate organic matter were observed in June than in January. We may deduce in the first case that the organic material is for a larger part composed by detritus (presence of dead cells). This assumption is enhanced by the study of detrital quality : variations in the ratios of the different metabolites (proteins – carbohydrates – lipids) are more important in June compared to those of January where the ratio Protein/Carbohydrate is always greater than 1 .

b) <u>M01 : coastal station sampled in January</u>

Considering the results reported on figures 7.3 and 7.4 it is to be observed from the quantitative point of view, that for none of the three parameters the daily fluctuations are important except for the sample of 24 January. In this last case, it is impossible to correlate the cell quantity nor with chlorophyll a, nor with particulate organic matter. This is perhaps to be linked to the important decrease of the species *Dimmerogramma minor*.

Considering now the qualitative aspect of the results, it must be pointed out that the heterogeneity in the qualitative distribution of particulate organic matter is linked to the coastal situation of the station and consequently to the tide.

Moreover, the quantity of particulate organic matter is large compared to the content in chlorophyll a and the pheo-pigments (degraded chlorophylls) are always more abundant than the active chlorophyll a . Both facts prove that this heterogeneity can be explained by a different detrital material.

c) <u>M16 : coastal station sampled in May and in June</u> (figs. 7.5, 7.6)

The results obtained on consecutive samples taken at the same hours (8 and 9 May, 12 h 30 and 26 and 27 June, 10 h) show a little increase of the phytoplankton biomass for all three parameters. This increase

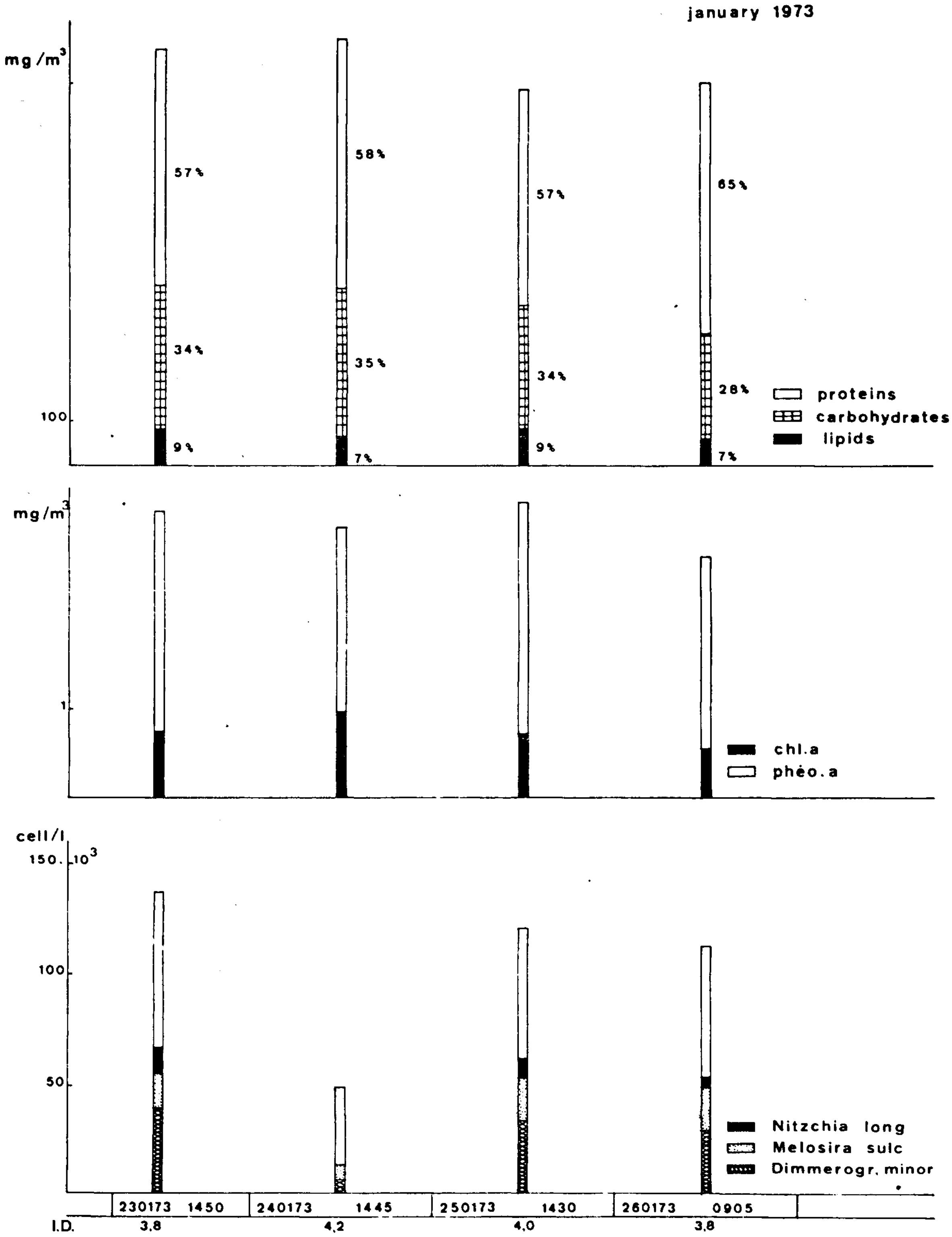


fig. 7.3.- Station M01, daily variations.

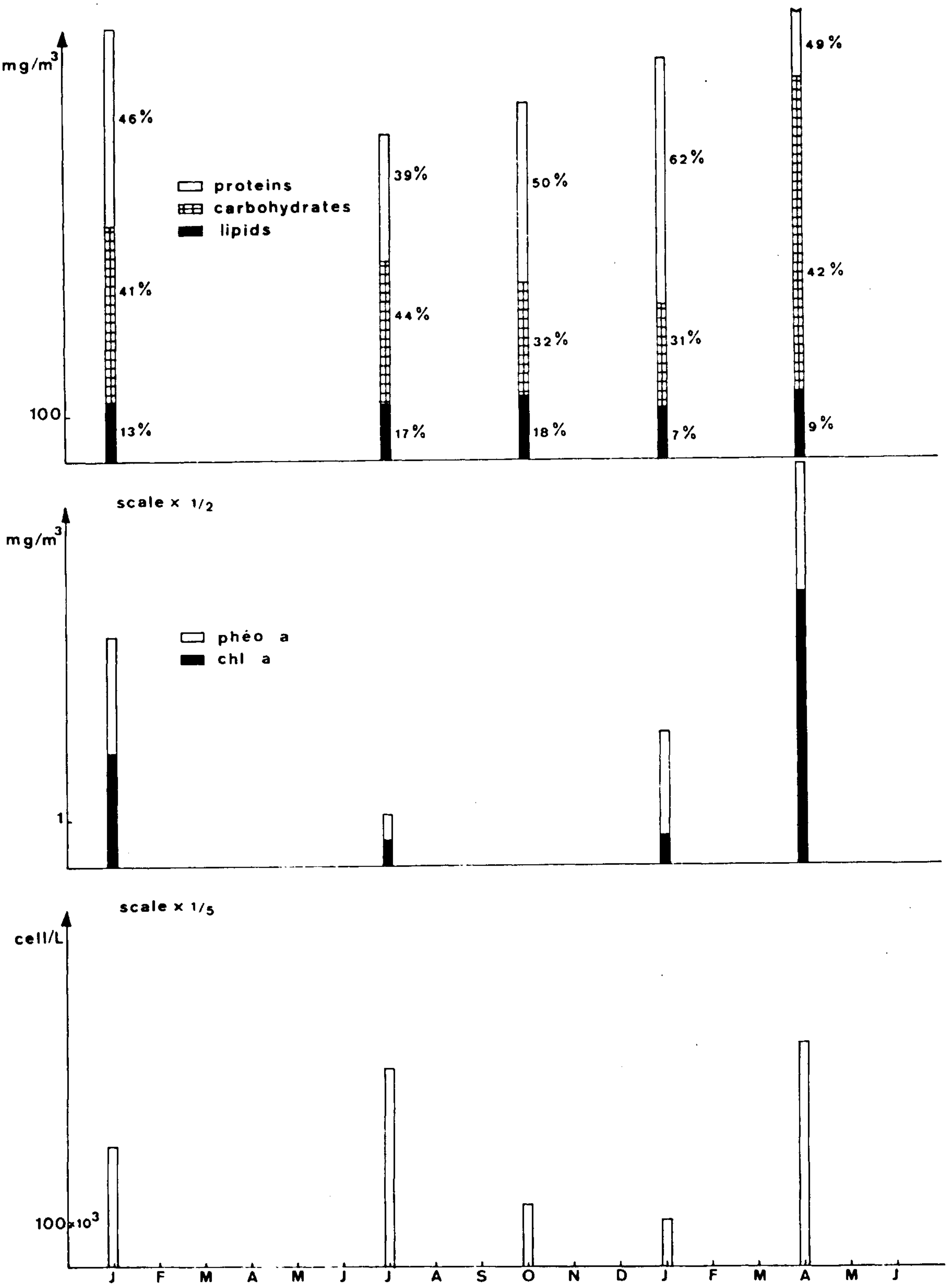


fig. 7.4.- Station M01, seasonal variations.

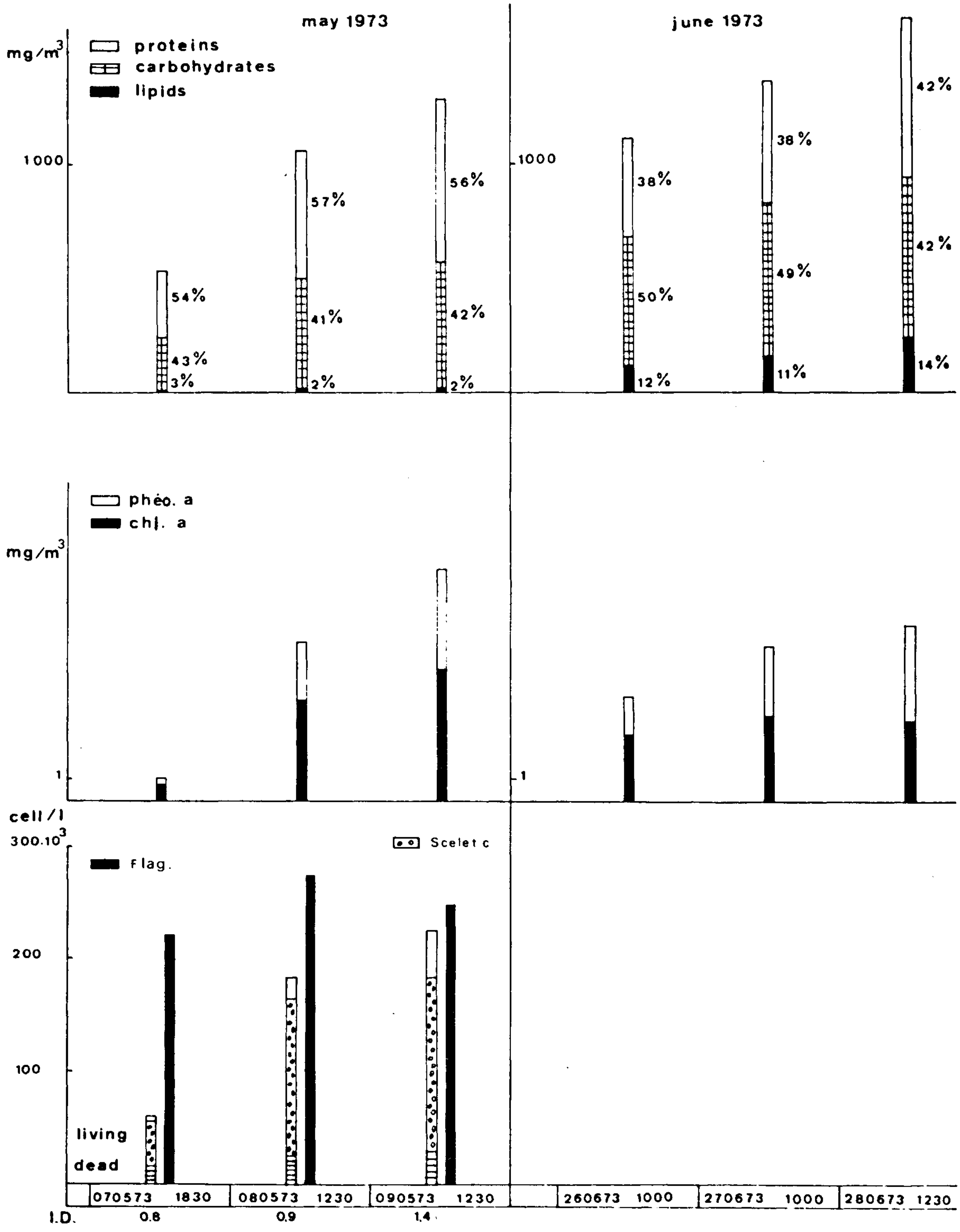


fig. 7.5.- Station M16, daily variations.

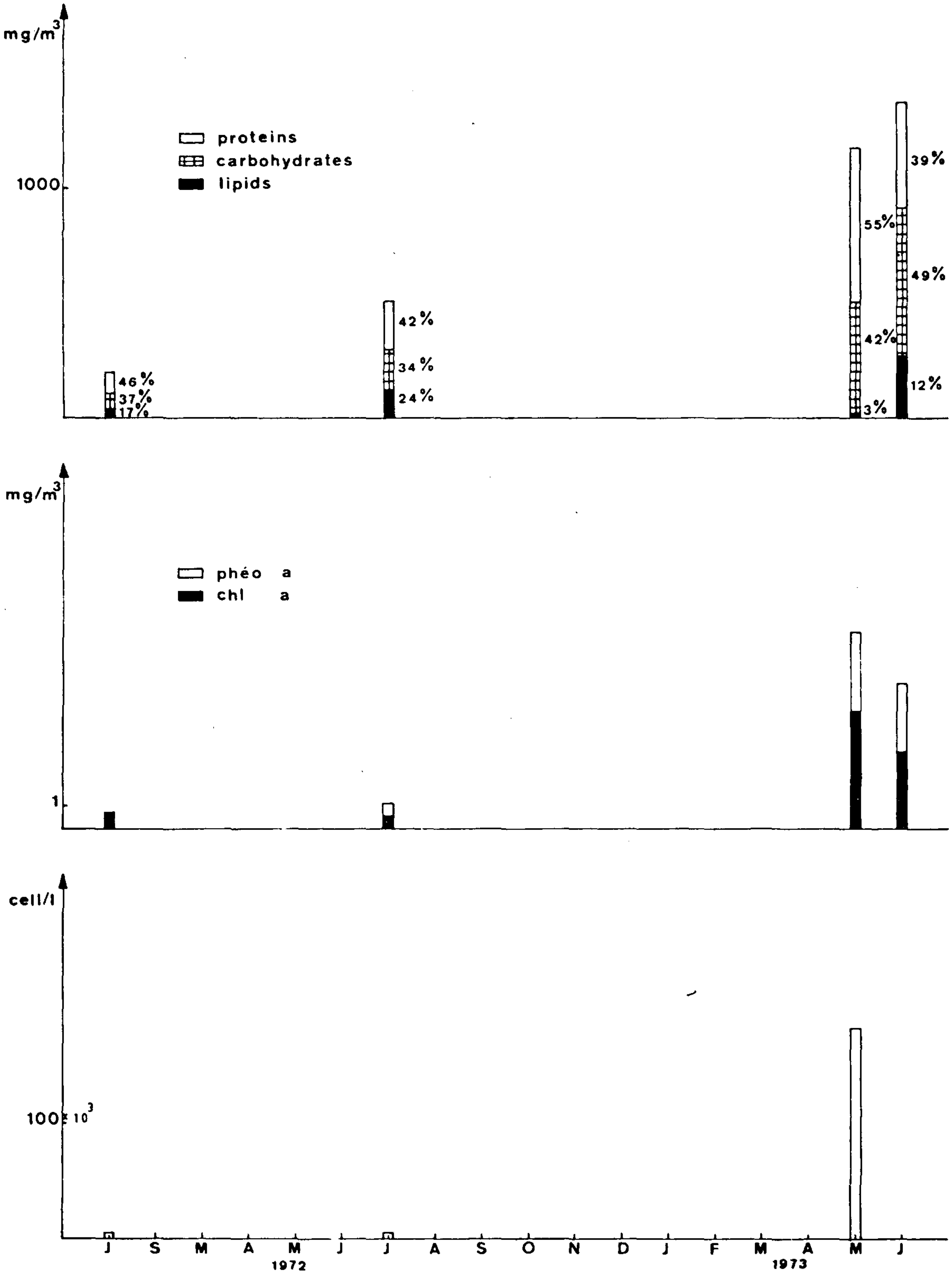


fig. 7.6.- Station M16, seasonal variations.

could correspond to the daily increment of the phytoplankton biomass (not consumed) resulting from the photosynthetic activity. However no conclusion may be drawn on the basis of only two consecutive samples.

In addition the analysis of the complete results point out important fluctuation of the biomass linked to the sampling time : 7 May 18h30, weak biomass; 8,9 May 12h30, high biomass.

The qualitative inventory of phytoplankton cells shows that the increase of biomass results essentially from an outburst of the spring species *Skeletonema costatum* whilst flagellates remain quite constant and always more abundant than diatoms.

Works on this subject [Lanskaya (1963)] mention indeed that the species *Skeletonema costatum* may contribute to fast variations of the biomass.

This statement may explain figure 7.7 showing a 24 h cycle of chlorophyll at the date of 8 May where a high biomass is recorded at 12h30 and a weak biomass at 18h30 .

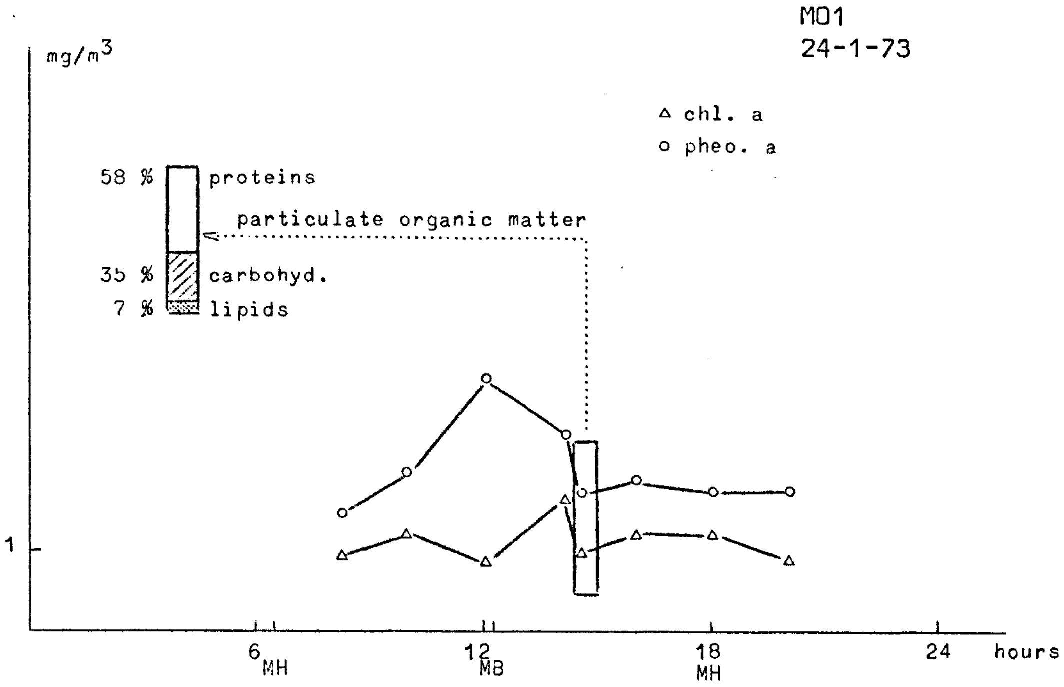


fig. 7.7a.- Fixed stations - 24 hours cycles.

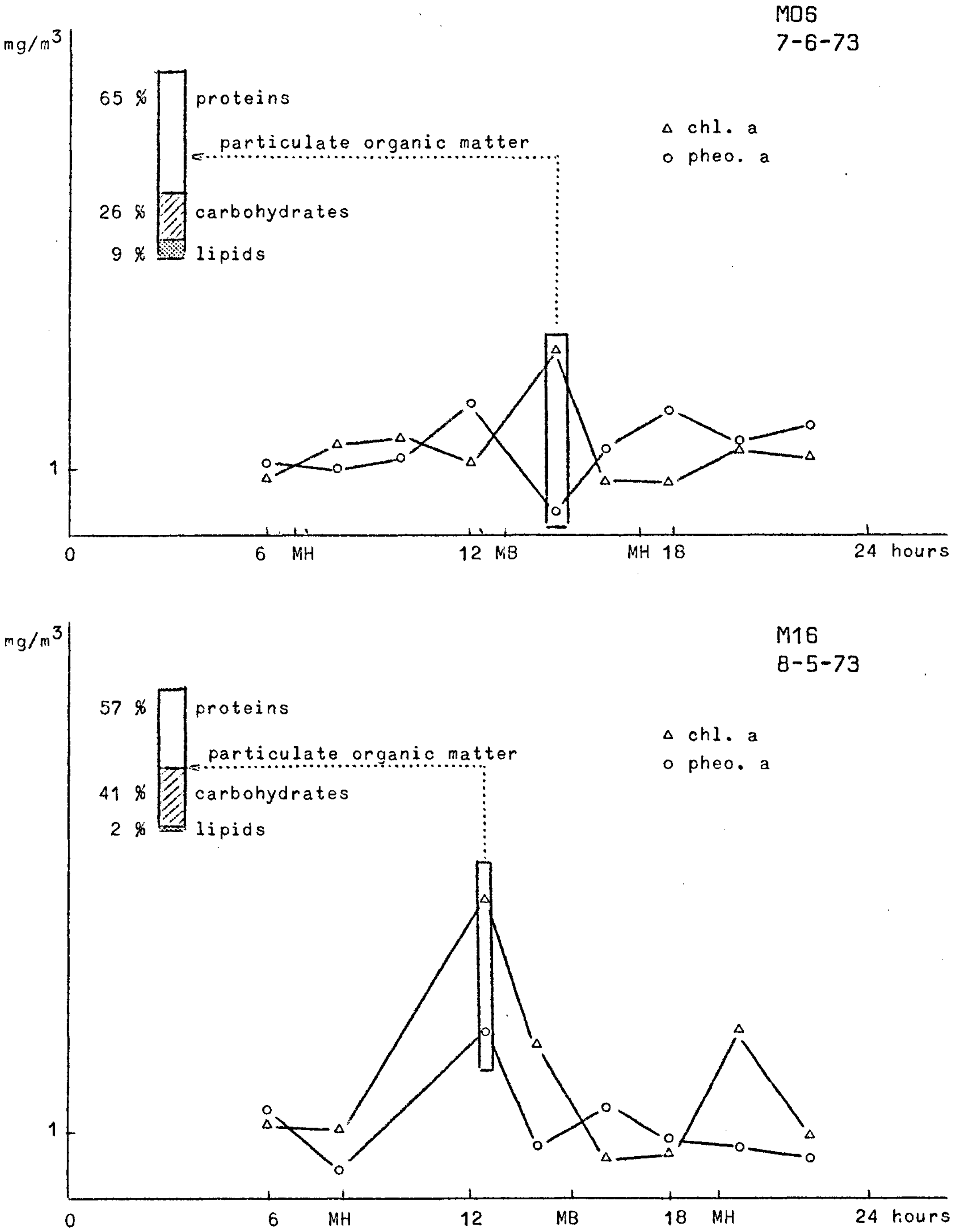


fig. 7.7b,c.- Fixed stations - 24 hours cycles.

Nevertheless, if the increase of the biomass is fast and selective and could be due to an endogenic rhythm of the species *Skeletonema costatum*, the fast decrease cannot be explained by a selective grazing of

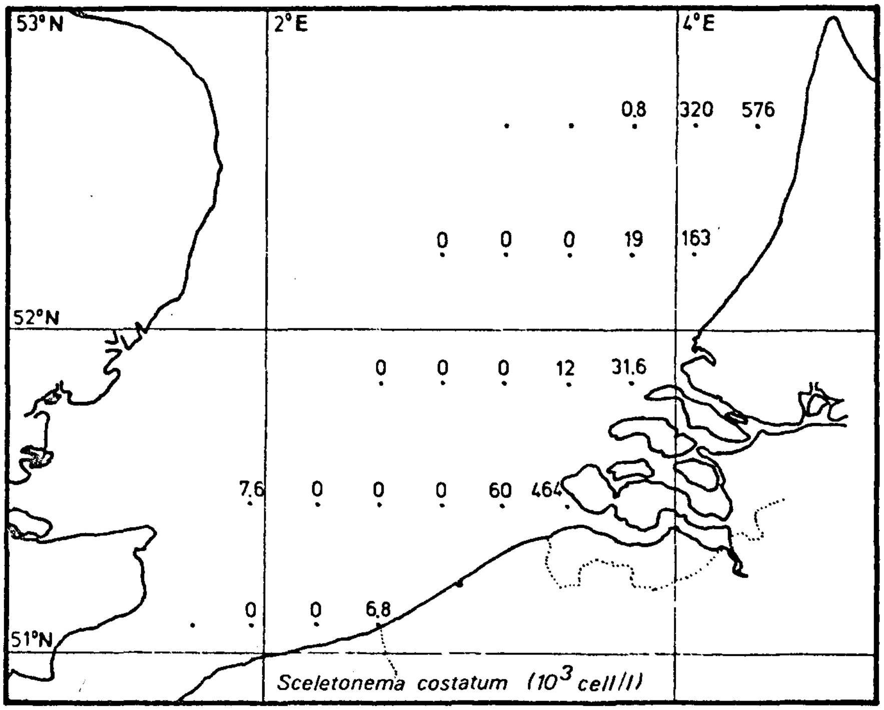


fig. 7.7d.

zooplankton {reference to the zooplankton results found in the Laboratory of Professor Polk [Daro-Bossicart : synthese 04 (1973)]}.

Consequently one can also assume that these spectacular variations of the phytoplankton biomass could be explained by the moving of waters. Refering to the map of distribution of the species *Skeletonema* during the cruise of April 1973 (figure 7.7d) the center of the bloom is indeed situated next to the stations M21, M22. The point M16 could therefore be more disturbed by fluctuations of the water mass because of its marginal position.

d) <u>M06 : coastal station in front of the estuary sampled in January and in June</u> (figs. 7.8, 7.9)

While the available energy flux (estimated by the particulate organic matter) do not present great seasonal variations, the fluctuations of the phytoplankton biomass (measured by chlorophyll and phytoplankton cells) are more pronounced :

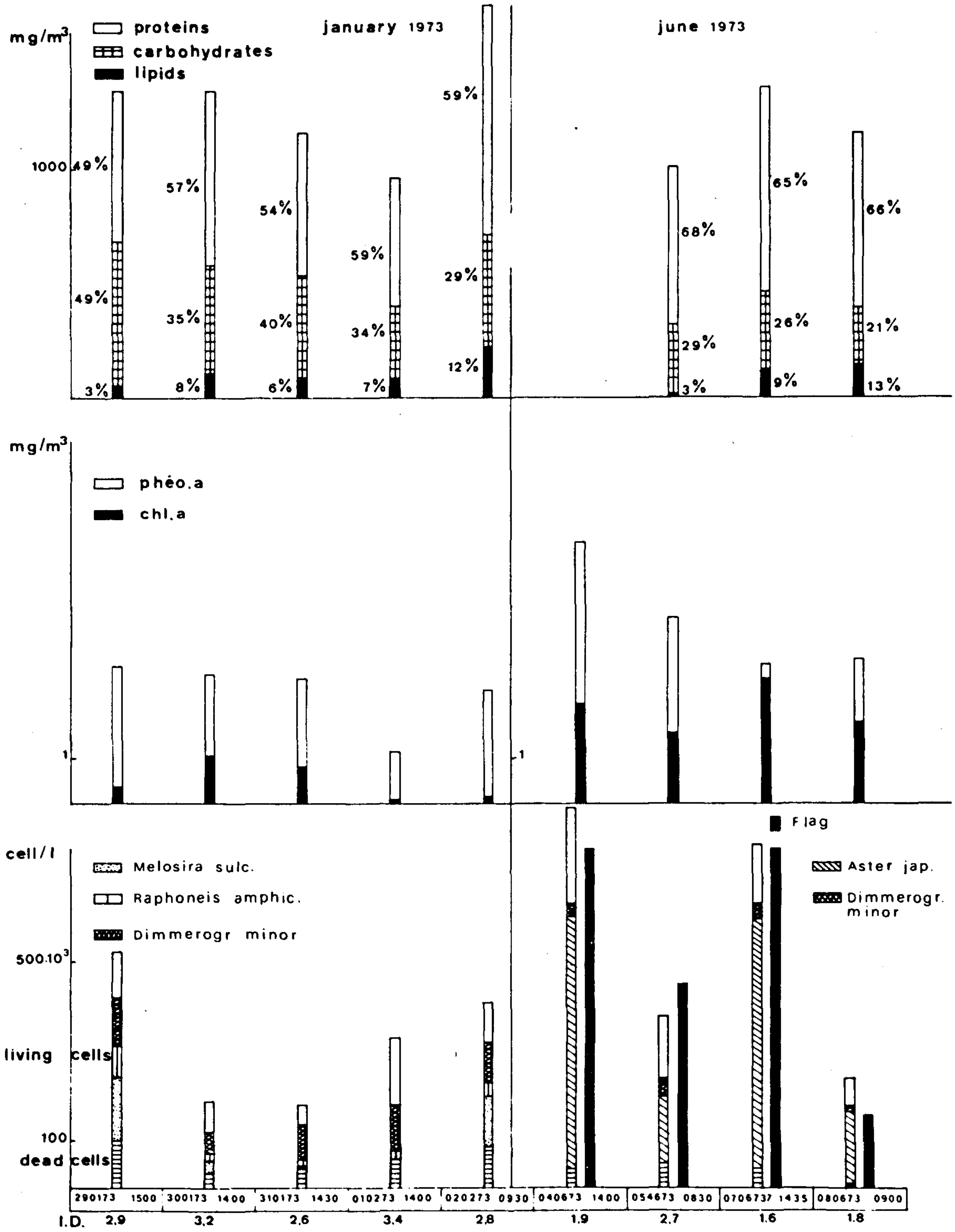


fig. 7.8.- Station MO6, daily variations.

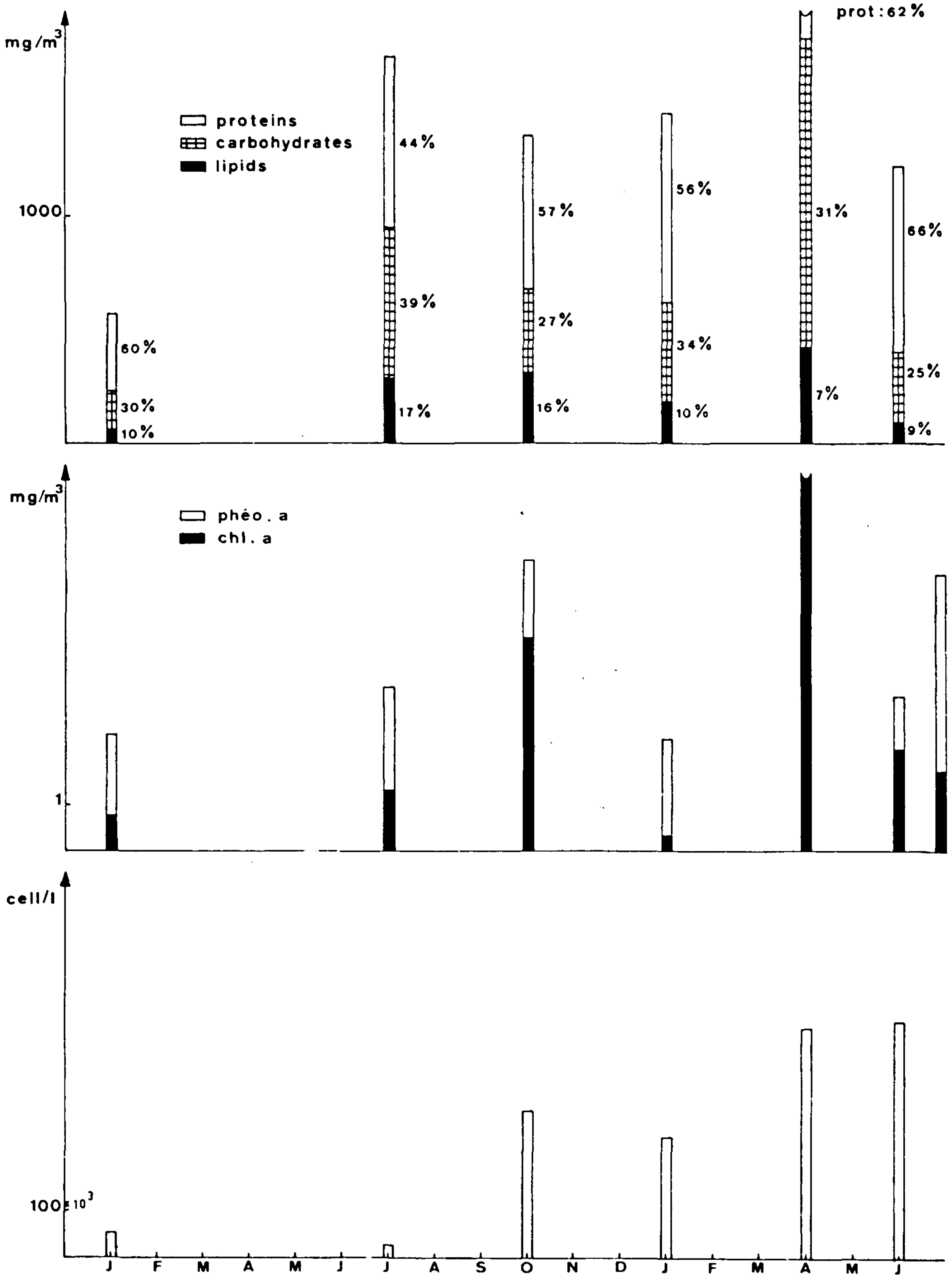


fig. 7.9.- Station M06, seasonal variations.

January

- Chlorophylls and phytoplankton cells are so weak that daily fluctuations are included in the error on the measure. In addition, many dead cells, an always greater quantity of degraded chlorophylls and large quantities of particulate organic matter associated with a weak content of chlorophyll a could represent an important drift of detritic material.

June

- Comparing only samples taken at the same hours, one records the same phenomenon than at station M16 in May : here biomass increase is due to the coastal diatom species *Asterionella Japonica*.

Located in front of the estuary station M06 undergoes the permanent stirring of different waters, but because no map of distribution of this species exists for the month of June in 1973, it is difficult to conclude to an effective bloom or to an arrival of water richer in *Asterionella*.

e) Vertical profiles (figs. 7.10, 7.11, 7.12, 7.13)

The study of variations with depth of photosynthetic pigments and particulate organic matter concerned stations M01 and M06 in April and June respectively. Results show larger quantities of pheopigments and particulate organic matter near the bottom.

This fact can correspond to a mixing of bottom sediments but can correspond as well with the Beklenishev's (1962) concept of detritus falling to the bottom mainly during periods of rapid phytoplankton growth when the zooplankton cannot assimilate all the plant cells. Stations M01 and M06 differ as following : the distribution of particulate organic matter with depth is identical to that of the pheo-pigments at station M01 while at station M06 it follows the distribution of the total amount of chlorophylls (living and degraded). It would mean that detritus are more considerable at station M01.

1.3.- Conclusions

While the daily variations for the quantitative and qualitative aspects are small, considering a period of five days, compared to the fluctuations observed at these same stations from one cruise to another, the study of a 24-hour cycle at stations M06 and M16 suggests that some

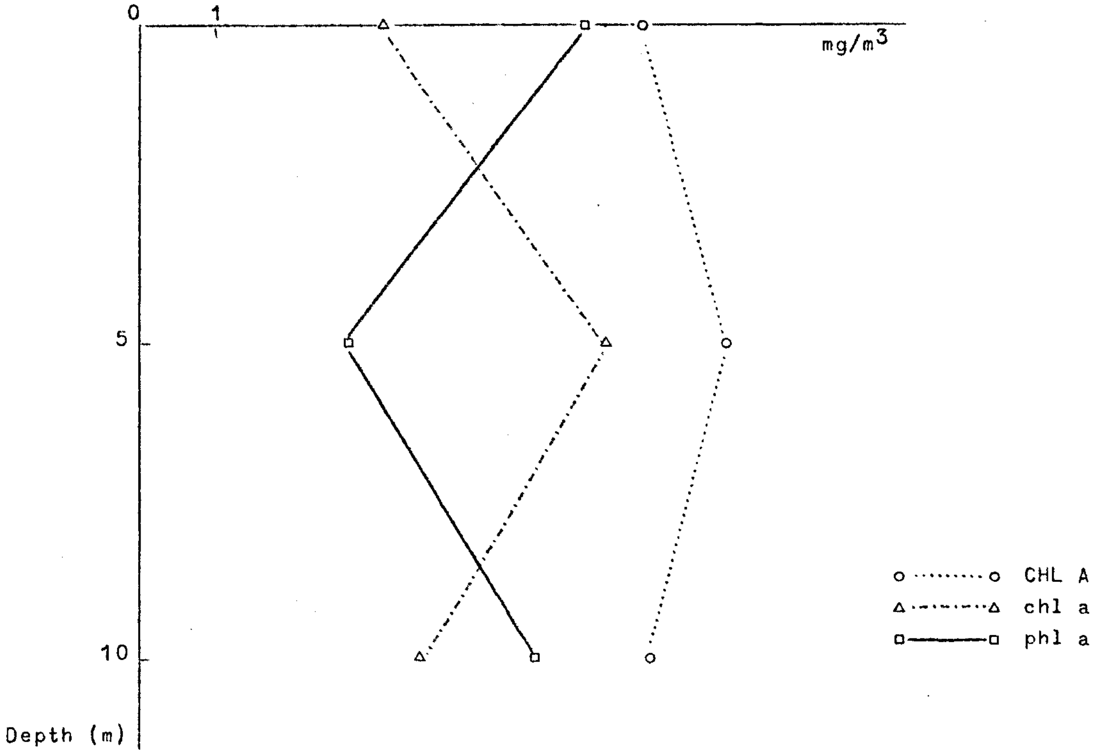


fig. 7.10.- Station M01 - Vertical profile.

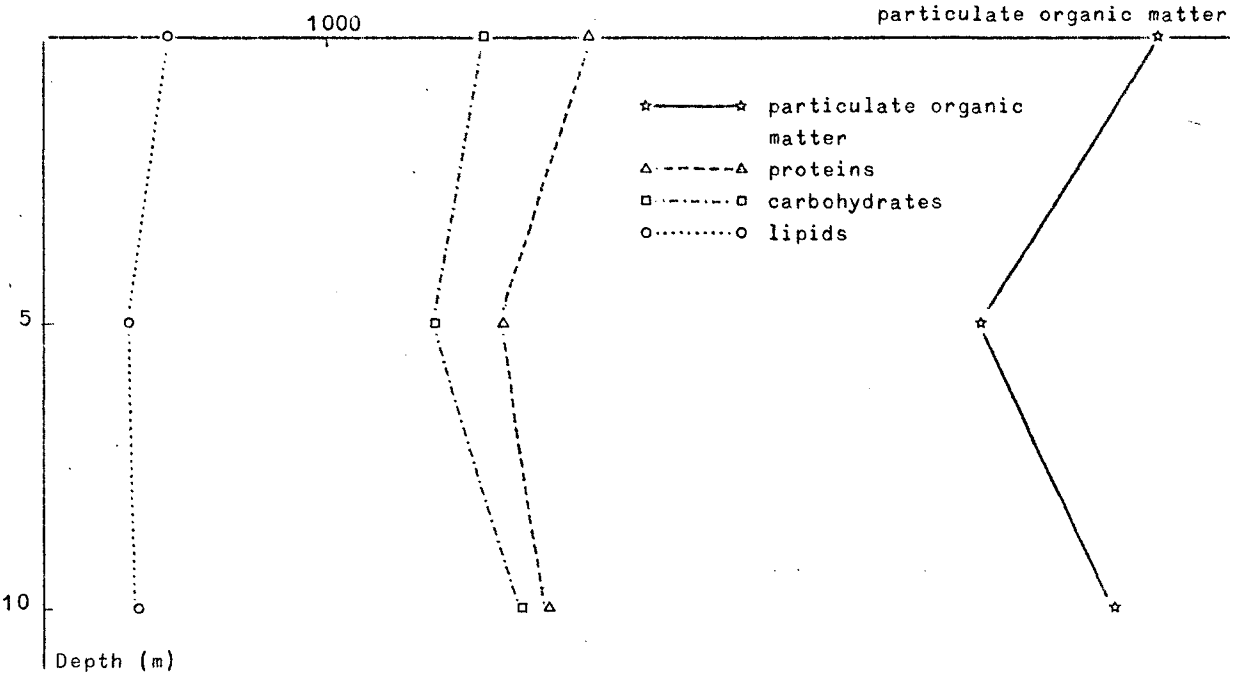


fig. 7.11.- Station M01 - Vertical profile.
18-4-73 13 h 30 .

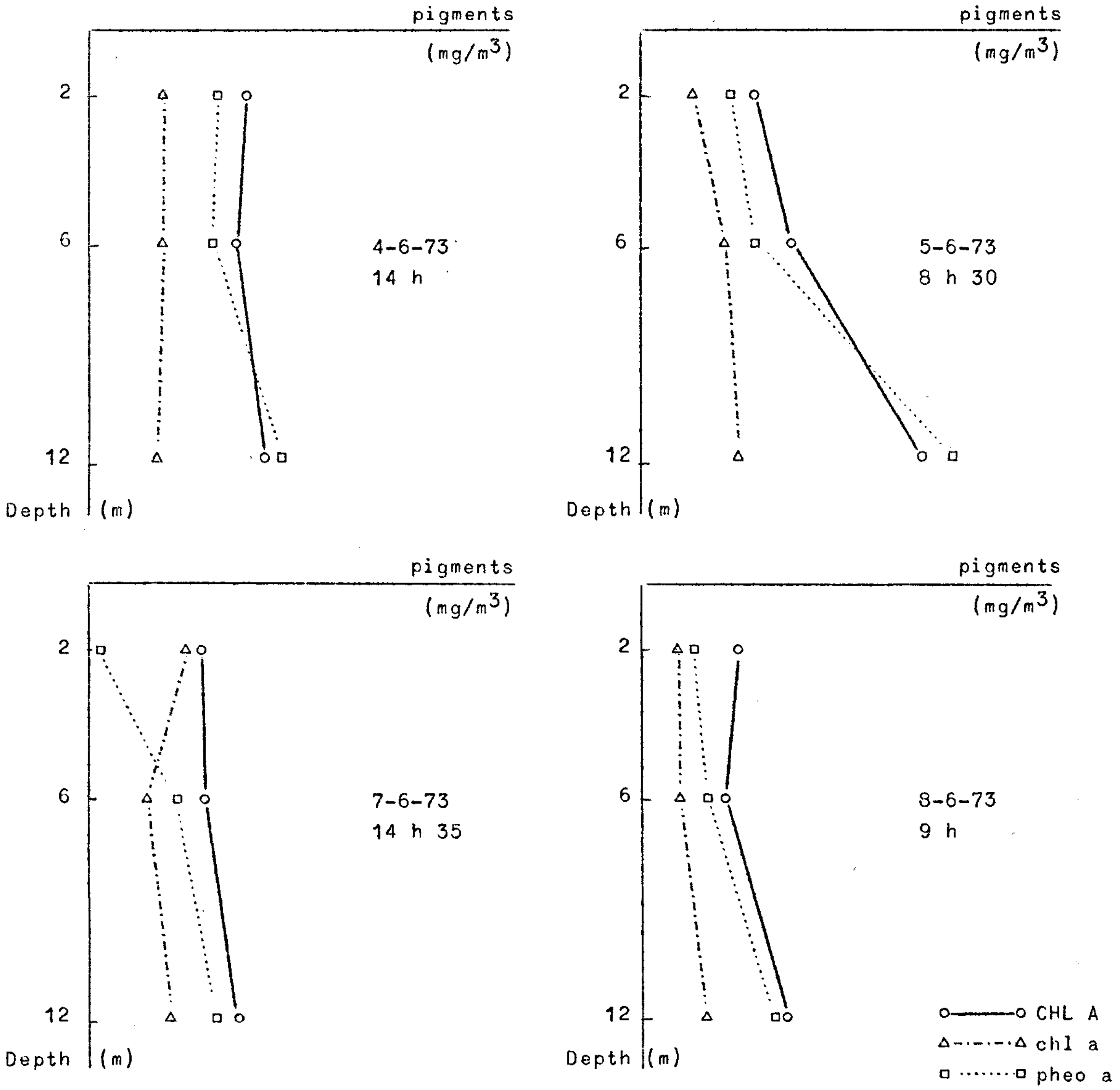


fig. 7.12.- Station M06 - Vertical profiles.

sharp variations of the phytoplankton biomass should be explained by the moving of the water mass rather than by the own physiology of the species. Both explanations are however acceptable.

Therefore, since within one week, significant variations of the phytoplankton biomass are not observable, a rapid spatial survey of the area delimited by the mathematical model will give a better picture of the biomass in the investigated area.

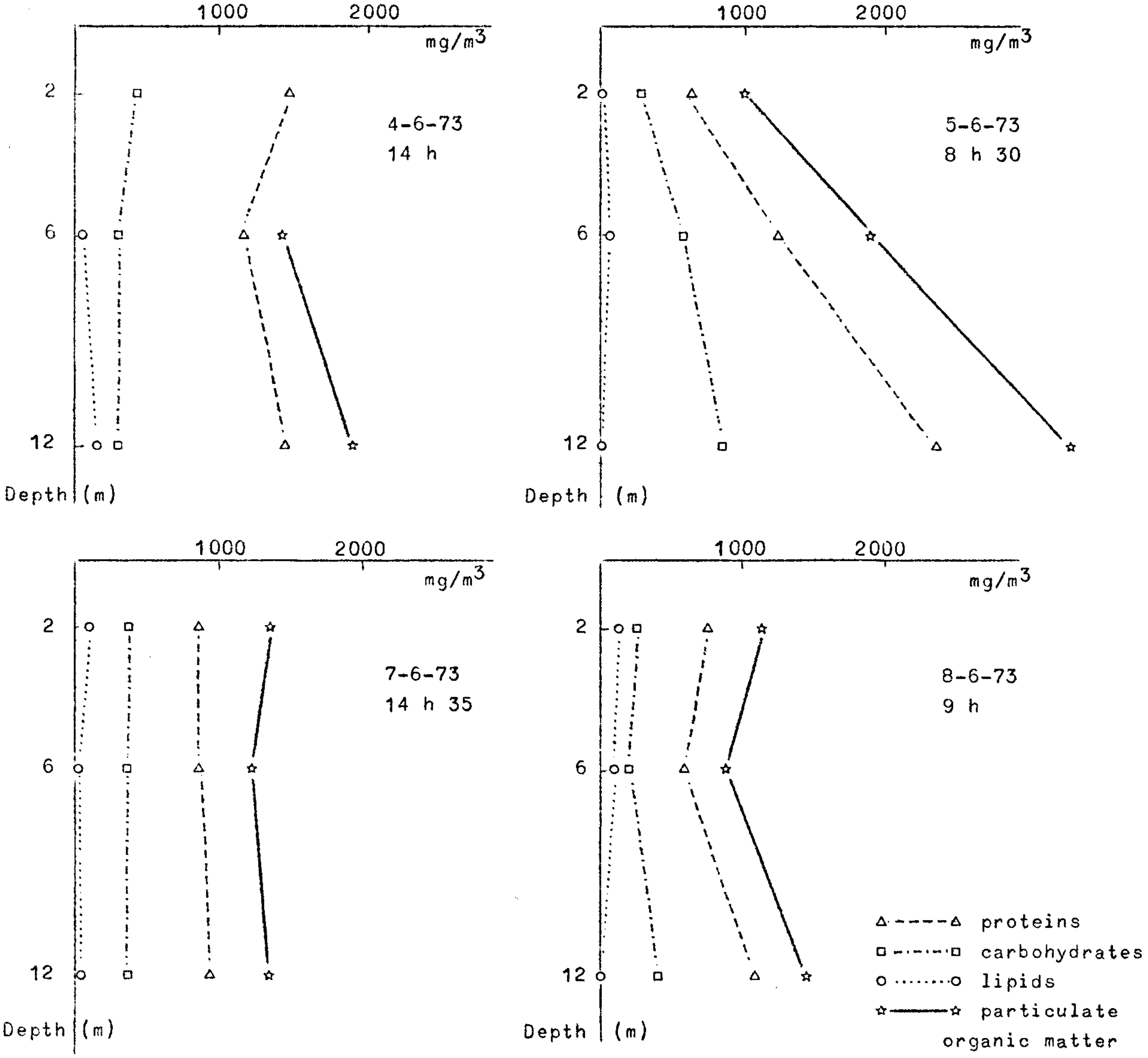


fig. 7.13.- Station M06 - Vertical profiles.

In addition, the purpose of the method of the fixed stations could be extended by intensive record of data connected with simultaneous sampling in some near points.

2.- Approach to the seasonal variation within the area delimited by the mathematical model

This study includes four parts treating of distribution of chlorophyll a, particulate organic matter and phytoplankton cells. The fourth part concerns the relative importance of detritus in the whole system.

Results will discuss about five cruises for chlorophyll and particulate organic matter and seven cruises for phytoplankton cells. The rapid changes of biomass and phytoplankton do not allow, on basis of such limited number of cruises to draw definite conclusions or to estimate the variation rate.

2.1.- Distribution of chlorophyll a

The complete data concerning chlorophyll a concentrations (SCOR, Lorenzen) were detailed in a precedent Technical Report (1972-1973). The present discussion will refer to the distribution of active chlorophyll a [Lorenzen (1967)], the considerable abundance of pheo-pigments a in the area (fig. 7.14) being a cause of error in the estimation of living biomass.

Results (expressed in mg/m^3) plotted on figure 7.15 show a marked decrease when the distance offshore increases. The highest concentrations are observed in Autumn and more especially in Spring.

January excepted (where the biomass seems shifted southwards) these higher concentrations are always located in the estuarine area (Stations M05, M06, M11) with a dilution parallel to the shore towards a direction in prolongation of the estuary. The decrease is particularly sharp near the stations M12 and M07.

This distribution of chlorophyll a allows a division of the area studied into areas of isoconcentrations, more complicated as the sampling period corresponds to a bloom period. This leads to the recognition in January of two zones, in July three zones, in September-October five zones (Autumn bloom) and in April six zones (Spring bloom).

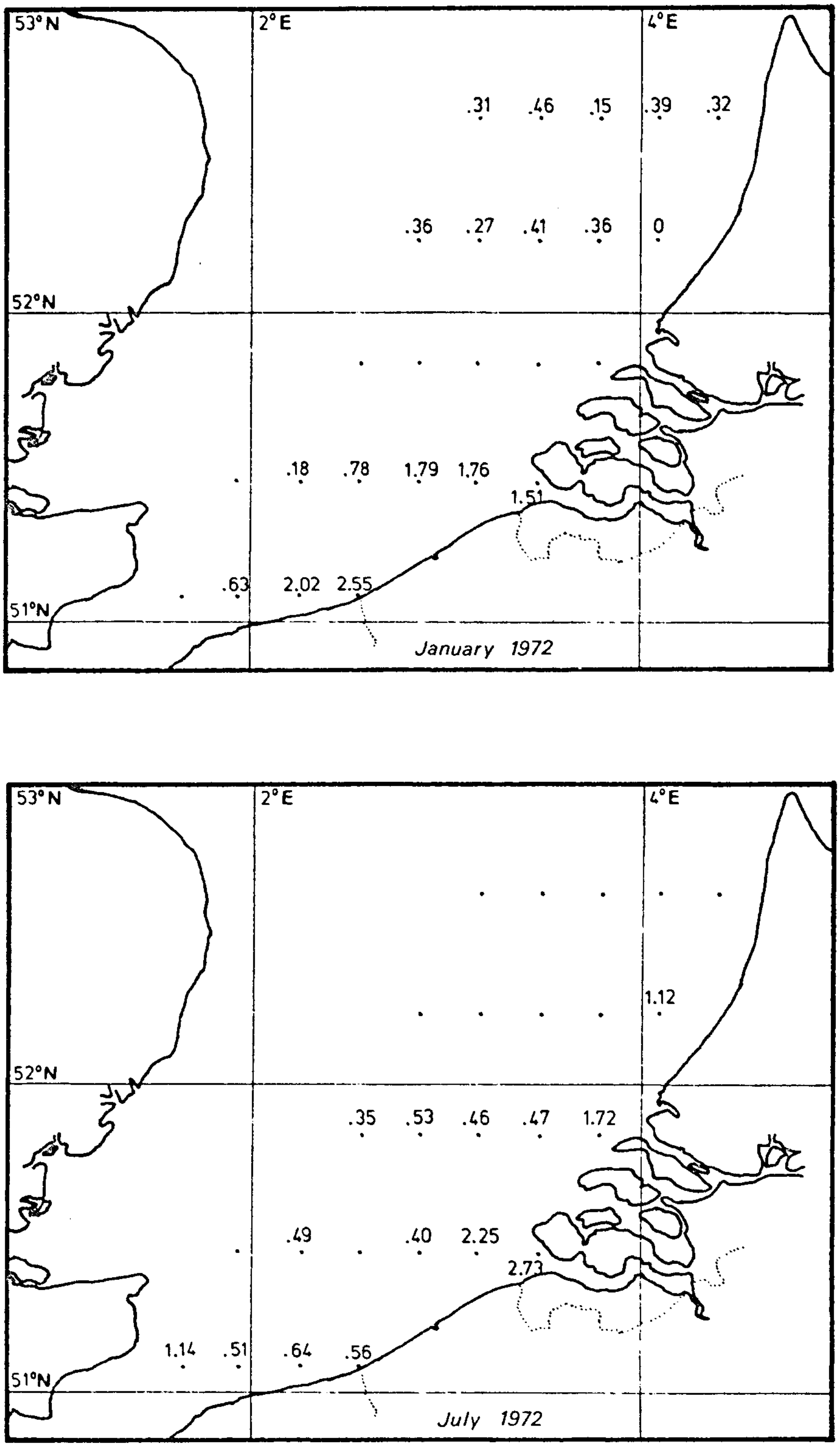


fig. 7.14.- Distribution of pheo-pigments a (mg/m^3).

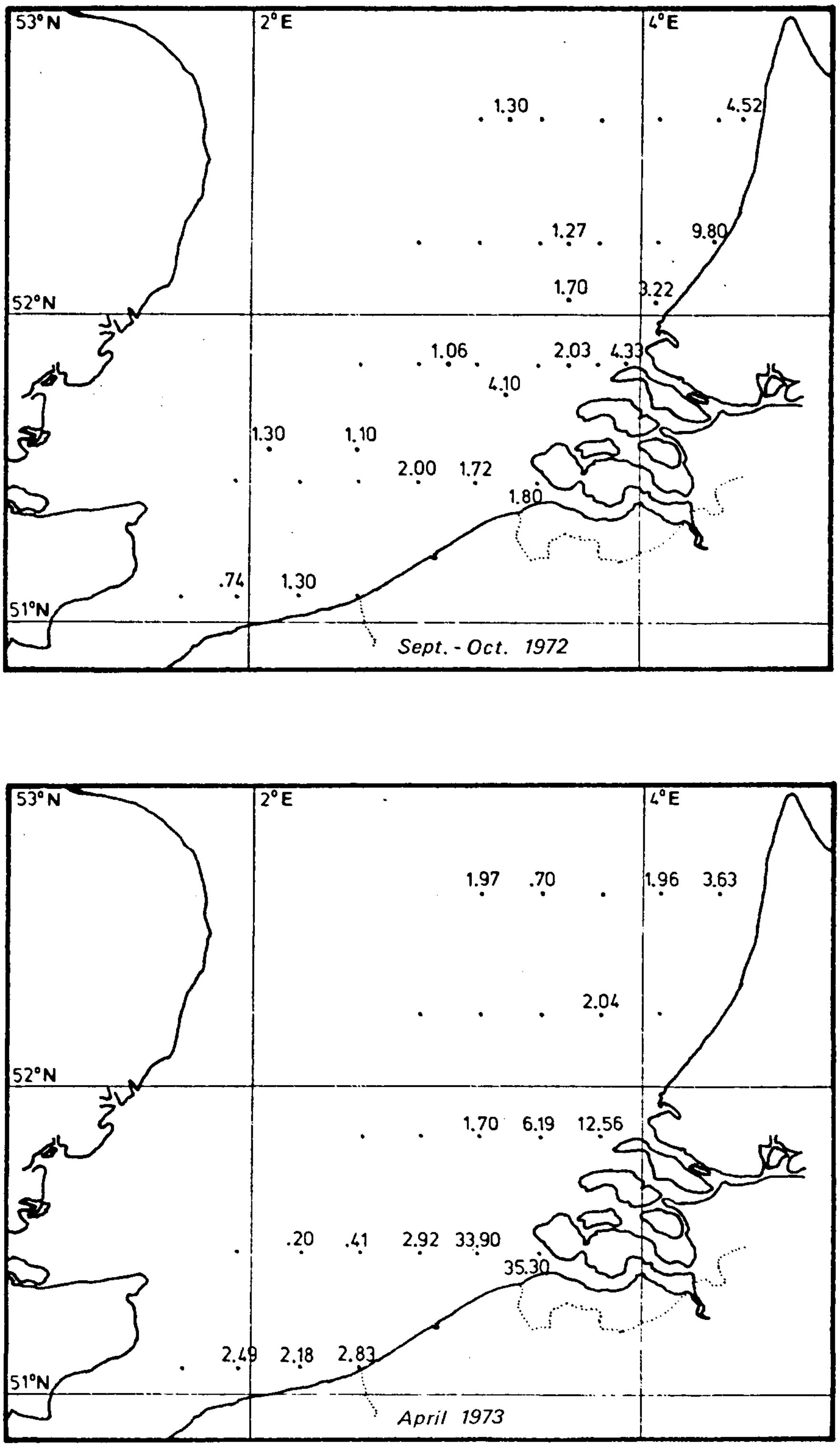


fig. 7.14.- Distribution of pheo-pigments a (mg/m^3).

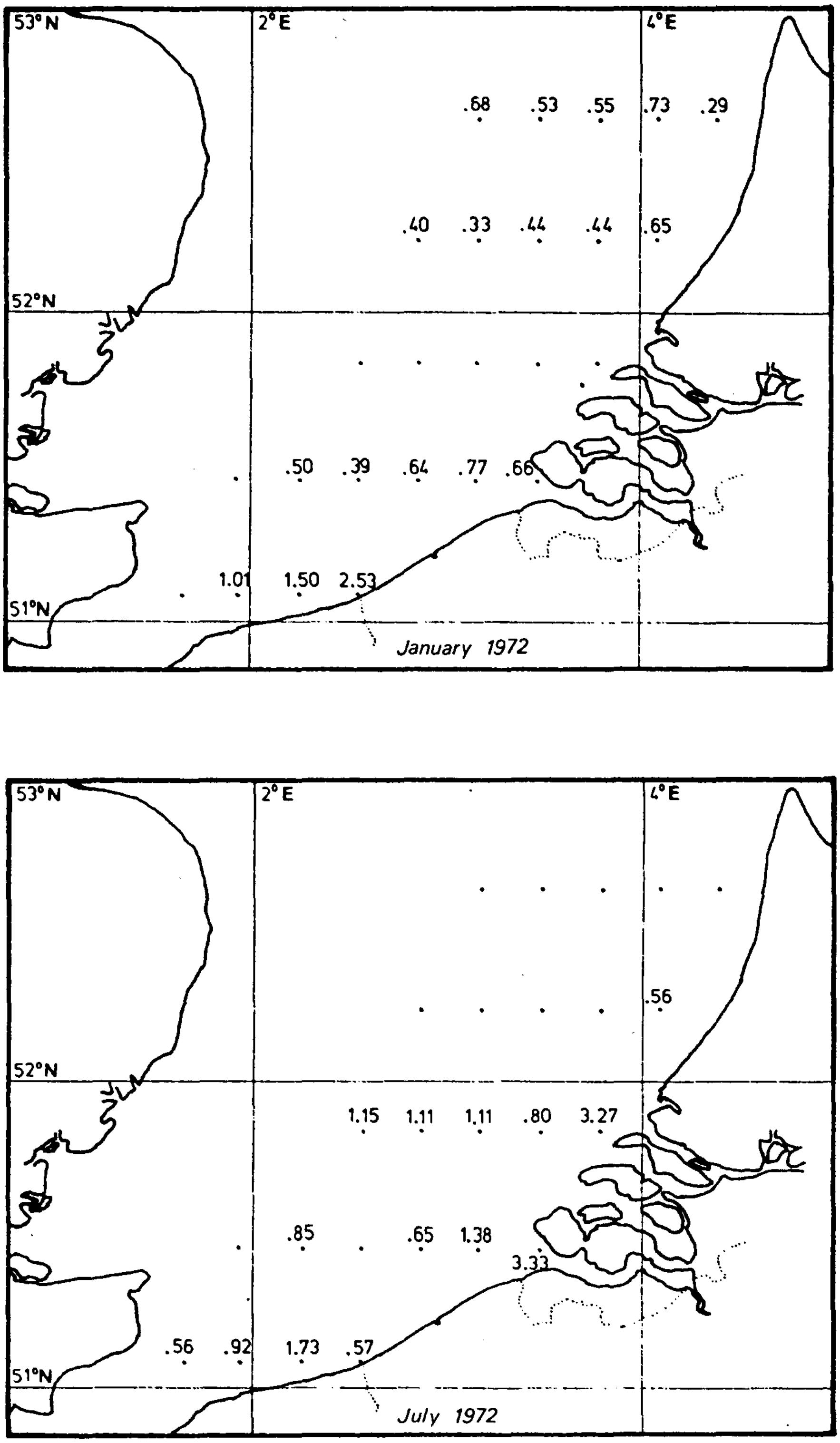


fig. 7.15.- Distribution of chlorophyll a (mg/m^3).

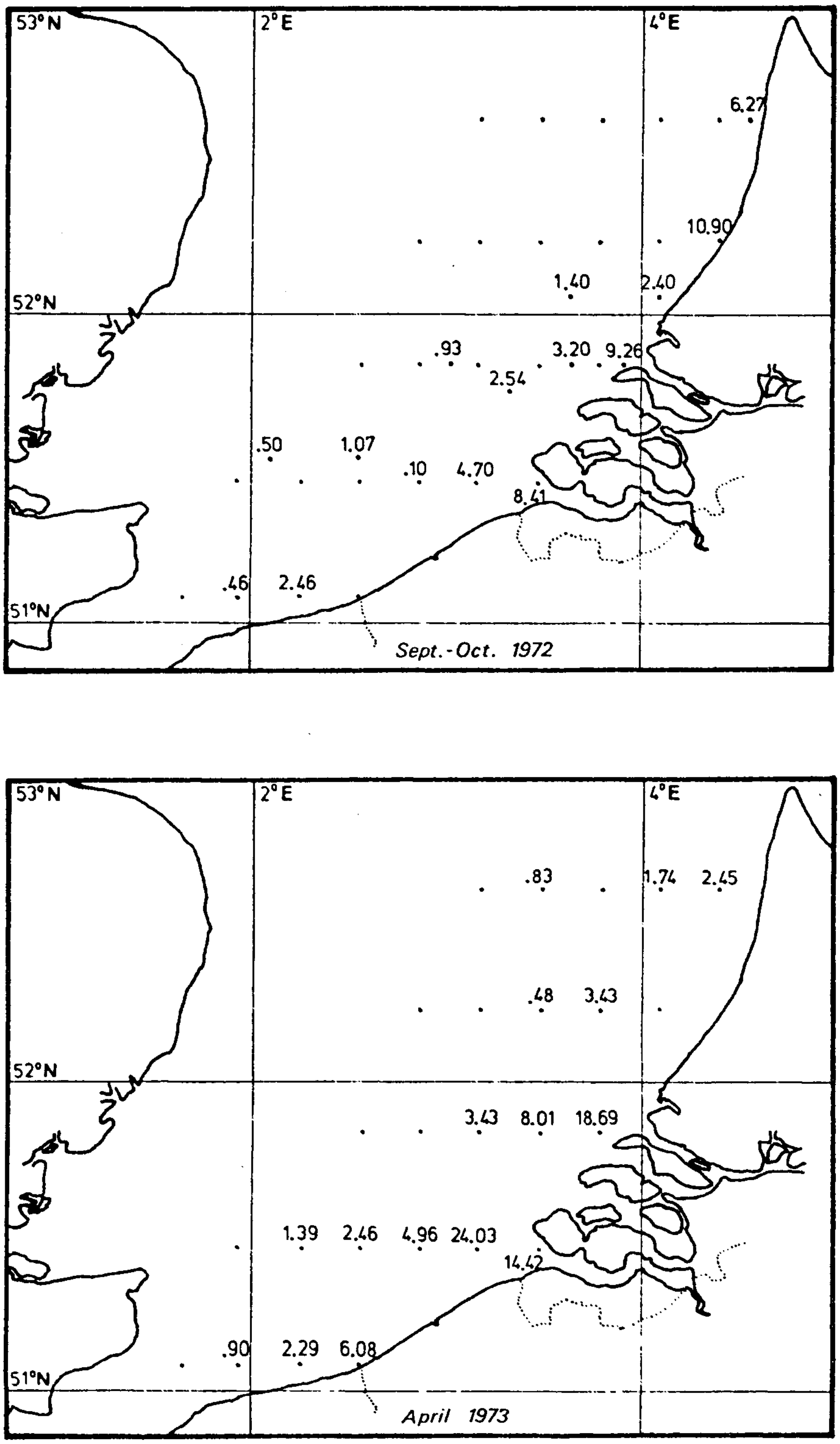


fig. 7.15.- Distribution of chlorophyll a (mg/m^3).

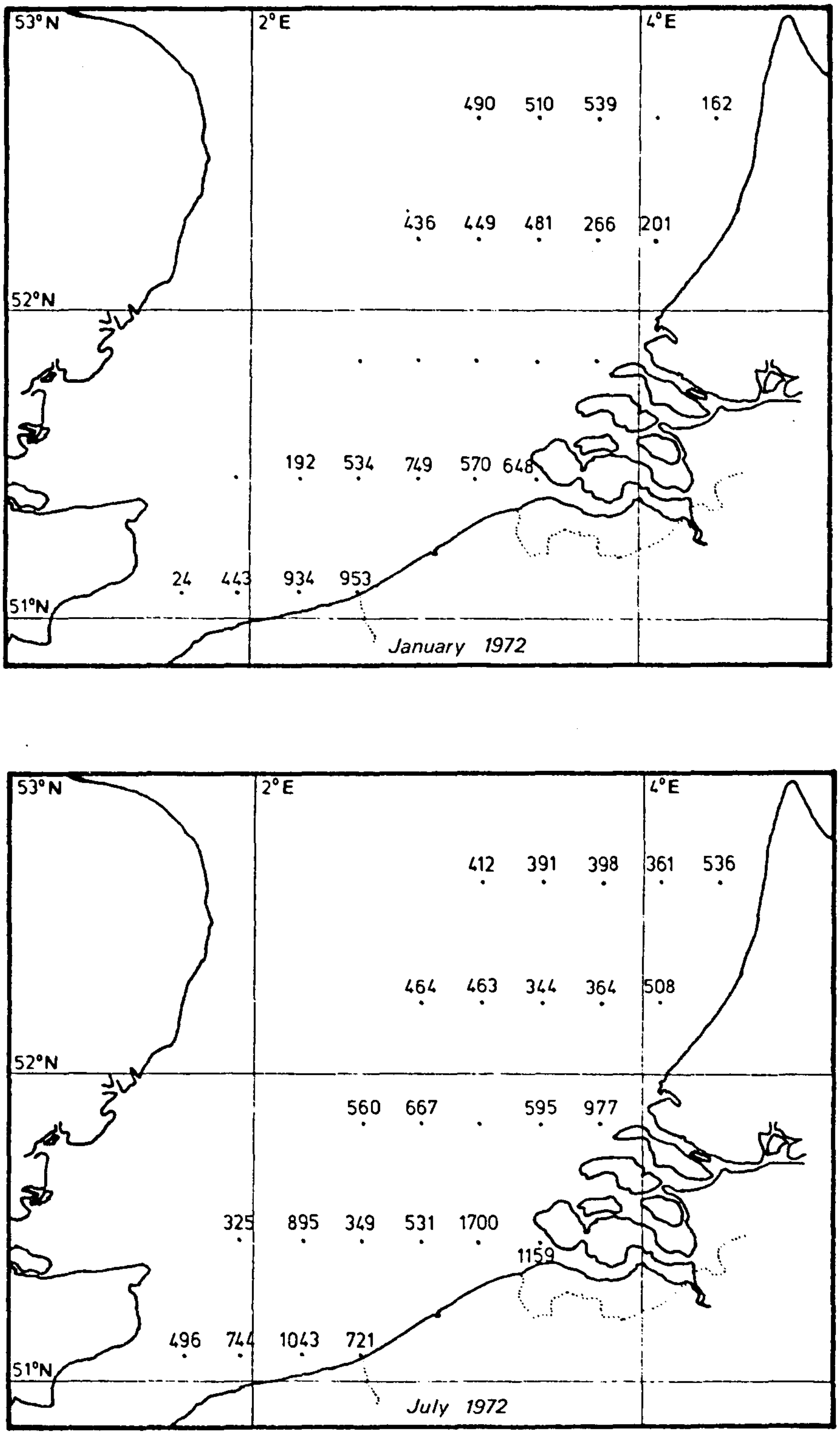
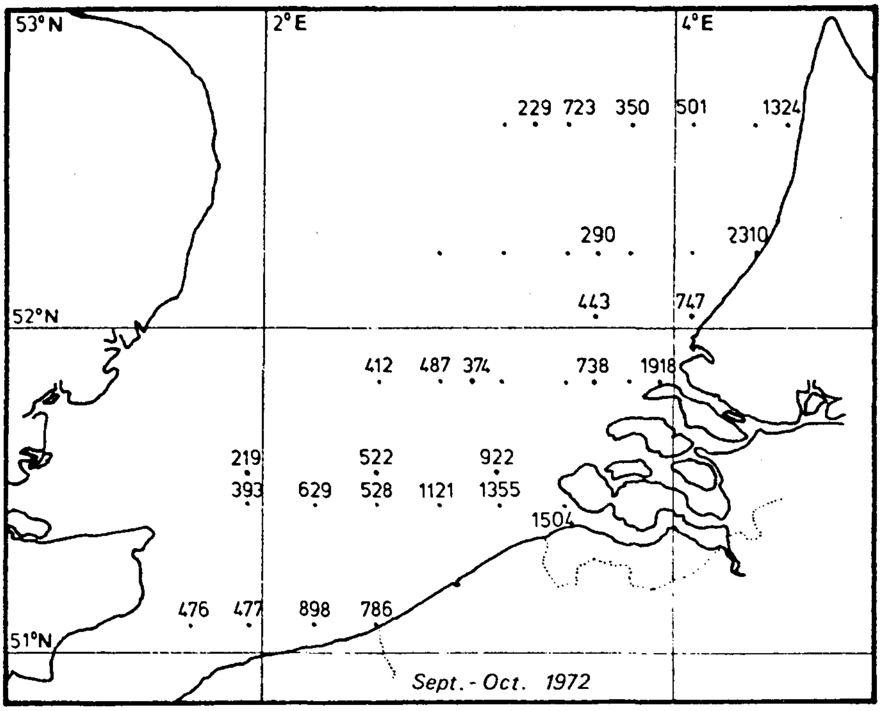


fig. 7.16.- Distribution of particulate organic matter.



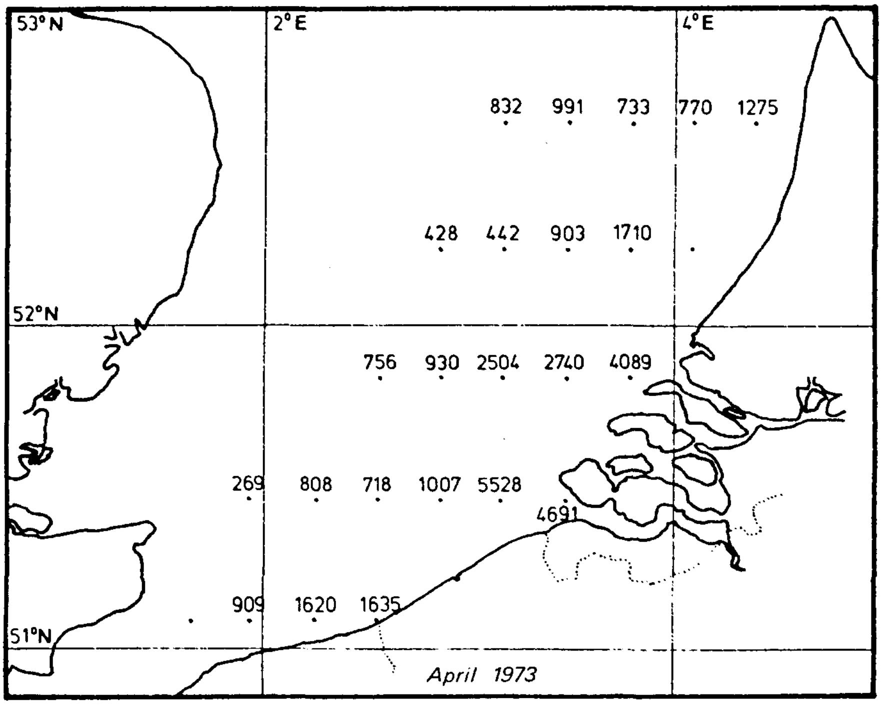


fig. 7.16.- Distribution of particulate organic matter.

2.2.- Distribution of particulate organic matter

Results (expressed in mg/m^3) are plotted on figure 7.16 and are generally in good agreement with chlorophyll a : higher particulate organic concentrations are in accordance with higher chlorophyll a. The lack of concordance corresponds always to an excess of particulate organic matter generally related to a detritus quantity greater than 50 % (see below).

In addition, particulate organic matter data being more complete, they enlight some additional particularities in relation with season : in January, the higher concentrations are not along the coast in the North of the model area; in July the reverse situation exists but with higher concentrations at stations M25, M20, M19; and in September, October, April, the areas subdivision is identical, station M22 excepted.

From these statements it may be concluded that the North part of the area characterizes always an important zone of weak concentrations.

2.3.- Distribution of phytoplankton

2.3.1.-Quantitative aspect

a) Total abundance

This includes living cells (flagellates excepted) and death cells calculated as the pondered average at each sampled station. Results are plotted on figures 7.17 and 7.18 and show the following characteristics :

- the maximum of the phytoplankton biomass occurs in Spring and Autumn along the shore;
- minima are observed in Winter;
- occurences of maximum quantities in Summer are at offshore stations.

These results are in good agreement with the classical picture of the phytoplankton distribution in coastal waters; nevertheless some particularities proper to the area are to be pointed out :

- in addition to seasonal fluctuations there are also annual variations due to the simultaneousness of the seasonal cycles (example cruises of 09/71 and 09/72) (figs. 7.17, 7.18);

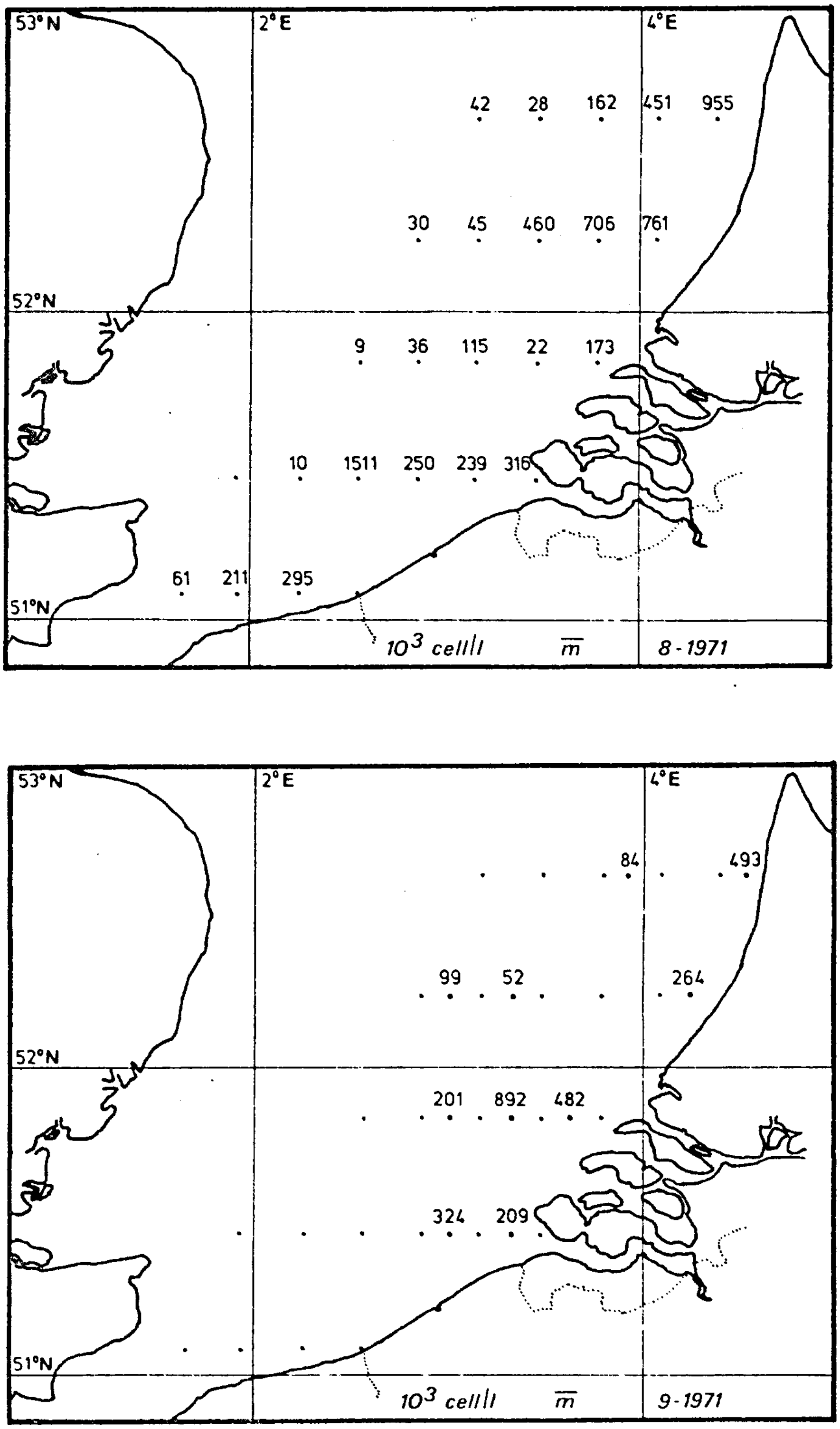
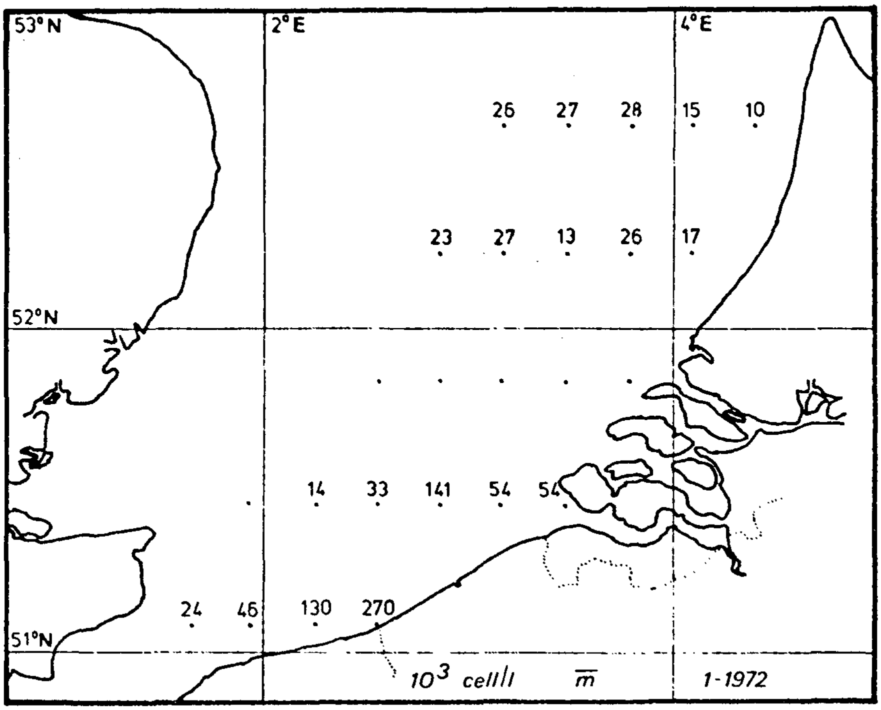


fig. 7.17.- Distribution of phytoplankton : total abundance.



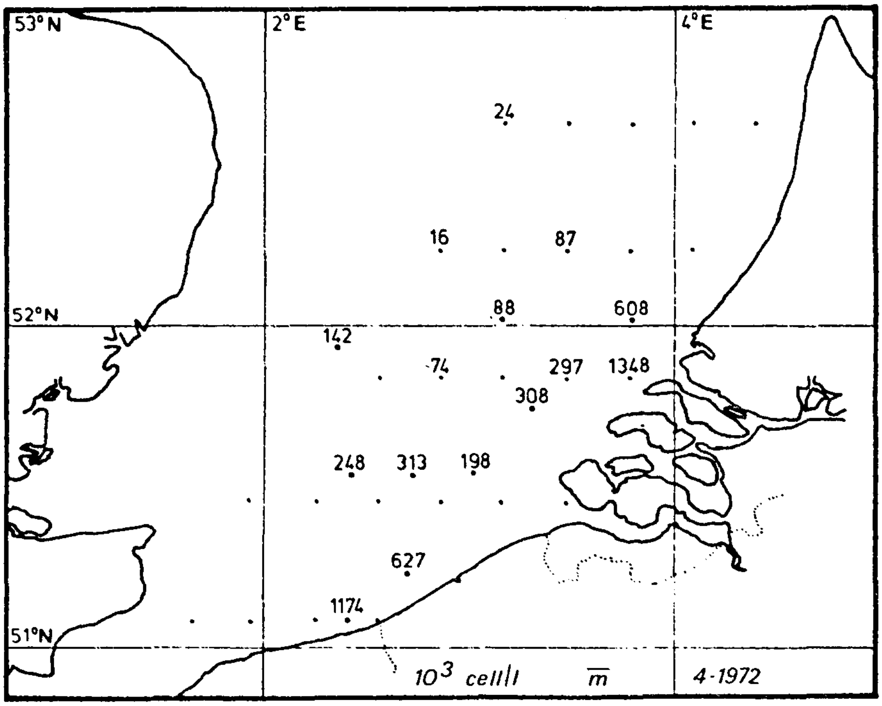


fig. 7.17.- Distribution of phytoplankton : total abundance.

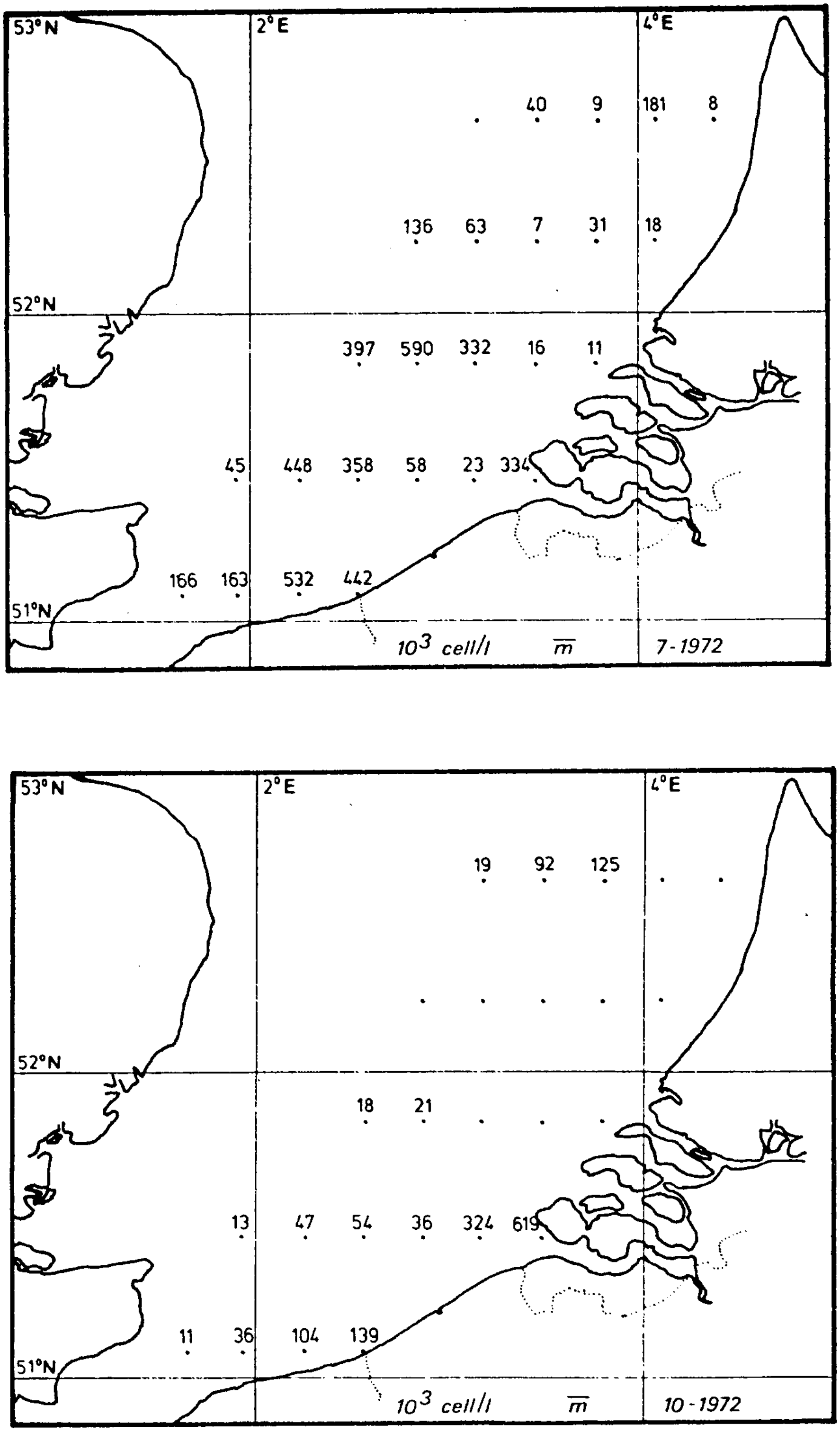


fig. 7.17.- Distribution of phytoplankton : total abundance.

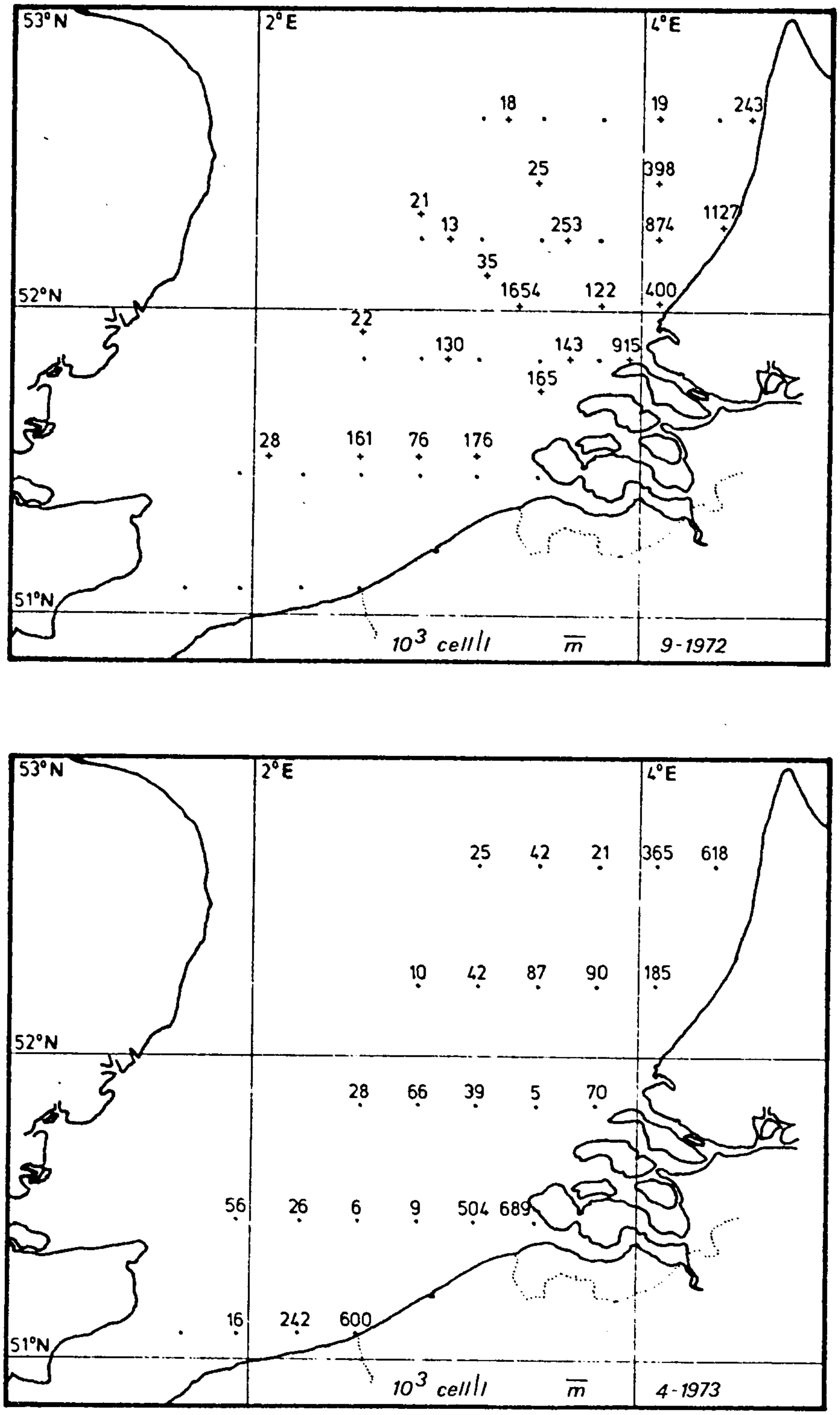


fig. 7.18.- Distribution of phytoplankton : total abundance.

- in spite of seasonal differences, the highest quantities are located in Autumn as well as in Spring, in two coastal centers, one in the northern part and the other in the southern part of the area;
- in any season, the southern zone of the area owns a higher density in cells than the northern zone with a minimum in the North-West;
- for any cruise there is a particular zone of lower concentrations located variably at stations M06, M07 or M12. These stations compared to those of immediate vicinity correspond probably to special conditions in relation with the extent of the estuarine influence.

b) Importance of flagellates

The counting of flagellates in coastal waters presents many difficulties and was therefore not regularly reported.

Results plotted on figures 7.19 and 7.20 show that the highest summer quantity occurs in the offshore area with nevertheless a higher flagellates percentage near the coast.

On the other hand, the Autumn maximum quantity is higher than that found in Summer and occurs along the coast and in front of the estuary, but does not correspond to a maximum percentage.

On the basis of too little simultaneous results, no correlation could be calculated between chlorophyll a and total cell number (flagellates included). Nevertheless the large quantity of chlorophyll and the high productivity recorded in the coastal areas and in front of the estuary point out the considerable importance of flagellates.

2.3.2.- Qualitative aspect

a) Species

More than 90 % of the total cell quantity (flagellates excepted) is made up by diatoms. The distribution of the most important species has been studied and reported in synthesis report (1973).

The data allow only a rough outline of the seasonal succession. A particular point must however be mentioned about the distribution of *Rhizosolenia Shrubsolei* : abundant where the total number of cells is reduced, this species is located principally in front of the estuary.

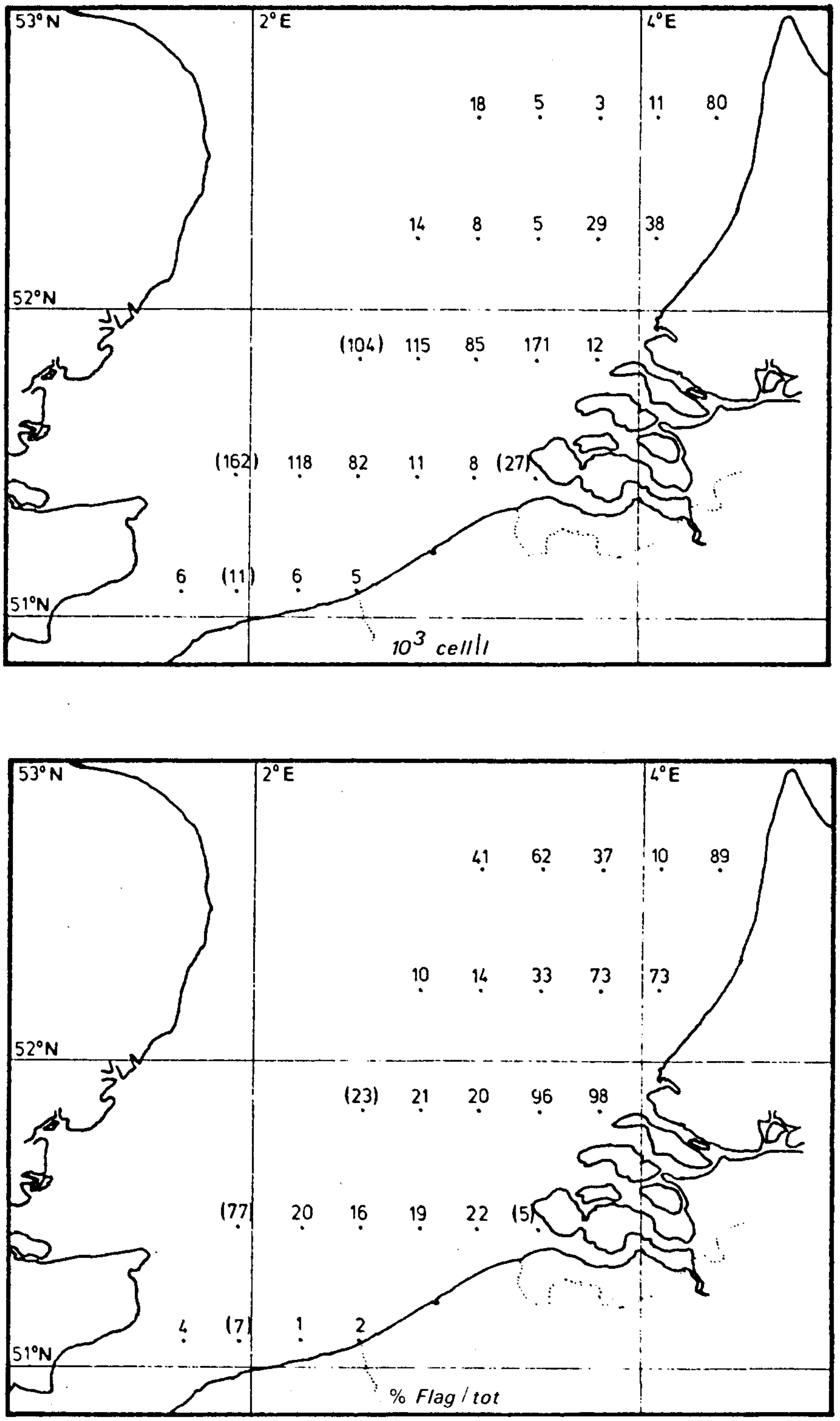


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fig. 7.19.- Distribution of flagellates : 0 m ( ) , 5 m .

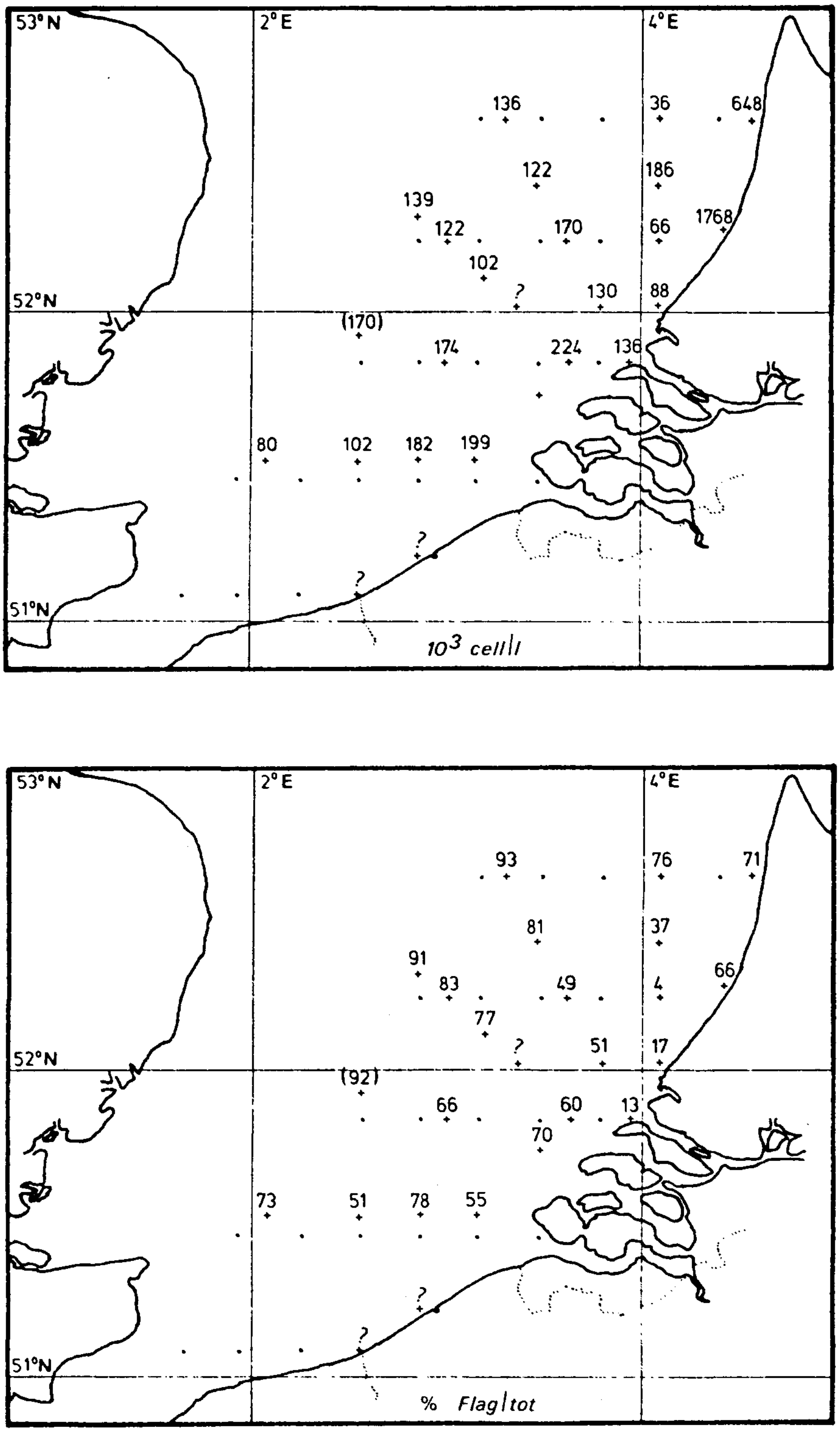

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fig. 7.20.- Distribution of flagellates : 0 m ( ) , 5 m .

Because of its particular behaviour, it could possibly be tested as an indicator species (in correlation with other factors).

b) Diversity index

The diversity index (Shanon) supplies information about the phytoplankton population as an entity and particularly indicates its degree of heterogeneity. As it is linked with the evolution of an ecosystem it indicates also the type of population which is concerned : a low index coupled with a high biomass is often associated to a high productivity; a high index with a lower quantity characterizes a succession; on the contrary, a high index linked with a large cell quantity indicates a mixing area and lastly a low index and a weak biomass do correspond sometimes to a selective influence.

In the present case, the diversity index has been computed on all phytoplankton cells, flagellates excepted. The results are plotted on figure 7.21 : the lowest values of the diversity index are found in Summer (07,08/1971 and 06/1972) explained by local blooms of the species *Rhizosolenia Stolterfoltii*. On the other hand, the concept of Spring bloom is confirmed at Stations M21, M22 (04/1973) where the index reaches values as low as 0.5 and 0.8 .

Large cell density associated with a low index corresponding with a high productivity are found, for instance, at Stations M01, M05, M21, M22 (04/1973) and M02, M03, M11 (07/1971).

Nearshore and in a more extended area in front of the estuaries, a high index of diversity is linked to a high biomass. It is the case for M01/01/1972, M07/01/1972, M01/10/1972, M02/M06/04/1973, M05/06/1972.

These stations support a mixed population and the area as such delimited could therefore be considered as corresponding to the estuary influence on phytoplankton populations.

At other stations, often situated at the limit of the above mentioned area (M16 ...) a particular weak biomass is linked to a high index of diversity. It could indicate in these particular points the end of a certain population type.

In fact, the variations between diversity index and cell number are more considerable in the estuarine zone and its limit. Effectively

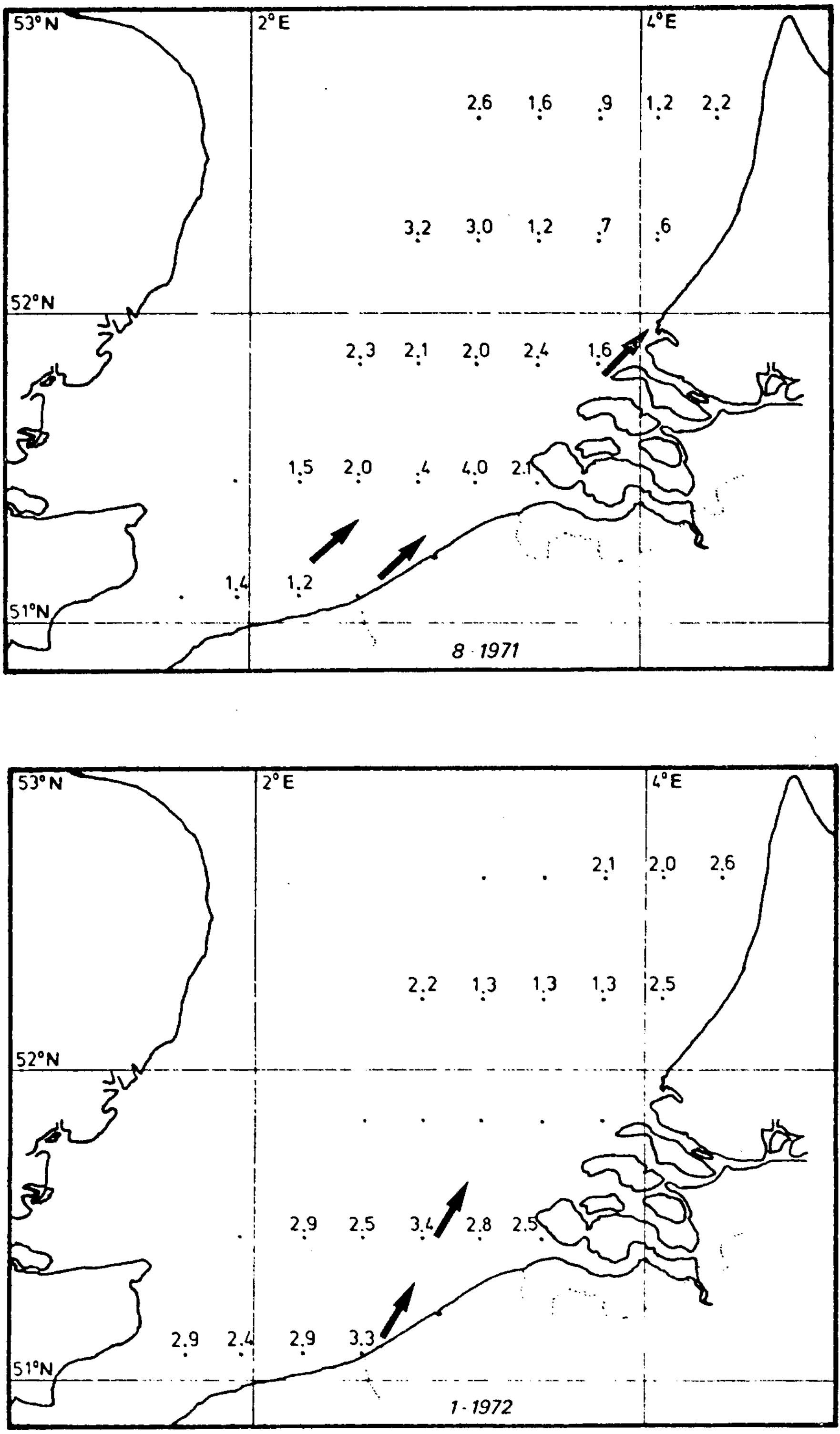
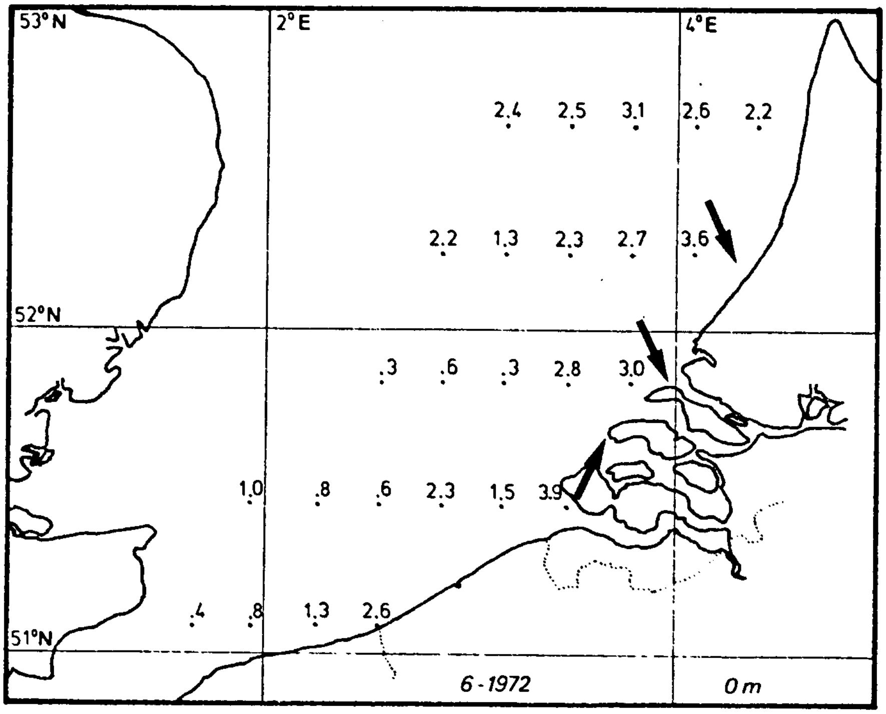


fig. 7.21.- Diversity index.



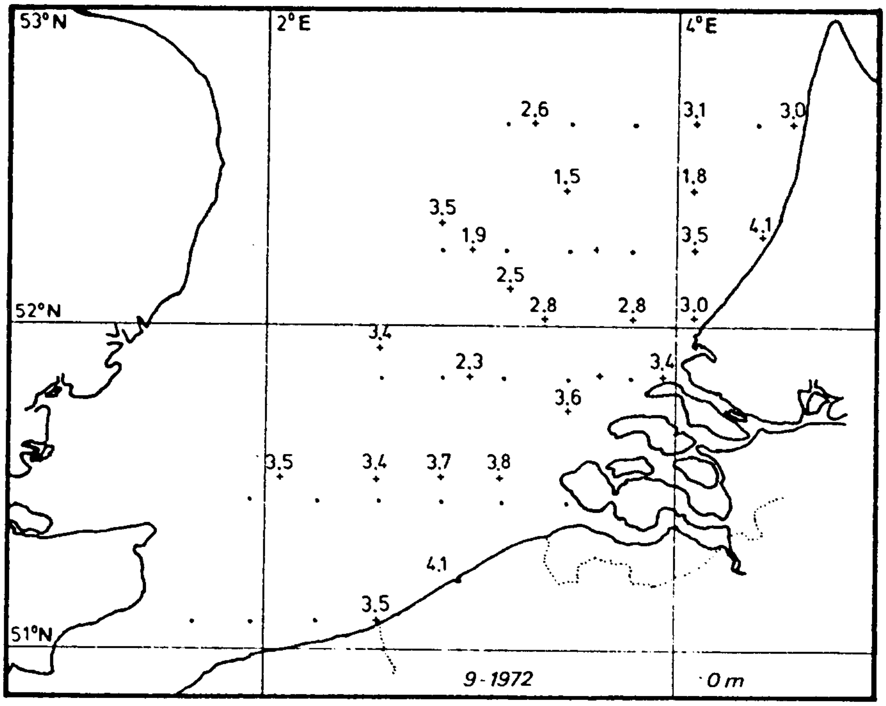


fig. 7.21.- Diversity index.

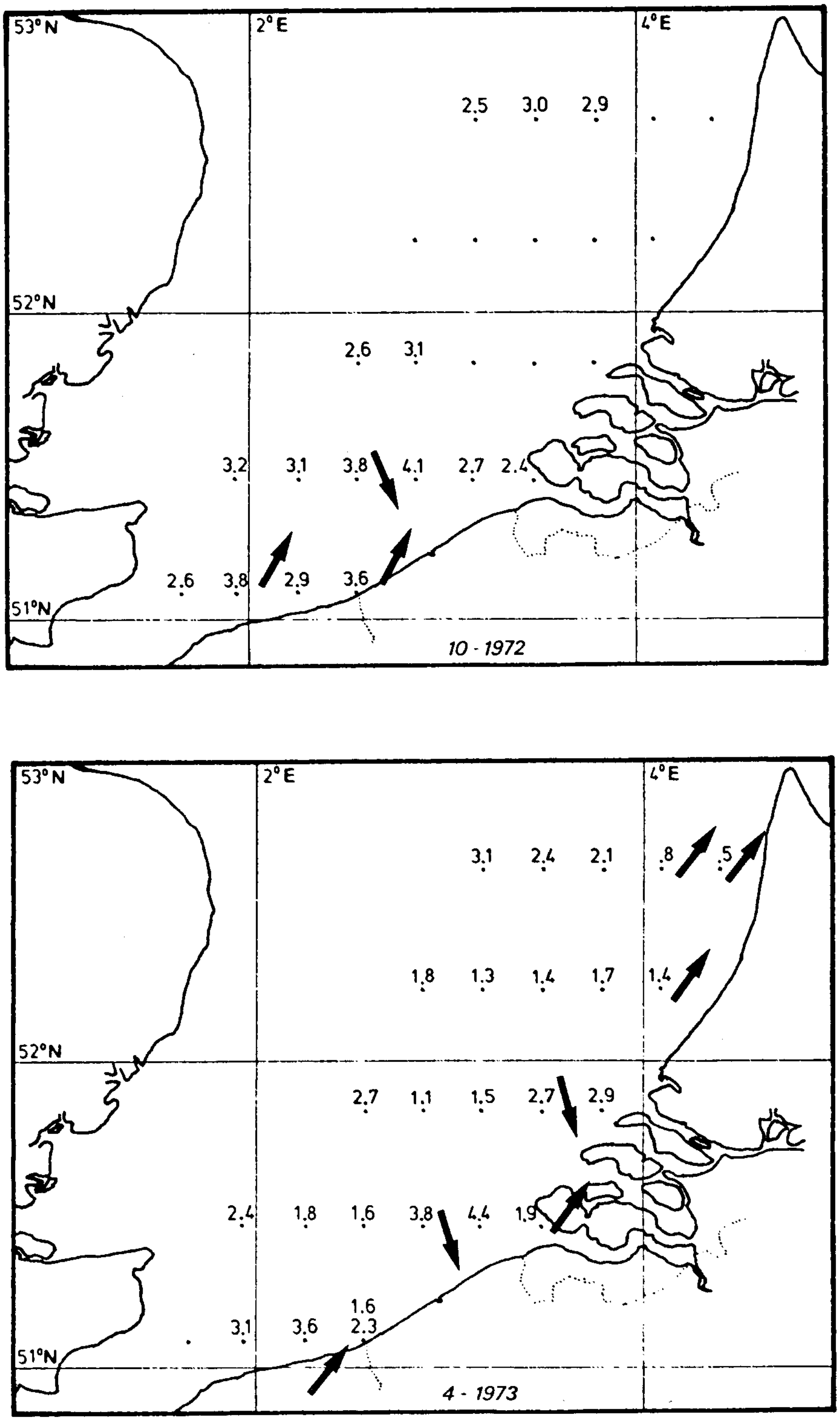


fig. 7.21.- Diversity index.

identical stations do belong at one time to the mixing area, at others to the productive area or the limit between the two. This is probably to be connected with the moving of the waters with tide and the variation of the estuarine influence with the season.

3.- Relative importance of dead cells and detritus in the area

In this study, the estimate of relative proportion of living phytoplankton and detritus is given by two parameters : one concerns the cell countings and is expressed by the ratio dead cells/total cells (unfortunately the counting of dead cells was not accomplished for each cruise and results plotted on figure 7.22 do not allow real conclusion); the other one gives an estimate of the quantity of detrital material evaluated by the regression particulate organic matters/pigments (Synthesis

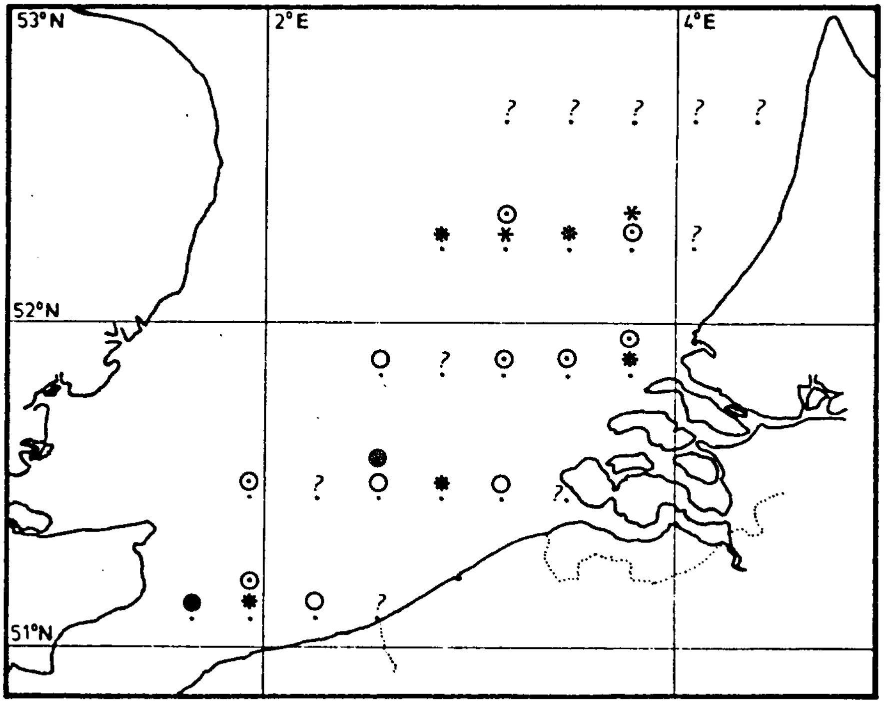


fig. 7.22.- % dead cells/total cells.

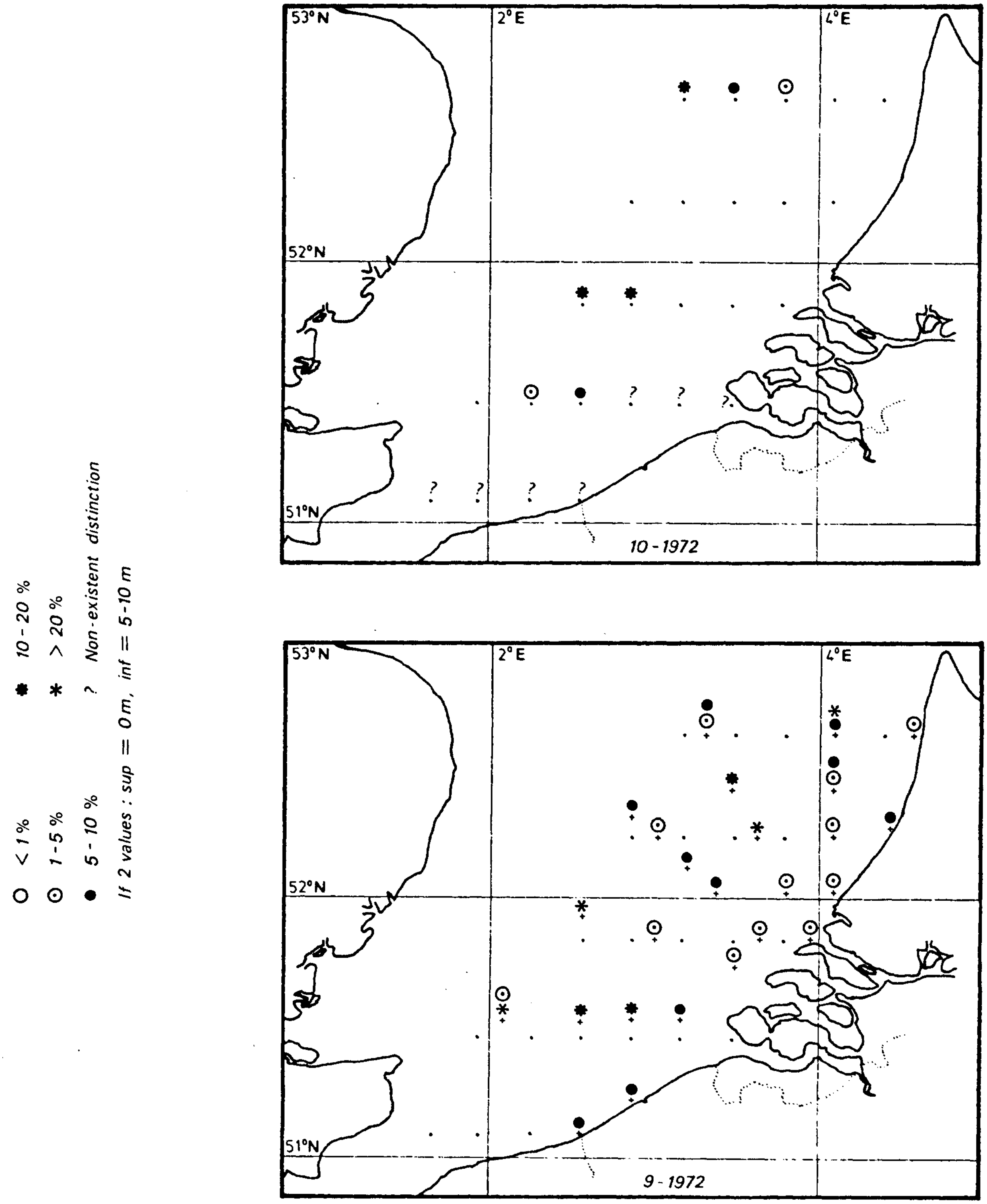


fig. 7.22.- % dead cells/total cells.

Report 1972, Technical Report 1973). This last gives numerous data concerning four surveys allowing a more detailed analysis. Results are plotted on Table 7.1.

Table 7.1

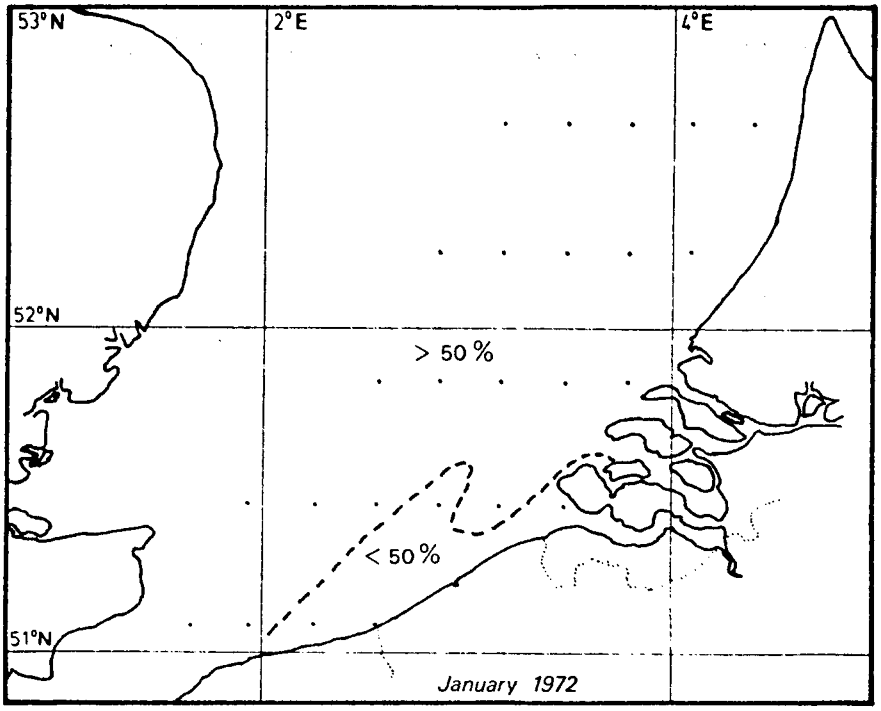
Chlorophylls / Particulate organic matters relationships

	r	P	Slope	Detritus	$\overline{POM}$	% detritus
A) Whole area delimited by the mathematical model						
1) pheo a + chl a						
January 1972	0.85	0.99	158	265	483	55
July 1972	0.70	0.99	159	469	815	57
September 1972	0.98	0.99	112	132	836	16
April 1973	0.95	0.99	79	832	1973	40
2) chl a						
January 1972	0.70	0.99	299	287	483	59
July 1972	0.55	0.95	240	522	815	64
September 1972	0.98	0.99	187	225	838	27
April 1973	0.96	0.99	210	661	1973	34
B) April cruise parted in two areas : inshore P/CH > 1 offshore P/CH < 1						
1) pheo a + chl a						
P/CH > 1	0.99	0.99	78	661	2479	24
P/CH < 1	0.94	0.99	144	552	1174	46
2) chl a						
P/CH > 1	0.95	0.99	202	470	2479	16
P/CH < 1	0.91	0.99	240	615	1174	52

r : correlation coefficient
P : safety of the correlation
$\overline{POM}$: particulate organic matter, average.

3.1.- Comparative study

It shows in front of the estuary a weak value of the ratio dead cells/total cells in good agreement with a weak quantity of detritus (fig. 7.23).



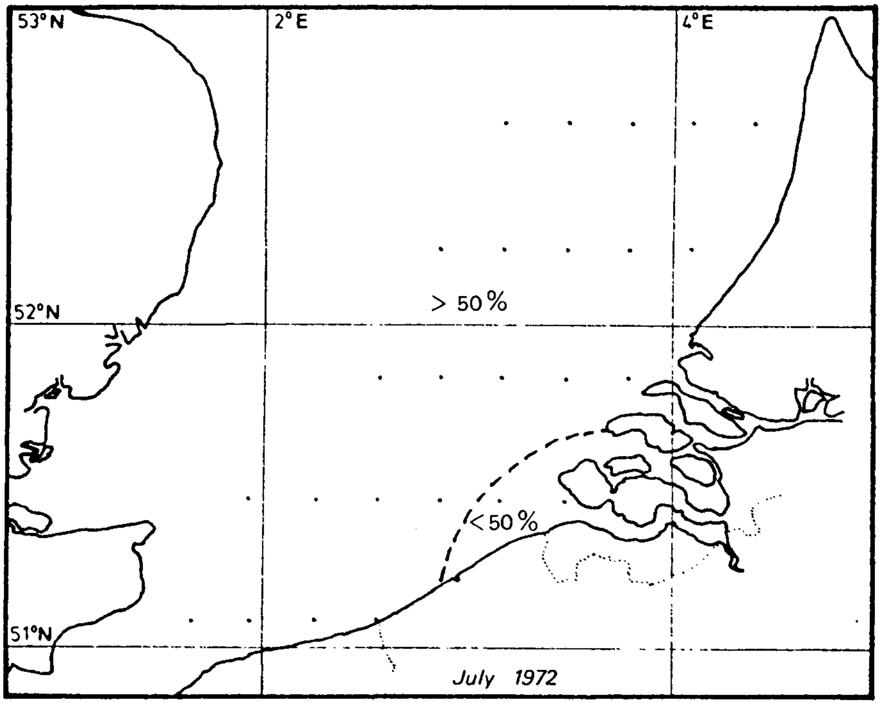


fig. 7.23.- Estimate of detrital particulate organic matter.

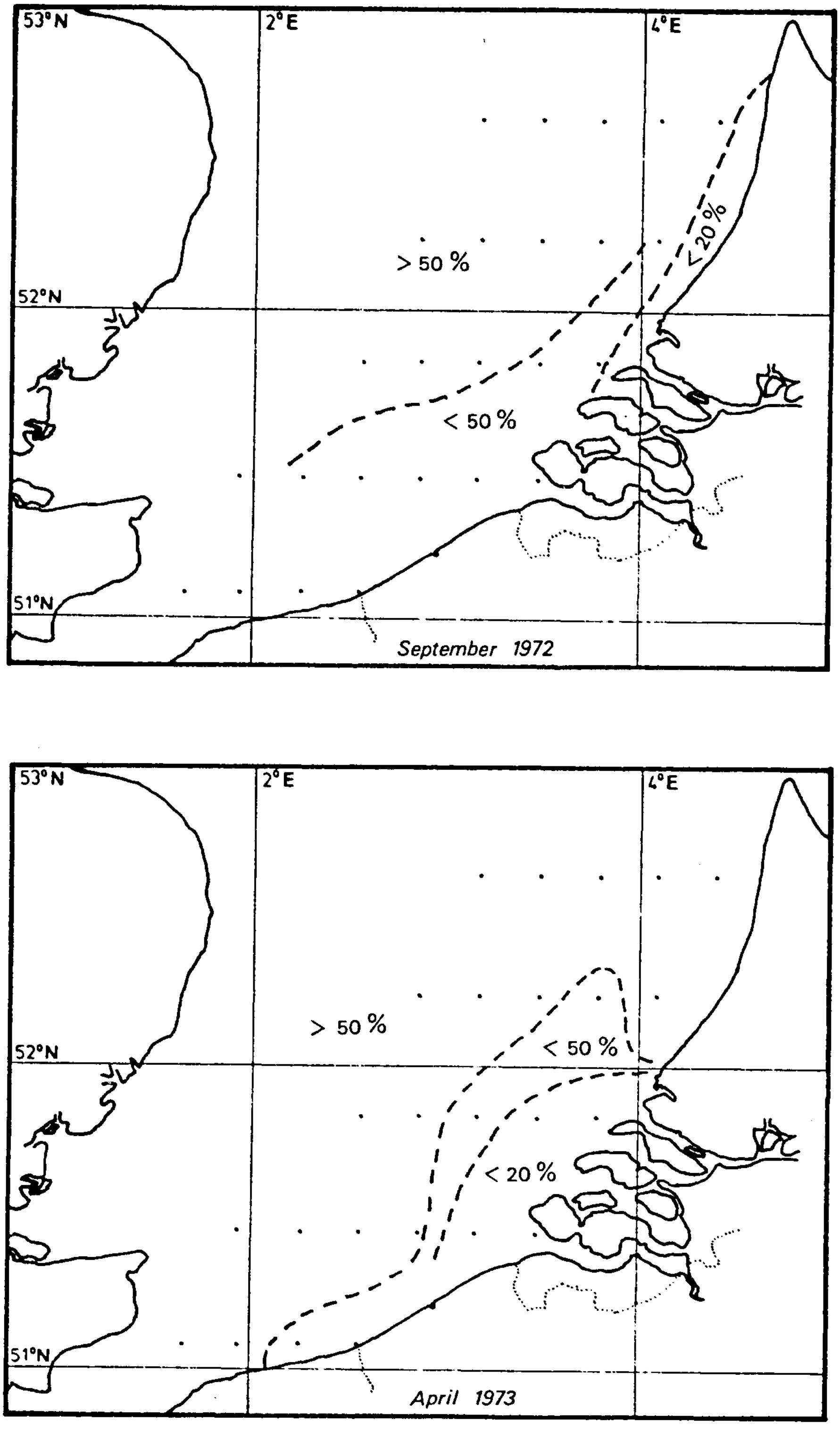


fig. 7.23.- Estimate of detrital particulate organic matter.

3.2.- What about detrital particulate organic matter and chlorophyll a in the whole system ?

Four surveys are not sufficient to give a real cycle on the particulate organic matter but allow certain comments in good agreement with the results of Steele and Baird for a similar study in the North Sea in 1961-1962 (1965).

3.2.1.- Particulate organic matter and pheo-pigments

Table 7.1 shows that for any correlation ($\frac{\text{chl a + pheo a}}{\text{POM}}$ or $\frac{\text{chl a}}{\text{POM}}$) the organic residues are similar hence the assumption that the quantity of particulate organic matter connected with pheo-pigments is not very important.

3.2.2.- Particulate organic matter and chlorophyll a

The ratio $\frac{\text{POM}}{\text{chl a}}$ given by the slope of the regression line characterizes the physiologic state of phytoplankton cells : it reaches a maximum value during months of low productivity (January and July 1972) and a minimum value during months of outburst (September 1972, April 1973). This is in good agreement with the data of the literature [Steele-Baird (1965)].

3.2.3.- Detrital particulate organic matter

a) Seasonal variations in the whole system

Detrital particulate organic matter corresponds to the value of particulate organic matter when the chlorophyll becomes off. The detritic quantity varies according to the season : it is higher in April, but the computation of relative proportions (in % on the tables) shows that during the periods of Spring and Autumn detritus form only 30 % of the total particulate organic matter present for a maximum of 64 % during Summer and Winter.

These results point out the importance of detritus in the energy flux.

b) In each station of the system

The estimate of the average detritic quantity peculiar to each cruise was used to evaluate roughly the relative proportions of detritus at each station. Results plotted on figure 7.23 show that the poorest areas in detritus coincide with the richest ones in phytoplankton.

In order to confirm this assumption, we have used results of April 1973 (owing to a larger number of data) : the system has been parted in two areas corresponding to the two areas delimited previously (Elskens, Synthesis Report 1972) — except for Station M12 — on the basis of the qualitative criterion [Parsons *et al.* (1961)] :

$$\frac{\text{protein}}{\text{carbohydrate}} > 1 \quad , \quad \frac{\text{protein}}{\text{carbohydrate}} < 1 \; .$$

Results show effectively an offshore higher detrital quantity.

c) Qualitative approach — April 1973

Table 7.2

	r	Slope	Detritus	% detritus
Proteins				
P/CH > 1	0.94	128	174	13
P/CH < 1	0.95	118	203	44
Carbohydrates				
P/CH > 1	0.92	74	236	25
P/CH < 1	0.86	122	354	47

Results obtained by the regression of the different metabolites on chlorophyll show not only a different participation of metabolites to detritus but also to the plant cells.

The analysis characterizes a high productivity month and the experiment should be therefore extended to low productivity months in order to draw more general conclusions.

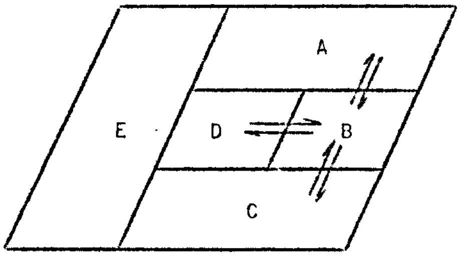
4.- Conclusions

The whole study on phytoplankton biomass (expressed by two parameters chlorophylls, quantity and specificity of cells) and particulate organic matter leads to the conclusion that some fluctuations are specific to the biological system of the investigated area.

- Studies at fixed stations have shown that the daily variations during a period of one week were negligible as compared with seasonal fluctuations; daily cycles, on the opposite, point out some significant variations in concentration, probably explained by the moving of the water mass (Stations M06 and M16 in June and May respectively).

- All parameters investigated confirm the subdivision of the system in two areas (Elskens Synthesis Report 1972) : a high productive coastal zone and one, more offshore, less productive.

The present seasonal study allows even more precision on this concept : the inshore area can be parted in four areas.



ABC : characterizes a high biomass, recorded by the three parameters : chlorophylls, particulate organic matter, cell number.

AC : similar behaviour with prevalence of high values for C .

B : situated in front of the estuary is often poorer in cell number (Diatoms) than A and C .

D : this part is subject to large fluctuations and the limit between D and B is itself variable depending on cruises. The abnormal stations are located in this region.

E : characterizes a low biomass and its character is more oceanic.

- Magnitude and variations of the parameters studied are depending first on the period of the year. The variation rate which is function of time, cannot be approached on the basis of date, as distant in time as those recorded. Indeed, results being too different in range of magnitude do not allow any connection between consecutive cruises.

- Comparative study of living chlorophyll a and particulate organic matter allows the assumption of a control of the carbon motion by the biota and this for any contribution of the detritic organic matter.

Arguments supporting this assumption are :

- the identical position of the areas presenting maximum concentrations of particulate organic matter and chlorophyll a;
- at fixed stations, the synchronism between variations of particulate organic matter and living chlorophyll a and not degraded chlorophyll a (pheo-pigments a);
- the excellent correlation between chlorophyll a and particulate organic matter.

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II. An index of fluctuations D_0 connected with diversity and stability of ecosystems : Applications in the Volterra-Lotka model and in an experimental distribution of species

by

Daniel M. DUBOIS

Abstract

Our purpose is to present a practical criterion for the stability of ecosystems.

As the Shannon-Weaver formula is largely used as an index of diversity, we have shown that the average index of diversity of an ecosystem $\overline{H}$ can be written as :

$$\overline{H} = H_0 - \overline{D}_0$$

where H_0 is the diversity of a reference state and $\overline{D}_0$ the average index of fluctuations.

Moreover, the index of fluctuations D_0 can be used as a criterion for the stability of an ecosystem.

The discussion of the time derivative of the index of fluctuations D_0 leads to the non-asymptotic stability of the Volterra-Lotka model for any arbitrary perturbations received from environment.

Finally, the variation of the distribution of *Mysidacea* at a point of the North Sea is discussed. The index of fluctuations appears to be a very attractive measure of the effects on the ecosystem of external perturbations such as tidal effects and turbulence.

Introduction

Ecosystems are subject to the law of conservation of matter and are open systems with respect to energy, usually light energy. Materials must cycle throughout the ecosystem following the general laws of energy transformation. High quality chemical energy degrades to lower quality energy under the influence of catalysts which control the rates of the various processes. We want to review briefly the response of an ecosystem to different variations of materials in the environment, of the conditions affecting the rates of processes and of the transport of energy. Physiological adaptability allows individual organisms to cope with variable conditions affecting the use of energy.

Variations in the activity or size of individuals imply variations in energy transformations and in energy storage. Due to time lag, variations in the number of individuals in the various species cause oscillations in the size of populations; the regrowth of a population may lag behind the reappearance of the energy supply. The ecosystem self-organizes with compensating variations when a decrease in the abundance of some chemical energy may be accomodated by an increase in the abundance of others.

In general, an ecosystem self-organizes as to reduce environmental variations (like Lenz's law in electricity).

A necessary condition for the stability of an ecosystem is the balance condition. An unbalanced system will change until it becomes balanced; the ecosystem must periodically re-establish its own cycle structure in changing its distribution of materials. In certain conditions, the ecosystem can be highly nonlinear and an ecosystem can be very stable even with large fluctuations. Reduction in the oscillation of one species must be compensated by an increase in the fluctuations of some other species. The change in number arising from populations oscillations will be reflected in a corresponding change of energy.

However, this change of energy can be minimized if the organisms of these oscillating populations are simple and can follow the variable energy supply without too much time delay.

Another stabilizing mechanism in an ecosystem is the development of multifunctionality with resultant increase in the number of possible pathways of energy flow in the food chain. The efficiency of an ecosystem increases with multifunctionality (parallel processing) and under these conditions the entire system is more stable because the flow of resources is distributed over a number of different paths.

The problem of stability and its relation to diversity has been discussed by a number of authors [Pielou (1966) measured diversity in different types of biological collections].

In particular, MacArthur (1955) has proposed an index of stability based on the fraction of the energy reaching the top of the web along each distinct pathway q_i of a food chain : his index is highest when q_i is the reciprocal of the number of possible pathways; it may be the same for food webs involving few species with many connections as for those with many species with few connections. Odum (1953) has suggested that stability increases with the amount of choice which the energy has in following the paths up through the food web. But these indexes are not practically utilisable.

Our purpose in this paper is to obtain a practical criterion of the stability of ecosystems which is in agreement with such theoretical model as, for example, the Volterra-Lotka model.

Starting from the Shannon-Weaver formula, Longuet-Higgins (1971) calculated the diversity for several theoretical distributions. He showed that if the distribution of species is a complete log-normal one, then the diversity depends only on the total number of species S and the variance σ_q^2 of the distribution of the species arranged in octaves.

In our paper, we have derived from the Shannon-Weaver formula a very simple relation which depends only on two quantities, the total number of species S and the variance σ^2 of the distribution of species around the mean. If the distribution is arranged in octaves, Longuet-Higgins' formula is rediscovered. (Note that the present derivation has the advantage of making no drastic assumptions about the distribution.)

When the distribution of species differs greatly from a uniform distribution, the derivation is no longer correct. Then, we introduce, for each proportion p_i , the space-time average $\overline{p}_i$ and we call the ensemble of the $\overline{p}_i$'s the "reference state". The diversity may be written as the difference between the diversity of the reference state minus a positive definite function in the sense of Lyapunov : the index of fluctuations D_0 which is the deviation of the distribution from the reference state.

Since the index D_0 is a positive definite function which is zero at the reference state, the time derivative of D_0 can be used as a criterion of stability of the ecosystem, in the sense of Lyapunov.

In order to test this index D_0 by studying the stability of a theoretical model, we discuss briefly the properties of the Volterra-Lotka model.

The Volterra-Lotka equations describe the dynamics of a predator-prey population. Considering the non-trivial case, any set of initial populations yields periodic population variations which are represented by a closed curve about the steady state. There is a whole family of these curves depending upon the initial conditions. Moreover, the time averages of populations during a cycle correspond to the populations at the steady state.

We adapt the index of fluctuations to the fluctuations of populations rather than to probability distributions. An integration over the whole cycle with period T is made to take into account all the different accessible states of the system. A simple relation between the mean diversity of an ecosystem and the mean index of fluctuations is presented. Moreover, another positive definite function $D_0^{(2)}$ is constructed symetrically to D_0 . A surprising property of $D_0^{(2)}$ is it differs from D_0 only beyond the second order. From these functions D_0 and $D_0^{(2)}$, the stability of the Volterra-Lotka model is discussed. In the case of small fluctuations of the system around the stationary state, the index of fluctuations D_0 is a constant of motion and the system possesses non-asymptotic stability. Moreover, the function $D_0^{(2)}$ is surprisingly a constant of a motion of the system for arbitrary fluctuations and the non-asymptotic stability is valid for any perturbation received from environment.

Finally, a comparison of all these indexes is made on an experimental example; the variation of the distribution of *Mysidacea* at a point of the North Sea over a period of 72 hours. The index of fluctuations appears to be a very attractive measure of the effects on the ecosystem of external perturbations, such as tidal effects and turbulence.

1.- Diversity of a log-normal distribution

The Shannon-Weaver formula is widely used as a measure of the diversity of ecological systems [Margalef (1958)]. If p_i is the proportion of the i^{th} species, the diversity is written :

(1) $$H = - \sum_{i=1}^{S} p_i \ln p_i$$

with the normalisation condition

(2) $$\sum_{i=1}^{S} p_i = 1$$

where S is the total number of species.

Longuet-Higgins (1971) proposed to arrange the numbers of species in octaves. Writing

(3) $$q \equiv \ln p$$

he supposed that, within some range of q ,

(4) $$- \frac{dn}{dq} = f(q)$$

where $f(q)$ is a universal function, characteristic of the parent population. To determine H , he has the following relations :

(5a) $$S = \int_{\epsilon}^{S} dn \qquad (\varepsilon \ll 1) ,$$

(5b) $$1 = \int_{\epsilon}^{S} p \, dn$$

and

(5c) $$H = - \int_{\epsilon}^{S} p \ln p \, dn .$$

Starting from the complete log-normal distribution :

$$f(q) = \frac{c}{\sigma_q \sqrt{2\pi}} \exp[- \frac{(q - \mu)^2}{2 \sigma_q^2}] \tag{6}$$

where μ and σ_q denote the mean and the standard deviation respectively, and c is a normalising constant, Longuet-Higgins obtained

$$H = \ln S - \frac{1}{2} \sigma_q^2 \ . \tag{7}$$

This very simple relation depends only on two quantities, the total number of species S and standard deviation σ_q .

As the first term of equation (7) is the maximum of the diversity, *i.e.*,

$$H_{max} = \ln S \tag{8}$$

which occurs when all the p_i 's are equal to the mean $\bar{p} = \frac{1}{S}$, we want to compare Longuet-Higgins formula with a series expansion around the mean $\bar{p}$.

2.- Diversity around the mean

Using Taylor's formula, the expansion of the Shannon-Weaver index of diversity [equation (1)] around its maximum [equation (8)]

$$\bar{p} = \frac{1}{S}$$

is then written to the second order

$$H = \sum_{i=1}^{S} \{- \frac{1}{S} \ln \frac{1}{S} + (- \ln \frac{1}{S} - 1)(p_i - \frac{1}{S}) + \frac{1}{2} (- S)(p_i - \frac{1}{S})^2 + O[(p_i - \frac{1}{S})^3]\} \tag{9}$$

which becomes with equation (2) :

$$H = \ln S - \frac{1}{2} S \sum_{i=1}^{S} (p_i - \frac{1}{S})^2 + O[(p_i - \frac{1}{S})^3] \ . \tag{10}$$

Neglecting the third term of equation (10), we define the index of diversity D_1 as

(11) $$D_1 = \ln S - \frac{1}{2} S^2 \sigma^2$$

with

(12) $$\sigma^2 \equiv \frac{1}{S} \sum_{i=1}^{S} (p_i - \frac{1}{S})^2$$

which includes only the total number of species S and the variance σ^2 of the distribution of species around its mean $\bar{p} = \frac{1}{S}$.

Writing

(13) $$q_i \equiv \ln p_i$$

(14) $$q_0 \equiv \ln \bar{p} = \ln \frac{1}{S} ,$$

we have

(15) $$q_i - q_0 = \ln[\frac{1}{S} + (p_i - \frac{1}{S})] - \ln \frac{1}{S}$$

$$= \ln[1 + S(p_i - \frac{1}{S})] \quad .$$

Hence, to the second order,

(16) $$q_i - q_0 = S(p_i - \frac{1}{S}) + O[(p_i - \frac{1}{S})^2] \quad .$$

From equations (12) and (16), we get

$$\sigma^2 \equiv \frac{1}{S} \sum_{i=1}^{S} (p_i - \frac{1}{S})^2$$

$$= \frac{1}{S^3} \sum_{i=1}^{S} (q_i - q_0)^2$$

(17) $$\sigma^2 = \frac{\sigma_q^2}{S^2}$$

and equation (11) becomes

(18) $$D_1 = \ln S - \frac{1}{2} \sigma_q^2$$

which is similar to Longuet-Higgin's result.

The diversity D_1 is fairly general but its validity is reduced to distributions of species not too far from the mean (uniform distribution). So, for very non uniform distribution, it is necessary to define mean values of each of the proportions $\overline{p}_i$. This will be done in the next section.

3.- Space-time averages and reference state

In a general way, the proportion of species is a function of the space and of the time, *i.e.*,

(19) $$p_i = p_i(\mathbf{r},t)$$

where $\mathbf{r}$ is the position vector and t the time.

To obtain some information on the diversity and the stability of ecosystems, it may be interesting to define a sort of local equilibrium of the ecosystem.

We shall call the reference state the local space-time averaged proportions $\overline{p}_i$ defined by

(20) $$\overline{p}_i = \frac{\iiint_{\delta V} \int_{\delta T} p_i(\mathbf{r},t)\, dV\, dt}{\iiint_{\delta V} \int_{\delta T} dV\, dt}$$

where δV is the neighbourhood of the local domain we want to study and δT a time sufficiently long with respect to the relaxation time of all phenomena.

It may be noted that equation (2) is always applicable, *i.e.*,

(21) $$\sum_{i=1}^{S} \overline{p}_i = 1$$

The state of the ecosystem will be found from its deviation from the reference state. In the next section, the diversity is given around the reference state.

4.- Diversity around the reference state

Using Taylor's formula, we expand the diversity [equation (1)] around the reference state of the ecosystem [equation (20)], *i.e.*,

$$(22)\quad H = \sum_{i=1}^{S} \{-\overline{p}_i \ln \overline{p}_i - (\ln \overline{p}_i)(p_i - \overline{p}_i) - (p_i - \overline{p}_i) + \frac{1}{2}(-\frac{1}{\overline{p}_i})(p_i - \overline{p}_i)^2 + O[(p_i - \overline{p}_i)^3]\}$$

which is written with equations (2) and (21)

$$(23)\quad H = \sum_{i=1}^{S} \{p_i \ln \frac{1}{\overline{p}_i} - \frac{1}{2}\frac{1}{\overline{p}_i}(p_i - \overline{p}_i)^2 + O[(p_i - \overline{p}_i)^3]\} \ .$$

Neglecting the third term of equation (23), we define the index of diversity D_2 by

$$(24)\quad D_2 = \sum_{i=1}^{S} (p_i \ln \frac{1}{\overline{p}_i} - \frac{1}{2}\frac{\sigma_i^2}{\overline{p}_i})$$

with

$$(25)\quad \sigma_i^2 \equiv (p_i - \overline{p}_i)^2 \ .$$

As the second term of equation (24) is positive definite and has only one zero at the point

$$p_i = \overline{p}_i \qquad (i = 1,2,\ldots,S) \ ,$$

we introduce an index D_0^* defined by

$$(26)\quad D_0^* = \frac{1}{2}\sum_{i=1}^{S} \frac{\sigma_i^2}{\overline{p}_i} \ .$$

We see that D_0^* is large when the ecosystem is far from its reference state. It may be a measure of its deviation from the reference state.

5.- An index of fluctuations D_0

Let us define a quantity D_0 by the following equation

$$(27)\quad H = \sum_{i=1}^{S} p_i \ln \frac{1}{\overline{p}_i} - D_0 \ .$$

The first term of equation (27) is identical with the first term of equation (24). So D_0 represents all the terms of the expansion in series of H beyond the first order.

From equations (1) and (27), the expression of D_0 is

(28) $$D_0 = \sum_{i=1}^{S} p_i \ln \frac{p_i}{\overline{p}_i}$$

expansion of which gives

(29) $$D_0 = D_0^* + O[(p_i - \overline{p}_i)^3] \quad .$$

Remarkably, the function D_0 is definite positive (in the sense of Lyapunov) and is zero only at the singularity $[p_i = \overline{p}_i$, $(i = 1,2,\ldots,S)]$. As the first term of the expansion of D_0 is D_0^* [equation (29)] we suggest calling D_0 the index of fluctuations.

With a view of applying this index D_0 to a theoretical model, we discuss briefly the Volterra-Lotka model.

6.- The Volterra-Lotka equations

Let us consider the kinetic equations describing the predator-prey model of Volterra (1931) and Lotka (1956) :

(30a) $$\frac{dN_1}{dt} = \alpha_1 N_1 - \lambda_1 N_1 N_2$$

(30b) $$\frac{dN_2}{dt} = \lambda_1 N_1 N_2 - \alpha_2 N_2$$

where N_i $(i = 1,2)$ is the population of species i and α_1 , α_2 and λ_i are positive constants.

The steady state is characterized by a set of populations $\{N_{j0}\}$ for which

$$\frac{dN_j}{dt} = 0$$

for $j = 1,2$.

The quantities N_{j0} $(j = 1,2)$ are the values of N_j satisfying the following equations :

(31a) $$N_{10}(\alpha_1 - \lambda_1 N_{20}) = 0$$

(31b) $$N_{20}(\lambda_1 N_{10} - \alpha_2) = 0 \ .$$

When none of the N_{i0} 's vanish, they satisfy :

(32a) $$N_{20} = \frac{\alpha_1}{\lambda_1}$$

(32b) $$N_{10} = \frac{\alpha_2}{\lambda_1} \ .$$

Volterra (1931) has shown that there is a constant of motion which depends on the $\{N_{i0}\}$. One defines :

$$v_j = \ln \frac{N_j}{N_{j0}}$$

or

(33) $$N_j = N_{j0} \ e^{v_j}$$

and we see that, as $N_j \rightarrow N_{j0}$, $v_j \rightarrow 0$ so that v_j is a measure of the deviation of N_j from the steady state.

The equations (30a), (30b) are expressed in terms of the v_j by :

(34a) $$\frac{dv_1}{dt} = \alpha_1(1 - e^{v_2})$$

(34b) $$\frac{dv_2}{dt} = \alpha_2(e^{v_1} - 1)$$

using equations (32a) and (32b).

Dividing (34a) by (34b), one obtains, after integration :

(35) $$N_{10}(e^{v_1} - v_1) + N_{20}(e^{v_2} - v_2) = C^{nt} = K_1$$

which is the constant of motion. Each individual term in equation (35) is positive : $v_j > 0$ implies $e^{v_j} > v_j$ and $v_j < 0$, $- v_j > 0$ and e^{v_j} is positive.

Hence we have $K_1 > 0$.

Any set of initial populations yields periodic population variations which are represented by a closed curve about the steady state. There is a whole family of these curves depending upon the initial conditions.

Moreover, it must be remarked that the time averages of N_1 and N_2 during a cycle of period T give, from equations (34a) and (34b), the relations :

(36) $$\frac{1}{T}\int_0^T \frac{dv_1}{dt}\, dt = 0 = \alpha_1 - \alpha_1 \frac{1}{T}\int_0^T e^{v_2}\, dt$$

or

(37a) $$\overline{N}_2 = \frac{1}{T}\int_0^T N_2\, dt = N_{20} .$$

Similarly

(37b) $$\overline{N}_1 = N_{10} .$$

The time averages of N_1 and N_2 calculated during a cycle correspond to the values of N_1 and N_2 at the steady state, N_{10} and N_{20} .

In order to apply the index of fluctuations to this model, the natural definition of proportions p_i is

(38) $$p_i = \frac{N_i}{\sum_{i=1}^{2} N_i} \qquad (i = 1,2)$$

but this definition causes mathematical difficulties, due to the fact that $N_1 + N_2$ is different of a constant. Indeed, equations (30a) and (30b) give :

(39) $$\frac{d}{dt}(N_1 + N_2) = \alpha_1 N_1 - \alpha_2 N_2$$

which is zero only at the stationary state.

It is convenient to take the following definitions of proportions p_i :

(40a) $$p_i = \frac{N_i}{N_0} \qquad (i = 1,2)$$

and

(40b) $$\overline{p}_i = \frac{\overline{N}_i}{N_0} = \frac{N_{i0}}{N_0} \qquad (i = 1,2)$$

with

(41) $$N_0 = \sum_{i=1}^{2} \frac{1}{T}\int_0^T dt\, N_i = \sum_{i=1}^{2} \overline{N}_i = \sum_{i=1}^{2} N_{i0} .$$

These definitions involve some rather delicate changes : in integrating equations (1) and (2) with respect to all the different accessible states of the system, we obtain :

(42) $$\overline{H} = -\frac{1}{T}\int_0^T dt \sum_{i=1}^{2} p_i \ln p_i$$

with

(43) $$\frac{1}{T}\int_0^T dt \sum_{i=1}^{2} p_i = 1 \quad .$$

However, there is no mathematical necessity to work in terms of cycle averages but it is only mathematically convenient.

With these new definitions, let us calculate the index of fluctuations D_0 .

Starting from

(44) $$H = -\sum_{i=1}^{S} \frac{N_i}{N_0} \ln \frac{N_i}{N_0}$$

let us expand it in series around $\frac{\overline{N_i}}{N_0}$ up to second order

(45) $$H = \frac{1}{N_0} \sum_{i=1}^{S} \{N_i \ln \frac{N_0}{\overline{N_i}} - (N_i - \overline{N_i}) - \frac{1}{2} \frac{(N_i - \overline{N_i})^2}{\overline{N_i}} + O[(N_i - \overline{N_i})^3]\} \quad .$$

Defining D_0 by the relation

(46) $$H = \frac{1}{N_0} \sum_{i=1}^{S} [N_i \ln \frac{N_0}{\overline{N_i}} - (N_i - \overline{N_i})] - D_0$$

we obtain immediately :

(47) $$D_0 = \frac{1}{N_0} \sum_{i=1}^{S} (N_i \ln \frac{N_i}{\overline{N_i}} + \overline{N_i} - N_i) \quad .$$

D_0 is a positive definite function (in the sense of Lyapunov) which is zero for $N_i = \overline{N_i}$ $(i = 1,2,\ldots,S)$. For small deviations of N_i from $\overline{N_i}$ $(i = 1,2,\ldots,S)$ D_0 reduces to

(48) $$D_0^* = \frac{1}{N_0} \frac{1}{2} \sum_{i=1}^{S} \frac{(N_i - \overline{N_i})^2}{\overline{N_i}} \quad .$$

The average of D_0 on a cycle of period T is

$$\overline{D_0} = \frac{1}{T}\int_0^T dt\ D_0$$

$$= \sum_{i=1}^{S} \frac{1}{T}\int_0^T dt\ \frac{N_i}{N_0}\ \ln \frac{(\frac{N_i}{N_0})}{(\frac{\overline{N_i}}{N_0})}$$

(49) $$\overline{D_0} = \sum_{i=1}^{S} \frac{1}{T}\int_0^T dt\ p_i\ \ln \frac{p_i}{\overline{p_i}}$$

which reduces to the average of function D_0 [equation (28)] given before.

Moreover, starting from equations (42) and (49), the relation (46) is written :

(50) $$\overline{H} = H_0 - \overline{D_0}$$

with

(51) $$H_0 = - \sum_{i=1}^{S} \frac{\overline{N_i}}{N_0} \ln \frac{\overline{N_i}}{N_0}$$

where H_0 is the value of H at the reference state. This relation shows that the mean diversity of an ecosystem $\overline{H}$ is equal to the diversity of the reference state H_0 minus the mean index of fluctuations $\overline{D_0}$. Thus, only two parameters can define the diversity $\overline{H}$ of an ecosystem : the first H_0 is the diversity of the reference state and the second $\overline{D_0}$ characterizes the fluctuations of the system about the reference state.

Remark

It is possible to define the function $D_0^{(2)}$ symetrically to D_0 by the following relation

(52) $$D_0^{(2)} = \frac{1}{N_0} \sum_{i=1}^{S} (\overline{N_i}\ \ln \frac{\overline{N_i}}{N_i} + N_i - \overline{N_i})$$

which is also positive definite and zero at

$$N_i = \overline{N_i} \qquad (i = 1,2,\dots,S)\ .$$

Expansion of function $D_0^{(2)}$ around $\overline{N_i}$ until the second order can be written :

$$D_0^{(2)} \sim D_0^{\star} = \frac{1}{N_0} \, \frac{1}{2} \sum_{i=1}^{S} \frac{(N_i - \overline{N_i})^2}{\overline{N_i}} \quad . \tag{53}$$

Thus the two functions D_0 and $D_0^{(2)}$ are different only beyond the second order.

Now let us apply the index of fluctuations D_0 to the study of the stability of the Volterra-Lotka model.

7.- Application of the index D_0 in the Volterra-Lotka model

Following Lyapunov, a perturbed system is stable if it is possible to find a function L which is positive definite and the time derivative of which is

$$\frac{dL}{dt} \leq 0 \ . \tag{54}$$

The equality characterizes a weakly stable system, *i.e.* a non-asymptotic stability. Under these conditions, fluctuations of the perturbed system do not decay with time; thus, the system remembers indefinitely perturbations received from its environment.

As we have defined two positive definite functions D_0 and $D_0^{(2)}$, in the sense of Lyapunov, which reduce to $D_0^{\star}$ for small fluctuations, let us apply these functions to study the stability of the Volterra-Lotka model.

Equation (47) is written, using equation (33) :

$$D_0 = \frac{N_{10}}{N_0} e^{v_2} (v_1 - 1) + \frac{N_{20}}{N_0} e^{v_2} (v_2 - 1) + 1 \quad . \tag{55}$$

For small fluctuations around the stationary state, D_0 reduces to

$$D_0^{\star} = \frac{N_{10}}{N_0} v_1^2 + \frac{N_{20}}{N_0} v_2^2 = \frac{K_1}{N_0} - 1 = K_2 = C^{nt} \geq 0 \tag{56}$$

expanding equation (35) up to second order.

Thus, the index D_0^* is a constant of motion of the Volterra-Lotka model and the stability of this system is non-asymptotic according to Lyapunov. As D_0^* is equal to K_2 in the case of small fluctuations, in the Volterra-Lotka model, equation (50) is written :

$$\overline{H} = H_0 - K_2 \tag{57}$$

where H_0 is the diversity of the reference state and K_2 the constant of motion.

We can conclude that, in the case of small fluctuations, the mean diversity of the Volterra-Lotka model is equal to the diversity of the stationary state H_0 minus the constant of motion K_2 .

Moreover, using equation (33), equation (52) is written :

$$D_0^{(2)} = \frac{N_{10}}{N_0} (e^{v_1} - v_1) + \frac{N_{20}}{N_0} (e^{v_2} - v_2) - 1 \tag{58}$$

which can be compared to equation (35) :

$$K_1 = N_{10} \ (e^{v_1} - v_1) + N_{20} \ (e^{v_2} - v_2) \geq N_0 \tag{59}$$

and we have

$$D_0^{(2)} = \frac{K_1}{N_0} - 1 = C^{nt} \geq 0 \ . \tag{60}$$

Thus, the index $D_0^{(2)}$ is surprisingly a constant of motion of the Volterra-Lotka model and we can conclude that the stability of this system is non-asymptotic for any arbitrary perturbation received from environment.

Now, let us apply this index of fluctuations in an experimental distribution of species in the North Sea.

8.- Application of the index D_0 in an experimental distribution of species

Hecq and Heyden (1971) have obtained experimental data on the variation of the proportions of five species of *Mysidacea* during 72 hours, between 4th and 9th December 1971, at Station MO6 (58°28'25" N,

Table 7.3

Proportions of five species of Mysidacea

sp 1 Schistomsis spiritus
sp 2 Schistomsis kervillei
sp 3 Mesopodopsis stelleri
sp 4 Gastrosaocus sanctus
sp 5 Gastrosaocus spinifer

Date	Hour	Sampling number	$P_1(t)$ %	$P_2(t)$ %	$P_3(t)$ %	$P_4(t)$ %	$P_5(t)$ %
6/12/71	17h20	1	47.2	31.5	4.6	4.6	12
	20h23	2	18.9	75.8	0.2	2.7	2.3
	23h23	3	31.6	54.16	6.6	6.6	1.04
7/12/71	2h35	4	23.2	49.1	2.1	16.1	10.7
	5h15	5	36	23.7	13.4	15.4	11.3
	8h55	6	10.3	87.4	0.2	1.5	0.6
	12h05	7	47.8	31.1	2.1	0	10.8
	15h00	8	43.3	36.6	3.3	3.3	13.3
	18h55	9	18.5	65.5	3.7	0	9.2
	21h30	10	8.9	87.9	0.3	1.1	1.7
8/12/71	0h15	11	18.28	70.91	0	8	2.7
	3h15	12	28.67	38.97	0	25.73	6.61
	6h30	13	33.3	33.3	13.3	10	10
	9h20	14	49.3	30.6	8	0	12
	13h05	15	69	25.3	1.4	0	9.1
	15h30	16	45.2	28.5	21.4	0	4.76
	18h30	17	49.3	23.9	16.9	0	9.8
	21h50	18	20.68	72.4	0	1.72	5.17
9/12/71	1h25	19	27.8	63	0.5	4.4	4.1
	4h30	20	25.39	43.65	0.79	30.95	7.14
	7h20	21	23.4	62.06	2.06	9.65	2.75
	10h15	22	40.62	53.12	6.25	0	0
	13h35	23	86.3	0	9	0	4.54
	16h54	24	23.68	71.57	0	4.2	0.5

Table 7.4

Mean proportions of the five species of Mysidacea

$\bar{P}_1$	$\bar{P}_2$	$\bar{P}_3$	$\bar{P}_4$	$\bar{P}_5$
0.3444	0.4833	0.0483	0.0608	0.0632

03°09'15" E), close to the Westerschelde Estuary in the North Sea. These haults were taken in the surface layer every three hours, so that four samplings were made by tidal period. Results are given in Table 7.3. The five species of studied *Mysidacea* are the following : *Schistomsis spiritus*, *Schistomsis kervillei*, *Mesopodopsis stelleri*, *Gastrosaocus sanctus*, *Gastrosaocus spinifer*. The first two species are in great abundance and the other three less numerous.

Let us say that the sea, relatively quiet during the first three tidal periods, became agitated, so that we have two distinct intervals from the point of view of turbulence of the sea.

In Table 7.4 we give the time averaged proportions of each species during the 72 hours. The first two species are the most abundant, whereas the last three are in small number.

Table 7.5 gives the time variations of the three indexes of diversity : H given by equation (1), D_1 by equation (11) and D_2 by equation (24). The indexes of fluctuations D_0 , equation (28), and D_0^* , equation (29) and the variance σ^2 , equation (17), are also given. The binary units (bit) were used, *i.e.* the indexes are expressed in terms of a logarithmic scale to the base 2 . The conversion formula is given by

$$\log_2 = (\ln 2)^{-1} \ln = 1.443 \ln \quad .$$

The comparison between the index D_2 with the exact H shows a very good agreement whereas the index D_1 is only applicable when the diversity is sufficiently large; for small diversity D_1 can be negative. An interesting fact is that the minima and the maxima of all the three indexes occur at the same time. Thus, qualitatively, the three indexes give identical information.

The index D_0 is in good agreement with D_0^* but the variance σ^2 is very bad. The variance σ^2 cannot be used as a measure of the intensity of the fluctuations of the ecosystem.

Figure 7.24 gives the evolution of the three indices H , D_1 and D_2 with time (sampling number). At first sight, it is seen that the diversity oscillates with a period in close relation with the tidal period. Recall that four samplings were made by tidal period; so, we see

Table 7.5

Indexes of diversity and fluctuations (bit)

Sampling number	H	D_1	D_2	$D_0 \times 2$	$D_0^* \times 2$	$S^2\sigma^2 \times 1.443$
1	1.81	1.59	1.75	0.218	0.231	1.018
2	1.04	0.18	0.97	0.508	0.455	2.972
3	1.59	1.27	1.59	0.120	0.087	1.457
4	1.88	1.66	1.78	0.322	0.357	0.923
5	2.18	2.11	1.96	0.554	0.663	0.296
6	0.66	- 0.67	0.53	1.016	0.889	4.147
7	1.50	1.44	1.35	0.172	0.319	1.227
8	1.77	1.58	1.71	0.182	0.210	1.025
9	1.34	0.84	1.28	0.312	0.305	2.060
10	0.67	- 0.70	0.53	1.026	0.910	4.195
11	1.23	0.53	1.19	0.446	0.370	2.481
12	1.81	1.78	1.41	0.686	1.026	0.756
13	2.11	2.01	2.00	0.272	0.349	0.432
14	1.69	1.50	1.63	0.444	0.377	1.140
15	1.27	0.61	1.17	0.956	0.799	2.377
16	1.72	1.62	1.34	0.800	1.078	0.968
17	1.76	1.60	1.55	0.758	0.820	1.000
18	1.13	0.40	1.09	0.446	0.370	2.670
19	1.36	0.87	1.33	0.184	0.157	2.010
20	1.88	1.68	1.29	1.084	1.559	0.897
21	1.50	1.10	1.46	1.980	1.90	1.809
22	1.26	1.10	1.31	0.384	0.208	1.802
23	0.70	- 0.57	0.48	2.406	1.971	4.008
24	1.07	0.40	1.04	0.474	0.365	2.672

six minima and six maxima. The mean current direction is also given, in Figure 7.24, successively we get current directions NW , SW , SE and NE . At first sight, the minima of the diversity corresponds to NW current direction. As the station M06 where the hauls were made is close to the Westerschelde Estuary, the NW current brings water from the Estuary where the diversity of *Mysidacea* is smaller than in water coming from the sea. So the transport of *Mysidacea* with a weak diversity is well visualized by the minima of the index of diversity. For the first three tidal cycles, the correspondance between the minima and the NW current is perfect, in this case, the sea is calm, whereas for the last three

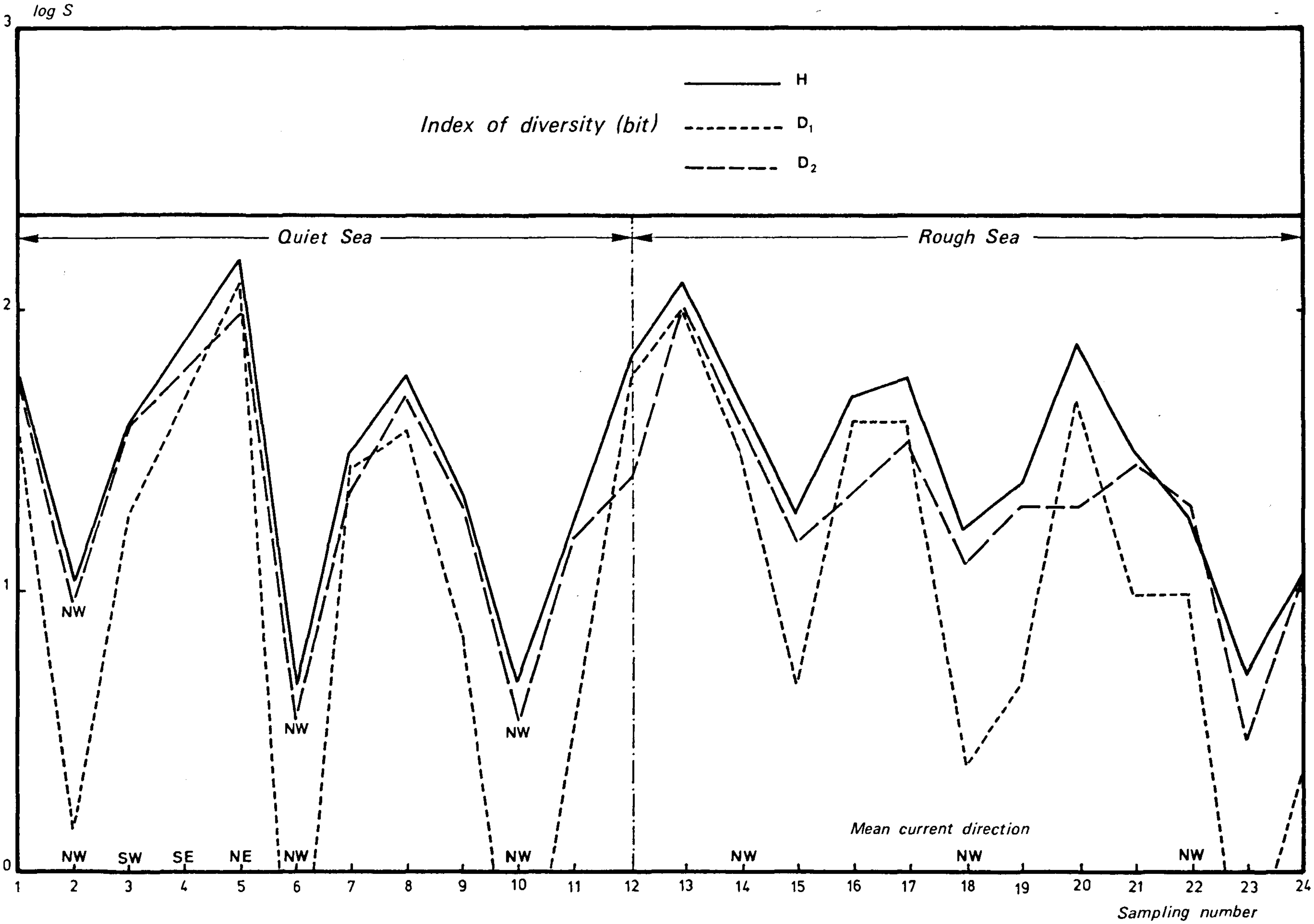

fig. 7.24.- H is the Shannon-Weaver index of diversity, D_1 is the development of H around the mean up to the second order and D_2 is the development of H around the reference state up to the second order.

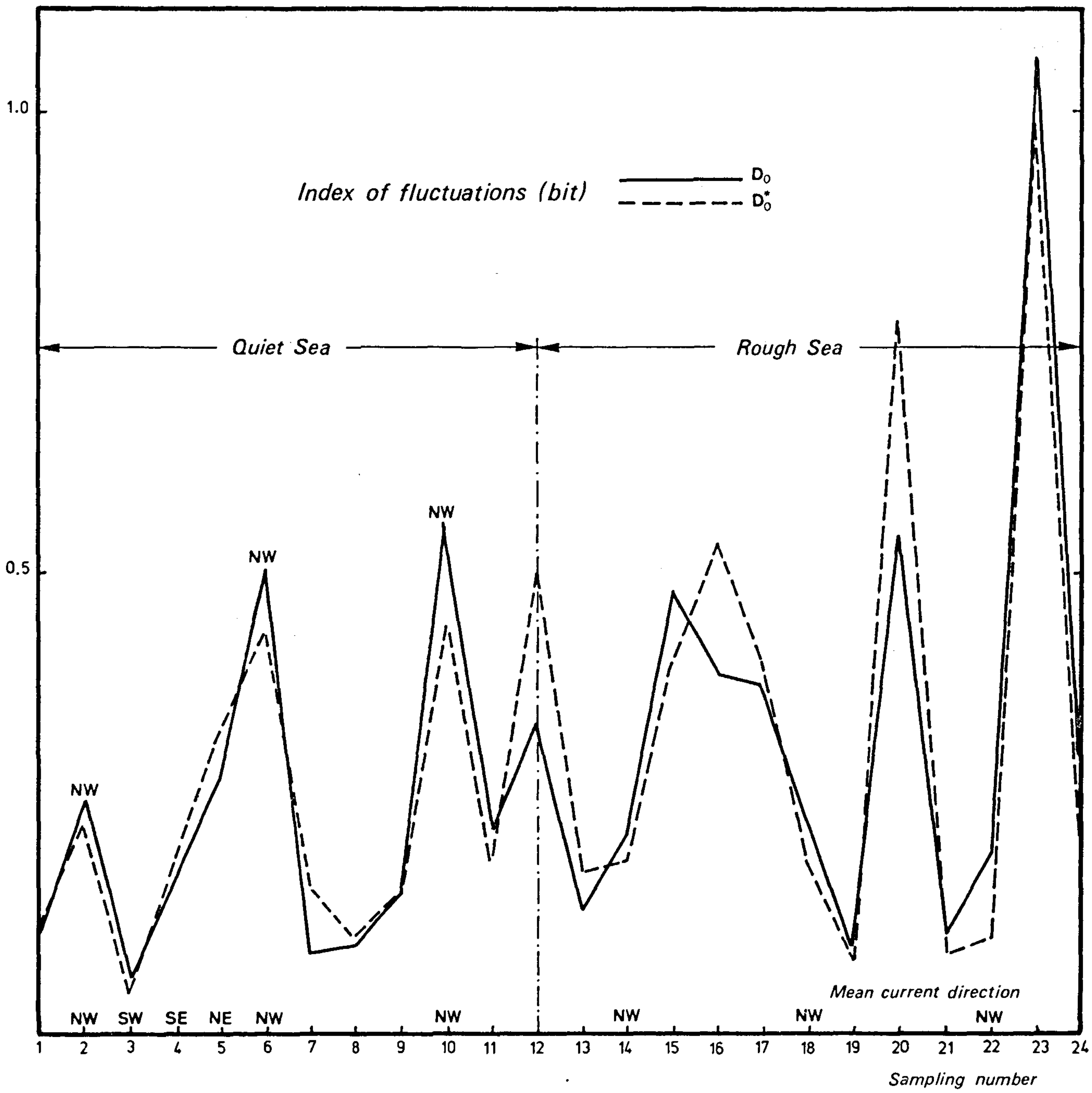

fig. 7.25.- D_o is the index of fluctuations and D_o^* represents the second order term of D_2 .

tidal cycles the effect of the turbulence of the sea is seen by a shifting of these minima. Moreover, the intensity of the oscillations of the diversity is relatively constant with time.

In Figure 7.25, the indexes of fluctuations D_0 and D_0^* are plotted in function of the time as in Figure 7.24. But, contrary to Figure 7.24, we observe oscillations of the index with the tidal cycles, only under calm conditions and the maxima of fluctuations occur when the NW current brings *Mysidacea* from the Estuary. So, maxima of the index of fluctuations corresponds to minima of the index of diversity, and so, the index of fluctuations gives a very attractive measure of perturbations of an ecological system around its reference state. On the other hand, for the turbulent sea region, the maxima of the index of fluctuations corresponds no more to NW current direction. Moreover, the maxima of the variation of the index becomes very large; at sampling number 23, the index is 1.203 whereas the other maxima are around 0.5 .

Now let us compare the behaviour of the index of diversity with the index of fluctuations. In the calm sea region the two indices follow the tidal cycle and the minima of the diversity correspond to the maxima of the index of fluctuations which occur with the NW current direction transferring *Mysidacea* of weak diversity from the Estuary.

On the other hand, in the turbulent sea region, no such correspondance exists between the two indexes, the index of diversity keeps the same behaviour as in the calm sea region whereas the index of fluctuation increases strongly with turbulence. Moreover, in sampling numbers 6 and 23, the indexes of diversity are the same 0.66 and 0.70 respectively and the indexes of fluctuations are 0.508 and 1.203 respectively. So, two identical values of the index of diversity can correspond to two strongly different values of the index of fluctuations. The second index gives more information about the deviation of an ecosystem from its reference state.

Finally, in Figure 7.26 we have plotted H_0 and H_1 which are defined as

$$(61) \qquad H_0 = - \sum_{i=1}^{S} \overline{p_i} \ln \overline{p_i}$$

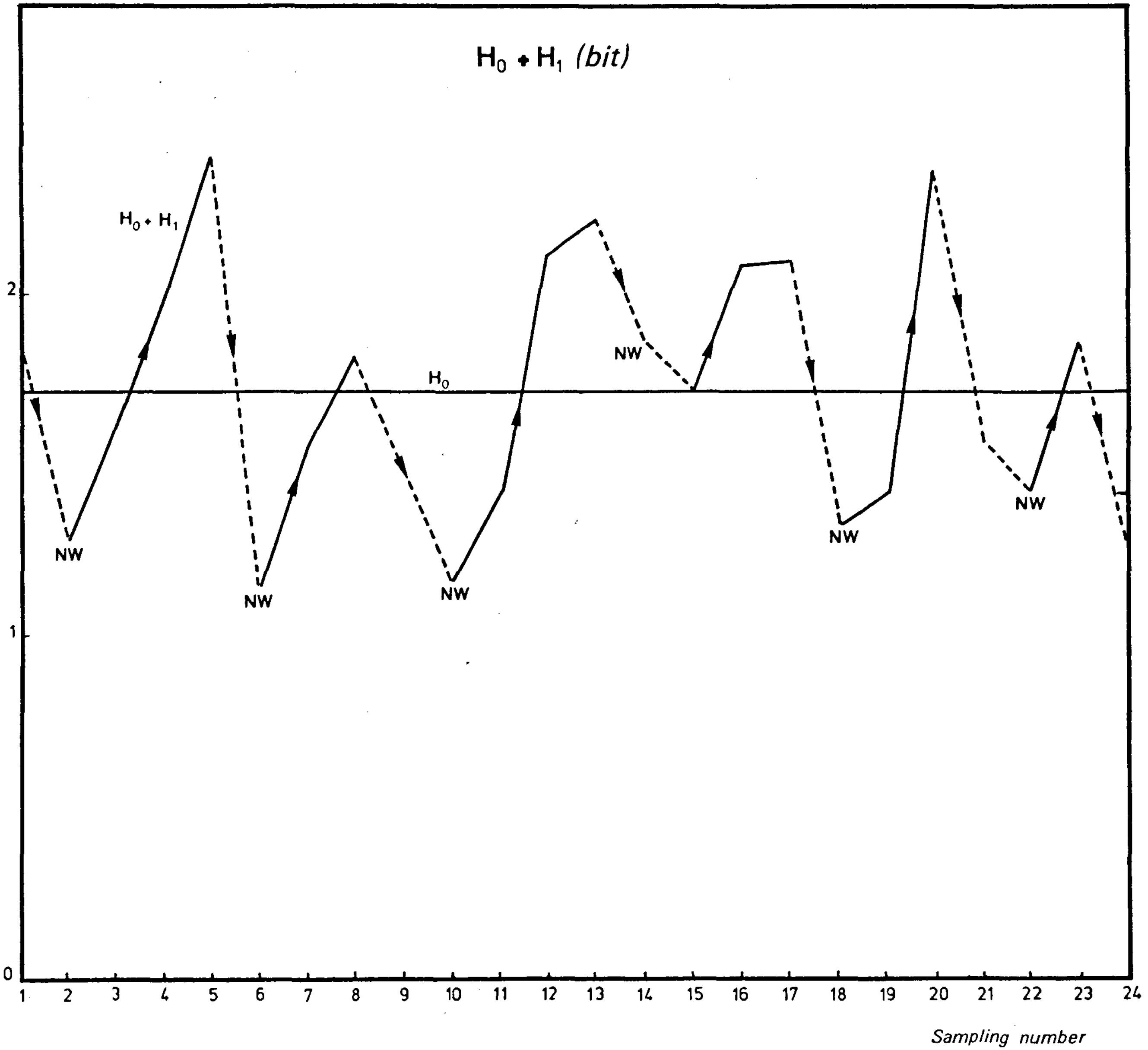

fig. 7.26.- H_o and H_1 represent the first two terms of D_2 .

and

$$H_1 = - \sum_{i=1}^{S} (\ln \overline{p}_i)(p_i - \overline{p}_i) \tag{62}$$

which are the first two terms of the series development of H around the reference state [equation (22)]. H_0 is the diversity of the reference state and is a constant with time whereas H_1 is a function of time.

In conclusion, two opposite phenomena influence the value of the diversity; first we observe a decrease of the diversity with time which corresponds to a flow of diversity from the Estuary (the diversity of the *Mysidacea* in the Estuary is smaller than in the sea). Second, the diversity increases because of diffusion phenomena. Thus the flow of diversity is, on the average, sufficient to maintain the ecosystem at its reference state and compensate the diffusion processes.

9.- Conclusion

Defining a "reference state" for a distribution of species as the ensemble of space-time average proportions of species $\overline{p}_i$, an index of diversity is derived from the Shannon-Weaver formula, which reduces to a simple relation depending on the total number of species S and the variance of distribution σ^2 around the mean.

For the study of fluctuations around the reference state, we introduce an index of fluctuations D_0 which is a positive definite function in the sense of Lyapunov, and zero at the reference state.

Considering the well-known model of Volterra-Lotka to describe a "predator-prey" population, the index of fluctuations D_0 is applied explicitely. Moreover, another function $D_0^{(2)}$, symmetrical to D_0 , is presented.

The discussion of the time derivative of the index of fluctuations D_0 leads to the non-asymptotic stability of the Volterra-Lotka model in the case of small perturbations of the stationary state : D_0 is a constant of motion. Moreover, the function $D_0^{(2)}$ is surprisingly a constant of motion of the Volterra-Lotka model for any arbitrary perturbation received from the environment.

Thus, the index of fluctuations D_0 can be used as a practical criterion of stability of an ecosystem. Moreover, an average of the index of diversity of an ecosystem $\overline{H}$ can be written as :

$$\overline{H} = H_0 - \overline{D_0}$$

where H_0 is the diversity of the reference state and $\overline{D_0}$ the average of the index of fluctuations D_0

$$\overline{D_0} = \frac{1}{T} \int_0^T dt \sum_{i=1}^{S} p_i \ln \frac{p_i}{\overline{p_i}} \quad .$$

Finally, all these indexes are compared on an experimental example : the variation of the distribution of *Mysidacea* at a point of the North Sea. The index of fluctuations appears to be a very attractive measure of the effects on the ecosystem of external perturbations.

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Chapter VIII

Physiological Effects of some Pollutants

by

A. DISTECHE

Based on experimental work from

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Ch. PERPEET and M. VLOEBERG [Brussels (ULB) University]
O. MARCQ and J.M. BOUQUEGNEAU (Liège University)

The main contribution of physiologists to the study of pollution of the marine environment lead :

1) to establish toxicity scales;

2) to evaluate the accumulation of pollutants in marine animals and plants either through the food chain or by direct contamination or by both processes.

The experiments are carried out either on whole organisms, organs or isolated tissues, to better understand not only the nature of the observed physiological perturbation, but in fine to explain possible ecological changes and eventual toxic effects on man.

1.- Toxicity scales

1.1.- Effect of heavy metals and organic pesticides on *Euplotes vannus MULLER* (Marine ciliate, Hypotrichida)

G. PERSOONE and G. UYTTERSPROT (1973a)

Euplotes is an ubiquitous marine benthic ciliate living in sand-mud sediments, of importance as nutrient regenerator and as food for other organisms. Significant increase or decrease in its population density should be reflected at other trophic levels.

The test organisms are cultured on a yeast-sea water suspension (Fleischmann's dry yeast and artificial sea water 35 ‰). Heavy metals (Pb, Cu, Cd, Zn, Hg) are added as chlorides; organic pesticides and PCB are first dissolved in acetone (1 cc for 1 ℓ sea water). After 48 h incubation at 28° C, the number of cell divisions is calculated from cell counts after fixation, and the inhibition is evaluated from :

$$\%\ \text{inhibition} = 100 - \left(100 \times \frac{\text{average number generations + pollutant}}{\text{average number generations control}}\right)$$

Figure 8.1 summarizes the results. The toxicity scale for heavy metals is Hg > Cu > Pb > Cd > Zn . It is however obvious that the growth of *Euplotes* is affected only at very high concentrations compared to those normally found in North Sea coastal waters and even in the Scheldt estuary as indicated in Table 8.1 :

Table 8.1

	North Sea coastal water (ppb)	Scheldt water (ppb)	North Sea sediments (ppm)	Scheldt sediments (ppm)
Zn	100	430	271	926
Cd	5	15	?	?
Pb	58	35	280	185
Cu	59	130	58	221
Hg	0.8	?	1.24	?

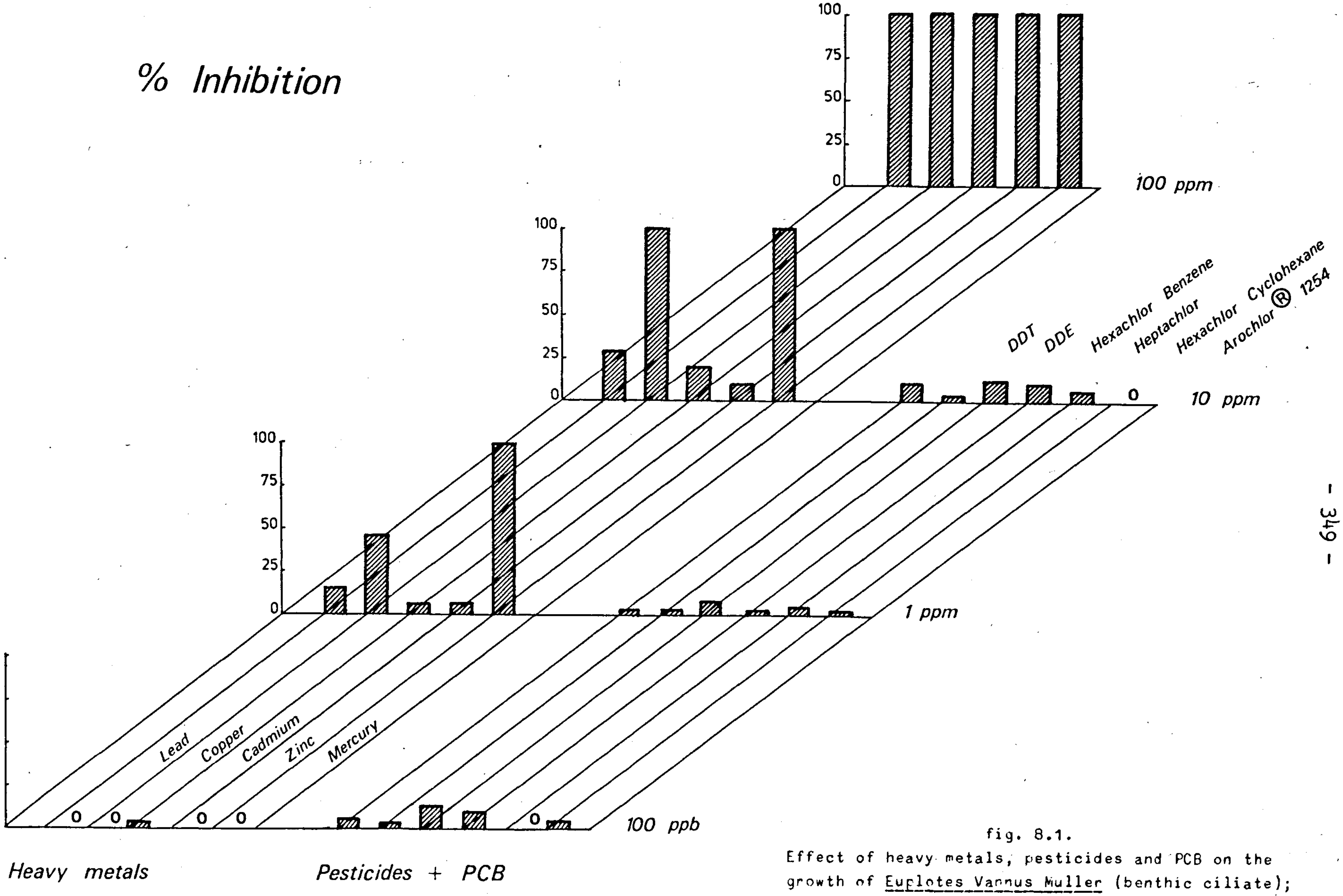

fig. 8.1.

Effect of heavy metals, pesticides and PCB on the growth of Euplotes Vannus Muller (benthic ciliate); % inhibition =

$$100 - (100 \times \frac{\text{average number generations + pollutant}}{\text{average number generations control}}).$$

It is however possible that in interstitial water in sediments, concentrations might be reached that affect *Euplotes*, but these concentrations are not known and one should further bear in mind that the heavy metals are generally bound to organic particulate matter or to minerals in sediments and only partially free in the surrounding solutions.

Euplotes's growth is extremely unsensitive to pesticides and PCB. The actual concentrations in sea water are of the order of 0.01 ppb, exceptionally up to 1.5 ppb ; in sediments one finds 1 ppb up to a few ppb, far below the lowest concentration used by Persoone and Uyttersprot in their experiments.

On the whole *Euplotes* appears as very resistant which is perhaps not surprising since it is commonly found among fouling organisms in harbours.

It would be interesting to find out whether this ciliate, because of its high resistance, does accumulate or not pollutants, for example DDT known to rapidly penetrate living cells as algae, being very soluble in lipids. If accumulation does occur *Euplotes* might turn out to be a dangerous input path to higher trophic levels for substances potentially toxic.

1.2.- Effect of methyl-Hg and organic pesticides on the activity of the isolated heart atrium of eels (*Anguilla anguilla*)

O. MARCQ (1973a,b)

Previous work [Marcq (1972)] has shown that the contractions of the isolated atrium of sea water adapted eels are decreased by heavy metals in the order $Hg > Cd > Pb > Cu > Zn > Mn > Ni$; Hg, Zn, Mn, Cu and Ni ions produce a transitory potentiation followed by progressive inactivation; Co^{++} and UO_2^{++} have only a potentiating effect.

Hg was studied in more detail. The atrium was found to accumulate large amounts of Hg^{++} in physiological solutions containing 2-3 ppm $HgCl_2$. The atrium beat is irreversibly altered; Hg^{++} decreases the action potential, the membrane permeability to all ions being increased. However intoxicated eels with Hg-blood contents of the same order show no alteration of the atrium beat amplitude.

The experiments described below have been carried out to learn more about the protective effect of plasma and to investigate the effect of CH_3HgCl and organic pesticides.

1) CH_3HgCl : the atria after 5 min intoxication in physiological solutions containing 2 ppm $HgCl_2$ or CH_3HgCl are washed during 25 min in mercury free solutions; an irreversible decrease corresponding to 60-70 % of the normal heat amplitude is observed for both $HgCl_2$ and CH_3HgCl but the effect of the methylated compound appears to be faster, especially during the initial potentiating phase (fig. 8.2). The accumulation in the tissue reaches 39.5 ppm and 20.8 ppm for $HgCl_2$ and CH_3HgCl respectively.

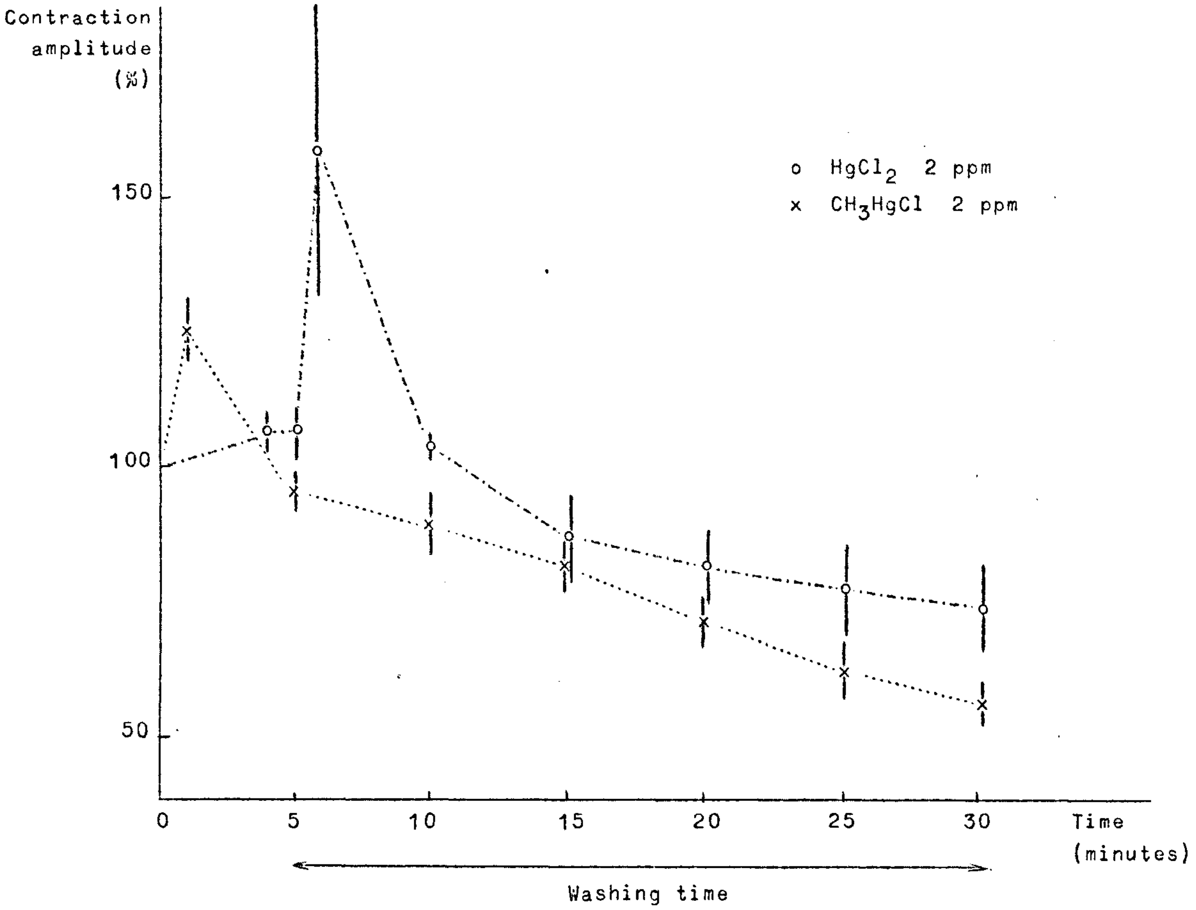

fig. 8.2.

Effect of $HgCl_2$ (2 ppm) and CH_3HgCl (2 ppm)on the contraction amplitude of the isolated eel atrium; 5 minutes intoxication followed by 25 minutes recovery in mercury free physiological solution.

2) Protective effect of plasma : Figure 8.3 shows the protective effect of plasma compared to the physiological solution, both containing

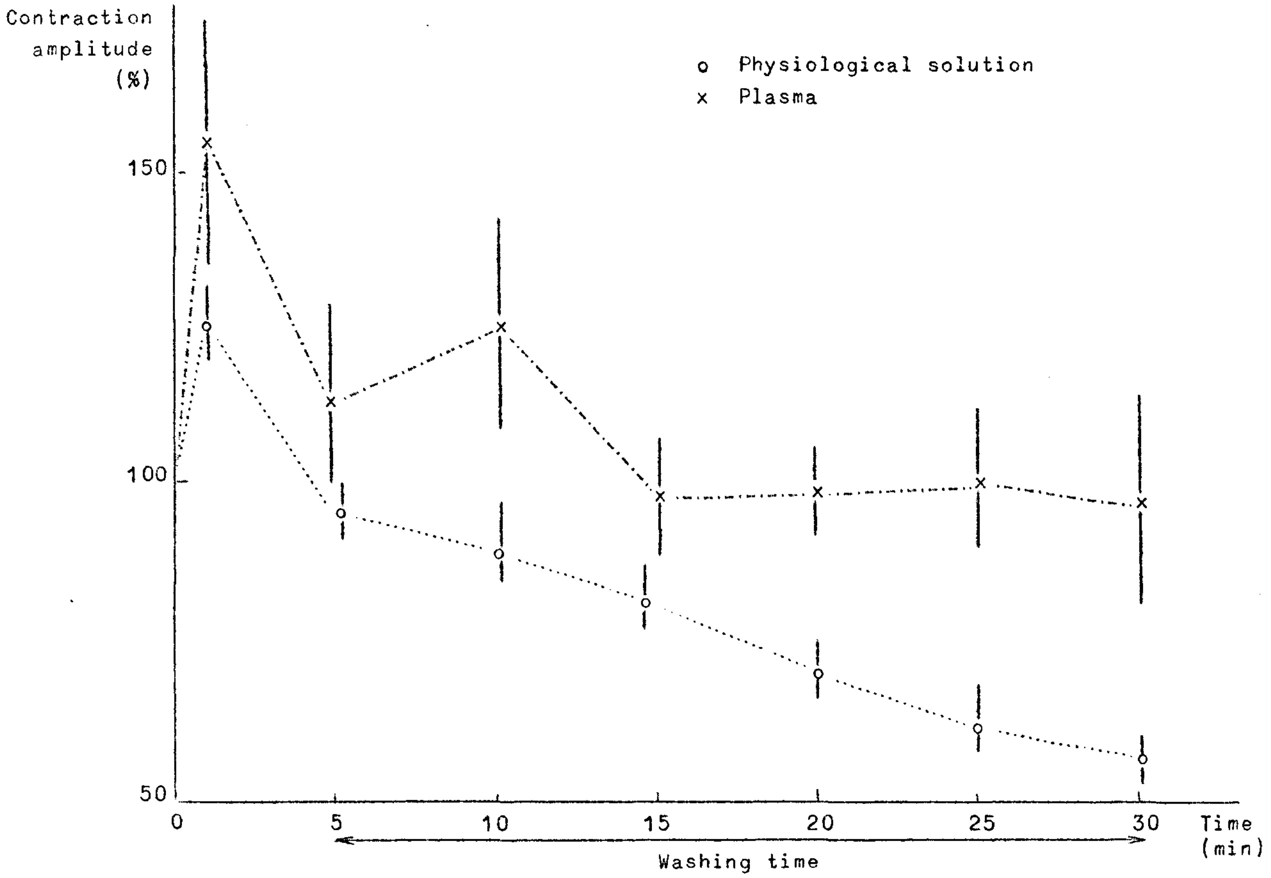

fig. 8.3

Protective action of plasma on the contraction amplitude of isolated eel atrium; intoxication in presence of 2 ppm CH_3HgCl lasts 5 minutes either in plasma or in physiological solution; mercury free fluids are used for washing.

2 ppm CH_3HgCl . The concentration of Hg in the atrium after 5 min intoxication in the physiological solution and 25 min washing reaches 21.0 ± 2.0 ppm Hg , and only 1.6 ± 0.4 ppm when plasma is used; after 30 min intoxication and 15 min washing these figures become respectively 166.0 ± 33.0 and 3.6 ± 2.0 . In plasma the final beat amplitude stays normal but is reduced to 50 % in the physiological solution. It is well known [Hugues (1946)] that serum albumin (SA) reacts with Hg which binds to SH groups, to finally form AS-Hg-SA . If the affinity of this albumin for Hg is greater than that of the reactive sites on

the atrium proteins, it might explain the protective action of plasma compared to physiological solutions devoided of SH bearing substances.

To test this hypothesis cystein has been added to the physiological fluid used to wash the preparation first intoxicated in the normal solution. The Hg concentration in the atrium in a series of experiments of this type falls from 24.0 ± 3.0 ppm when no cystein is used to 18.0 ± 4.0 ppm , 3.0 ± 1.0 ppm and 4.0 ± 1.0 ppm in presence of respectively 2.5 and 8 mM cystein in the washing solution.

Cystein thus binds the Hg first attached to the atrium proteins; however no improvement in the amplitude of the contractions is observed. On the contrary, they decrease and arythmicity is observed. This effect can be observed in absence of Hg but in presence of cystein and is probably due to the formation of Ca and Mg undissociated cystein complexes, upsetting the normal ionic conditions required for normal activity of the contractile tissue.

3) Toxicity of pesticides : the following pesticides have been tested : DDE , DDD , heptachlor epoxide, aldrin, dieldrin, endrin, heptachlor, lindane, polychlorobiphenol (PCB), pyrethrin I and II. The atrium proved to be exceedingly resistant and the effects of the toxic substances cannot be distinguished from that of the solvent used : acetone or cyclohexane; for example, 210 ppm DDT in a physiological solution containing 2.5 % acetone produces the same decrease in the beat amplitude as the acetonic solution alone.

Only pyrethrin was found to be active at low concentrations (0.6 ppm) in presence of 0.06 % cyclohexane : it accelerates the beat frequency by 50 % , but the amplitude falls to 20 % of the normal value in 0.06 % cyclohexane with or without pyrethrin.

The toxicity of the solvents, the precipitation of the pesticides in the aqueous solution alone, the extreme resistance of the tissue, carries the inevitable conclusion that the eel isolated atrium is useless even to evaluate the relative toxicity of the tested organic pesticides.

Since the preparation is also relatively immune to large doses of heavy metals its use as bioassay has to be abandonned.

The resistance to toxics shown by many marine organisms emphasizes the danger of possible accumulation at sublethal doses, leading to toxic effects at higher trophic levels, including man.

1.3.- Synergic effects of pollutants extracted from North Sea sediments on the growth of *Dunaliella viridis Teodoresco* (flagellate alga)

G. PERSOONE and G. UYTTERSPROT (1973b)

The method used by Persoone and Uyttersprot has been developped to try to test the potential quality or toxicity of sediment material by measuring the growth of pure algae inocula in sediment extracts.

The sediment samples (Van Veen grab samples) are taken at 25 grid points located as shown in figure 8.4 in the test region where their content in organic matter (difference between dry weight and ash weight) is indicated.

Extracts are prepared using the amount of sediment required to provide 10 g of organic matter, suspended in 1 ℓ of artificial sea water, followed by filtration on 0.45 Millipore filter. Extract samples (100 cm^3) are inoculated with 100.000 algae cells [either with addition of Vlasblom culture medium ($FeSO_4$, NaH_2PO_4, $NaNO_3$, $MnCl_2$, glycine) or not]. Controls are run on artificial sea water either or not enriched with the Vlasblom substrate. To compare the growth of the different cultures the surface of the S-shaped growth curve is used or the number of cells counted after 5 days .

Relative enhancement or decrease of the growth compared to control samples is expressed by

$$\% \frac{\text{S-growth curve sample}}{\text{S-growth curve control}} \quad \text{and} \quad \% \frac{\text{N cells sample}}{\text{N cells control}} \quad \text{after 5 days.}$$

Figures 8.5 and 8.6 show the results of these experiments. Fig. 8.5 indicates that in presence of the culture substrate, the difference between the growth in sediment extracts and the control is small, the mean for all points being practically zero. The only exception is point 5 where 30 % inhibition is observed.

Figure 8.6 shows what happens in sediment extracts in absence of culture substrate. On the average there is growth stimulation (65 %) .

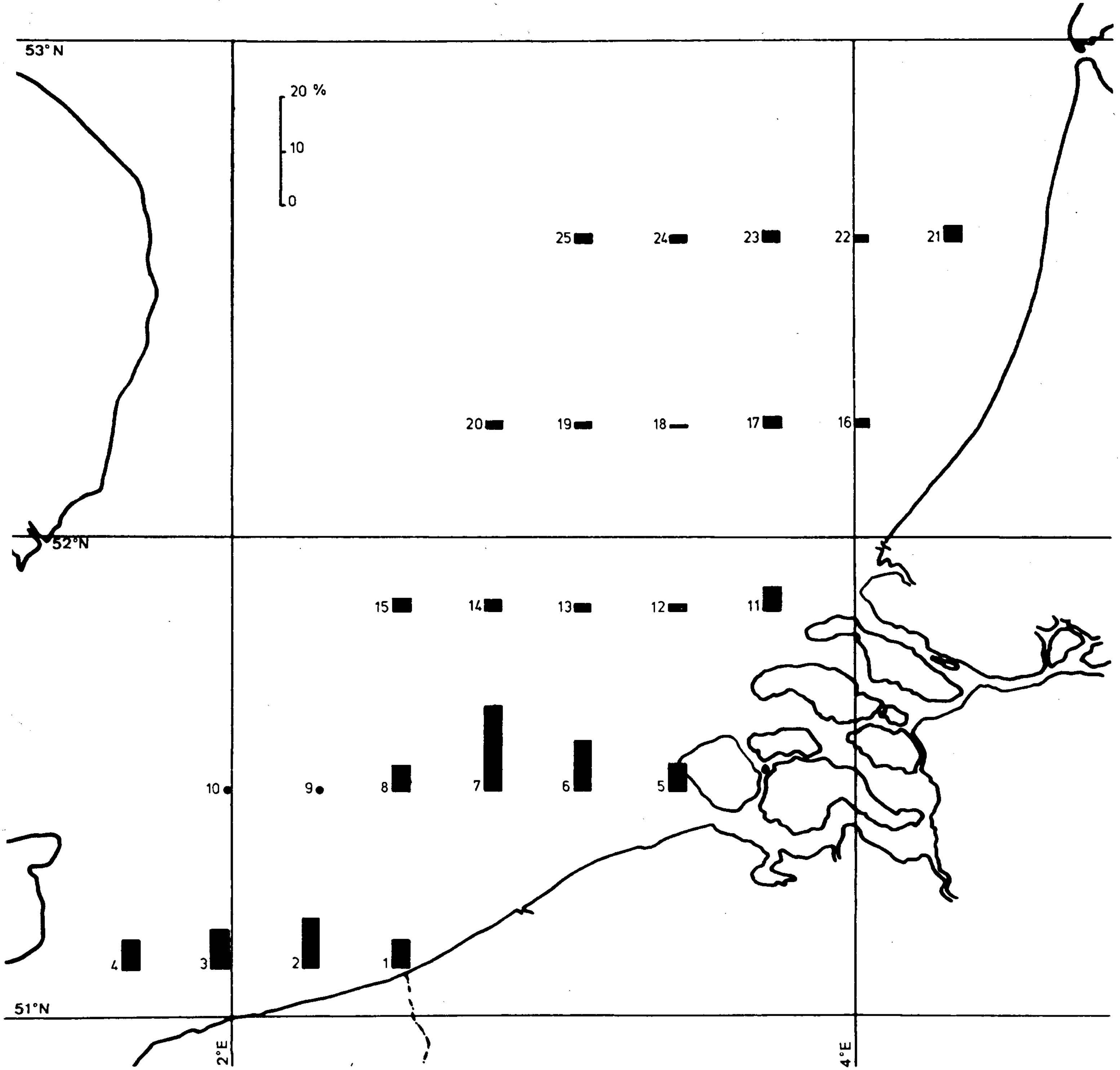

fig. 8.4.- % organic matter of sediment.

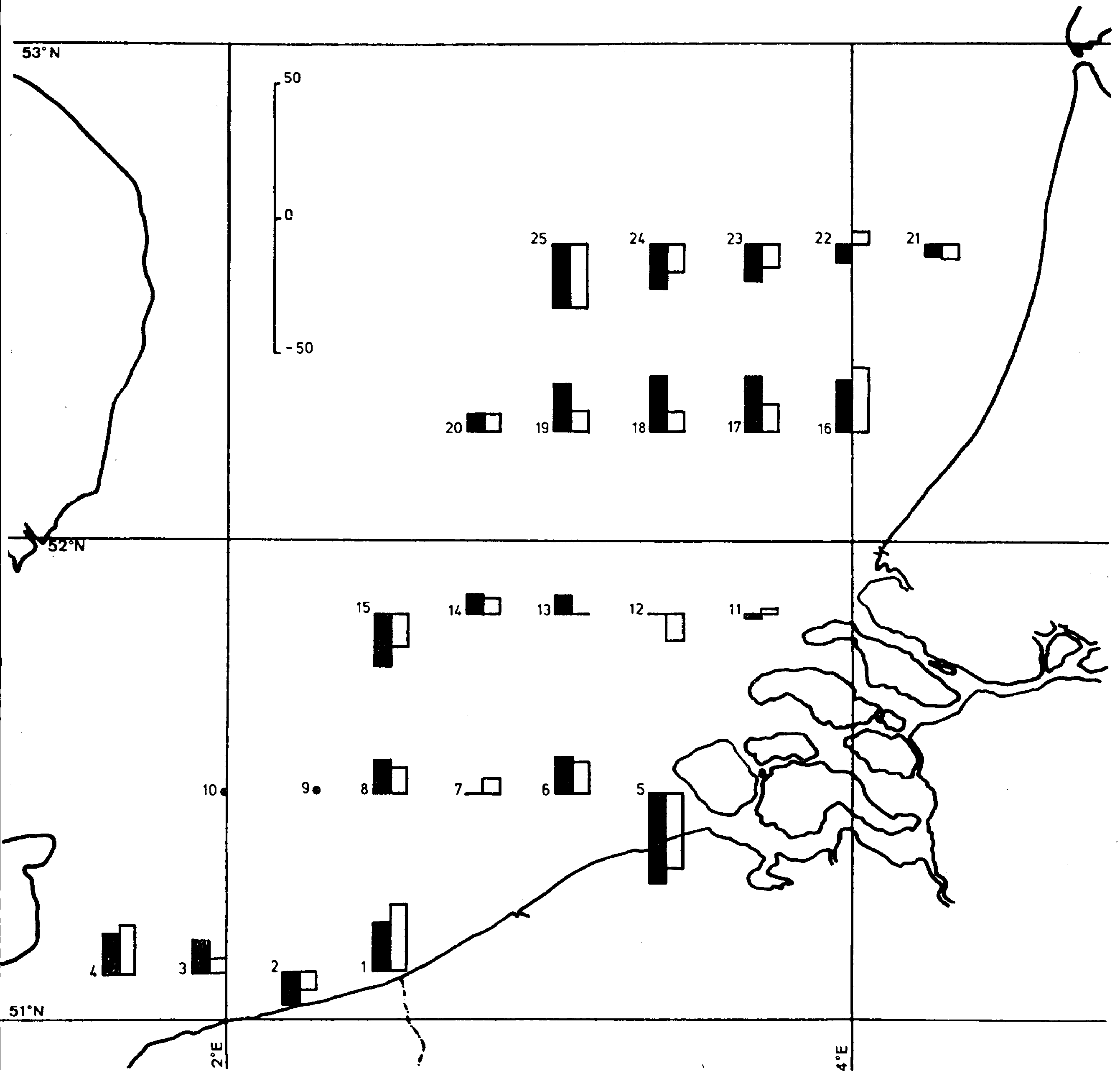

fig. 8.5.- Growth of Dunaliella viridis in usual culture medium with extract of sediment.

■ $\% \frac{\int \text{growth curve sample}}{\int \text{growth curve control}}$ ☐ $\% \frac{N_{sample}}{N_{control}}$ after 5 days

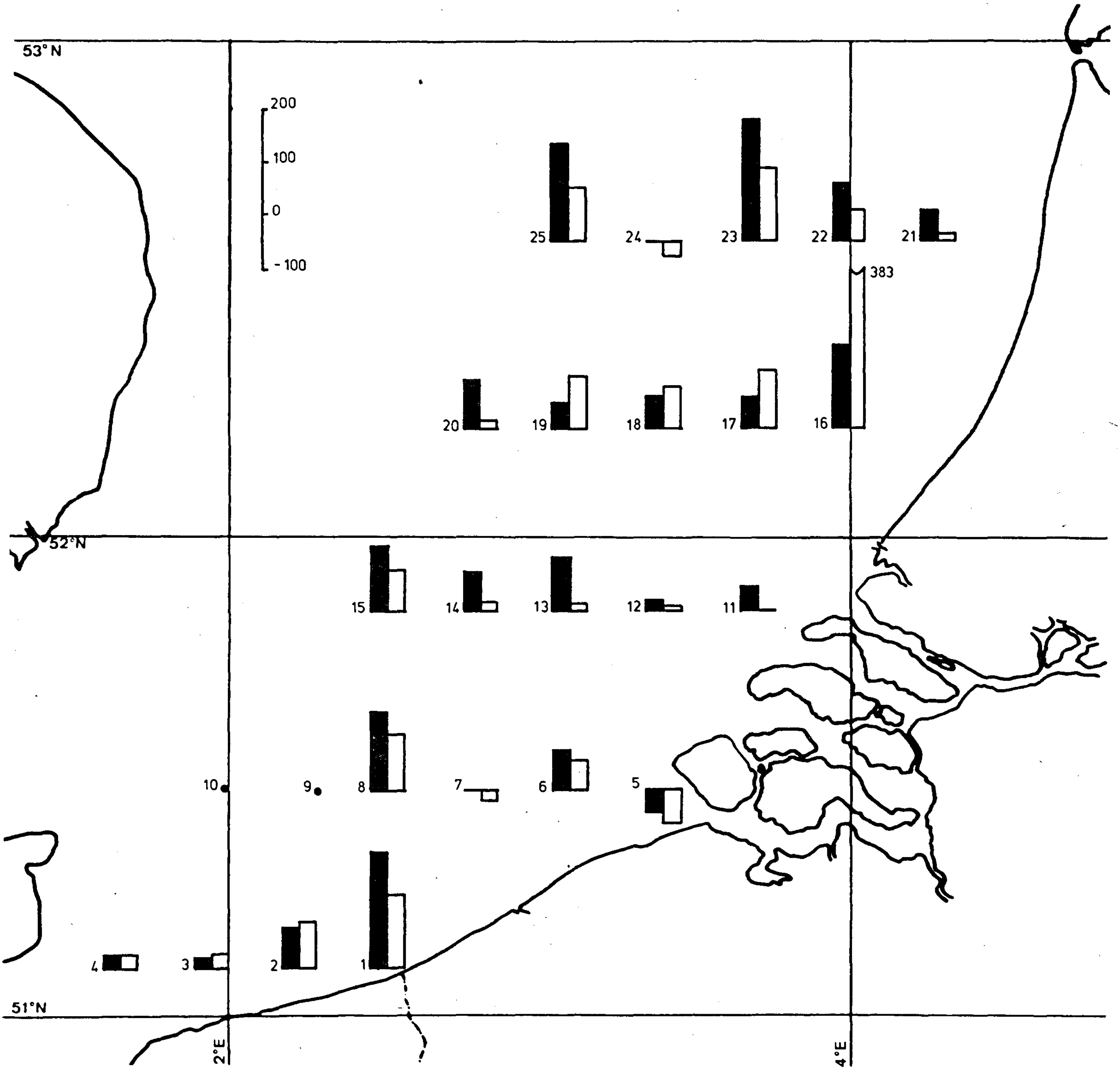

fig. 8.6.- Growth of Dunaliella viridis on extract of sediment solely.

■ $\% \frac{\int \text{growth curve sample}}{\int \text{growth curve control}}$ □ $\% \frac{N_{sample}}{N_{control}}$ after 5 days

Point 5 reveals 50 % inhibition. The growth rate is smallest around the estuarine region but it increases with distance from the coast; on the contrary growth is highest near the coast in transects 1-4 and 16-20 but a different and more complicated situation is found in 20-25.

It is obvious that when culture medium is added, there is no substrate limitation, which might explain that the algae grow at the same rate in control and sample; in absence of culture medium, although general stimulation is observed, it seems clear from what happens at point 5 that the influence of toxic substances increases when the environmental conditions become worse, the organism being submitted to multiple stress.

Point 5 is known to be in the vicinity of dumping sites for industrial waste. Evaluation of benthic biomass and fish population around points 5 and 6 shows however a relative increase, in contradiction with the laboratory results of Persoone and Uyttersprot.

Although figure 8.6 probably shows how growth of *Dunaliella* is activated by sediment extracts and modulated by synergic effects of toxic or inhibiting substances localised in the organic matter of these sediments, it remains doubtful whether this picture can be taken to reveal the global pollution situation in the test region. It should be remembered that Persoone and Uyttersprot (1972) obtained similar results when growing *Dunaliella* in natural sea water sampled at the 25 gridpoints but almost an opposite picture when using the flagellate *Monochrysis lutheri*.

It seems obvious for the author of this report that the use of a single organism for water or sediment quality tests is very much questionable, the more that the nature of the pollutants remains totally unknown as well as the nature of nutrients and eventual natural growth inhibitors or potentiators.

It is clear that *in situ* primary production measurements, zooplankton evaluation and inventories of the biomass of benthic and pelagic populations, including diversity indexes, is by far much more reliable (see reports by Polk and De Coninck).

The methodology developped by Persoone and Uyttersprot for mass culture of algae leads however to important future possibilities to determine incorporation rates of given pollutants either heavy metals or pesticides, and to initiate experimental food chains (see § 2.2.2 below).

2.- Accumulation processes

2.1.- Accumulation of heavy metals in mussels (*Mytilus edulis*)

Ch. PERPEET and M. VLOEBERGH (1973)

2.1.1.- *In situ* accumulation at different localities between Morgat Bay (Finistère, France) and the Scheldt Estuary

Mussels samples (70-90) collected at Morgat, Knokke, Hoofdplaat, Terneuzen and Perkpolder have been divided in groups of ten according to size and the tissues have been analyzed for Hg , Cu , Zn , Pb , Cd , Fe , Cr , using atomic absorption methods. The results shown in figures 8.7 and 8.8 are given in ppm dry weight except for mercury where one refers to wet weights (ppb).

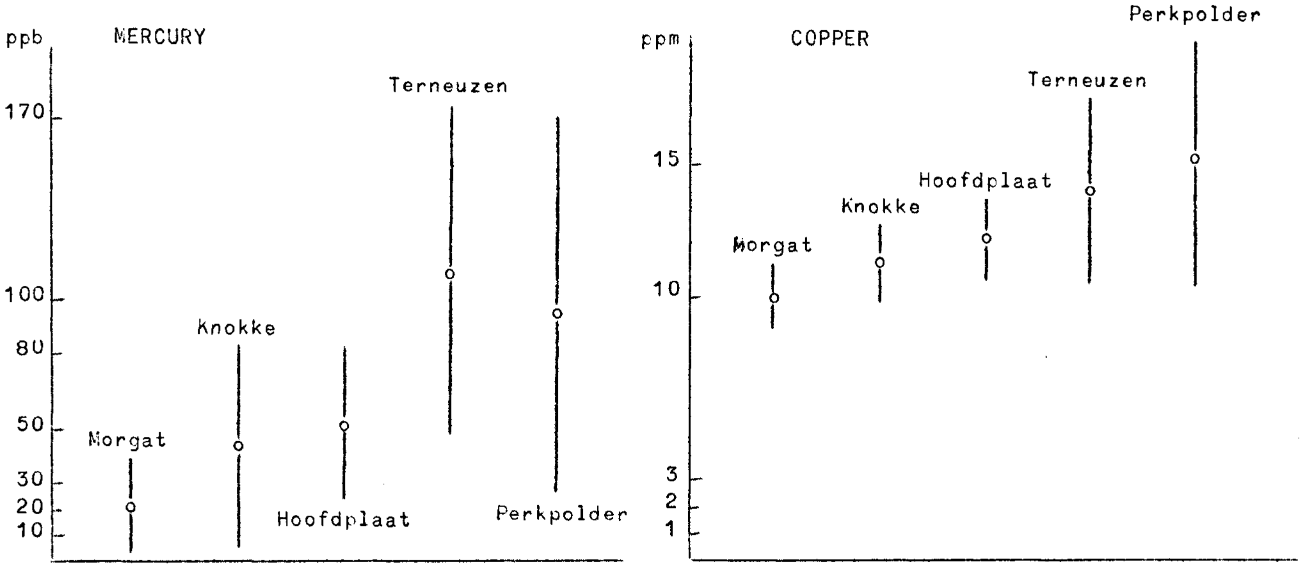

fig. 8.7.
Heavy metal content of mussels collected at various localities in the North Sea and the Scheldt estuary (Hg ppb wet weight; other metals ppm dry weight; height of vertical bars corresponds to the dispersion of the results).

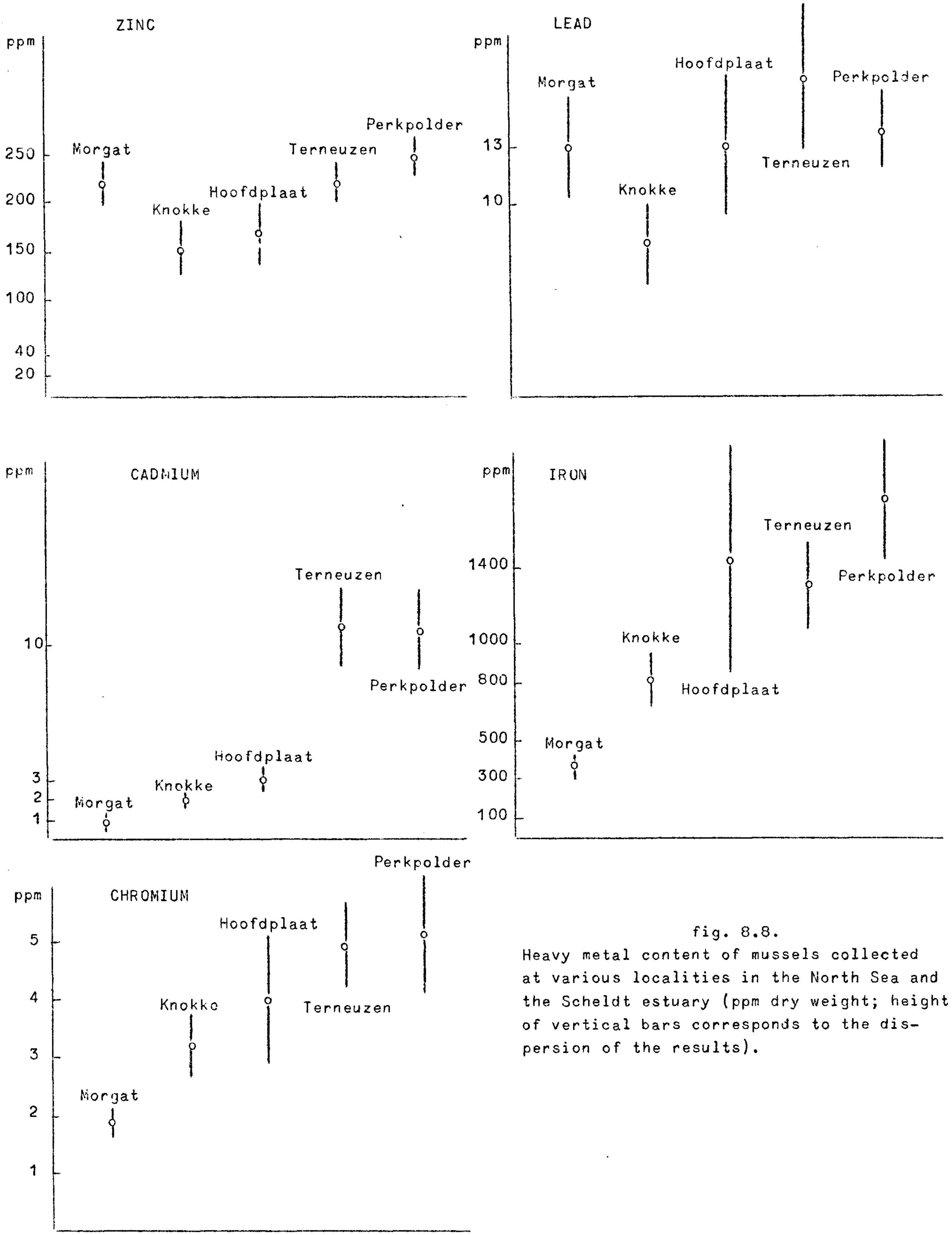

fig. 8.8.

Heavy metal content of mussels collected at various localities in the North Sea and the Scheldt estuary (ppm dry weight; height of vertical bars corresponds to the dispersion of the results).

No correlation is found with the size of the mussels and the results vary greatly at the same locality as is indicated by the size of the vertical bars centered on the mean value in the different graphs. It is however obvious that generally the heavy metal load increases going from Morgat towards the Scheldt. Exceptions are found for Pb and Zn , rather high at Morgat probably because of local industry.

Comparison with data of Bertine and Goldberg (1972) on mussel tissues sampled at Nieuwpoort in 1971 shows reasonable agreement : these authors give values ranging between 400-1400 ppm for Fe , 0.5-2.0 ppm for Cr , 0.5-1.6 ppm (dry weight) for Hg , but their values for Zn lie between 30 and 60 ppm , that is about 4 times less than those reported here.

Although these results tend to suggest that mussel might prove a good indicator for pollution, they do not necessarily mean that the heavy metals are really accumulated in the tissues. A large amount of the pollutants is probably simply located in the digestive tract and it should be interesting to repeat these analysis on mussel tissues separated from the digestive tract. It is known (see Bertine and Goldberg) that in the case of museum specimens a great part of the metals, Fe for instance, in the tract slowly pass into solution and contaminate the tissues.

If this is true then whole mussels should be regarded more or less as receptacles for suspended matter having undergone the effect of total or partial digestion, removing organic material. This would add to the eventual accumulation in other tissues either from food or due to the water flow and perhaps explain the scattering of results and the absence of correlation with size.

2.1.2.- Accumulation of ^{203}Hg in mussels kept in aquaria

Figure 8.9 shows preliminary results on the accumulation in mussels of ^{203}Hg added to artificial sea water. Concentration reaches the highest levels in the gills and the digestive tract after respectively 72 and 130 hours , then declines. The authors believe this to be due to changes in the ^{203}Hg concentration in the water because of precipitation or adsorption on mucus, organic particles, or on the aquarium

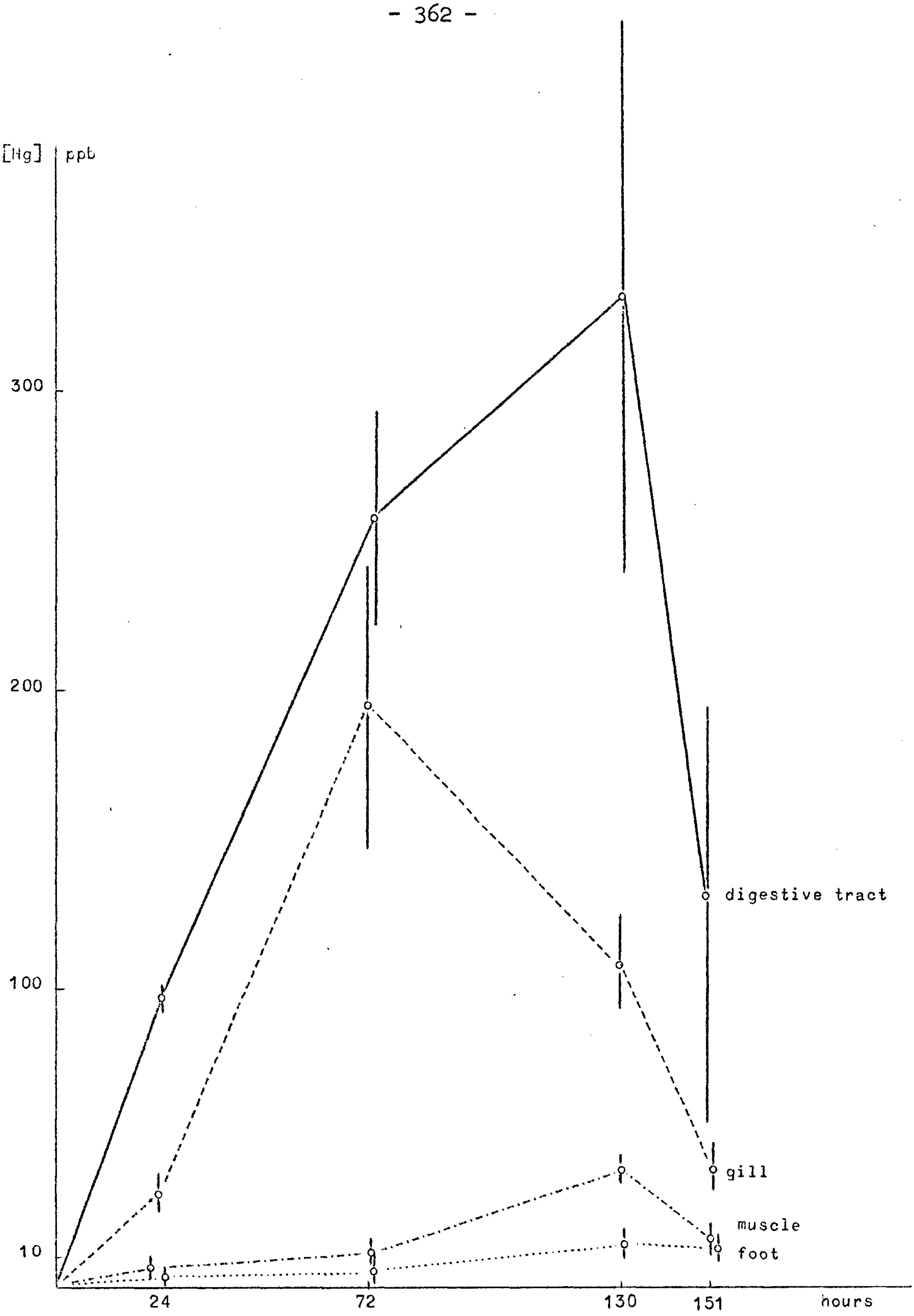

fig. 8.9.
Accumulation of ^{203}Hg in the tissues of mussels exposed to an initial concentration of 5 ppb ^{203}Hg in artificial sea water.

walls. If it is true, then obviously fixation and release of Hg in the gills and the digestive tract are fast compared to what happens in the other tissues.

At 1 ppm Hg , 100 % mortality is observed within a few days, and heavy accumulation is noticed in the gills.

Although the experiment must be repeated, sea water and the mussels being analyzed simultaneously and the Hg level being kept constant, it shows that accumulation can result from direct contact with contaminated water containing only 5 ppb Hg . This is still about 10 times more than what is found in the coastal region of the North Sea, but is a realistic figure and shows how promising the use of radio-isotopes is.

One will of course have to bear in mind the possibility of adsorption on organic particulate matter or bacteria in suspension in the sea water, which as food might contribute to the intoxication of the test animals; redistribution between different organs is also not to be neglected.

2.2.- Accumulation of heavy metals in the food chain

2.2.1.- Mussel-Starfish (*Mytilus edulis – Asterias rubens*)

Ch. PERPEET and M. VLOEBERGH (1973)

Figure 8.10 shows the accumulation of the radio-isotope ^{203}Hg in *Asterias rubens* fed on mussels having been 24 hours in sea water containing 5 ppb ^{203}Hg (see fig. 8.9 for the isotope distribution in the mussel tissues). Accumulation by *Asterias rubens* is particularily noticeable in the pyloric and rectal caeca.

In the case of Cu^{++} , Perpeet and Vloebergh (1972) have shown that copper is much more toxic for starfish than Hg or Pb : a concentration of 0.4 ppm Cu^{++} in sea water affects respiration and produces 100 % mortality within 5 days ; Cu^{++} is principally accumulated in the podia where it produces important tissue damage [Perpeet and Vloebergh (1973)]. Cu^{++} accumulation in pyloric caeca seems not to affect the animals.

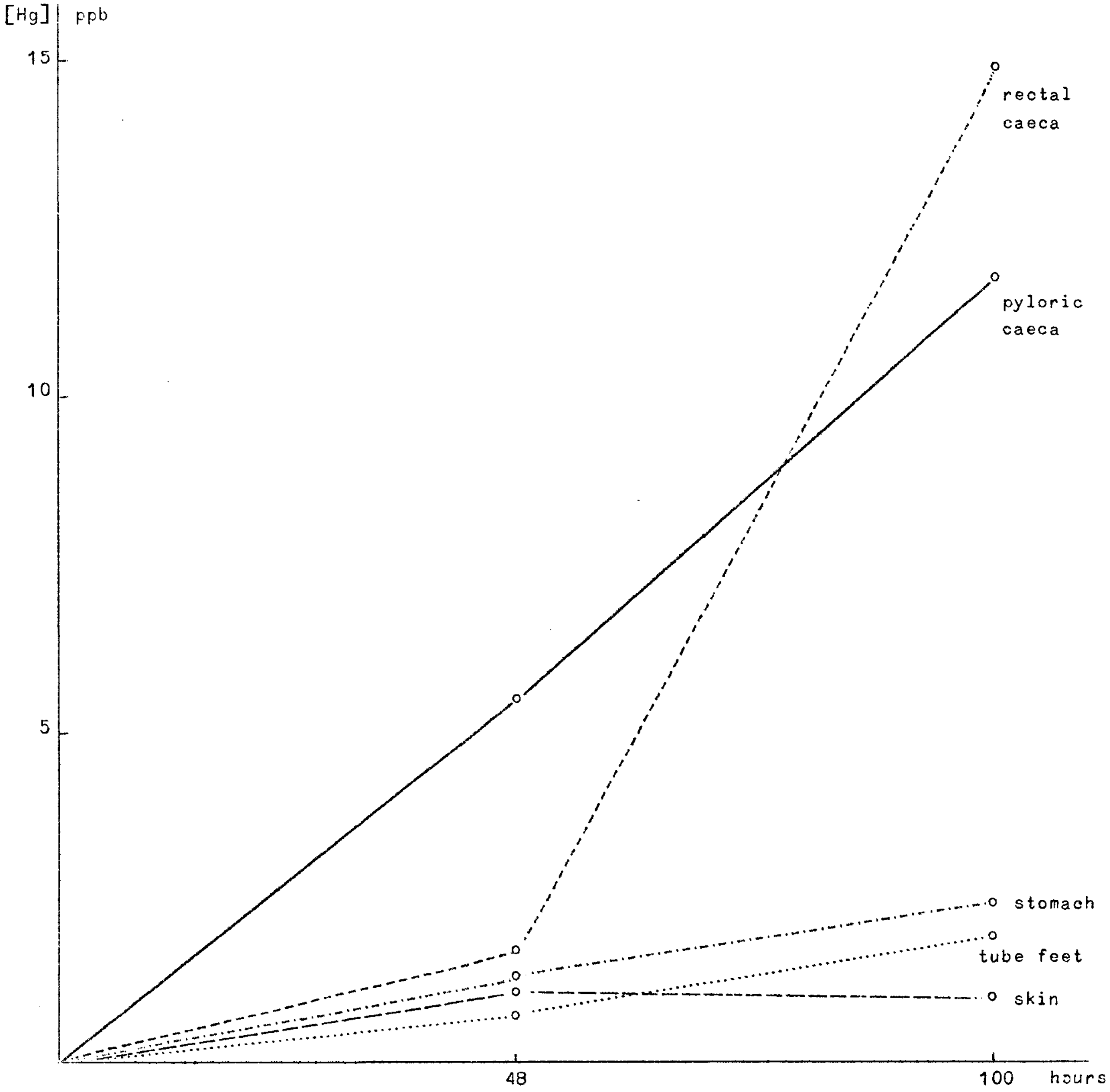

fig. 8.10.

Accumulation of ^{203}Hg in organs of Asterias rubens fed with mussels first intoxicated in presence of 5 ppb ^{203}Hg .

2.2.2.- *Dunaliella viridis* (alga) – *Artemia salina* (Entomostraca) – *Brachydanio rerio* (fresh water fish)

G. PERSOONE and G. UYTTERSPROT (1973c)

The experiments have been carried out as follows :

1) Mass culture of *Dunaliella* in 30 ℓ natural sea water sampled at 22 points of the test region (1.1 to 3.2 × 10^6 cells/cm^3) .

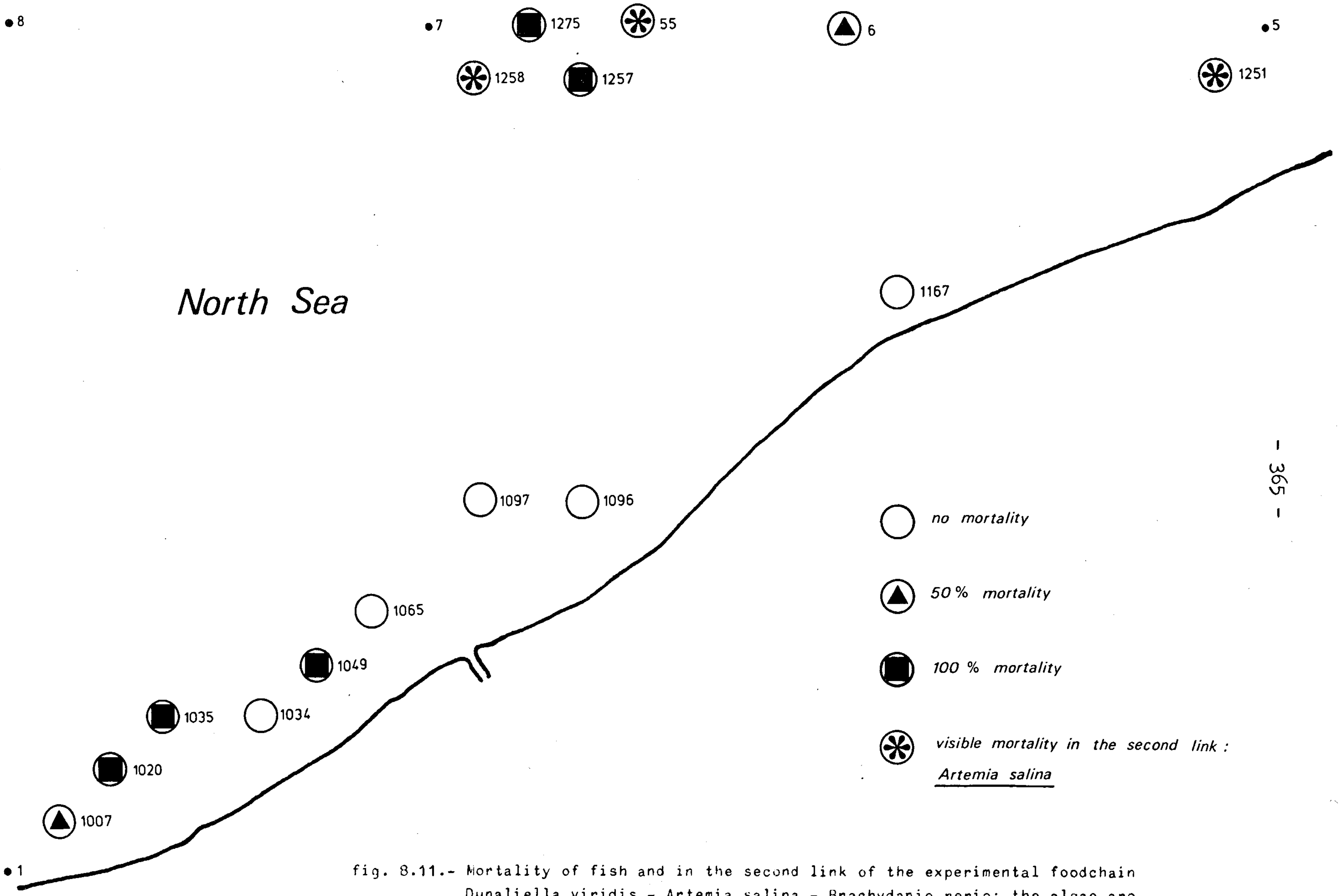

fig. 8.11.- Mortality of fish and in the second link of the experimental foodchain Dunaliella viridis - Artemia salina - Brachydanio rerio; the algae are grown on sea water sampled as indicated on the map (see fig. 8.4 for location of points 1 and 5 to 8).

2) Feeding of 100.000 *Artemia salina* larvae during 2 days with the harvested algae.

3) Feeding of two fishes for about one month with the deep frozen *Artemia* larvae.

Controls are carried out starting with artificial sea water ($1.6 \times 10^6/cm^3$ algae cells).

The results obtained are still in a very preliminary stage and only refer to the observed fish mortality as seen in figures 8.11 and 8.12 where the sites of sea water sampling are clearly indicated, if one further refers to figures 8.4, 8.5 and 8.6 to locate points 1 and 5 to 8 . No chemical data are so far available except in a few cases for the composition of the water samples, that of the algae, the artemia or the fish.

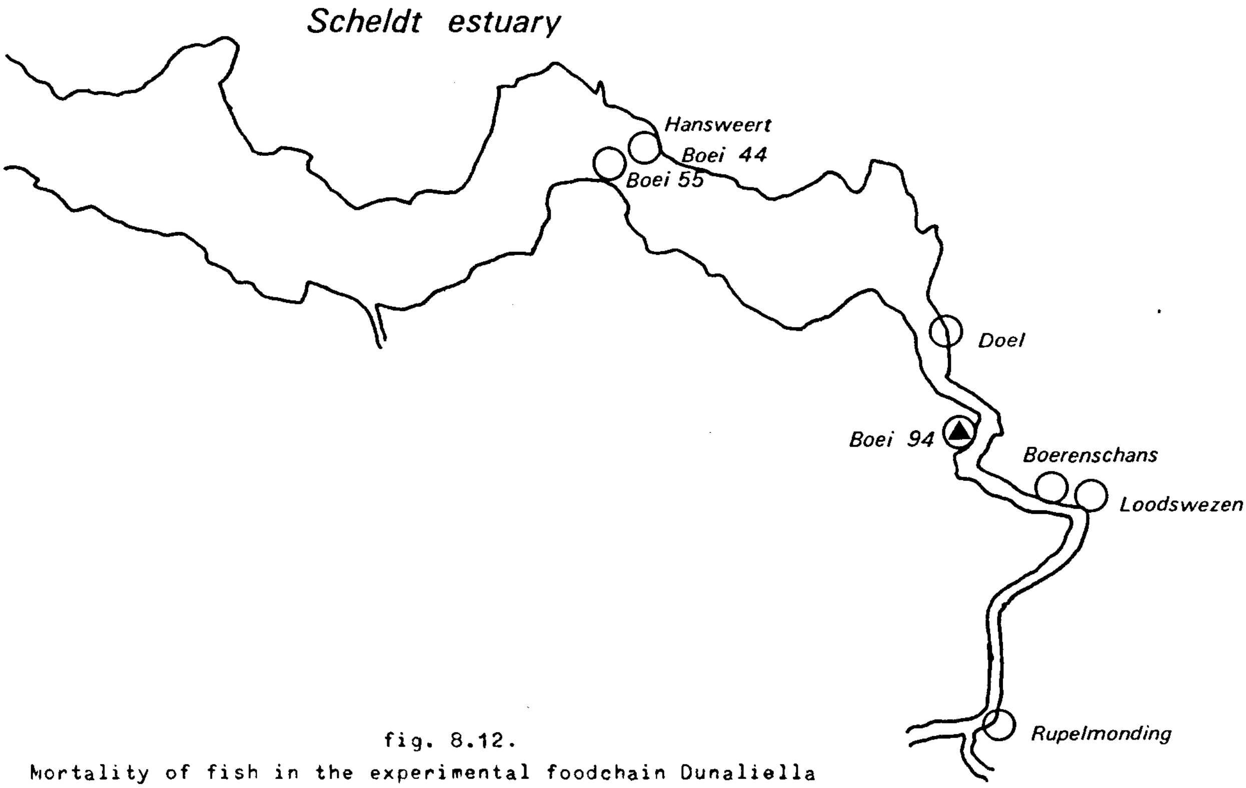

fig. 8.12.
Mortality of fish in the experimental foodchain Dunaliella viridis - Artemia salina - Brachydanio rerio; the algae are grown on water sampled in the Scheldt estuary as indicated on the map.

Generally speaking the Scheldt water samples seem less toxic than the coastal sea water samples and among these higher toxicity was found between Nieuwpoort and Oostende. High mercury level (3.5 ppm) in the algae was detected at point 1035. Water from points 6 and 7 and neighbouring sites is toxic either at the second or the third trophic level. They lie in zones where large amounts of organic and mineral waste are dumped (H_2SO_4 and $FeSO_4$ solutions from titanium industry and industrial yeast and fungi residues).

Correlation with the *in situ* measurements regarding primary and secondary production, fish and benthic fauna is by no means evident. Coastal eutrophisation, increase of biomass of resistant species, effects of predation in complex communities, food selection are factors among many others which cannot be simulated in short artificial food chains of the type used by Persoone and Uyttersprot and where extreme conditions exist.

It is felt by the author of this report that designing a bioassay as complicated as a three stage food chain to test water quality is practically hopeless : the amount of chemical analysis is enormous to trace all possible pollutants, the results remain far from representing what really happens in the true ecological system.

The fact that some laboratories are capable of maintaining experimental food chains on a large scale, is however of greatest interest because it opens large possibilities in the study, under different conditions, of rates of uptake and release of various pollutants, added one by one or simultaneously to sea water. One should however be careful in selecting the test organisms and try different ones. It is for instance important to know that Hg is lethal at some level on fresh water fish because it stops respiration, and that it is toxic for sea water fish because it acts on osmoregulation in the gills before it interferes with respiration. It would certainly be more realistic to use *Cottus scorpius* for example instead of *Brachydanio rerio* (tropical fresh water fish), as is done by Persoone and Uyttersprot.

2.3.- Accumulation and release of Hg in fish [sea water adapted eels (*Anguilla anguilla*); plaice (*Pleuronectes platessa*), dab (*Limanda limanda*); *Cottus scorpius*]

J.M. BOUQUEGNEAU

2.3.1.- Sea water adapted eels

Bouquegneau has shown (1972) that Hg accumulates in the different organs of eels exposed to natural sea water containing controlled amounts of Hg . The main site of entry (the animals normally do not feed in sea water) is located at the gills, which rapidly accumulate large amounts of Hg . At 10 ppm Hg in the sea water, lethal effects are observed within a few hours and the osmotic balance of the animal is totally upset; at 0.1 ppm , sublethal effects are noticed. Adaptation occurs : the animals maintain their osmotic balance but accumulate in the gills amounts of Hg larger than those found to be lethal when the fish is exposed to 10 ppm . Figure 8.13 shows typical mortality curves for both the lethal and sublethal effects and it is clear that fish first exposed to 0.1 ppm are more resistant when in presence of 10 ppm and CH_3HgCl is more toxic than $HgCl_2$.

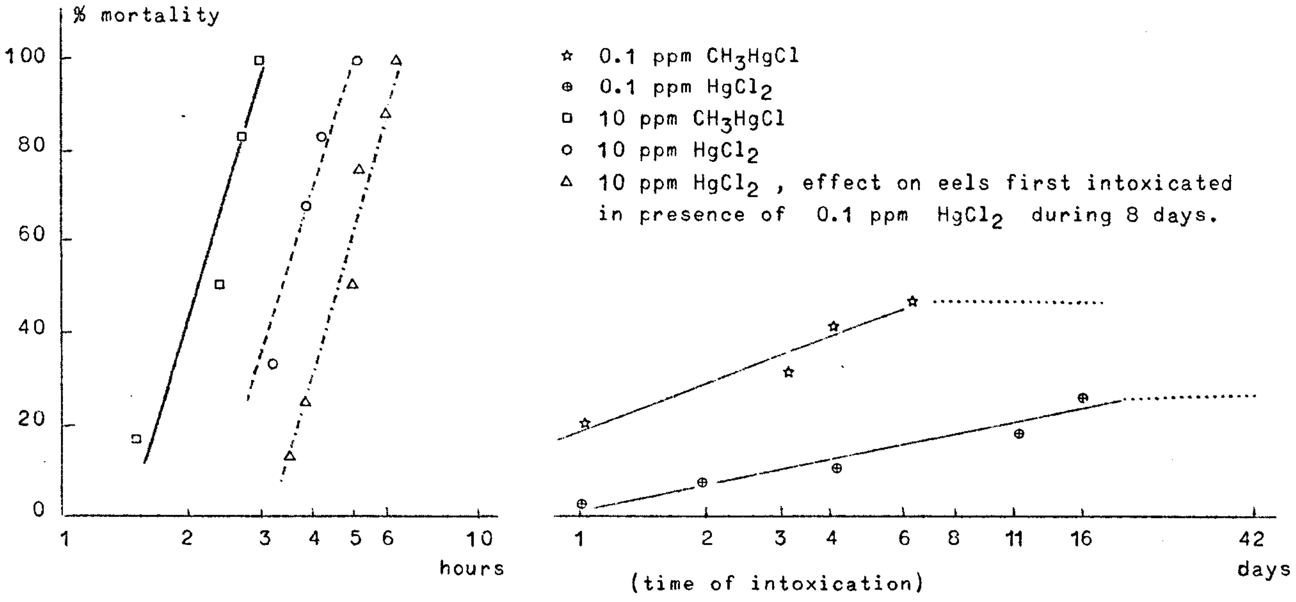

fig. 8.13.

Mortality of sea water adapted eels exposed to constant concentrations of $HgCl_2$ and CH_3HgCl in natural sea water.

The kinetics of accumulation of mercury and subsequent release in Hg free sea water has been followed in sublethal conditions at the 0.1 ppm level, either for $HgCl_2$ or CH_3HgCl . The concentration factors (ppm Hg in tissue/ppm in water) for the different organs at a given intoxication time (8 days) are listed below in the order of increasing importance :

$HgCl_2$	CH_3HgCl
Gas bladder and muscles	Gas bladder and muscles
Bile and digestive tract	Bile
	Digestive tract
Skin	
Brain	Brain
	Skin
Liver	Liver and kidney
Kidney	
Spleen	Spleen
Gills	Gills

Accumulation is faster in the gills during the first days, but after 12 days higher concentrations are found in the spleen and kidney in the case of HgCl· .

Figures 8.14 to 8.18 show the curves obtained respectively for muscle, gills, kidney, liver and brain for accumulation and subsequent release.

In blood, after 8 days intoxication in presence of 0.1 ppm , the mercury is distributed as indicated in Table 8.2 :

Table 8.2

	CH_3HgCl		$HgCl_2$	
	ppm Hg	µg Hg/g blood	ppm Hg	µg Hg/g blood
Blood	31.2	31.2	2.7	2.7
Plasma	2.7	1.8	2.1	1.2
Erythrocytes	90.3	29.4	3.5	1.5

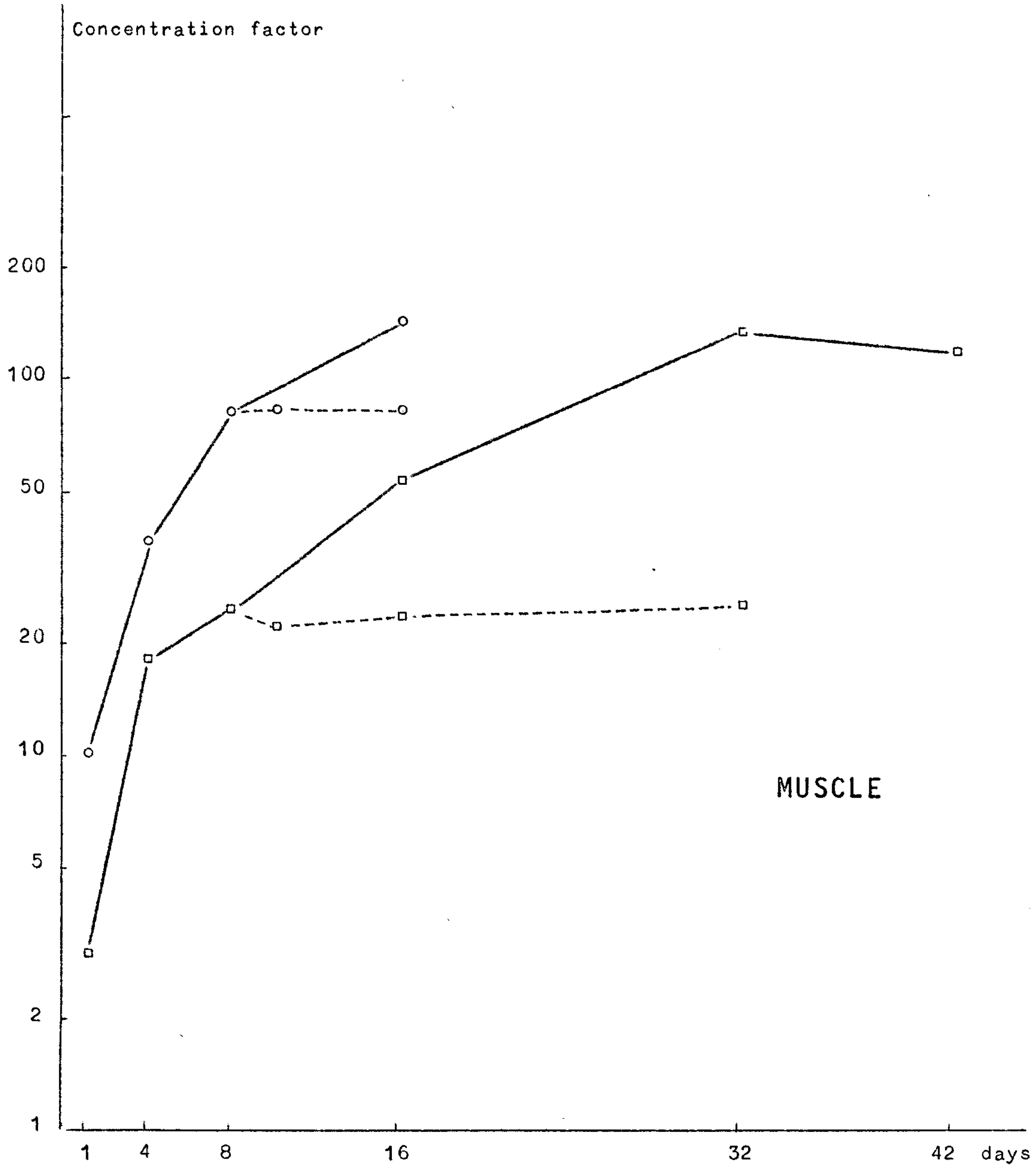

fig. 8.14.- Concentration factor in function of time ppm Hg in tissue / ppm Hg in water for mercury in eel muscles; the animals are exposed (heavy curve) to 0.1 ppm $HgCl_2$ (o) and 0.1 ppm CH_3HgCl (□) in natural sea water; dashed curves show release of Hg when the animals intoxicated during 8 days are exposed to mercury free sea water.

The difference between CH_3HgCl and $HgCl_2$ is striking : ten times more mercury is transported by blood in the case of CH_3HgCl poisoning, most of it attached to red cells. Precipitation of plasma

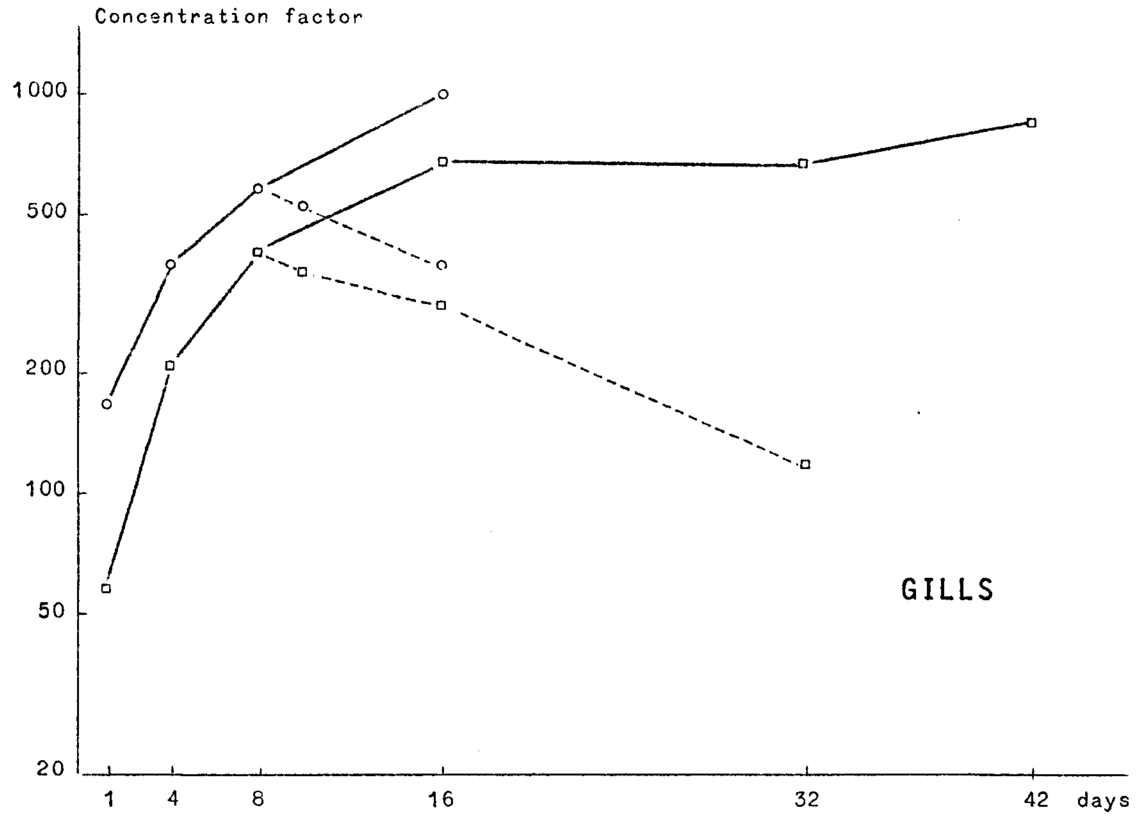

fig. 8.15.- Concentration factor for mercury in eel gills (see legend of fig. 8.14 for explanation).

proteins with trichloracetic acid shows that mercury from $HgCl_2$ stays practically attached to the precipitate and that mercury from CH_3HgCl remains almost completely in solution.

The differences observed between $HgCl_2$ and CH_3HgCl intoxication at the level of the organs and of blood suggest that, at least in first approximation, these toxic substances keep their initial chemical speciation and that probably very little undergoes metabolic changes (methylation of Hg^{++} for instance).

From the accumulation and release curves of the different organs and the weight fractions of these, total Hg-load of the animal can be calculated as a function of time. The result is given in figure 8.19. The calculations show that 87 % of the load is carried by muscle, skin and gills. It is also of interest to notice that the total load curves are mathematically much simpler than the curves for the individual organs.

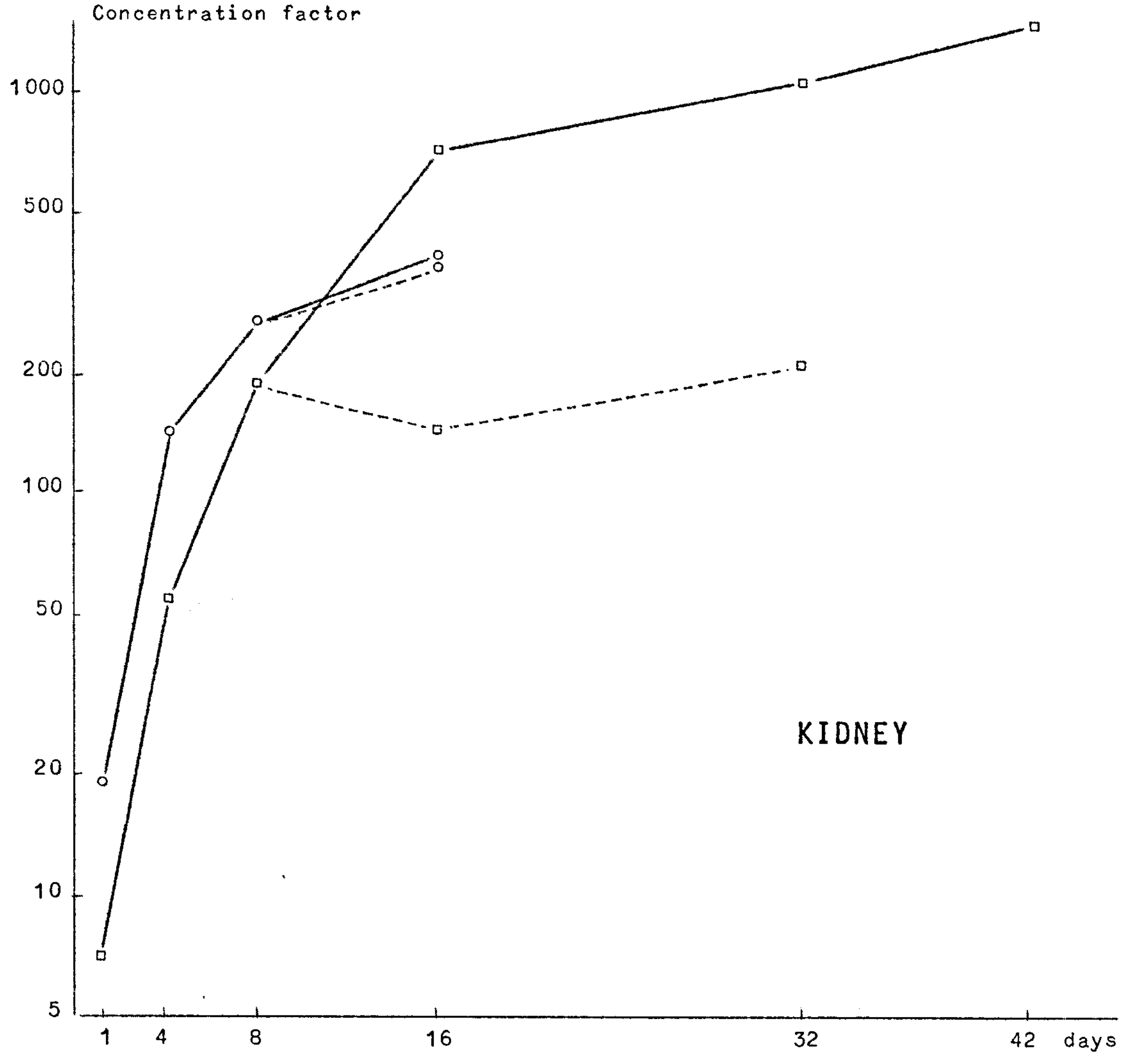

fig. 8.16.- Concentration factor for mercury in eel kidney (see legend of fig. 8.14 for explanation).

It is clear that global elimination is a slow process compared to accumulation. When one compares what happens at the level of the different organs differences do appear which allow to classify them in three categories :

1) Organs where Hg has a short half-life :

gills, skin (in the case of $HgCl_2$)
liver, air bladder (in the case of $HgCl_2$)
spleen, brain (in the case of $HgCl_2$)

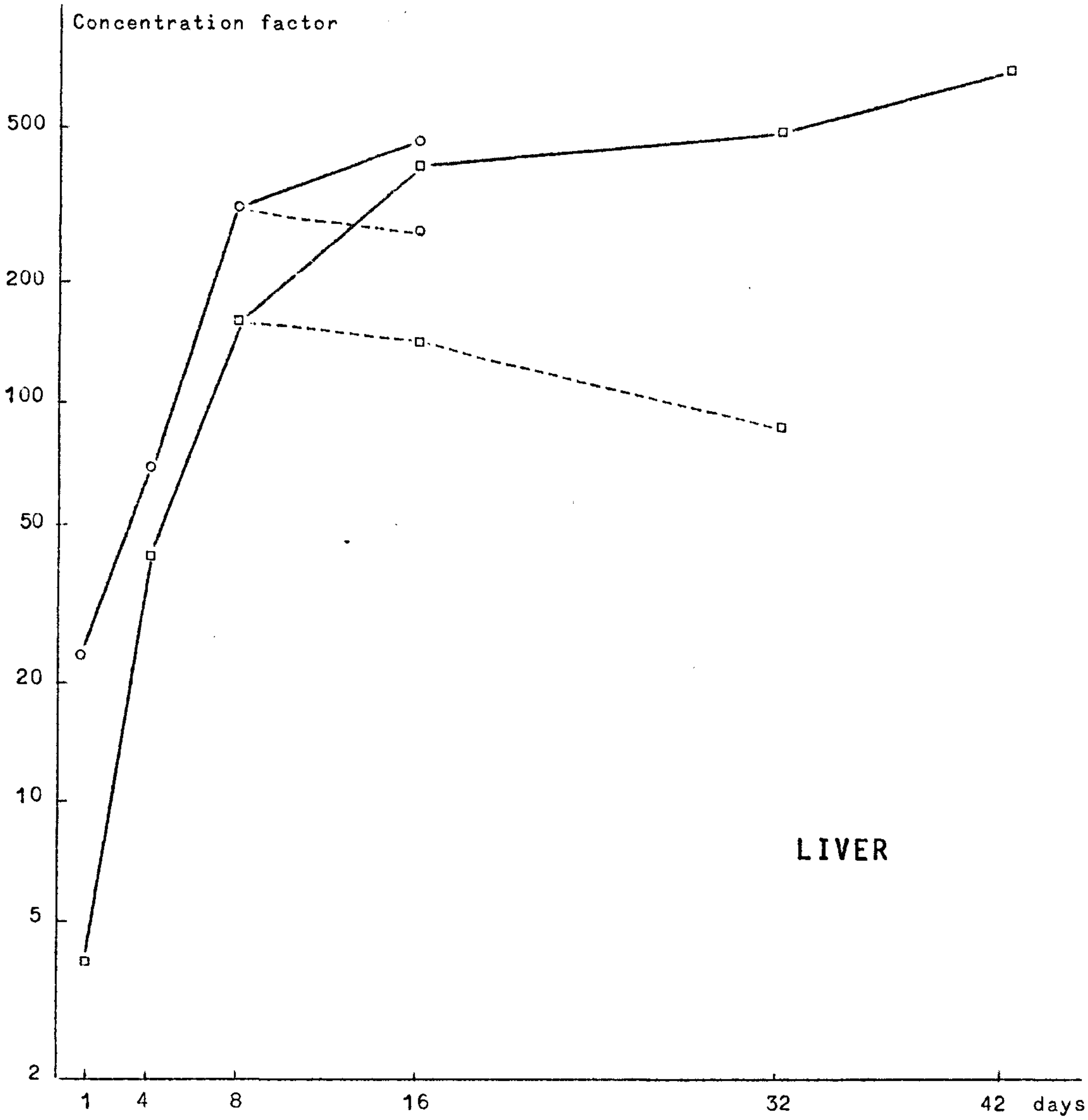

fig. 8.17.- Concentration factor for mercury in eel liver (see legend of fig. 8.14 for explanation).

2) Organs where Hg has a long half-life :

muscles
skin (in the case of CH_3HgCl)
air bladder (in the case of CH_3HgCl)

3) Organs where accumulation continues after return in the Hg-free sea water :

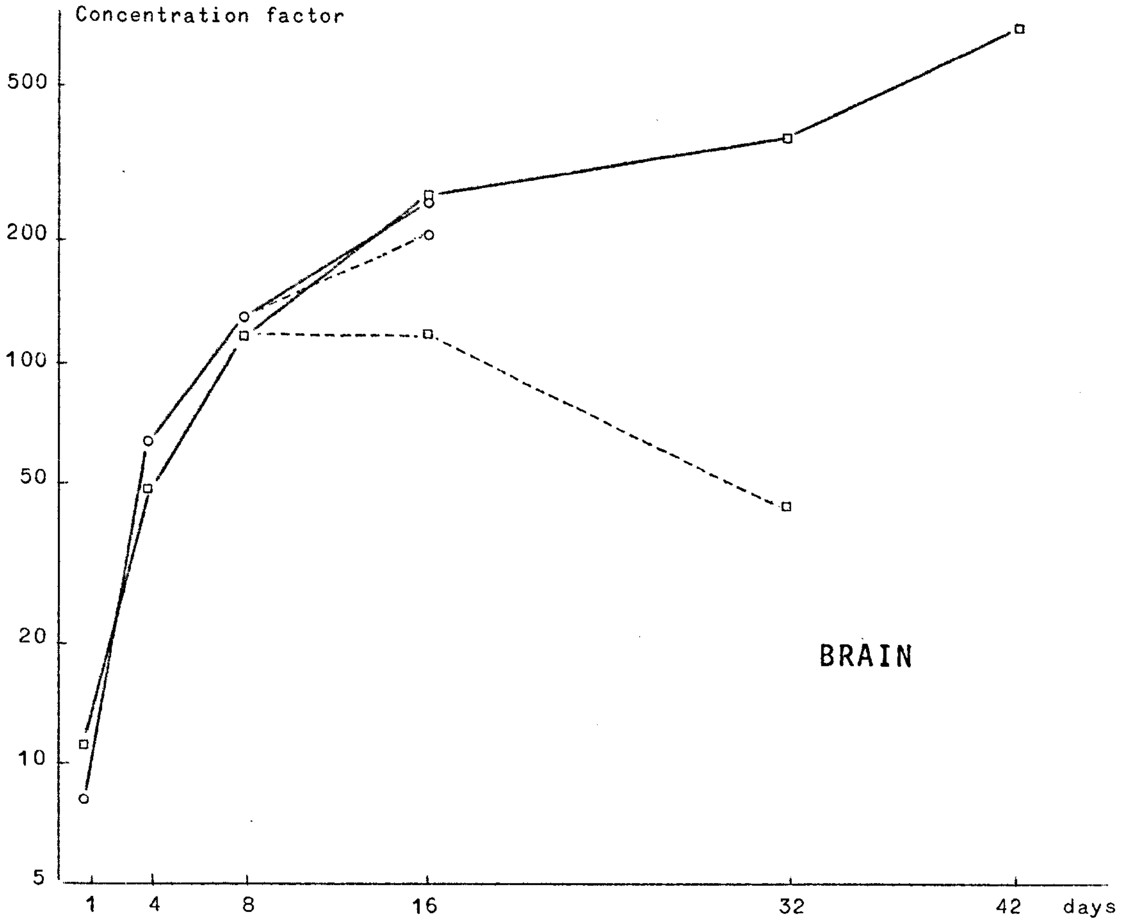

fig. 8.18.- Concentration factor for mercury in eel brain (see legend of fig. 8.14 for explanation).

digestive tract
kidney } involved in excretion
bile
brain (in the case of CH_3HgCl)

These observations fit with the results of Järvenpää, Tillander and Miettinen (1970) who injected $CH_3{}^{203}Hg^+$ in eels through the mouth and followed the elimination of the radio-isotope : 2 compartments were found one with a falf-life of 10 days , another with a half-life of 1000 days and involving 70 % of the total radioactivity. The first would correspond to the gills and liver the second to muscles according to Bouquegneau.

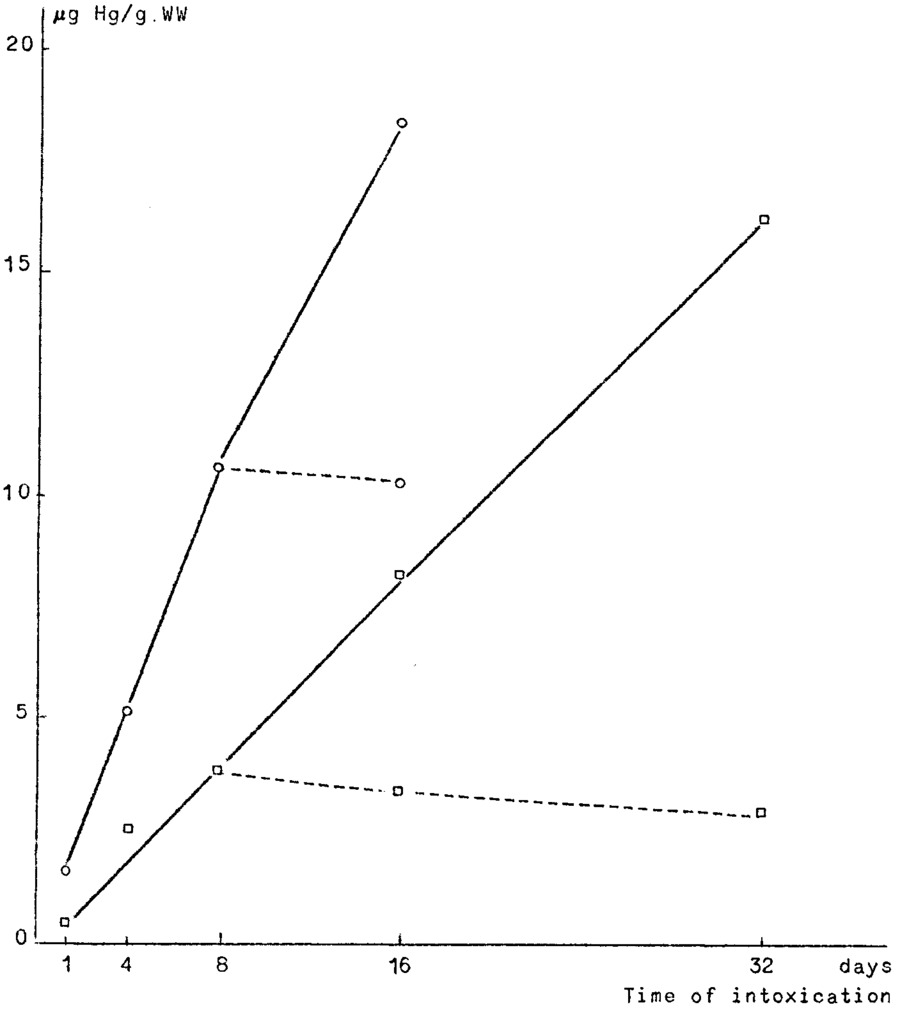

fig. 8.19.- Calculated total load of mercury (µg/g wet weight) in sea water adapted eels exposed to 0.1 ppm Hg (o $HgCl_2$, □ CH_3HgCl) as a function of time (heavy curve); dashed curve corresponds to the release of Hg when the animals intoxicated during 8 days are exposed to mercury-free water.

His findings are summarized in figure 8.20 representing a model of the different compartments and exchanges to be considered in eels intoxicated with $HgCl_2$ or CH_3HgCl at sublethal levels.

Methyl mercury is incorporated at twice the rate of $HgCl_2$. The mercury penetrates principally via the gills, but also through the skin and the digestive tract. In the case of CH_3HgCl blood red cells accumulate Hg to a great extent but free CH_3HgCl seems to be present in blood. In the case of $HgCl_2$ most of the Hg^{++} is attached to plasma proteins, and the total blood content is ten times less than in the case

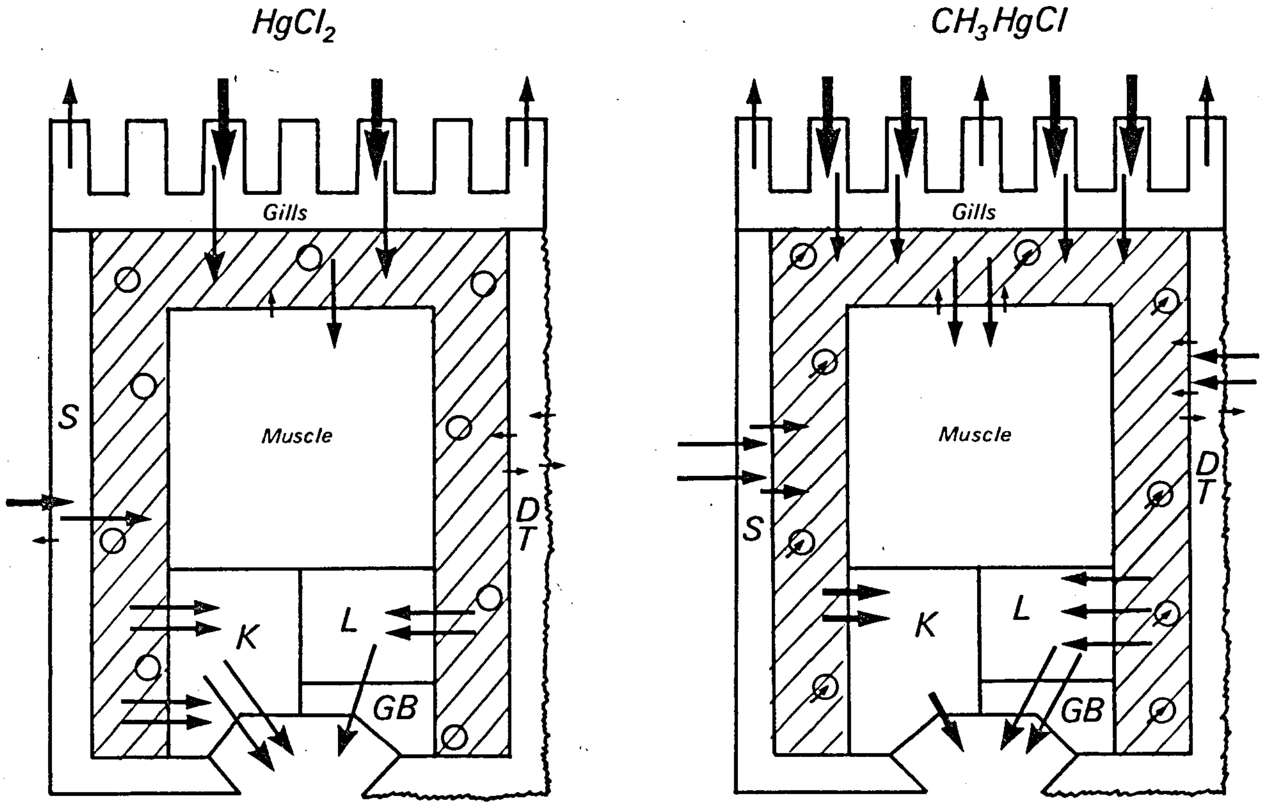

fig. 3.20.- Schematic representation of the various compartments corresponding to the organs of the eel and of the pathways leading to accumulation, release and excretion of mercury.
S = skin , K = kidney , L = liver , GB = gal bladder , DT = digestive tract , O = erythrocytes , /// = plasma ; number and size of arrows indicate approximated relative fluxes.

of CH_3HgCl . Hg is transported by blood to the different organs. Nearly 70 % of the total load is in the muscles and removal from this tissue is very slow. The kidney and the liver eliminate the mercury and the kidney is more efficient; skin and the digestive tract participate to a much lesser extent in this elimination. The continued accumulation observed in some tissues during leaching-out period in Hg-free water is obviously linked to redistribution among the various organs depending on their respective half-lives for Hg and the volume of blood circulation.

The results obtained by Bouquegneau indicate clearly that direct contamination by water containing Hg results in high accumulation levels in eels. This is in agreement with the observations of Hannerz (1968) who estimates that in pike poisoning from water is more effective than through food.

The fact that muscle releases Hg at a much slower rate, than liver and that liver accumulates faster than muscle, explains that the ratio Hg in muscle/Hg in liver will be small for fish living in highly polluted water [as observed by Cumont *et al.* (1972)] and will increase when the fish lives in less polluted regions; the value of the ratio is therefore linked to the history of the fish.

Another interesting practical conclusion is that a control of the Hg level in red blood cells might prove a useful test to distinguish between organic and inorganic mercury intoxication.

2.3.2.- Plaice, dab, cottus

Table 8.3 indicates how mercury ($HgCl_2$) is accumulated in the various organs of plaice, dab and cottus having lived 4 , 8 and 16 days in natural sea water containing 0.1 ppm $HgCl_2$. The fish received no food during the test. The results are very similar to those obtained for sea water adapted eels. The turnover however seems faster in some organs with low half-lives : after 16 days the Hg concentration in the muscle of cottus rises from 0.5 to 5 ppm for both fishes but the level in the gills are respectively ~ 40 and ~ 68 ppm in cottus and in eel.

It seems thus that the observations of Bouquegneau, made mainly on eels, are also valid for other marine teleosts, at least for the accumulation processes.

2.3.3.- Interpretation

According to Bouquegneau, Hg at lethal doses (10 ppm) inhibits the active transport of Na^+ in the gills at the level of the enzyme Na^+K^+ATPase , but interestingly enough seems to decouple the Na and K transport. No effect is observed on respiration, so that marine teleosts behave differently from fresh water species, where respiration [Lindahl and Hell (1970)] is affected.

Table 8.3

Accumulation of mercury in different organs of eels, plaices, dabs and Cottus living for 4 , 8 or 16 days in sea water containing 0.1 ppm Hg ($HgCl_2$).

	Fishes intoxicated by 0.1 ppm Hg in seawater for 4 days		
	Eel	Dab	Cottus
Gills	21.1	21.4	25.7
Kidney	5.4	38.6	13.3
Spleen	13.9	38.6	12.0
Skin	4.3	-	3.4
Muscle	1.8	2.1	2.5
Liver	4.1	11.6	7.9
Digestive tract	2.1	4.7	2.1

	Fishes intoxicated by 0.1 ppm Hg in seawater for 8 days		
	Eel	Plaice	Dab
Gills	40.4	35.0	40.1
Kidney	18.9	39.5	63.9
Spleen	27.1	22.2	47.7
Skin	6.7	3.2	-
Muscle	2.4	1.1	2.1
Liver	16.3	16.6	16.3
Digestive tract	3.4	4.8	11.1

	Fishes intoxicated by 0.1 ppm Hg in seawater		
	for 16 days		for 24 days
	Eel	Cottus	Cottus
Gills	67.8	42.6	52.0
Kidney	70.1	38.8	54.1
Spleen	87.5	20.3	23.8
Skin	13.0	8.6	15.1
Muscle	5.4	5.1	6.6
Liver	39.6	20.7	46.3
Digestive tract	8.9	2.3	5.3

Fig. 8.21 gives the composition of gills of eels intoxicated in presence of 10 ppm Hg , regarding H_2O , K^+ and Na^+ content, for $HgCl_2$ and CH_3HgCl respectively.

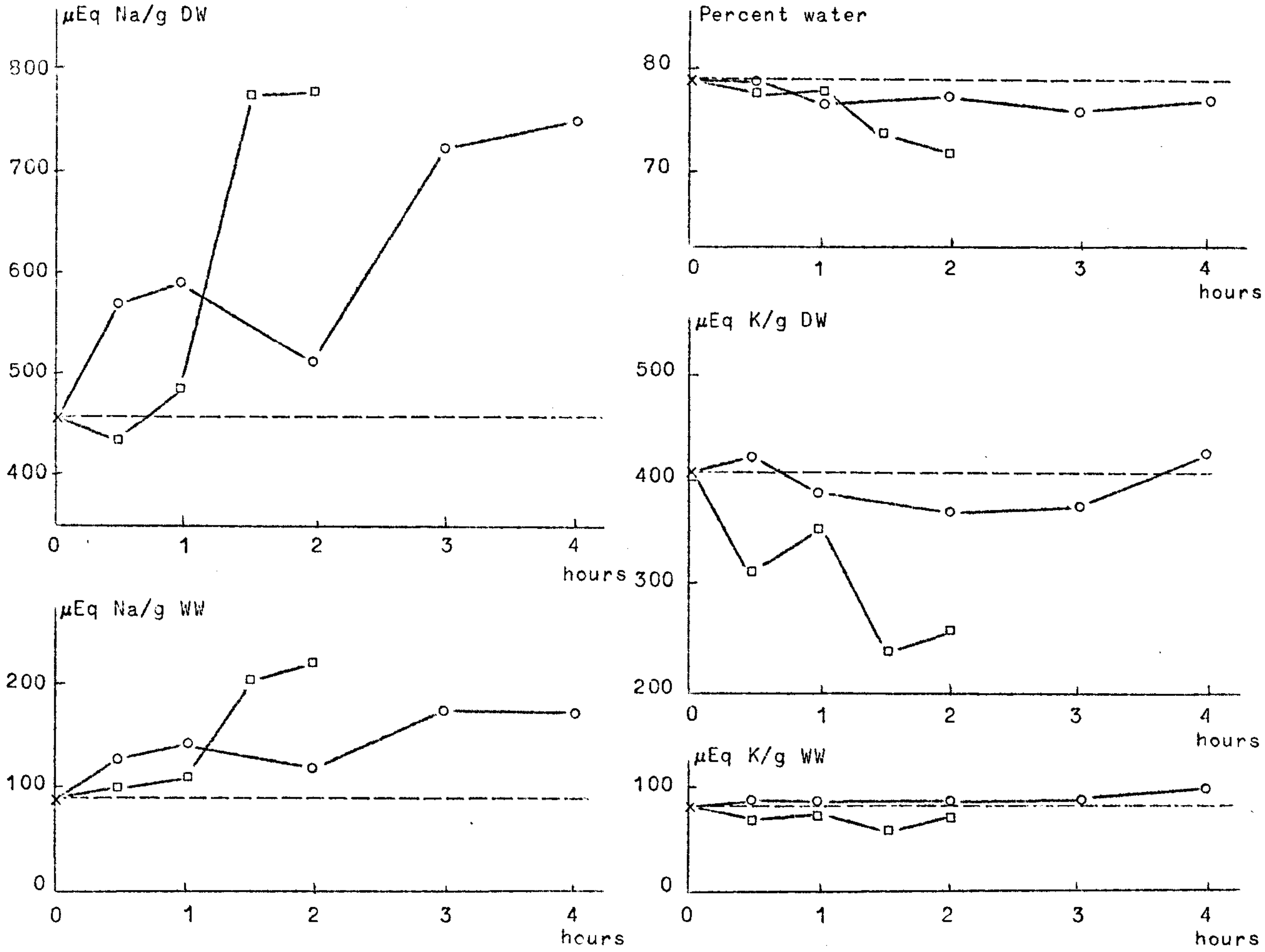

fig. 8.21.- Change in function of time of the concentration of Na^+ , K^+ and water in the gills of eels intoxicated in natural sea water in presence of 10 ppm Hg (o $HgCl_2$, □ CH_3HgCl); WW = wet weight; DW = dry weight.

In sea water containing $HgCl_2$ there is a slight loss of water, a large increase of Na^+ , the K^+ concentration remains constant, any change being explained by the water loss. When CH_3HgCl is used after 1 hour there is a slight loss of water and K^+ , an increase of Na^+ , but after 2 hours a large loss of water is observed, a fall of K^+ which is partly explained by the water movement, a further increase in Na^+ .

The osmotic balance is thus completely upset and similar results are obtained when isolated gills are exposed to mercury poisoning. This confirms the observations made by Bouquegneau on the plasma composition of intoxicated eels in 1972. The difference between CH_3HgCl and $HgCl_2$ lies in the sudden large loss of water which might reflect necrosis of the gill tissues as observed by Lindahl and Hell with phenylmercury.

There is so far no final explanation as to the mechanism which makes adaptations possible at sublethal doses, while accumulation proceeds in the gill itself. Bouquegneau suggests that the most likely system is the building up of high concentrations of SH-bearing substances in the gills, which would compete for the mercury otherwise attracted to the active sites of the ATPase. The gills would then be protected as the heart is protected by plasma proteins, as indicated by Marcq's results on the isolated eel atrium. One might also think of a higher turnover in the biosynthesis of the enzyme itself.

3.- General conclusions

It seems to the author of this report that the contribution of physiologists within the framework of the modelling of a sea region must be more and more directed towards the understanding of the kinetics of uptake and release of pollutants, either in the food chain or because of direct water contact.

The often encountered great resistance of many marine animals and even of their isolated tissues to heavy metals and pesticides explains their potential danger for human consumption, but makes work on bioassay methods unrealistic because of the high doses to be used to observe some effects. It seems too that water quality tests based on the sensitivity of some organism of even experimental food chains are in the realm of utopia, and that the efforts to the experimenters will be better repaid by turning their full attention to the dynamics of accumulation and release processes.

It might turn out from these laboratory observations that substances like Hg for example show such a high affinity for SH-groups that in oxic basins there is nowhere to go for these toxic substances than to stay in the food web. To try and find out the fate of such poisons, their rate of accumulation, their transit time in the food chain, their eventual removal in particular environmental conditions is of the greatest importance for the study of pollution and its possible regression.

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Chapter IX

Study of the pollution in sea fish and shell fish

by

P. HERMAN and N. BOUQUIAUX

I. Mercury content in fish and shrimps caught off the Belgian coast

Introduction

In recent years, the concentration of heavy metals, pesticides and other pollutants in fish has become a cause for concern and has received increased interest. Mercury especially is regarded as a problem since the outbreak of mercury poisonings in Japan was found to originate from the consumption of heavily contaminated fish. Comprehensive reviews on the problems related to mercury in fish were published by Meyer (1972) and Holden (1973).

As in several other countries, a large-scale survey of the levels of contaminants in fish was started in Belgium. This report is the result of a study of mercury concentration in representative fish species, *viz.* plaice *(Pleuronectes platessa LJ*, whiting *(Merlangus merlangus L.)*, cod *(Gadus morhua L.)*, sprat *(Clupea sprattus L.)* and shrimps *(Crangon crangon L.)* caught off the Belgian coast.

This area was surveyed specifically because of the increased risks of pollution in coastal waters. In this connection, the vicinity of the Scheldt estuary should be stressed. Furthermore, Belgian coastal waters are known to be a nursery ground for several important fish species and shrimps. For that reason, special attention was also paid to the pre-recruitment stock (0 , I and for some fish species the II-age groups). Emphasis was laid on the possible relationship between mercury levels and different biological parameters (age, sex, length, weight) of fish. For shrimps, which are sedentary organisms, the fishing ground and the season were taken into account.

1.- Methods and materials

1.1.- Sampling

Experimental fisheries were carried out during a one year's period (October 1971 — October 1972) by the R.V. *Hinders* in an area up to 10 miles off the Belgian coast. Fishing took place during day time with the otter trawl (mesh size 18 mm). Hauling time was 15 min .

Two areas were sampled on a monthly basis, *viz.* five Western stations in the *Westdiep* ground off Nieuport and five Eastern stations in the *Vlakte van de Raan* ground off Zeebruges. Furthermore, an overall survey of 30 stations scattered over the whole area was undertaken in October 1971, May and October 1972. In total, 800 samples were taken.

The whole catch of plaice, whiting and cod was examined and classified in age-groups. The average composition per hour fishing of the catches was :

- plaice : 0-I : 55 % ; II : 16 % ; III + : 29 % ;
- whiting : 0-I : 93 % ; II + : 7 % ;
- cod : 0-I : 67 % ; II + : 33 % .

The samples of these three fish species were analyzed individually and the following parameters were determined :

- length (in cm),
- weight (in g),
- age (otolith readings),
- sex (gonads and testes).

The samples of sprat consisted of 1 to 10 specimens, depending upon their availability.

For shrimps a sample of 250 g was taken. For practical reasons, the shells were not removed.

1.2.- Mercury analysis

Digestion method with H_2SO_4/H_2O_2 ; reduction of Hg with $NaBH_4$. Determination with A.A. (M.A.S. 50) .

1.3.- Statistical analyses

Regression analyses and analyses of variance were carried out as outlined by Snedecor and Cochran (1971).

2.- Results and discussion

The results of the mercury analyses are reported in Table 9.1.

The age-groups of plaice, whiting and cod were considered separately. An estimate of the average mercury content on an individual animal basis of the three populations was also made by taking into account the average composition of the experimental catches in the period under survey.

The population standard deviation was estimated by pooling the age-group variances.

An analysis of variance was carried out to test the differences between males and females per age group but showed no significant differences at the 95 % probability level.

The mercury concentrations tended to increase with the age of the fish.

The increase in mercury levels with age was also reported by several other workers [Johnels *et al.* (1967), Bligh and Armstrong (1971), Thibaud (1971), Forrester *et al.* (1972)].

The nature of this relationship was studied further by calculating the regression between mercury content and length of the fish :

- Whiting, male :

$$y = 8.8 \times 10^{-3} x - 23 \times 10^{-3} \qquad r = 0.566$$

Table 9.1

Mercury analyses of fish and shrimp caught off the Belgian Coast

Species	Age-groups	Number	Hg (ppm)		
			Average	s	v (%)
Plaice	0 - I	66	0.172	0.093	54
	II	91	0.171	0.068	40
	III	73	0.153	0.067	44
	IV	26	0.174	0.070	40
	V-IX	11	0.216	0.094	44
	Total *	-	0.168	0.077	46
Whiting	0 - I	97	0.151	0.059	39
	II	112	0.173	0.087	50
	III	26	0.202	0.090	45
	IV-V	4	0.245	0.072	29
	Total *	-	0.153	0.079	52
Cod	0 - I	37	0.106	0.051	48
	II	37	0.137	0.046	34
	III	5	0.180	0.085	47
	Total *	-	0.116	0.055	47
Sprat	Total	66	0.144	0.064	44
Shrimp	Total	148	0.101	0.039	39

* On an individual animal basis, taking into account the average composition of the catch.

- Whiting, female :

$$y = 7.3 \times 10^{-3} x + 26 \times 10^{-3} \qquad r = 0.383$$

- Whiting, male and female :

$$y = 7.0 \times 10^{-3} x + 19 \times 10^{-3} \qquad r = 0.410$$

- Cod, male :

$$y = 4.1 \times 10^{-3} x - 24 \times 10^{-3} \qquad r = 0.616$$

- Cod, female :

— r = 0.098

- Cod, male and female :

$$y = 2.4 \times 10^{-3}\ x + 33 \times 10^{-3} \qquad r = 0.378 .$$

For the sake of completeness, the equations expressing the relation mercury content to weight are :

- Whiting, male :

$$y = 31.4 \times 10^{-3}\ x^{0.4}$$

- Whiting, female :

$$y = 33.2 \times 10^{-3}\ x^{0.3}$$

- Whiting, male and female :

$$y = 49.6 \times 10^{-3}\ x^{0.3}$$

- Cod, male :

$$y = 18.8 \times 10^{-3}\ x^{0.3}$$

- Cod, male and female :

$$y = 34{,}4 \times 10^{-3}\ x^{0.2}$$

where r is the correlation coefficient, the significance is 99.9 % . As the relation between weight and length is curvilinear, these equations were of the type $y = ax^b$ where y is the mercury content in ppm and x the body weight in g . For plaice, no significant regressions were found. The regressions for whiting and cod are shown graphically in figures 9.1 to 9.4.

Male and female whiting and male cod showed rather low but very significant (99.9 % probability) regressions. The relationship mercury content to length (or weight) however appeared to be not significant in female cod, indicating different behaviour towards mercury accumulation.

In order to have a better knowledge of the variations in mercury levels, frequency distributions were also calculated. Figures 9.5, 9.6 and 9.7 show the histograms per age-group. The highest age-group of the three species was not taken into consideration owing to the low number of specimens available. The overall frequency distribution of the whole population was also determined by taking the composition of the catches into account.

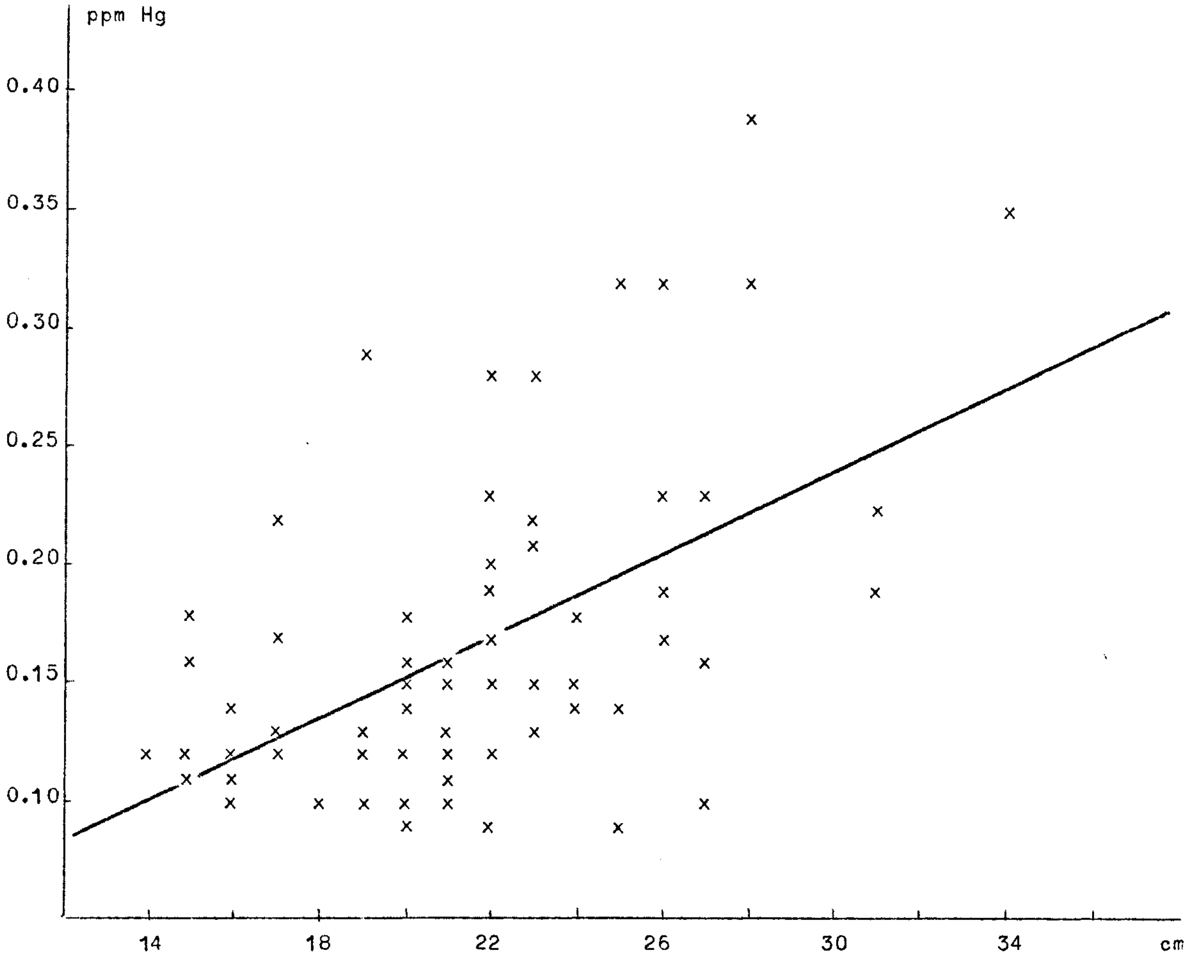

fig. 9.1.- Regression between mercury content and length of male whiting.

The histograms show the Hg concentrations to be fairly well distributed. It should be noted in this respect that the standard deviations of the different groups were very similar (Table 9.1).

The greater portion of values were situated below 0.250 ppm , and were probably within the natural range for the species considered [Holden (1973)]. The highest frequencies occurred between 0.100 and 0.250 ppm .

These data are in general agreement with results obtained in other countries for coastal areas (less than 25 miles from the coast). For plaice, Portmann (1972) reported an average of 0.25 ppm (n = 51) in British coastal waters, Koeman *et al.* (1971) 0.21 ppm (n = 8) in the Dutch Wadden Sea and Antonacopoulos (1973) 0,25 ppm in the Elbe estuary. Greve and Wit (1971) on the other hand mentioned five analyses

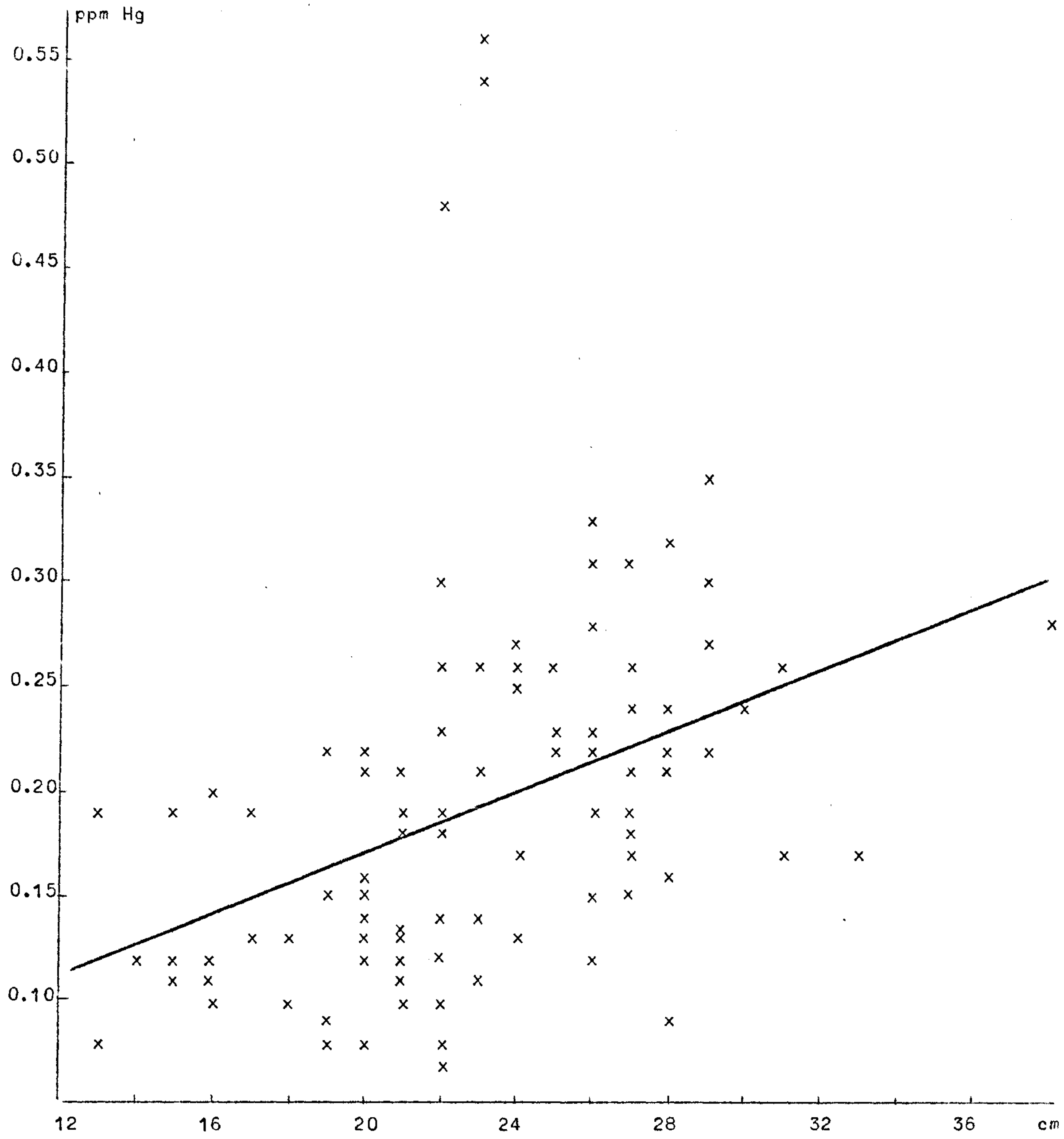

fig. 9.2.- Regression between mercury content and length of female whiting.

of plaice caught off the Southern Dutch coast with a markedly lower range of 0.05 to 0.14 ppm .

For cod, Portmann (1972) found an average value of 0.26 ppm (n = 37) in British coastal waters, Greve and Wit (1971) 0.18 ppm (n = 5) off the Southern Dutch coast and Bligh and Armstrong (1971)

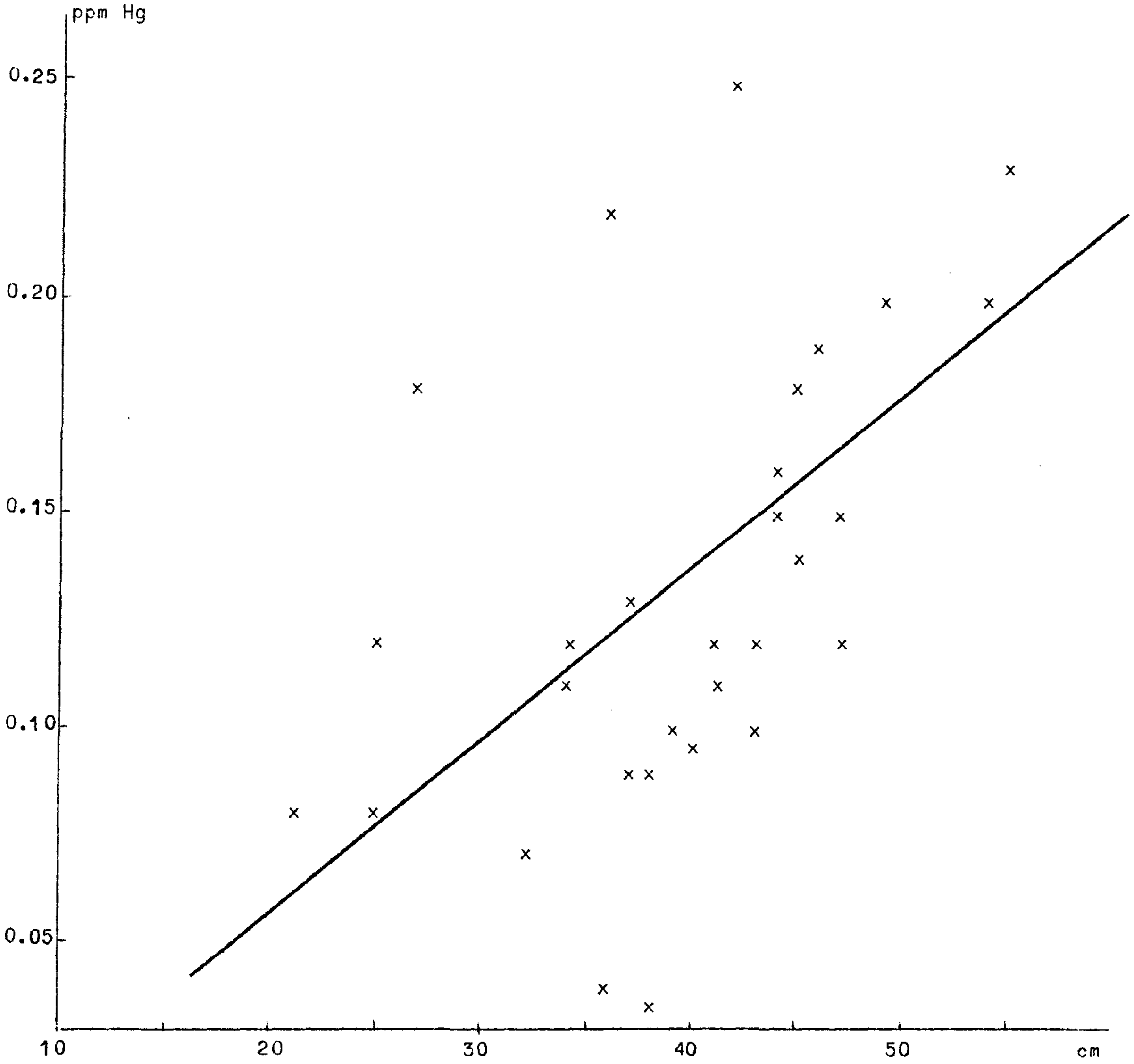

fig. 9.3.- Regression between mercury content and length of male cod.

0.02 to 0.23 with an average of 0.12 ppm (n = 163) off the Canadian Atlantic coast.

For shrimps, an average value of 0.12 ppm (n = 50) was reported in the Wadden Sea [Koeman *et al.* (1971)] whilst a range of 0.15 to 0.21 ppm was found in British coastal waters [Ministry of Agriculture, Fisheries and Food (1971)].

It should be noted that all analyses on shrimps in this work were for practical reasons carried out on whole crustaceans. However, a specific investigation was conducted on the mercury distribution in the

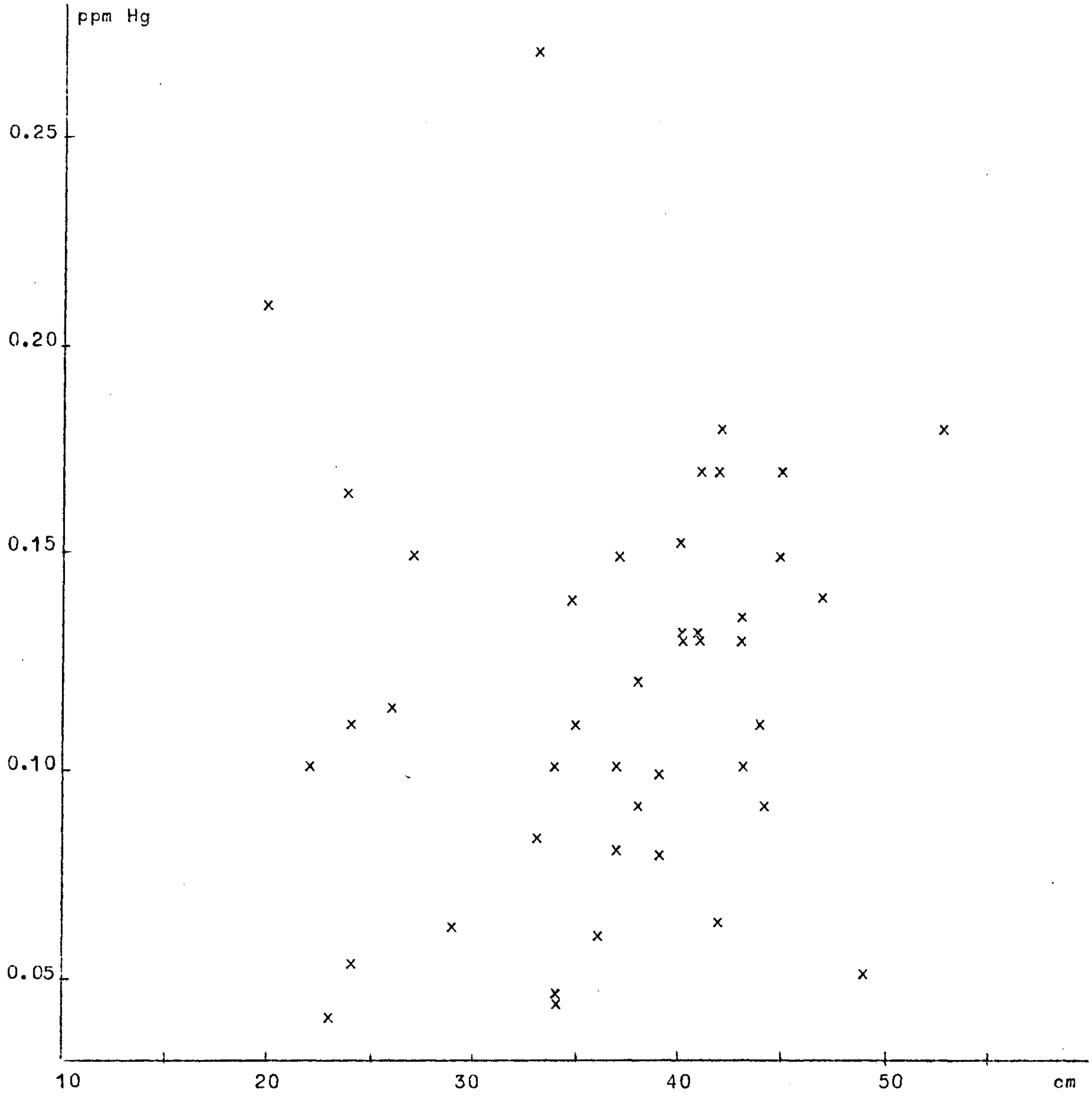

fig. 9.4.- Relationship between mercury content and length of female cod.

body of the shrimps. The results showed a distribution of 56 % in the flesh, 32 % in the cephalothorax, 12 % in the shell and 0 % in the telson. Hence, taking into account an average percentage of 30 % shrimp flesh, a mean content of 0.186 ppm (standard deviation 0.072) was present in the shrimp muscle.

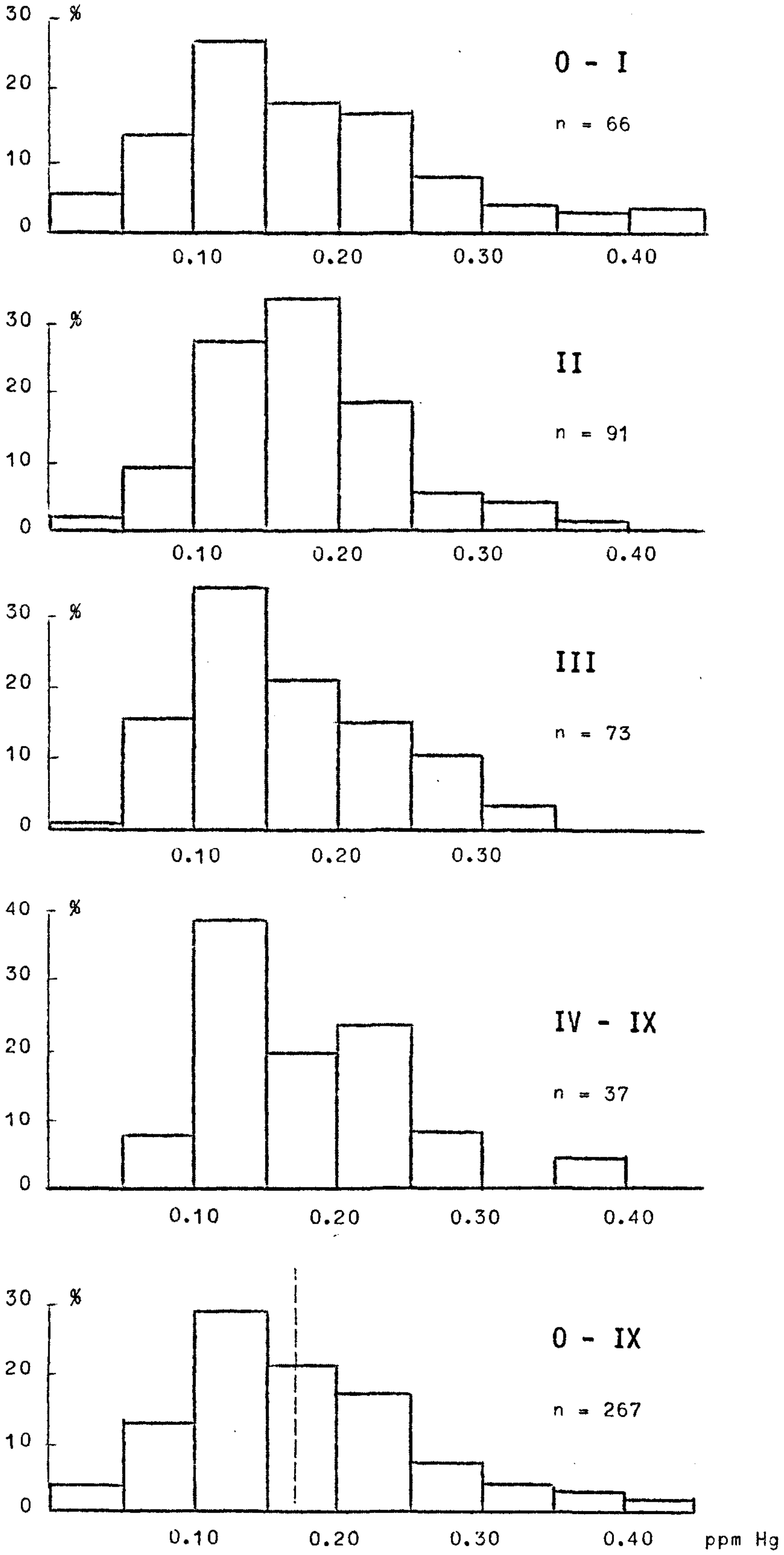

fig. 9.5.- Histogram per age-group of plaice.

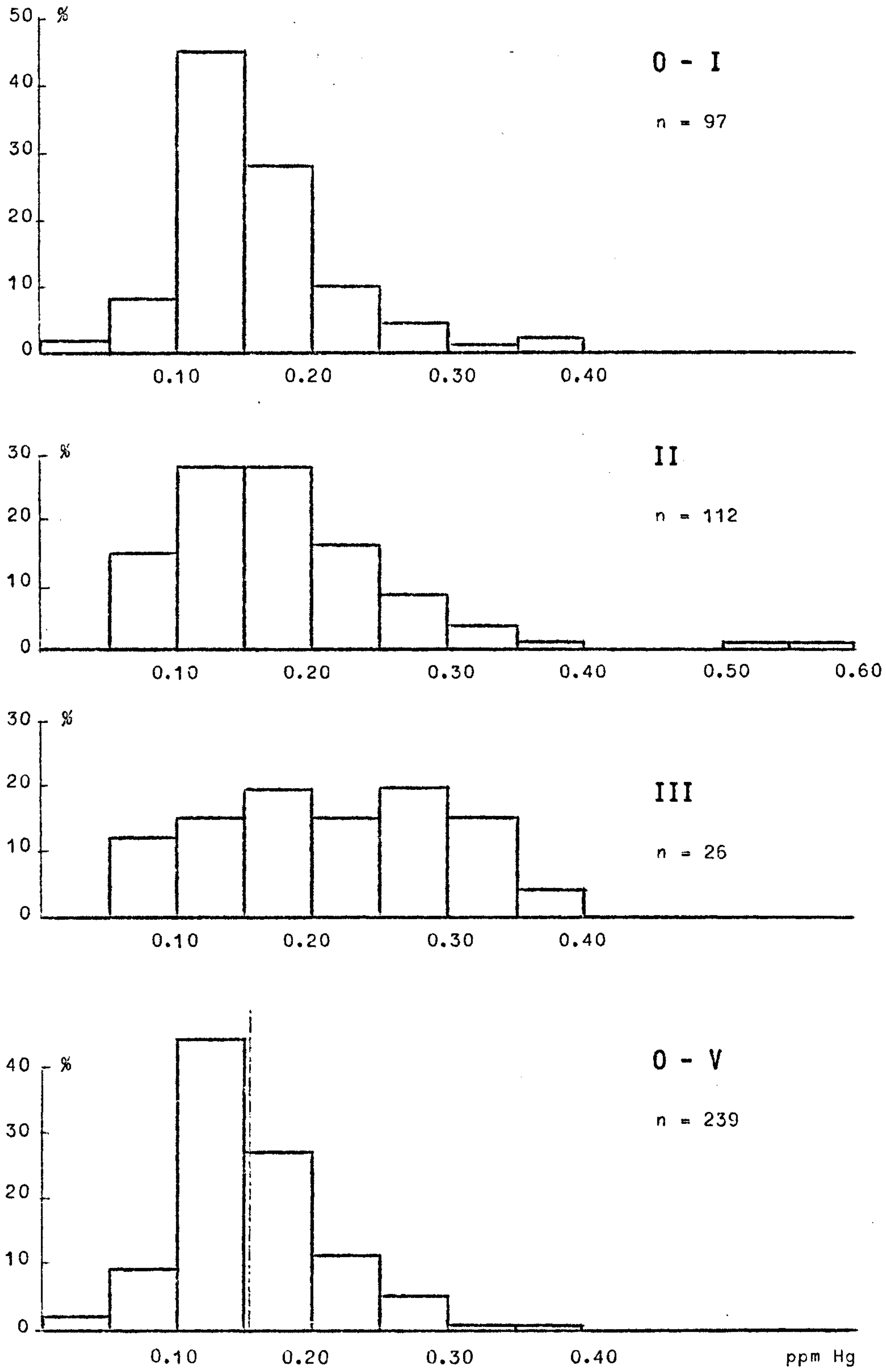

fig. 9.6.- Histogram per age-group of whiting.

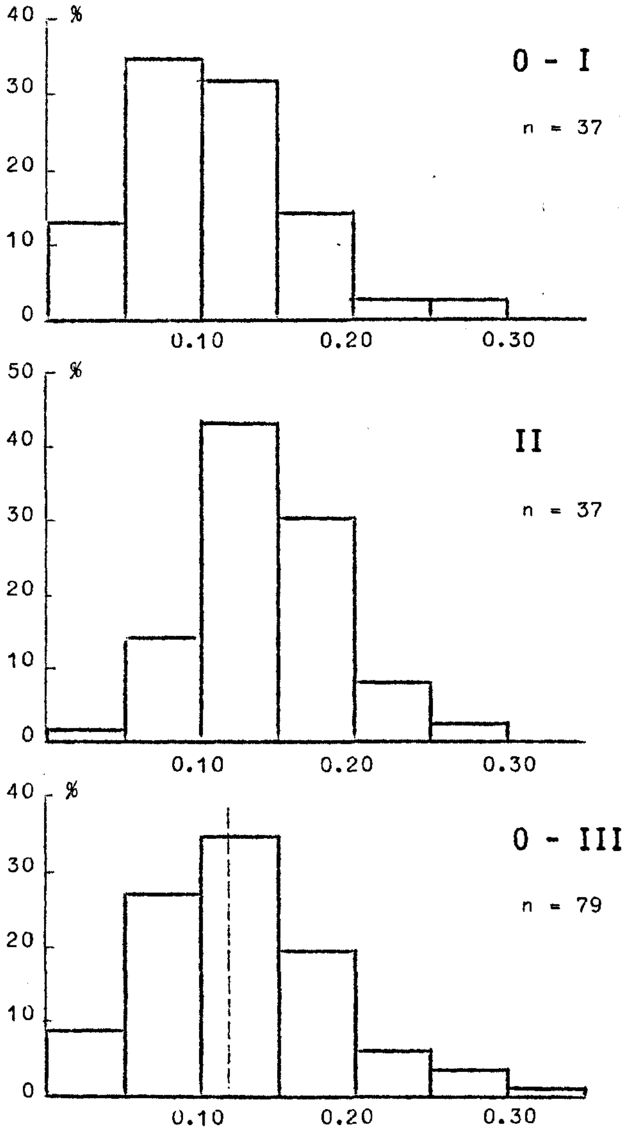

fig. 9.7.- Histogram per age-group of cod.

Shrimps being sedentary animals, migrating over distances not exceeding 10 to 15 miles [Tiews (1963)], the possible influence of the area (West and East coast) (Table 9.2), and the season was evaluated statistically.

Neither the t-test carried out on the mercury contents of the West and East coast nor the regression analysis between mercury and time of catching appeared to be significant, stressing again the fairly uniform distribution of mercury levels over the whole area.

Table 9.2

Mercury content (ppm) of shrimps from the East and West coast

Area	Number	Average	s	v (%)
Eastern	65	0.099	0.040	40
Western	83	0.103	0.039	38

The mercury concentration in sea water off the Belgian coast averages 0.15 ppb [C.I.P.S. (1972)] which seems to be normal for surface waters [Sillen (1963), Beasley (1971)]. Sediments on the other hand contained about twice as much mercury as in more distant waters (0.27 versus 0.15 ppm) [C.I.P.S. (1972)]. Hence, it is not surprising that mercury concentrations in Belgian inshore fish appeared to be higher than in fish caught in distant waters where reported levels are almost exclusively below 0.100 ppm [Westöö (1967), Bligh and Armstrong (1971), Thibaud (1971), Antonacopoulos (1973), Portmann (1972), Icelandic Fisheries Laboratories (1973)].

On the other hand, the reported values contrast with the high concentrations recorded in heavily contaminated fishing grounds. Ackefors (1968) reported values up to 3.1 ppm for plaice and 2.7 ppm in cod caught in the Oresund. Also in cod, Boëtius (1971) found an average of 0.667 ppm (n = 15) with maximum concentrations of 1.29 ppm in the Sund (Denmark). In a survey covering 13 Norwegian fjords, Berge and Palmork (1971) recorded maximum levels of 4.70 (n = 215) and 1.88 ppm (n = 18) in cod and whiting respectively.

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II. Mercury and other pollutants
in sea fish and shell fish of Belgian fishing

1.- Mercury and other metallic pollutants

1.1.- Generalities

This study refers to fish caught off the Belgian coast as well as in other areas.

The results are given in function of some parameters (age, geographical localization of the fishing, season) and relate to specimens caught from autumn 1971 till the end of autumn 1972.

The fish studied in I.R.C. were all caught or brought by the Fisheries Research Station of Ostend which carries out the biometric measurements.

The purchases done in the "fish auction" relate to fish caught by Belgian fishers in the North Sea, the Irish Sea, the English Channel and the Bristol Channel.

The fish caught off the Belgian coast by the Fisheries Research Station of Ostend originate from areas for which the coordinates have already been given before.

The determination of total Hg was made on all the specimens; the determinations of Cu , Zn and Pb commenced in April 1972 in function of the development of our determination technics.

The total results are given in Tables 9.3 to 9.7 hereafter.

The determination of cadmium in the same specimens is in progress.

1.2.- Seasonal variation of the average amounts of Hg

According to the results obtained for different fishing periods, we observe an increase of the Hg amount in the fish we have examined

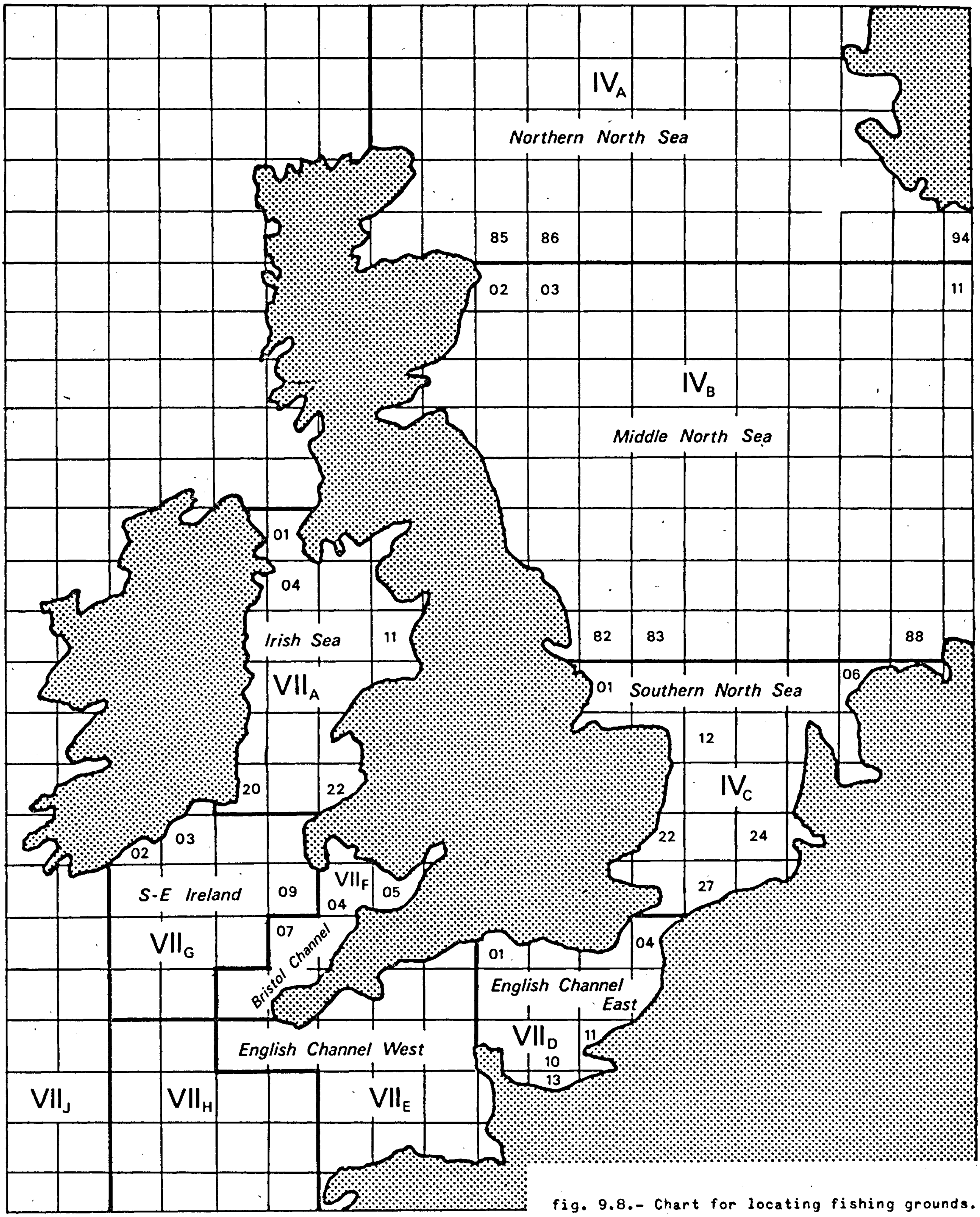


fig. 9.8.- Chart for locating fishing grounds.

Table 9.3

Mercury in ppm - Collection 1972

Species	Area	Square n°	Year class.	N	X_{max}	X_{min}	$\bar{X}$	σ
Plaice	IV_C	27	1967	5	0.36	0.18	0.24	0.09
	IV_C	27	1968	23	0.39	0.06	0.17	0.08
	IV_C	27	1969	76	0.32	0.04	0.16	0.06
	IV_C	27	1970	60	0.39	0.04	0.13	0.08
	IV_C	27	1971	37	0.39	0.03	0.22	0.09
	IV_C	12	1968	5	0.37	0.13	0.26	0.10
	IV_C	17						
	VII_G	09	1966	7	0.37	0.08	0.17	0.1
	VII_F	04						
	VII_F	07						
	VII_G	09	1968	8	0.42	0.13	0.23	0.09
	VII_F	04						
	VII_F	04	1969	6	0.34	0.06	0.19	0.11
	VII_A	11	1964	6	0.84	0.09	0.39	0.30
	VII_A	10	1965	4	0.60	0.19	0.38	0.17
	VII_A	11						
	VII_A	11	1966	5	0.46	0.10	0.34	0.15
	VII_A	11	1967	7	0.71	0.10	0.34	0.19
	VII_A	11	1968	7	0.37	0.13	0.27	0.09
	VII_A	11	1969	5	0.46	0.07	0.33	0.15
Whiting	IV_C	27	1969	18	0.37	0.08	0.29	0.08
	IV_C	27	1970	93	0.56	0.07	0.19	0.09
	IV_C	27	1971	40	0.36	0.11	0.17	0.06
Sprats	IV_C	27	-	47	0.29	0.04	0.15	0.06
Sole	IV_C	02	1968 to 1971	13	0.48	0.036	0.21	0.12
	IV_C	26						
	IV_C	27						
	VII_F	04	1963 1966 1969	10	0.38	0.04	0.16	0.10
	VII_F	09						
Cod	IV_C	27	1969	4	0.20	0.03	0.15	0.06
	IV_C	27	1970	52	0.27	0.04	0.13	0.05
	IV_C	27	1971	8	0.21	0.04	0.11	0.02
Shrimps	IV_C	27	?	99	0.25	0.04	0.11	0.04

from the first sending of autumn 1971 till the summer 1972, for almost all fishing places. It appears that the average amount of Hg in the fish caught in the summer of 1972 is distinctly highest and consequently

Table 9.4

Copper in ppm - Collection 1972

Species	Area	Square n°	Year class.	N	X_{max}	X_{min}	$\bar{X}$	σ
Plaice	IV_C	27	1967	5	1.33	0.56	0.74	0.33
	IV_C	27	1968	14	1.30	0.51	0.74	0.25
	IV_C	27	1969	51	1.67	0.26	0.63	0.24
	IV_C	27	1970	39	1.63	0.42	0.66	0.29
	IV_C	27	1971	12	1.20	0.41	0.77	0.32
	IV_C	12	1968	5	0.81	0.34	0.55	0.20
	IV_C	17						
	VII_G	09	1966	5	0.77	0.35	0.58	0.16
	VII_F	04						
	VII_F	07						
	VII_G	09	1968	7	1.66	0.45	0.91	0.47
	VII_F	04						
	VII_F	04	1969	6	0.88	0.26	0.62	0.25
	VII_A	11	1964	6	0.83	0.31	0.58	0.20
	VII_A	10	1965	4	0.92	0.32	0.61	0.32
	VII_A	11						
	VII_A	11	1966	5	0.82	0.39	0.50	0.18
	VII_A	11	1967	7	1.17	0.25	0.57	0.31
	VII_A	11	1968	7	0.75	0.31	0.48	0.15
	VII_A	11	1969	5	1.10	0.39	0.76	0.27
Whiting	IV_C	27	1969	16	1.39	0.44	0.88	0.28
	IV_C	27	1970	78	1.84	0.34	0.98	0.38
	IV_C	27	1971	26	3.36	0.27	1.26	0.90
Sprats	IV_C	27	-	47	2.41	0.74	1.31	0.43
Sole	IV_C	02	1968 to 1971	8	1.36	0.53	0.74	0.31
	IV_C	26						
	IV_C	27						
	VII_F	04	1963 1966 1969	10	0.86	0.31	0.47	0.19
	VII_F	09						
Cod	IV_C	27	1970	35	1.24	0.30	0.67	0.29
Shrimps	IV_C	27	?	89	22	6.6	12.8	3.2

positively affects the total year average for each considered species (except shrimps).

In table 9.8 we noted the average amount in Hg for a number n of fish caught off the Belgian coast, relative to each of the fishing seasons.

Table 9.5

Zinc in ppm - Collection 1972

Species	Area	Square n°	Year class.	N	X_{max}	X_{min}	$\bar{X}$	σ
Plaice	VII_G VII_F VII_F	09 04 07	1966	4	5.97	3.70	4.69	0.94
	VII_F	07	1968 1969	4	4.79	3.00	3.97	0.82
	VII_A VII_A	10 11	1964 1965	5	6.46	3.66	5.44	1.12
	VII_A	11	1967	5	5.94	3.83	5.10	0.85
	VII_A	11	1968 1969	6	5.49	2.52	4.47	1.10
Whiting	IV_C	27	1969 to 1971	16	8.2	4.9	5.9	1.1
Sprats	IV_C	27	-	23	29.3	16.7	23.8	3
Cod	IV_C	27	1970	14	5.07	3.26	4.16	0.51
Shrimps	IV_C	27	?	24	44.44	17.23	26.1	7.28

Table 9.6

Lead in ppm - Collection 1972

Species	Area	Square n°	Year class.	N	X_{max}	X_{min}	$\bar{X}$	σ
Plaice	VII_G VII_F VII_F	09 04 07	1966	4	0.22	0.15	0.20	0.03
	VII_F	07	1968 1969	4	0.20	0.11	0.15	0.04
	VII_A VII_A	10 11	1964 1965	5	2.81	0.13	0.68	1.18
	VII_A	11	1967	5	1.69	0.18	0.65	0.67
	VII_A	11	1968 1969	6	0.80	0.17	0.29	0.25
Whiting	IV_C	27	1969 to 1971	16	4	0.2	0.83	1.06
Sprats	IV_C	27	-	23	5.3	0.1	1.98	1.5
Cod	IV_C	27	1970	14	0.83	0.21	0.30	0.16
Shrimps	IV_C	27	?	22	16.8	0.40	4.32	4.4

Table 9.7

Mercury, Copper, Zinc, Lead in ppm
Fishing period : January-May 1972

Species	Area	N	Hg			Cu		
			$\bar{X}$	X_{max}	X_{min}	$\bar{X}$	X_{max}	X_{min}
Plaice	Belgian Coast	57	0.14	0.36	0.04	0.67	1.33	0.32
	Middle North Sea	10	0.15	0.43	0.05	0.55	0.83	0.31
	Southern North Sea	8	0.17	0.50	0.05	0.6	0.95	0.40
	Eng. Channel	9	0.17	0.32	0.10	0.54	0.91	0.26
	Bristol Channel	12	0.16	0.34	0.06	0.73	1.80	0.26
	Irish Sea	19	0.27	0.84	0.07	0.66	1.17	0.25
Whiting	Belgian Coast	25	0.17	0.33	0.04	0.84	1.98	0.27
Cod	Belgian Coast	43	0.14	0.27	0.04	0.7	1.3	0.27
Sprats	Belgian Coast	23	0.15	0.24	0.06	1.2	1.42	0.74
Shrimps	Belgian Coast	57	0.10	0.22	0.04	12.2	21.9	6.6

Species	Area	N	Zn			Pb		
			$\bar{X}$	X_{max}	X_{min}	$\bar{X}$	X_{max}	X_{min}
Plaice	Belgian Coast	53	6.48	11	3.10	0.30	0.51	0.20
	Middle North Sea	9	4.3	5.52	2.8	0.17	0.22	0.14
	Southern North Sea	8	4.86	6.88	3.63	0.21	0.32	0.14
	Eng. Channel	9	5.10	6.70	2.52	0.23	0.29	0.15
	Bristol Channel	11	5.33	13.8	3	0.19	0.25	0.11
	Irish Sea	19	4.93	6.46	2.42	0.57	2.88	0.13
Whiting	Belgian Coast	16	5.9	8	4.75	0.84	0.97	0.19
Cod	Belgian Coast	43	4.8	8.01	3.04	0.32	0.83	0.21
Sprats	Belgian Coast	23	23.9	29.3	16.7	2.22	5.3	0.10
Shrimps	Belgian Coast	23	26.3	45.2	19.2	4.7	16.8	0.3

The values quoted in the table 9.8 seem to confirm that the Hg amounts are effectively rising for the fish caught during the summer campaign.

As the causes which may involve an increase of the Hg amount in the fish during the summer they are perhaps relative to the increase of primary productivity in the North Sea : 100 mg/m^2.day in winter,

Table 9.8

Average contents
(total Hg in ppm)

Fishing campaigns	Plaice		Whiting		Sprats		Cod	
	$\bar{X}$	n	$\bar{X}$	n	$\bar{X}$	n	$\bar{X}$	n
Autumn 1971	0.14	46	0.14	67	0.14	12	0.10	34
Winter 1972	0.14	57	0.17	25	0.15	23	0.14	43
Spring 1972	0.16	41	0.17	59	0.11	9	-	-
Summer 1972	0.22	86	0.23	59	0.17	16	-	-
Autumn 1972	0.19	73	0.13	34	0.12	6	-	-
$\bar{X}$: 1 - 3	0.15	144	0.16	151	0.14	44	0.12	77
$\bar{X}$: 1 - 4	0.18	230	0.18	210	0.15	60	0.12	77

1500 mg/m^2.day in summer (*cf. Modèle Mathématique, Rapport de Synthèse II*). If we take the absorbtion capacity of phytoplankton into account, in respect to heavy metals, it seems logic to record a conjugated increase of the amounts of those elements in the fish.

The increase of the total Hg amount is again more characteristic if we compare fish of the same age (see Table 9.9).

Table 9.9

Species	Age	Fishing ground	Fishing period			
			January-15 June		15 June-September	
			$\bar{X}$	n	$\bar{X}$	n
Plaice	1969	Southern North Sea	0.14	53	0.20	23
"	1970	"	0.14	30	0.21	30
"	1971	"	0.13	7	0.25	30
Whiting	1970	"	0.16	61	0.24	32

As far as the respective distribution of the amounts in one species of the same age is concerned, it appears that the greatest frequency is located between the same limits, whatever the fishing period. On the other hand, the distribution curve is more spread out towards the high values for the summer fishing (see Table 9.10).

Table 9.10

Plaice; year class : 1970; fishing period : 1972

Southern North Sea n = 30	Frequency	
Hg total (ppm)	January-June	June-September
0.17 - 0.21	33 %	33 %
0.04 - 0.09	25 %	0 %
0.26 - 0.39	0 %	25 %

Recall, average summer : 0.21 ; winter : 0.14 .

Further work will permit us to know whether it is really a periodic increase as desirable.

In this case, it would be necessary to study the correlation which might exist between the quoted phenomenon and the subsequent elimination of mercury by sea organisms.

1.3.- Supervision of pollution

The discussion of the numerous chemical results already obtained permits to bring out the bases of a methodology useful for the supervision of the pollution of fish destinated for consumption, from a chemical point of view. First of all, the number of specimens of the same species must be large enough to be representative for the fishing place in regard to the unavoidable large distribution of the amounts. According to the foregoing, and for all security, it is necessary to include the parameter "fishing period". On the other hand, it is not evident that the age should be taken into consideration as an essential parameter, although there is a correlation between age and amount of Hg .

About the systematic supervision to be ensured after the period of investigation, which has to be spread over a period of at least two years, we expect that a minimum of thirty specimens of the same fish species, caught during the same season, will be necessary in order to characterize the pollution of the fish originating from one fishing area. On the one hand the solution may be to hold inspections within sufficiently spaced periods. On the other hand, we could effectuate more frequent studies of one species from one fishing area immediately when anomalies are observed. As to the frequencies to be observed they have to be determined for each species separately in function of the actual average amounts.

The dispositions mentioned above should permit the competent authorities to decide in time what measures have to be taken, for a defined species of fish or fishing area, with respect to the protection of the consumers.

1.4.- Other heavy metals

As for the other heavy elements, we observed important average amounts in Zn and Pb for sprats; in Cu, Zn and Pb for shrimps ($\overline{X}$ = 12.8 ppm Cu ; more than 60 % of the results are situated between 10 and 15.5 ppm Cu) (see Tables 9.4 to 9.7).

If we have to take care of the normal amounts for these species, it is not less true that the toxic character of the mentioned elements must be taken into consideration.

The histograms amounts-frequencies (reason = $\sqrt{1.5}$ particularly appropriate for the majority of the studied cases), reveal a quasi log-normal distribution for Hg and Cu. For plaice the distribution is rather normal for Zn and presents some discontinuities for Pb.

In Table 9.7 we notice the following increasing order of average amounts for plaice and cod : Hg (about 0.2 ppm) ; Pb (about 0.3 ppm) ; Cu (about 0.6 ppm) ; Zn (about 5.5 ppm).

For whiting the same order is maintained, but the amounts are slightly higher (with Pb = Cu = 0.89 ppm).

On the other hand, for sprats, the order is : Hg, Cu, Pb, Zn. The amounts in Zn of the sprats and shrimps are distinctly higher. In the shrimps the Cu content reaches 12.2 ppm and the Pb content 4.7 ppm. Here we must also take into consideration the normal amount for the species.

The search after possible correlations between amounts in pollutants (Hg, Cu, Pb, Zn) for the different fish species studied did not yield any positive results. As a matter of fact the calculated correlation coefficients generally had non significant values and even reverse signs for the same fish species.

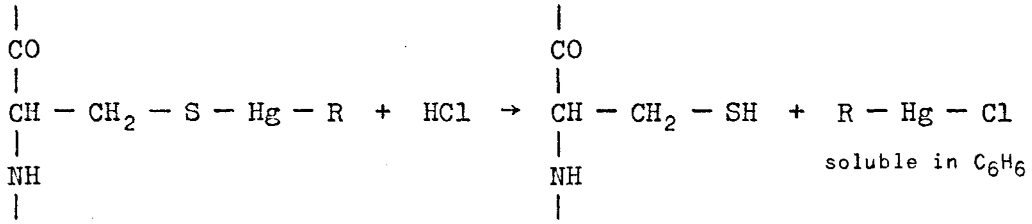
Nevertheless for cod we may reckon on a significant correlation between zinc and lead. Indeed, from 43 cods of the Belgian coast, the 23 of the Westdiep had an $r = 0.32$; $Zn = 2.98\ Pb + 4$ (significant at ± 95 %) and the 15 cods originating from Sierra had an $r = 0.67$, $Zn = 4.87\ Pb + 2.96$ (significance higher than 99 %).

2.- Total organic mercury

The method for the determination of the total organic mercury was perfected and then systematically applied to a first series of samples; the results were compared with those of the total Hg .

2.1.- Method

- 10 g fish + 10 mℓ water are homogenized in a mixer and brought in an obturable centrifugation tube and rinced with 5 mℓ water.
- add pepsine and 1 mℓ of concentrate HCl ; incubate at 37 °C during 2 days. In doing so the protein chains are partially destroyed.
- extraction with 8 mℓ HCl and 20-24 mℓ C_6H_6 (shake)



$$\begin{array}{l} | \\ CO \\ | \\ CH - CH_2 - S - Hg - R \\ | \\ NH \\ | \end{array} + HCl \rightarrow \begin{array}{l} | \\ CO \\ | \\ CH - CH_2 - SH \\ | \\ NH \\ | \end{array} + \underset{\text{soluble in } C_6H_6}{R - Hg - Cl}$$

- centrifugation of the suspension
- 5 mℓ of the benzene solution + 5 mℓ CCl_4

$$+ \left\{ \begin{array}{lll} 1\ m\ell & Ca(NO_3)_2 & 10\ \%\ \text{solution} \\ 10\ m\ell & Na_2S & 10\ \%\ \text{solution} \end{array} \right.$$

The organic mercury passes into the waterphase.

$$R - Hg - Cl + Na_2S \rightarrow \underset{\text{soluble in water}}{R - Hg - S - Na} + NaCl$$

- oxydation of the waterphase with Cl_2 (dissolved in CCl_4)

$$\begin{tikzcd} R-Hg-SNa \arrow[r, "Cl_2"] & HgCl_2 \arrow[dr] & \\ & & \text{MAS 50} \end{tikzcd}$$

Blank

1) The solution in water of $CH_3-Hg-Cl$ is treated with concentrated HCl and C_6H_6 and the above mentioned method applied.

Results : theoretical : 1.19 µg Hg ; 1.19 µg Hg ; 1.16 µg Hg ;
found : 1.12 µg Hg ; 1.04 µg Hg ; 1.28 µg Hg .

2) Addition of $HgCl_2$ or $CH_3-Hg-Cl$ after incubation;
- application of the method.

2.2.- Results

Table 9.11

Tests on fishes

Species	Addition of Hg to fish (ppm)	Total organic Hg			Total Hg (ppm Hg)
		Theoretical (ppm Hg)	Found (ppm Hg)	Found %	
		(1)	(2)		
Plaice (890)	-	-	0.17	-	0.39
"	0.046 ($HgCl_2$)	0.17 (2)	0.16	-	0.44
"	0.074 (CH_3-Hg-Cl)	0.239	0.22	92	0.46
Cod (897)	-	-	0.28	-	0.51
"	0.2 (CH_3-Hg-Cl)	0.48	0.45	94	0.71
" (bis)	0.2 (CH_3-Hg-Cl)	0.48	0.40	84	0.71
Cod (730)	-	-	0.32	-	0.30
"	0.08 (CH_3-Hg-Cl)	0.40	0.39	97	0.38
" (bis)	0.10 (CH_3-Hg-Cl)	0.42	0.39	89	0.40

Conclusions

1) The addition of $HgCl_2$ has no effect on the determination of the total organic mercury $R-Hg-Cl$, because of the clear separation between the water phase

$$HgCl_2 + 2\,HCl \rightarrow H_2(HgCl_4)$$

and the organic phase ($R-Hg-Cl$ dissolves in C_6H_6).

2) Addition of $CH_3-Hg-Cl$ increases the amount of organic Hg. Allthough there is some less.

Table 9.12

Analysis of fish and shrimps

Hg in ppm. First figures total organic Hg; second figures total Hg.

Cod	Belgian coast	0.37/0.51	0.38/0.30		
Plaices	Belgian coast	0.17/0.39	0.22/0.20		
	Irish Sea	0.07/0.77 (1962)	0.28/0.42 (1965)	0.06/0.18 (1961)	
		0.14/0.43 (1960)	0.10/0.46 (1964)	0.29/0.43 (1963)	
	Bristol Channel	0.15/0.18 (1964)	0.19/0.14 (1963)	0.11/0.37 (1966)	
		0.08/0.15 (1966)	0.07/0.11 (1968)	0.10/0.21 (1963)	
Sprats	Belgian coast	0. /0.06			
Shrimps	Belgian coast	0.01/0.08	0.02/0.10	0.06/0.07	0.08/0.07
		0.02/0.11	0.13/0.14	0.09/0.16	0.09/0.07
		0.09/0.08	0.05/0.15		
Sole	North Sea	0.15/0.19	0.38/0.32		
Pike	?	0.03/0.21			
Calamary	?	0.17/0.30			

2.3.- Comments

It appears from the examination of our first results, some of which are given above, that the total organic mercury is most frequently situated between $\frac{1}{3}$ and $\frac{2}{3}$ of the total Hg amount.

Note also that we find sometimes higher values for total organic Hg than for total Hg (sampling, precision !). This can be explained by the sampling procedure and the lack of precision in the determinations. However, we have undoubtedly to do with specimens in which the proportion of organic mercury is very high.

Those results represent the first elements of the practical application of the method. A method for the determination of $CH_3-Hg-Cl$ was also perfected; the first applications are in progress. This determination will be effectuated systematically and will permit us to evaluate the proportions of total organic Hg and $Me-Hg$ in relation to different parameters retained for total Hg.

3.- Pesticides and PCB

3.1.- Analytical method for determining pesticides and PCB in fish

3.1.1.- Extraction

Sample weight : 10 g of fish fillet mixed with Na_2SO_4 anhydrous.
Solvent : petroleum ether (Boiling range : 65 to 70 °C).
Apparatus : non-siphoning (plain tube) extractor.
Extraction time : at least 6 hours.
Extract concentrated in Rotavapor apparatus and then to 1 mℓ .

3.1.2.- Clean-up

- on alumina micro-column de-activated with 5 % water [adapted from Law and Goerlitz, JAOAC 53 (6) 1276 (1970)].
- elution with 7 mℓ petroleum ether. Extract concentrated to 1 mℓ .

3.1.3.- Pre-GLC separation

a) Silicic acid – celite microcolumn

Adapted from Armour and Burke [JAOAC 53 (4) 761 (1970)]

- mixture silicic acid + 3 % water (4 parts) and Celite 545 (1 part)
- first elution with 6 mℓ petroleum ether. This eluate contains : PCB's, aldrin, the most part of DDE and of heptachlor. Eluate concentrated to 1 mℓ → GLC .
- second elution with 4 mℓ of eluting mixture : acetonitrile (1 part) petroleum ether (19 parts), dichloromethane (80 parts). Eluate concentrated to 1 mℓ and then separated on b).

b) Alumina microcolumn

Alumina de-activated with 5 % water.

- first elution with 2 mℓ petroleum ether. This eluate contains pp'DDT, DDD, the most part of lindane and the remainder, if any, of DDE and heptachlor. Eluate concentrated to 1 mℓ → GLC .
- second elution with 5 mℓ petroleum ether. This eluate contains dieldrin, endrin, heptachlor epoxide and the remainder, if any, of lindane. Eluate concentrated to 1 mℓ → GLC .

3.1.4.- GLC determination

Apparatus : Varian 1200.
Detector : ECD, tritium source.
Column : glass, 1.80 m × 3 mm o.d.
Column packing : 4 % OV.1 / 6 % QF.1 on Chromosorb W. 80/100 mesh.
Carrier gas : N_2 flow rate : 30 mℓ/min.
Temperature : Column 170 °C , Injector 220 °C , Detector 280 °C .
Injection : 8 µℓ .

3.1.5.- Peak measurements

- for pesticides, area or height reported on a calibration curve, checked up from time to time with reference solutions.
- for PCB's , profile method with 5 peaks (Reference : Arochlor 1254).

3.1.6.- Identification of peaks (not always as routine method, but as checking up where necessary)

a) first eluate after silicic acid — celite separation
- alcoholic NaOH hydrolysis : PCB and DDE are stable;
- CrO_3 — HAc : DDE → dichlorobenzophenone.

b) first eluate after alumina separation
- alcoholic NaOH hydrolysis : pp'DDT → DDE
  DDD → 2.2-bis (p-chlorophenyl)-1-chloroethylene
  lindane → disappears.
- as supplementary checking up where necessary CrO_3 — HAc : DDE → dichlorobenzophenone.

c) second eluate after alumina separation
- H_2SO_4 concentration : dieldrin and endrin disappear.

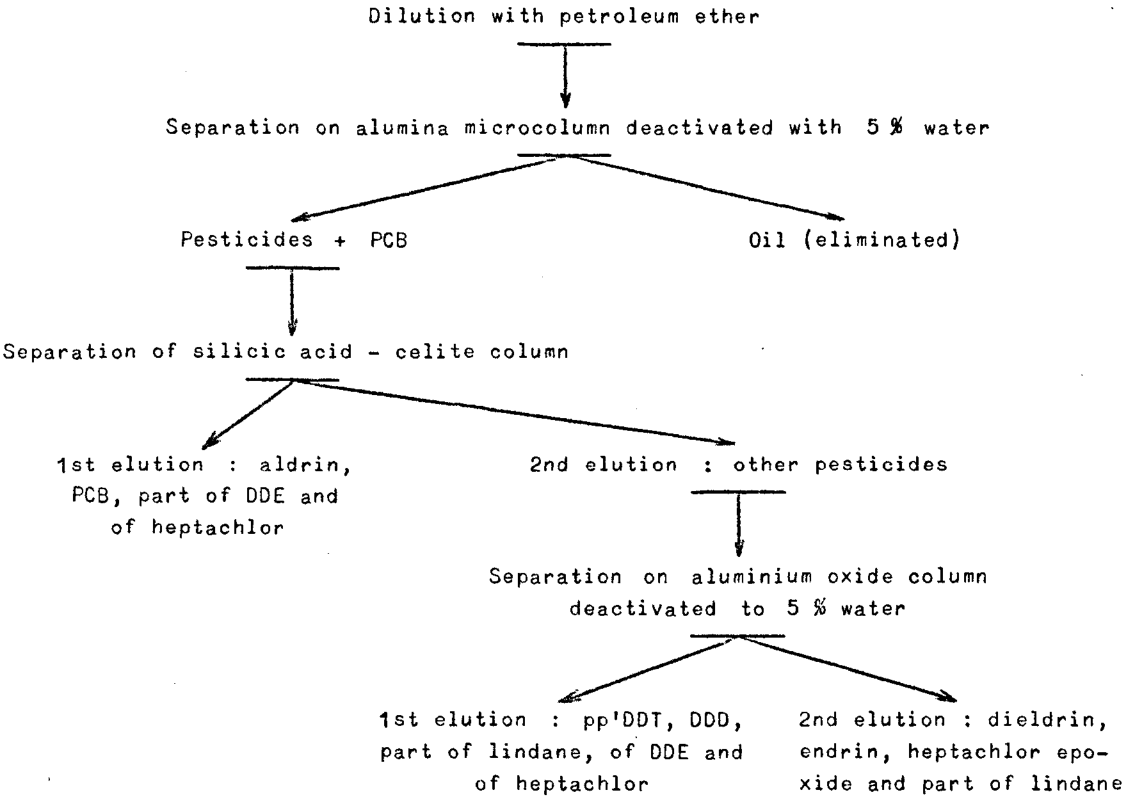
3.1.7.- Alternative methods

According to the difficulties encountered in the analysis for some samples of fish, the usual method (as described here above) is sometimes modified as follows, only for the clean-up procedure :

- a liquid-liquid partition clean-up with DMF (adapted from Richardson and Coll, *Pestic. Monit. Journ., 4* (4) 169, March 1971).

- Florisil microcolumn clean-up. Elution with petroleum ether-diethyl ether.

Scheme of the method used for determining pesticides and PCB in the fish oil samples



3.2.- Comments

From the comparison of the average results obtained for pesticides and PCB in the species caught during the two periods mentioned in Table 9.13, it appears that :

- the contents are higher in the autumn 1971;
- for one and the same species, we notice an influence of the fishing area, especially for PCB ;
- a differentiation according to the species may also exist, particularly on the basis of the PCB contents.

Table 9.13

Average amounts of pesticides and P.C.B.
(results in ppm)

Fishing campaigns Autumn 1971									
Species	Number	pp' DDT	DDE	DDD	Dieldrine	Endrine	Lindane	PCB	
Belgian Coast - Westdiep									
Cod	8	0.023	0.005	0.002	0.006	< 0.001	0.003	0.074	
Plaice	5	0.027	0.007	0.003	0.010	< 0.001	0.008	0.210	
Whiting	6	0.022	0.004	0.002	0.008	< 0.001	0.007	0.117	
Shrimps	5	0.021	0.003	0.001	0.006	< 0.001	0.006	0.082	
Belgian Coast - Sierra									
Cod	5	0.038	0.008	0.005	0.010	< 0.001	0.006	0.173	
Plaice	5	0.025	0.004	0.004	0.010	< 0.001	0.006	0.252	
Whiting	4	0.014	0.004	0.001	0.007	< 0.001	0.005	0.084	
Shrimps	5	0.018	0.002	0.001	0.007	< 0.001	0.007	0.078	
Belgian Coast									
Plaice	7	0.023	0.004	0.008	0.010	< 0.001	0.007	0.189	
Belgian fisheries outside the Belgian Coast									
Plaice	8	0.025	0.010	0.002	0.006	< 0.001	0.007	0.126	
Sole	7	0.034	0.010	0.003	0.007	< 0.001	0.005	0.207	
Fishing campaigns January-May 1972									
Species	Number	pp' DDT	DDE	DDD	Dieldrine	Endrine	Lindane	PCB	Hept. epoxide
Belgian Coast									
Cod	23	0.004	0.002	0.001	0.001	-	0.002	0.059	< 0.001
Sprats	5	0.037	0.013	0.053	0.022	0.002	0.007	0.518	0.002
Shrimps	9	0.011	0.003	0.002	0.002	-	0.003	0.108	< 0.001
Plaice	18	0.005	0.002	0.002	0.002	-	0.002	0.058	-
	16	0.004	0.002	0.003	0.003	-	0.001	0.068	-

These are relatively more abundant in the plaice and the sole and distinctly higher in the sprats.

For this last species the amounts of the different kinds of pesticides and PCB are clearly higher than in all the other investigated species. Besides we have to remind that sprats have also a high amount of heavy metals.

In the I.C.E.S. reports relative high amounts of pesticides and PCB in fish of the Southern North Sea are mentioned. If however we take into account the low toxicity of these products we can conclude that in both cases they do not present any danger for men. However, care must be taken with dieldrine, highly toxic for mammals.

According to Egon (1967) it is recommended that dieldrine in food should not exceed 0.1 ppm (on fresh material).

The amounts we have found and those given by I.C.E.S. are much lower than this value.

Chapter X

Some aspects of the dynamic behaviour of metallic and other pollutants in the water column and the associated sectors

by

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Based on experimental work from :

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2.- Laboratoire de Chimie des solides, Prof. R. WOLLAST, Université libre de Bruxelles.
3.- Laboratorium voor Organische Chemie, Prof. G. VAN BINST, Vrije Universiteit Brussel.
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and coworkers.

Introduction

As global population, material standard of living and consequential industrialization continue to grow, specially around the Southern Bight of the North Sea, it becomes necessary to understand and if possible to manage the consequences of this situation within the context of *interactions* between the domestic and industrial wastes continuously transported and the finite and relatively small water mass of the southern bight of the North Sea.

Although the global impact of the Southern Bight on the whole North Sea seems to be unimportant at this time [ICES (1973)], one must take into account that at *local scale*, this situation implies very high stationary concentrations of pollutants and possible modifications in the system within a relatively short time scale.

Although the quantitative description of interactions and transfers, temporally and spatially integrated, gives a *"frozen" picture* of the real system, no other method is available to describe, in a global report and in a first approach, the dynamic distribution of the pollutants. In such a representation, the patch formation concepts, the seasonal influences, the irregularities due to sporadic dumpings and so many other influences are emasculated in such a way that the only perfect tool will be the mathematical one. Nevertheless, we will use the "frozen" picture in a first approach, but the sensitivity of the proposed figures, specially concerning the determination of the influence of the boundary conditions, and the magnitude of some chosen parameters will be given by simulation with the mathematical tool fully described elsewhere [Nihoul (1974a)].

For that purpose we surveyed our results (and also those from the literature) on the individual chemical and physical aspects of the movement of some pollutants through the ecosystem in the water column, taking into account exchanges with benthos and atmosphere.

The picture is incomplete and in places apparently contradictory but our purpose, at this stage, is to show how, after selection, the results of many individual studies may be assembled into a useful policy tool. There may be errors in the studies reviewed, but the sensitivity analyses mentioned above either suggest that their impact on our basic conclusions is small, or indicate where the need for further information appears, although our understanding of the real system will never be perfect.

1.- Nutrients

The nutrient content analysed in the water column (phosphorus, nitrogen, silicium) shall not be examined in this chapter, insofar as their evolution in time and space is the subject of a detailed interpretation associated with the study of the *activities* of the different organisms (primary and secondary production, heterotrophic activity, etc.) already presented in chapter VI (Podamo).

In view of the conclusions of that important chapter, we will, at most, express a few comments which may have an impact on the discussion of the other chemical parameters under study.

In the last paragraph, dealing with the nitrogen transfers in the southern bight of the North Sea, it is mentioned that the data concerning the activity of phytoplankton, zooplankton and (pelagic and benthic) bacteria justify *a posteriori* the validity of the division of the network in three zones where significantly different types of biological mechanisms seem to be demonstrated. In fact, although our previous work [Elskens (1972)] had shown only a zone differentiation corresponding to different hydrodynamic regimes, we will in further discussions adopt the *three* subdivisions, fully aware that these different types of activity will play a specific role in the distribution of pollutants engaged in or circulated into the food web.

As stated in the conclusions of this same paragraph, the unbalanced ecological behaviour in *zone 1 north*, where the greatest part of the primary production occurs at the expense of exogenous nutrients without important recycling, is the consequence of *eutrophication* of this part of the North Sea. This statement, based on an annual balance of nitrogen transfers, may be supported by other techniques of approach [Anderson (1972)] and should be more finely detailed, simultaneously considering other nutrient budgets [Beckers (1973)] since a zone's trophic state is characterized not only by its nutrient content but also by the quantity and above all the *type of biota* it supports [Mommaerts (1973)].

The abnormal situation in zone 1 north (see fig. 6.42, chapter VI) partly confirmed by other investigators [Hagel (1973)] illustrates quite well that in developping a formal model for a system, one must begin by defining the system boundary not only in time but also in space. As a matter of fact, the boundary is chosen *in response* to the questions the model seeks to answer. The responses would be quite different if we were thinking of a one day period or a twenty year period, if we were considering the global North Sea system or the local southern North Sea, or even one part of the latter. This explains the formal discrepancy of some conclusions [ICES (1974)] : "... however, although *no effects* have been noted which might indicate a danger of eutrophication arising in the North Sea, there is some evidence of increases in nutrient levels in the waters of the southern North Sea in recent years ...". The first statement is based on a global budget, taking into account the inputs of nitrogen and phosphorus in sewage, and on the consequential oxygen demand of the present organic matter, this load being *evenly* distributed over the *total* surface of the North Sea.

As shown by Nihoul (1974a), the evolution of a marine constituent results from advection, migration, dispersion and also from ecological interactions. If pollution damage may theoretically be controlled in two ways [Meadows (1972)], *i.e.* by decreasing the rate of pollution generation or by naturally or artificially removing the pollutant from those areas where it causes harm, we may conclude that eutrophication is one pollution problem in which the second response is spontaneously effective for the total North Sea, at this stage at least, but that for the zone 1 north (and probably very soon for the zone 1 south) only the first response may be effective, considering the coupled hydrodynamical and ecological reasons.

2.- Metals

Regular surveys of the distribution of selected trace metals in the waters of the North Sea have been conducted by laboratories in Belgium, the Netherlands and the United Kingdom. A preliminary examination of the results had shown differences in the *mean* level of "dissolved" metals measured by the three groups. An international intercalibration program was therefore established (under sponsorship of the ICES), to investigate this problem. A working document [Elskens (1973a)] including computations on the 1971-1973 data representative of the whole belgian survey network was presented to an *ad hoc* working group in charge of the preparation of the report concerning the distribution of trace metals in the waters of the North Sea.

The final document [ICES (1974)] presents a compilation of the available data produced by the three countries, completed with a critical study of the apparent anomalies. In those regions of the North Sea where surveys by the three groups coincided geographically, the mean levels of most metals recorded by the belgian investigators where higher than the U.K. figures, and the Netherlands data occupied an intermediate position. There is evidence, however, that these apparent anomalies may be attributed to variation in the fraction of metal passing the membrane filter after sample collection. Prior to analysis, seawater samples were filtered through membranes of pore size 0.22 , 0.45 and 0.8 µm by the U.K., Netherlands and belgian laboratories respectively.

Although this explanation will be satisfying in a first approach and for the determination of the overall spatial trends in the distribution of "dissolved" metals, we presume that other factors must play a rôle in some of the observed discrepancies. First one must take into account that any physical treatment (freezing, filtering, extraction, etc.) changes the "matrix" of the treated sample and very often not in a simple way.

Peptonization and flocculation processes may occur [Steen (1974)] and even the comparisons made by filtering natural water through membranes of different pore sizes can provide rather unexpected results [Jones (1974)]. This is an example where a coupling of the measured parameter with a series of other incompletely or not at all defined parameters appears and plays the major role. In the same field, one must indubitably consider the influence of speciation [Kamp-Nielsen (1972)], the indirect consequences of speciation [Gillain (1974)] and the heterogeneous nature of suspended or particulate phases; especially in some regions where the very fine material is definitely richer in adsorbed metals, as compared to the "mean" suspended material very similar in terms of composition to the "recent" sediments [Duinker (1973)].

In order to establish a more detailed geographical picture of metal distribution and especially to define precisely the representative concentrations[1] of trace metals in water masses, well defined in regards to the spatial boundaries, the same statistical treatment [Elskens (1973)] was made for *each* zone (zone 2, zone 1 north, zone 1 south; see fig. 6.38, chapter VI) of the belgian sampling network.

Table 10.1 summarizes the mean values for cadmium, zinc, copper and lead. The purpose is to define as closely as possible the specific characteristics of each bulk. There is then no reason to exclude *a priori* the very high values[2] observed in coastal zones (confirmed in other respects by further intercalibration experiments, *cf.* cruse Clione, Sept. 1973, samples K6 and J10), these values playing an outstanding role in the calculation of the fluxes. Fully aware that some of those high values appear sporadically, our problem is to integrate these values in an adequate time scale, in the same way one must average some parameters over a certain number of tidal periods.

The first question arising from the examination of the results of table 10.1 concerns the physical sense that one must or may give to those "mean" concentrations in view of their practical use. Despite the fact that these concentrations (relative to the water column alone) are isolated from the other compartments, we know, as stated by Nihoul (1974b), that the exploitation of this kind of result is not meaningless. When the *interaction* processes are not yet entirely understood and cannot be formulated with sufficient accuracy to use in a reliable simulation model, it is then preferable to base the predictions on the estimates of a *passive* dispersion model, until new experimental and theoretical data are available and the interaction forms can be determined with the required precision. Such models always provide valuable estimates of the distribution of *non passive* constituents by at least appraising their possible transport by the overall motion of the Sea.

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[1] Arithmetic weighted mean, in the sense of optimization of the number of samples with the effective volumes of the water masses.

[2] Or to emphazise the low values, using the geometrical mean.

Table 10.1

Mean measured metal concentrations in the Belgian sampling network (µg/dm^3)

Metals	Zone	Year	Mean	Nb	σ	Range	Med.	Distrib. 5 classes	Nb runs	Excl.	Methods
Cd	1N	1971	0.25	5	0.18	0.15-0.56	0.19	4- 0-0-0-1	1	0	ASV
Cd	1N	1972	0.38	16	0.24	0.16-1.0	0.28	9- 3-2-1-1	1	0	ASV
Cd	1S	1971	0.19	12	0.07	0.06-0.34	0.19	2- 3-2-4-1	2	1	ASV
Cd	1S	1972	0.37	24	0.21	0.10-0.84	0.31	9- 6-2-5-2	2	1	ASV
Cd	2	1971	0.18	21	0.09	0.05-0.42	0.19	7- 6-5-2-1	2	1	ASV
Cd	2	1972	0.30	37	0.23	0.09-1.01	0.21	23- 6-4-2-2	2	2	ASV
Zn	1N	1971	3.6	5	1.7	0.8 -5.0	4.0	1- 0-1-1-2	1	0	ASV
Zn	1N	1972	15.5	15	17.5	1.0-52.4	10.4	9- 2-1-1-2	2	1	ASV
Zn	1S	1971	9.0	12	6.6	1.2-21.8	8.5	5- 3-1-1-2	2	1	ASV
Zn	1S	1972	23.9	24	23.6	1.5-91.7	13.2	15- 4-3-0-2	2	1	ASV
Zn	2	1971	5.9	21	5.1	0.2-18.8	5.9	9- 7-3-0-2	2	1	ASV
Zn	2	1972	15.4	35	16.7	2.0-65.4	9.1	26- 2-2-2-3	2	3	ASV
Cu	1N	1971	4.8	5	3.1	1.5- 8.3	5.3	2- 0-1-0-2	1	0	ASV
Cu	1N	1972	9.8	16	3.9	3.2-17.6	10.0	2- 5-5-3-1	1	0	ASV
Cu	1N	1972	7.1	4	5.9	1.9-14.8	5.9	2- 0-1-0-1	1	0	AAS (0.22 µm)
Cu	1S	1971	4.7	6	4.4	0.8-12.7	3.5	3- 1-1-0-1	1	0	ASV
Cu	1S	1972	12.0	24	12.2	3.2-56.5	7.6	19- 1-3-0-1	2	1	ASV
Cu	1S	1972	5.3	6	4.5	0.4-11.6	4.5	2- 1-1-0-2	2	1	AAS (0.22 µm)
Cu	2	1971	3.9	14	2.6	0.6-10.4	4.1	5- 4-4-0-1	2	1	ASV
Cu	2	1972	7.9	38	3.5	2.6-15.2	7.6	10-10-8-6-4	2	1	ASV
Cu	2	1972	4.4	10	4.4	1.0-15.2	2.3	6- 2-1-0-1	2	1	AAS (0.22 µm)
Pb	1N	1971	2.0	6	1.8	0.6- 5.6	1.4	4- 1-0-0-1	1	0	ASV
Pb	1N	1972	4.1	14	2.9	1.0-10.8	3.1	6- 5-1-0-2	2	1	ASV
Pb	1S	1971	3.1	12	1.8	1.1- 7.5	2.7	5- 5-0-1-1	2	1	ASV
Pb	1S	1972	7.2	24	5.3	0.5-17.6	6.4	10- 3-5-3-3	2	1	ASV
Pb	2	1971	2.3	20	1.8	0.6- 6.2	1.8	9- 6-1-2-2	2	2	ASV
Pb	2	1972	5.0	36	3.4	1.2-14.5	4.1	16-10-5-3-2	2	3	ASV
Pb	2	1972	3.2	10	1.9	0.2- 6.5	2.3	1- 5-0-3-1	2	1	AAS (0.22 µm)
Pb	2	1972	10.1	10	4.3	4.1-18.2	10.1	2- 3-3-1-1	2	1	AAS (0.8 µm)

In fact, this first approach can be used to describe the general features of the space and time variations for *active constituents* as long as some *conditions* are satisfied. When one considers the relatively short residence times of the water masses in each zone : 20 , 23 and

34 days[1] for zone 1 south, zone 1 north and zone 2 respectively, it seems evident that the most important part of the transfers must be the transport by the sea motions. The calculation of the residence times is based on the estimates of the hydrodynamicians [Ronday (1973)]. Considering in a second step the transfer mechanisms in the food web presented elsewhere by the biologists [Podamo (1974)], computing the mean productivity value and the grazing coefficient (respectively 140 g carbon/m^2/year and 46.2 g carbon/m^2/year , for zone 2 for example) with the mean cadmium content of zooplankton (20 mg Cd/kg carbon, for the same zone, see table 10.2), it can be calculated that the maximum quantity of cadmium involved (engaged in and circulated into) in the plankton box of zone 2 is about 4.25 tons/year [Jacob (1974)]. Compared with the several hundred tons of the same material transported through the water mass of zone 2, this leads to the same conclusion as above.

To come back to the above mentioned example, this does not at all mean that, in these conditions, cadmium never plays an outstanding role in the food chain and that one should minimize or even neglect the cadmium pollution problems. In another paragraph, a rough estimate of a circulation model inside the food chain will be discussed, with some comments on interactions, translocations and the consequential influences on a passive dispersion model.

In any case, if the interactions play a significant role (recycling in the food chain as a modification of the reservoirs, sedimentation processes, etc.), they can be taken into account in a passive dispersion model if one assumes that their net result is a production or destruction of the considered constituent, which can often be expressed as a function of the concentration of that constituent alone [Nihoul (1974b)].

The criteria presented above, applied for example to the cadmium budget, led to figure 10.1 where the fluxes are expressed in tons/year,

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[1] We simultaneously ascertain a given value for the future time scale of the samplings, in order to improve the "mean" values presented here.

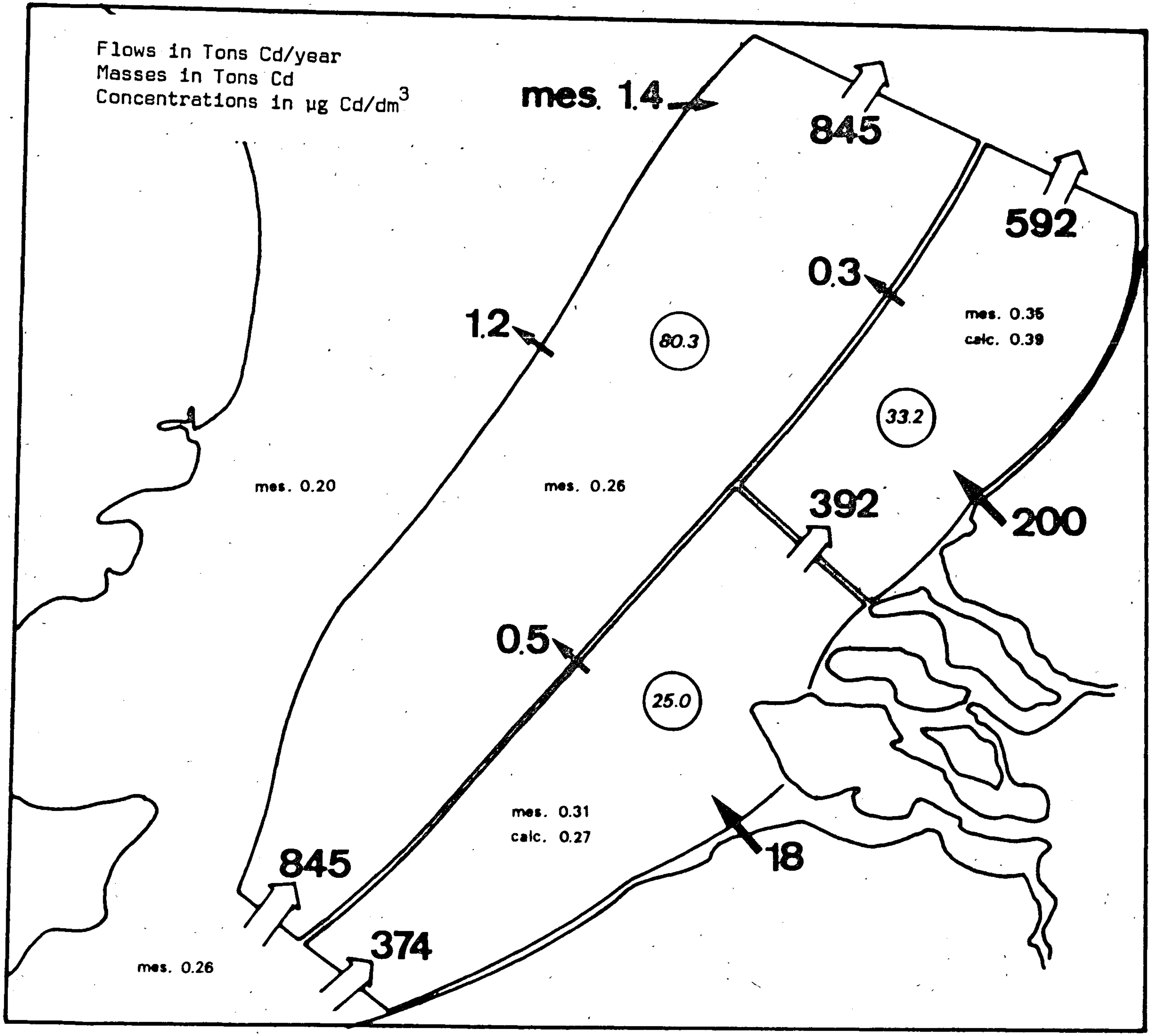

fig. 10.1.- Passive dispersion patterns for cadmium.

the engaged masses in tons, the concentrations in micrograms per liter [Steen (1974)]. The calculated concentration values were derived from the hydrodynamical data and a proper choice of inputs and boundary concentrations. The measured concentration values are those derived[1] from the weighted means taking into account the results collected during 1971 and 1972, since a monthly survey is not an acceptable time scale, as regards the residence times, for a convenient integration. Here again appears the superiority of the mathematical tool.

Figure 10.1 suggests a few comments.

The tremendous sensitivity of such a circulation model to the choice of the boundary conditions implies that one must give more information about the chosen values. The input figures, Rhine (200 T/y , for an outflow of 75×10^9 m^3/year) and Scheldt (18 T/y , for an outflow of 3.3×10^9 m^3/year) are respectively extracted from the literature [Weichart (1973)] and from our own previous results [Elskens (1972)]. The direct inputs of cadmium along the belgian [IHE, IRC (1973)] and probably also the dutch coast can be neglected as compared with the adopted values for the Rhine and the Scheldt. The concentration at the border between the belgian network and the Channel (0.26 μg Cd/dm^3) equalized to the mean concentration of zone 2, is in agreement with the *overall mean* value of our observations (1971-1973) in this region (0.28 μg Cd/dm^3), although very important fluctuations[2] have been observed (range 0.10 - 1.01) or reported; the values cited in the literature range from 0.06 μg Cd/dm^3 [Preston (1973)] to 1.6 μg Cd/dm^3 [Dutton (1973)].

Finally the border concentration along the belgian network and the U.K. coast (0.20 μg Cd/dm^3) is derived from the ICES figures [Jones (1973)].

The difference between the calculated value (0.27 μg Cd/dm^3) and the measured value (0.31 μg Cd/dm^3) in zone 1 south, is in agreement

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[1] Restricting our attention to mean vertical concentrations, the profiles are discussed elsewere [Steen (1974)].

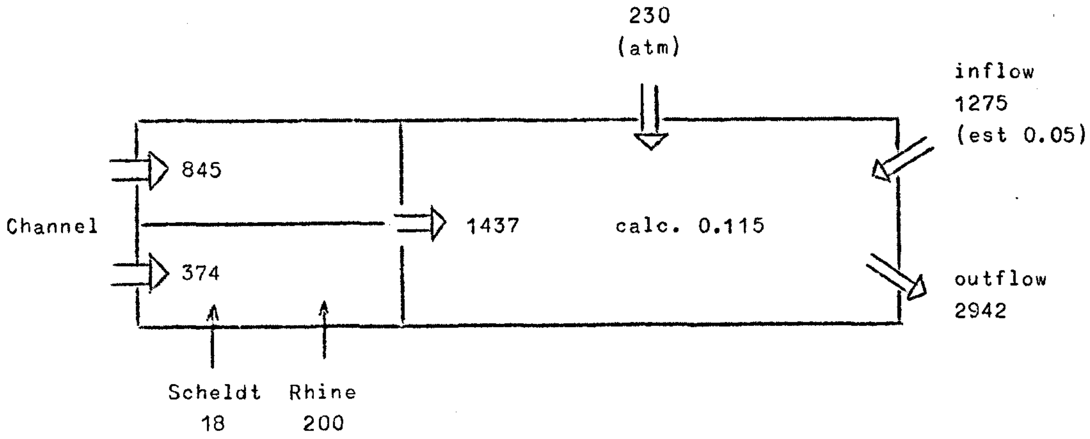
[2] In an other paragraph we will discuss the sporadic influence of the dredging products dumped in this region.

with the same kind of discrepancy observed between estimation and measurement for the salinity (see fig. 6.38, chapter VI). The final answer to this problem probably lies in the influence of the "tidal stress" on the residual circulation [Nihoul (1974c)]. Apparently the real residence time in this zone must be a little longer than the value obtained by formal calculation; this also concurs with the silt accumulation in the same zone (see this chapter, § 4). As a result, the net flux between zone 1 south and zone 1 north must be somewhat deflated; and moreover, taking into account the fact that the mean concentration associated to the zone 1 north is probably overly influenced by the number of samples located under the Rhine estuary, one may consider that the agreement between the estimated and the experimental values is fairly good.

Introducing the fluxes due to dispersion will improve the figure. These values are mentioned at each border-line between zones, averaged all along the border for the mean values of the dispersion coefficients [Nihoul (1974d)] and oriented in the direction of the concentration gradient. One exception appears to the north of the outside border-line; the great axis of the iso-concentration ellipse is oriented at 72° - 05 referred to the geographical north and the concentration gradient may be reversed during some periods. This explains why, on that line, some spots of high concentrations are detected, as shown by our own results and simultaneously in some U.K. surveys [Jones (1973), fig. 1a, Corella cruises 1971]. The feeding element is probably a combination of the Straits of Dover and the Thames.

Last, the figure 10.2 schematically presents the global influence of the part of the southern bight under study on the global North Sea system [Steen (1974)] simultaneously considering the atmospheric input [ICES (1974b)]. The induced concentration gradient Δc equals 0.07 μg Cd/dm^3 .

The same figures may be constructed for zinc and copper but at this stage of our knowledge no further information on the possibilities of the passive dispersion models will be gathered, with the possible exception of direct information on the sensitivity of such a model as



Note : same units as for fig. 10.1.

fig. 10.2.- Contribution to the North Sea.

concerns the inputs. The only excluded value in the copper survey (AAS determination, table 10.1, p. 421) concerns a sampling point located in the Straits of Dover, precisely where dredging products were dumped a few days before the sampling. The recorded value (about 64 µg Cu/dm^3) was used to simulate the influence on the nearby sampling points and to determine the time constant of the induced perturbation [Jacobs (1973)].

The lead budget also suggests a few specific comments. Although admitting that many previously published lead concentrations in sea water are probably too high, we cannot agree with all the conclusions of the workshop sponsored by the IDOE Conference (May 1972) and especially with those concerning the AAS and the ASV analytical methods [Patterson (1974)]. The "particulate" nature of most of the lead in the sea water samples has been confirmed by systematic ultrafiltration processes on the same sample. A regression analysis on the contents of the corresponding filtrates shows that for a theoretical porosity zero, one obtains concentrations of lead "in solution" ranging from 50 to 250 nannograms/dm^3 , values concurring with the theoretical definition of a "true" solution in sea water [Goeyens (1973)].

Therefore, in considering a global lead budget in a passive dispersion model, one must consider the important fraction of lead transportation under particulate form, assuming that a minute portion of that fraction is collected by sediments (see § 4). Simultaneously, one must incorporate into the model the non negligible atmospheric input [ICES (1974b)].

Due to some important gaps in our information in its actual state, it seems untimely to present even a rough estimate of the lead budget in the several zones of the network under study. Nevertheless, some information dealing with the inputs may be of interest.

The mean concentration of lead in the rainwater we surveyed from March 1972 to March 1973, *i.e.* 27 micrograms Pb per liter (range 3-160 μg Pb/ℓ) concurs with the figure presented by the UKAEA Research Group, *i.e.* 34 micrograms Pb per liter [Pattenden (1974)], and also with the estimate of the annual fall out on the North Sea published by the ICES [Jefferies (1973)]. The enhanced washout factors observed at the sea-based stations in respect to the land stations is probably due to reextraction processes in the upper layer of the sea [Nihoul (1972)].

Assuming that 27 μg Pb/dm^3 represents the true amount of fall-out through rain on the sea surface and for an average rainfall of 80 cm/year , the net annual contribution is 216 t/year , 113 t/year and 100 t/year for zone 2, zone 1 south and zone 1 north, respectively. In these conditions, the ratio — atmospheric contribution/estuaries contribution — in the belgian network is completely different from that of the whole North Sea, since the contribution of the Rhine alone is 2000 t lead/year [Weichart (1973)]. This is in accordance with the existence of a negative concentration gradient along the on shore — off shore profiles in the water column and in the sediment distribution (see § 4).

From another point of view, the relatively small contribution of fresh waters in the lead budget (in the absence of direct injection of wastes) is due to the fact that lead does not seem *to move* after it has come in contact with soil and humus particles, *except* when the soil particles themselves move. As regards the rainfall on land, this assumption is strengthened by the fact that leaves, the best receptacle for lead contained in rainwater [Impens (1973)], fall to the ground every year, carrying with them whatever lead is on their surface. The figure generally offered for the solution half-life of lead, that is, the time required to remove 50 percent of the lead in soils by suspension of particles in rivers *only*, is in the order of 30 years. This value is of course only a very rough estimate. However, all we need to know is that this processes (mobilization on land) is very slow indeed, compared to other direct transportation mechanisms (rainfall on sea).

The data given by the biologists [Podamo (1974)] concerning the food chain pattern in zone 2, may be summarized in a flow diagram as shown in figure 10.3 where the biomasses are expressed in g carbon/m^2

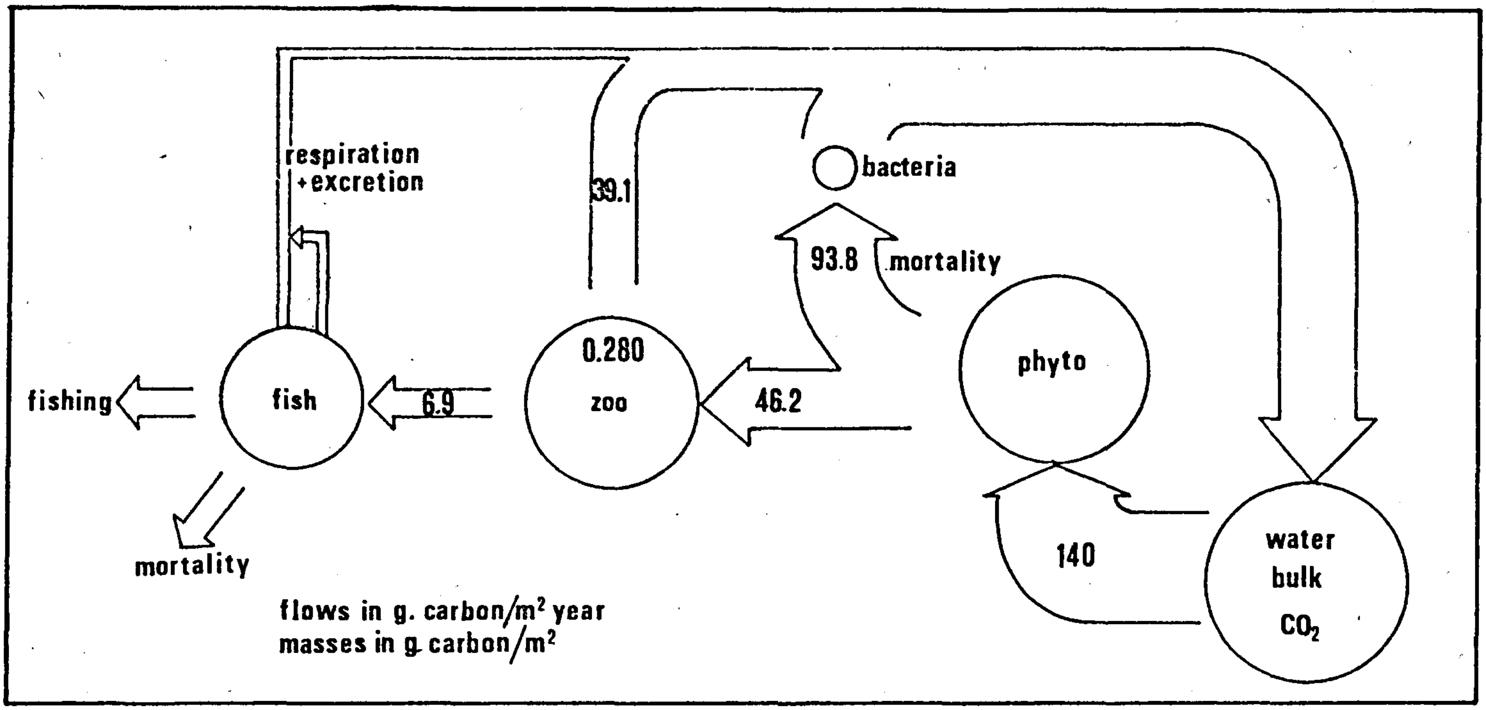


fig. 10.3.- Food chain pattern, water column zone 2.

and the flows in g carbon/m^2.year . This figure is, of course, not completely detailed; the unimportant flows, such as, for instance, excretion by zooplankton, are neglected.

Taking into consideration the zooplankton mean mercury content for zone 2 (see table 10.2), *i.e.* 20 mg Hg/kg carbon[1] , and assuming

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[1] Attention to the units chosen; in order to obtain the concentration on <u>wet</u> material, the best figure is to multiply by a factor 0.08 for zooplankton.

Table 10.2

Concentration of heavy metals in lyophilisated plankton

Identification	Hg mg/kgC	Zn 10^3.mg/kgC	Cd mg/kgC	Pb 10^3.mg/kgC		Cu 10^3.mg/kgC	
	AAS	ASV	ASV	AAS	ASV	AAS	ASV
1S-M05	37.3	8.3	11.6	0.39	0.31	0.93	0.86
M06	28.4	5.9	17.8	0.51	0.63	0.60	0.64
M1343	11.4	8.9	12.1	0.42	0.45	0.73	0.71
M1450	7.6	14.6	32.9	0.25	0.40	0.67	0.57
M1452	25.6	24.5	30.4	0.21	0.24	2.44	1.01
M60	8.8	3.3	21.1	0.89	0.39	0.91	0.23
M1097	12.0	-	-	0.29	-	0.29	-
M1101	19.3	6.8	6.8	0.35	0.44	0.37	0.43
M02	15.4	7.1	28.9	0.27	0.35	1.12	1.61
M07	16.9	7.7	11.6	0.097	0.15	0.62	0.46
M52	17.9	11.3	15.5	0.24	0.61	0.19	0.43
Mean	18.2	9.8	18.9	0.36	0.40	0.80	0.70
1N-M59	16.0	5.0	1.9	0.10	0.24	0.17	0.35
M2689	39.2	19.0	95.1	1.03	1.92	1.11	2.41
M21	13.2	15.7	11.9	0.29	0.24	0.40	0.60
M1989	27.2	48.7	646	0.69	0.41	0.44	0.38
M1695	8.9	102	-	0.33	0.23	0.44	0.27
M64	44.8	48.5	-	0.24	0.31	4.42	2.60
M17	10.5	4.6	70.6	0.12	0.15	0.32	0.36
M63	58.6	37.4	-	1.15	0.031	13.7	8.0
M1993	134.-	20.6	2.0	0.24	0.054	2.42	0.95
Mean	39.2	33.5	36-138	0.47	0.40	2.60	1.80
2 - M14	46.3	6.0	-	0.23	0.029	0.94	1.84
M23	5.6	12.4	46.1	0.077	0.146	0.15	0.19
M22	6.3	4.4	1.4	0.14	0.09	0.20	0.17
M18	18.0	1.2	12.2	0.008	0.048	0.78	0.68
M65	32.7	93.6 *	44.7	0.11	0.74	0.45	0.98
M1995	11.3	20.1	5.1	0.15	0.073	0.54	0.16
Mean	20.0	8.8	21.9	0.12	0.19	0.51	0.67

AAS : Atomic absorption spectroscopy.
ASV : Anodic stripping voltametry.

* Some values were excluded, because they are located at the frontier of the zone and under direct influence of another zone, or because the observed ratios C/N and C/P are not consistent with the composition of zooplankton.

quasi stationarity, at least on a short time scale, the consequential flows for the mercury budget *inside* the food chain can be calculated (figure 10.4). The theoretical mercury content in phytoplankton derived

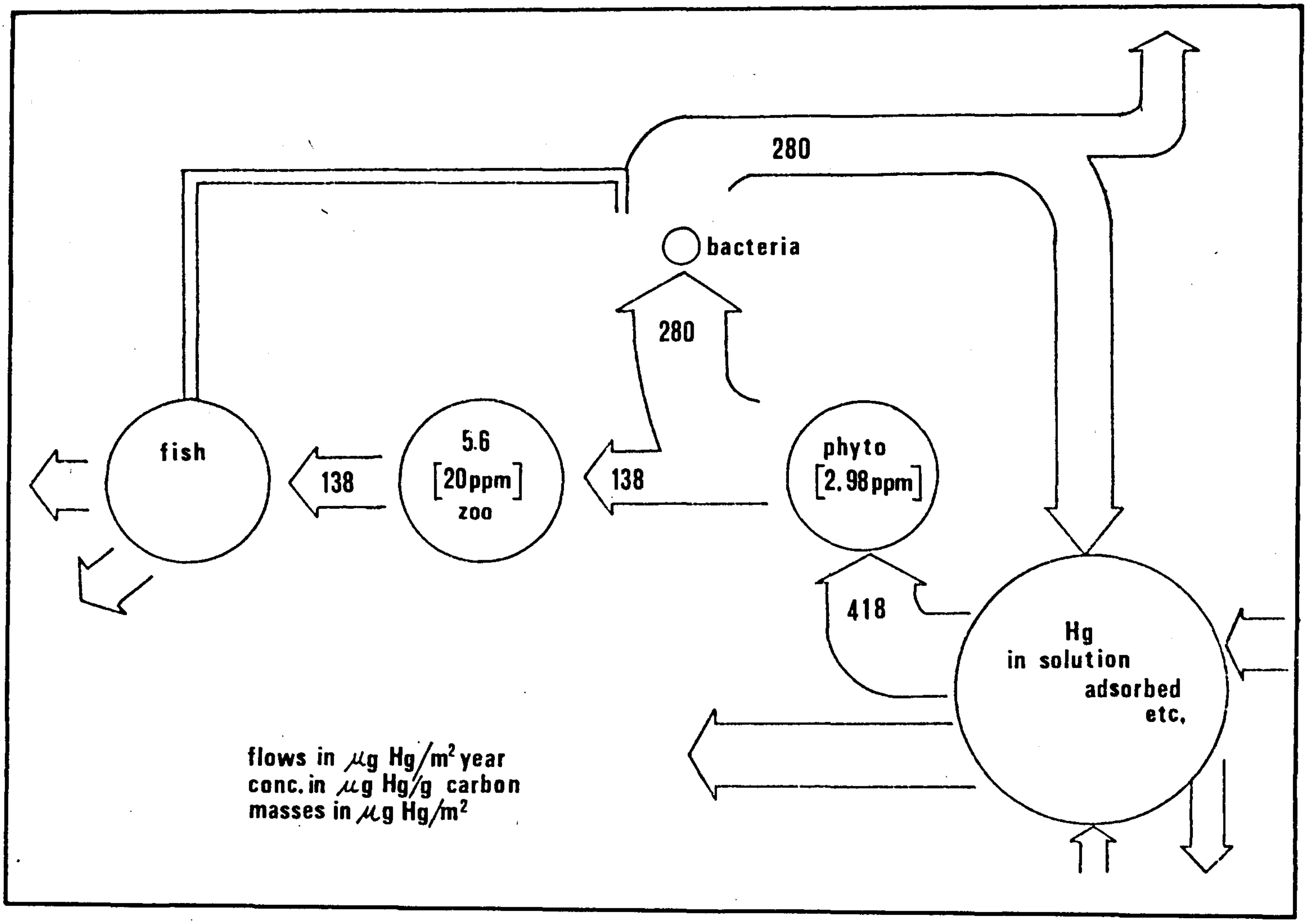


fig. 10.4.- Mercury pattern inside zone 2.

from this calculation is 2.98 mg Hg/kg carbon ; this means a concentration factor of about 6.7 , in agreement with the value obtained by tracer techniques. It is noticeable that the *practical* concentration of mercury *in* phytoplankton is almost impossible to determine experimentally with accuracy, considering the tremendous adsorption properties of mercury as regards organic and suspended matter [Cranston (1972)].

Finally, combining these data with those given by a passive dispersion model, one may present a rough estimate of mercury circulation in zone 2 (figure 10.5). This figure may be completed with a few considerations relative to interactions at the border-line of the water column [Jacob (1974)].

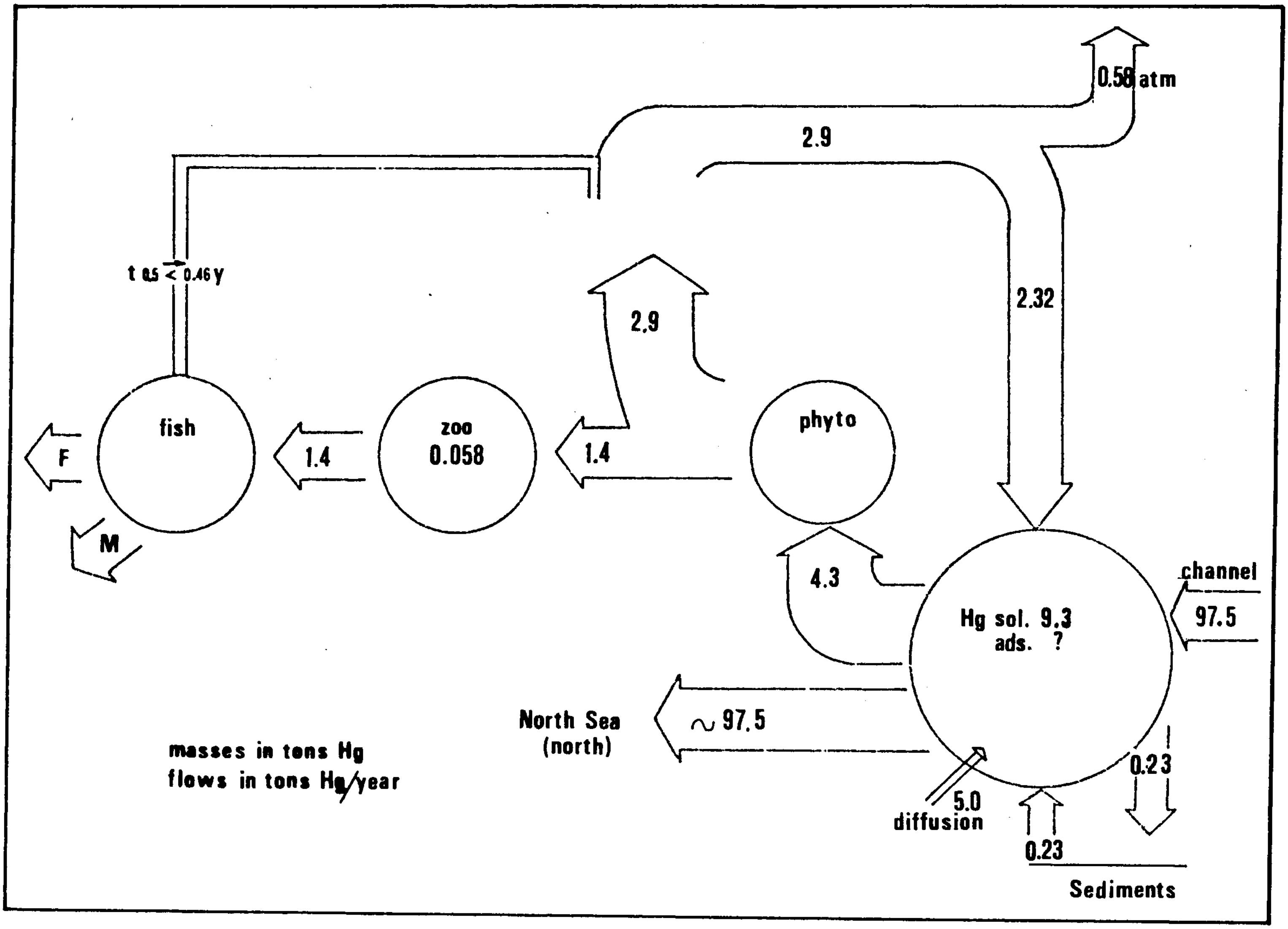


fig. 10.5.- Mercury pattern zone 2 global.

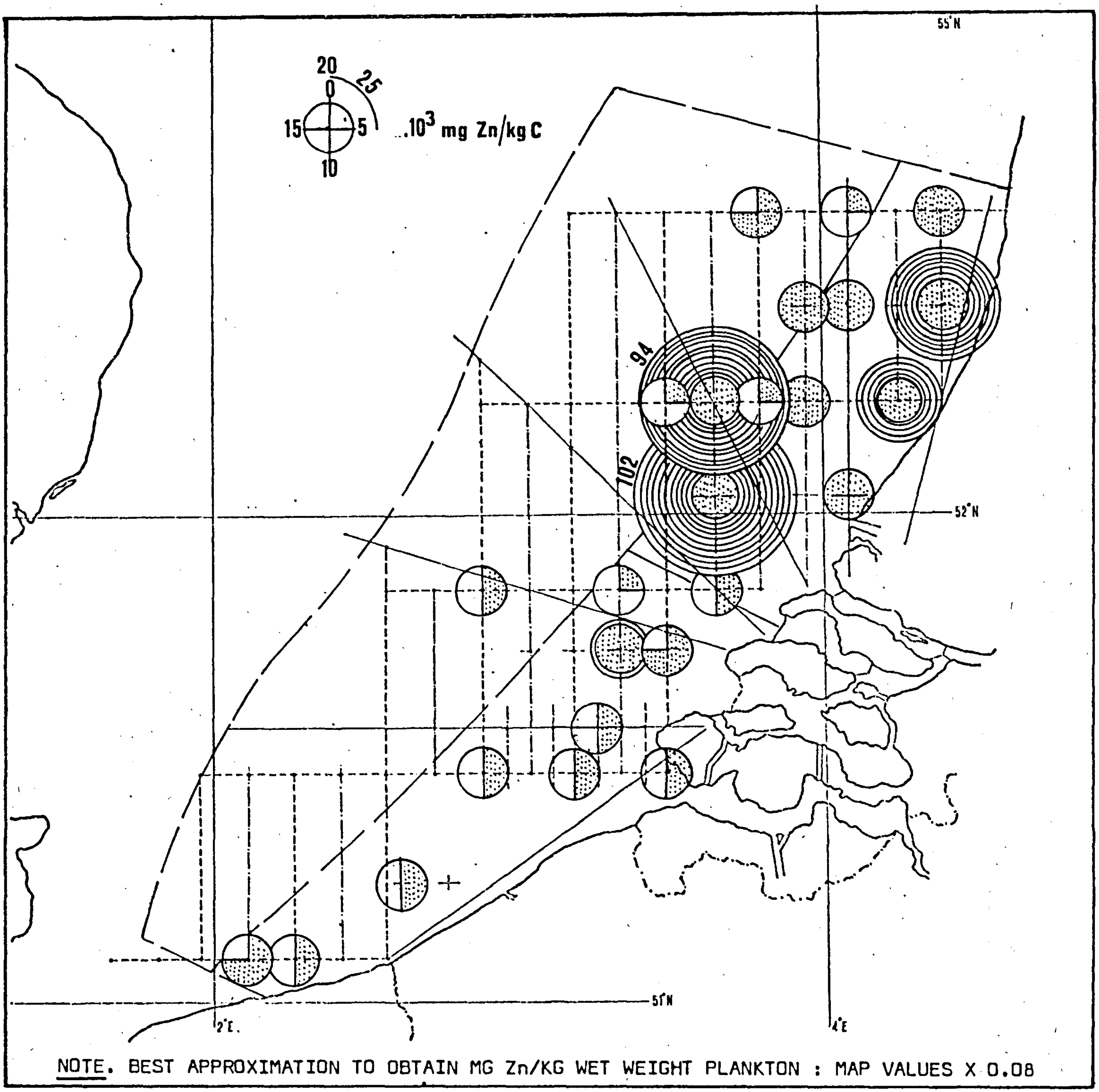
In a tentative model for the present *global* cycle of mercury [Wollast (1974)] the authors point out pathways between atmosphere and water column where the fallout of mercury by rain on ocean exceeds the evaporation by about 20 % . Considering the residual stationary concentration of *dissolved* mercury in the North Sea [ICES (1974)], we observe a deflation by a factor of 3 as regards the "equilibrium" concentrations generally admitted for the water column in global models [Anderson (1973)]. This fact may not be completely supported by the "promotion of productivity" observed in coastal regions, considering that the fraction of mercury engaged in the food chain is only 4 % of the total circulation (*cf.* fig. 10.5). In these conditions, one must admit that, somewhere, mercury escapes from the water column. We admit, in a first approach, that in zones like those under study, the water column feeds the atmosphere (so that the net balance is reversed as regards to the global cycle). As a consequence, figure 10.5 gives an output to the atmosphere of about 20 % of the flow provided by treatment of dead cells by bacteria. This flow represents, of course, the net balance between fallout by rain and evaporation of mercury. It is a rough approximation for a problem still under study, knowing that other mechanisms such as transportation by suspended matter may also support the depleted residual concentration observed in "dissolved" mercury.

As most of the mercury from phytoplankton is recycled in the water column, the dynamic behaviour of the two sectors (food web and hydrodynamic circulation) is determined in the final analysis by the uptake of mercury by fish, the excretion of mercury by fish, the death of the fish and the fishing activities. Fish have a typical feeding rate equal to 1,5 percent of body weight per day, *i.e.* 10 times a fish's body weight per year [Randers (1973)]. Since in zone 2 the total amount of plankton available and grazed per year is given by figure 10.3, the total mass of fish corresponding to zone 2 amounts to about 7100 t of carbon. The quantity of mercury in fish (see chapter IX) is but a small fraction of the total involved in the model; therefore, errors in the assumptions just made can have *little effect* on the behaviour in the other sectors of the model. But, as concerns the fish box, considering the yearly uptake of mercury, the average life time of fish, *i.e.* about three years [Randers (1973)] and supposing no overfishing problems occurs, one must admit, in order to explain both the relatively low mean content of mercury in fish and the increment of that mercury content in time, that the half-life of mercury in the excretion processes of fish is a little shorter than the value generally admitted in the literature, *i.e.* 0.46 year [Montague (1971)].

Finally, as concerns the border-line water column-sediments, we assume that the *net* balance is zero, since, except for some coastal regions where silt deposit occurs, no accumulation of mercury was detectable. The relative values of the flows returning to the water column and the fraction attaining the bottom is given by comparison to a similar figure for the silicium budget in the North Sea [McCave (1973)], still considering that the relatively short residence time of the water masses in the zones under study, rendered negligible the direct contribution of mercury in solution, when compared with the mercury transported by the detrital material.

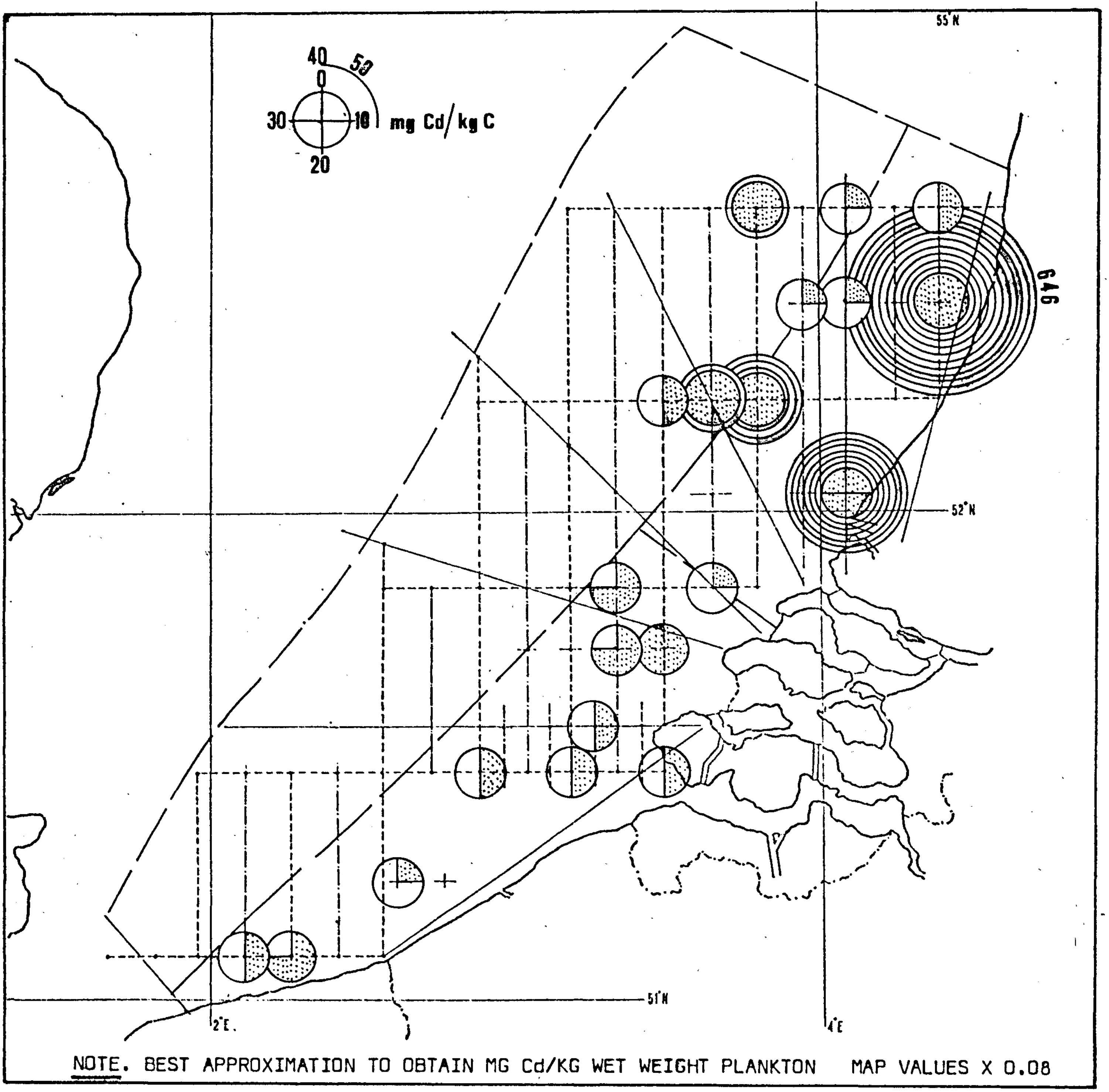
In another field, and in order to complete our knowledge of the interactive part of the pollutant's dispersion models, a complete survey of trace metals in plankton material was prepared. The samples were lyophilisated, after collection on a decreased mesh size net. Intercalibration experiments for low temperature dry ashing technique and wet digestion of the residues (EPA methods) were conducted [Gillain (1973)]. For practical reasons, the results (see table 10.2) are given in milligram of metal per kilogram of carbon in the considered samples (mostly zooplankton) and corrected for the presence of phytoplankton and other impurities, considering the simultaneously determined content of silicium, the carbon-nitrogen and the carbon-phosphorus ratio's [Jacob (1974)].

This list requires no further comment, since the values presented were directly used in some of the above described budgets. Nevertheless, the figures 10.6 to 10.10 show the spatial distribution of zinc, cadmium, copper, mercury and lead respectively, in the considered plankton compartment.



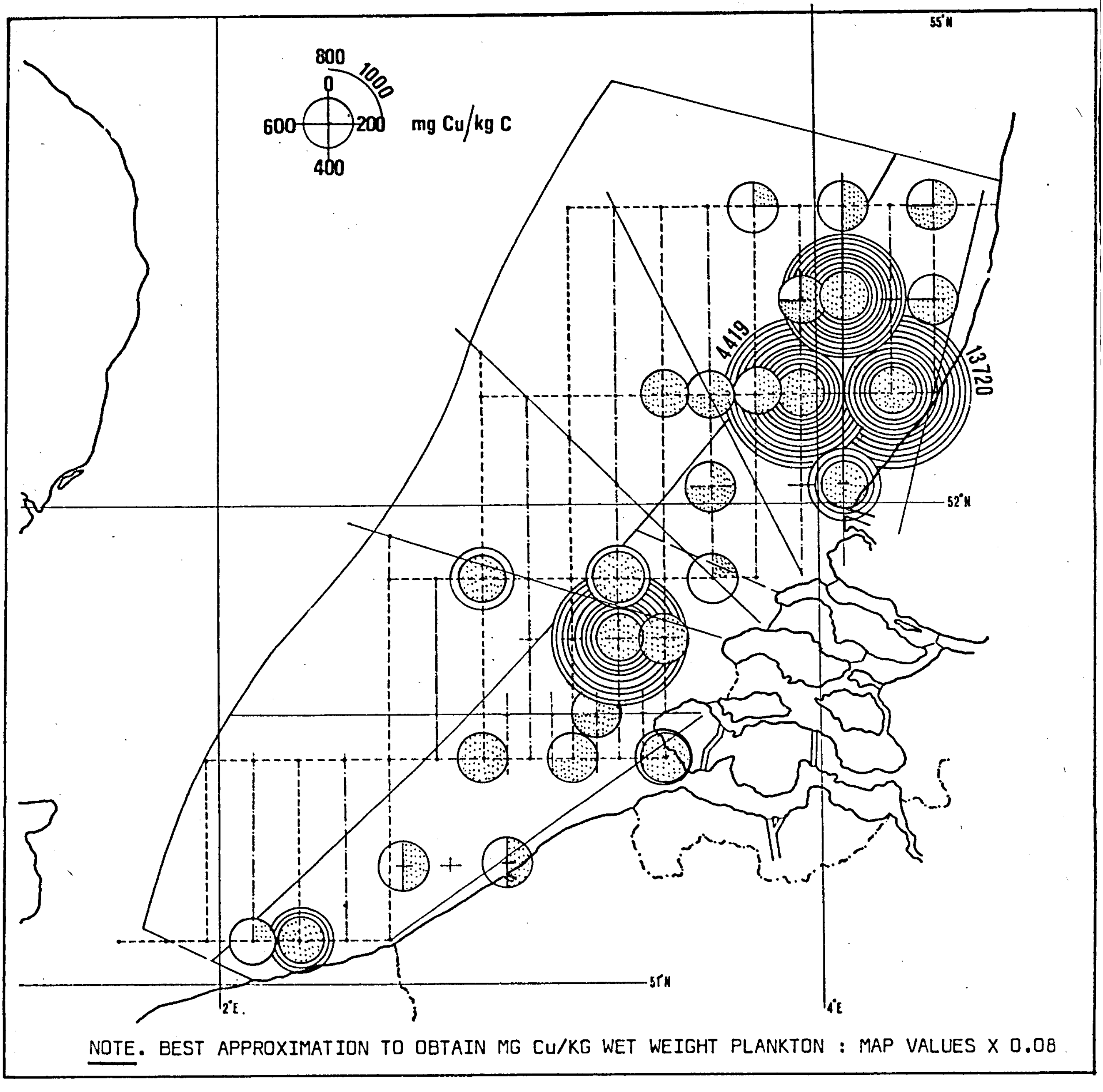
NOTE. BEST APPROXIMATION TO OBTAIN MG Zn/KG WET WEIGHT PLANKTON : MAP VALUES X 0.08

fig. 10.6.- Zinc content of lyophilisated plankton samples.



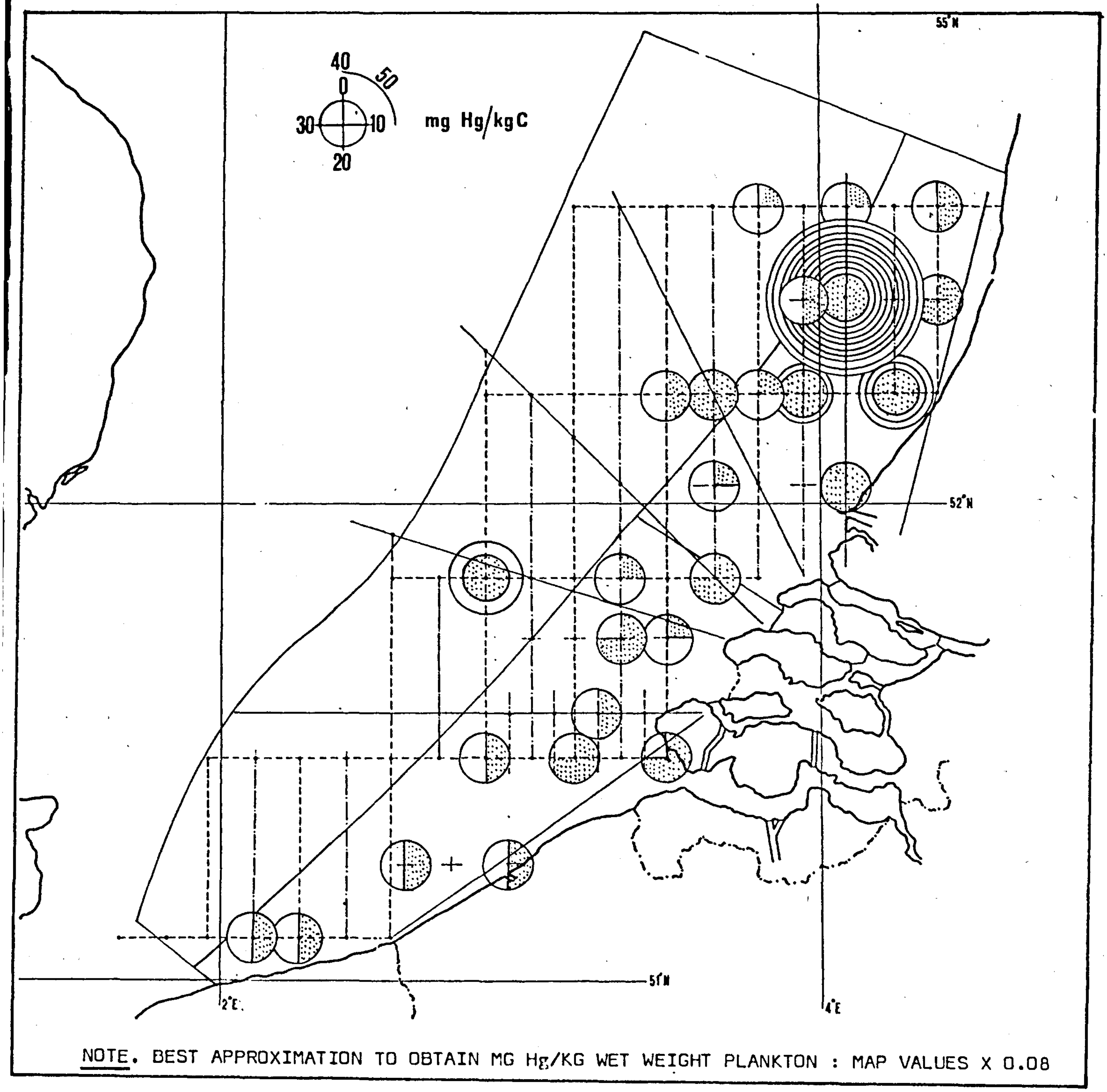
NOTE. BEST APPROXIMATION TO OBTAIN MG Cd/KG WET WEIGHT PLANKTON MAP VALUES X 0.08

fig. 10.7.- Cadmium content of lyophilisated plankton samples.



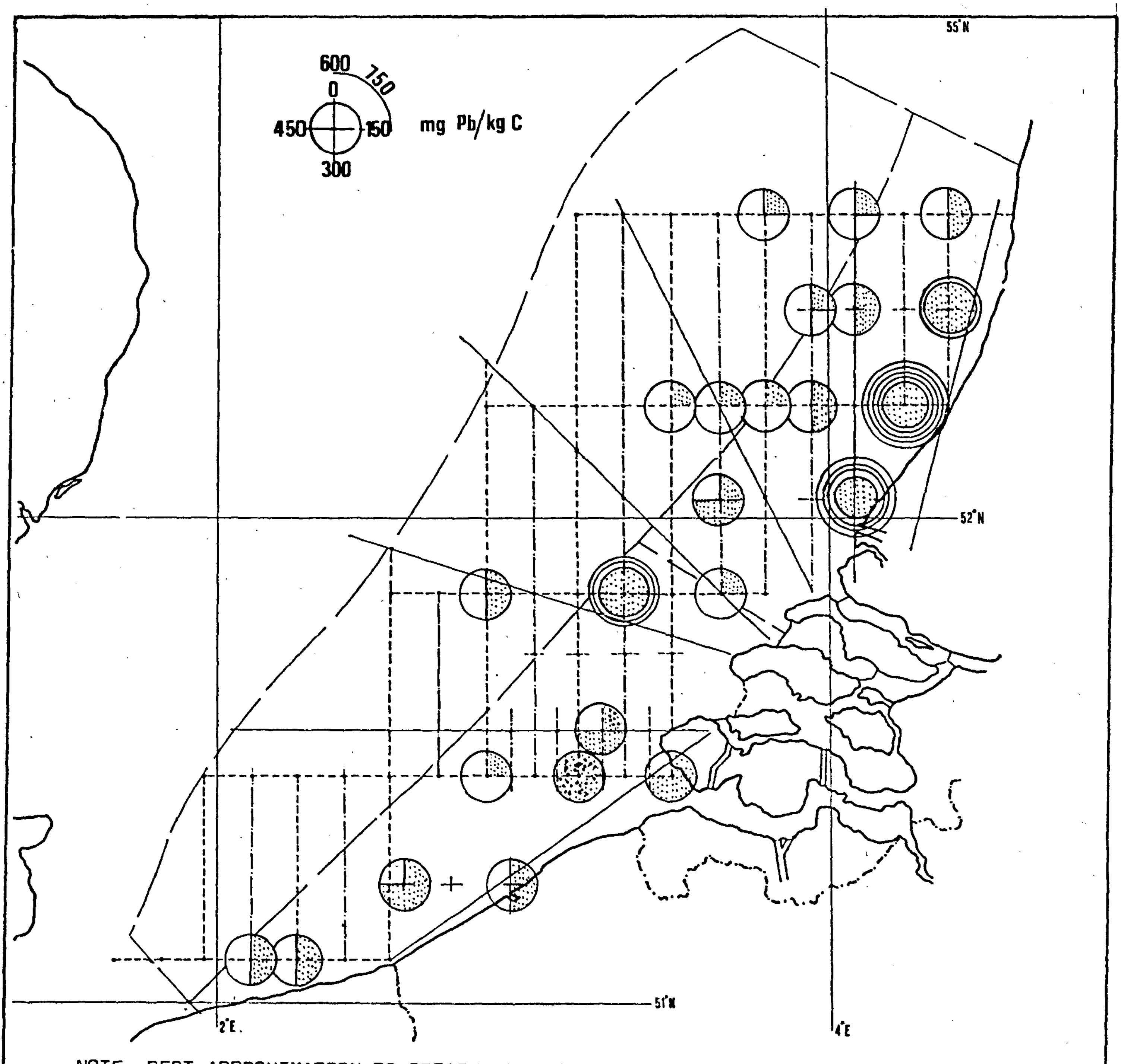
NOTE. BEST APPROXIMATION TO OBTAIN MG Cu/KG WET WEIGHT PLANKTON : MAP VALUES X 0.08

fig. 10.8.- Copper content of lyophilisated plankton samples.



NOTE. BEST APPROXIMATION TO OBTAIN MG Hg/KG WET WEIGHT PLANKTON : MAP VALUES X 0.08

fig. 10.9.- Mercury content of lyophilisated plankton samples.



NOTE. BEST APPROXIMATION TO OBTAIN MG Pb/KG WET WEIGHT PLANKTON : MAP VALUES X 0.08

fig. 10.10.- Lead content of lyophilisated plankton samples.

3.- Chlorinated pesticides and PCB's

A complete inventory of chlorinated pesticides and PCB's in the water column, sediments and plankton was made between November of 1970 and December of 1973, but, in view of the considerable task which is the inventory alone, the dynamics study of the distribution has not yet been undertaken. Indeed, the technical problems arising in the application of the traditional methods of analysis : extraction, followed by gas-chromatographic determination, are well known.

The figures 10.11, 10.12 and 10.13 give a global outlook of the distribution of these pollutants in the three sections under study[1].

A preliminary report [Salsmans (1973)] exposes the working philosophy used in the dynamics study of the chlorinated pesticides distribution, mainly as regards the definition of interaction coefficients and the flow of materials within the food web. Mass spectrometry and its possibilities in this field of investigation are the subjects of a complementary paper [Van Binst (1974)].

4.- Sediments

The chemical study of the sediments in the network is, as we know, based upon a sampling net of 1000 points [Wollast (1973)]. The collected samples of sediments taken in this network were analyzed by ashing between 550° and 1000° . Moreover, the heavy metal contents (Zn, Pb, Cu, Mn and Fe) were determined by atomic absorption on some 180 samples.

As has been previously shown [Wollast (1972)], weight loss at 550° is directly related to the presence of silt[2]. The corresponding chart (fig. 10.14) shows the belgian coast to be a privileged zone of silt accumulation in relation to the whole of the network studied. The

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[1] The "fish box" is treated separately, see chapter IX.

[2] As proposed by McCave (1973) the term "mud" is taken to comprise all material of quartz-equivalent sedimentation diameter $< 63\ \mu m$, i.e. silt and clay sizes.

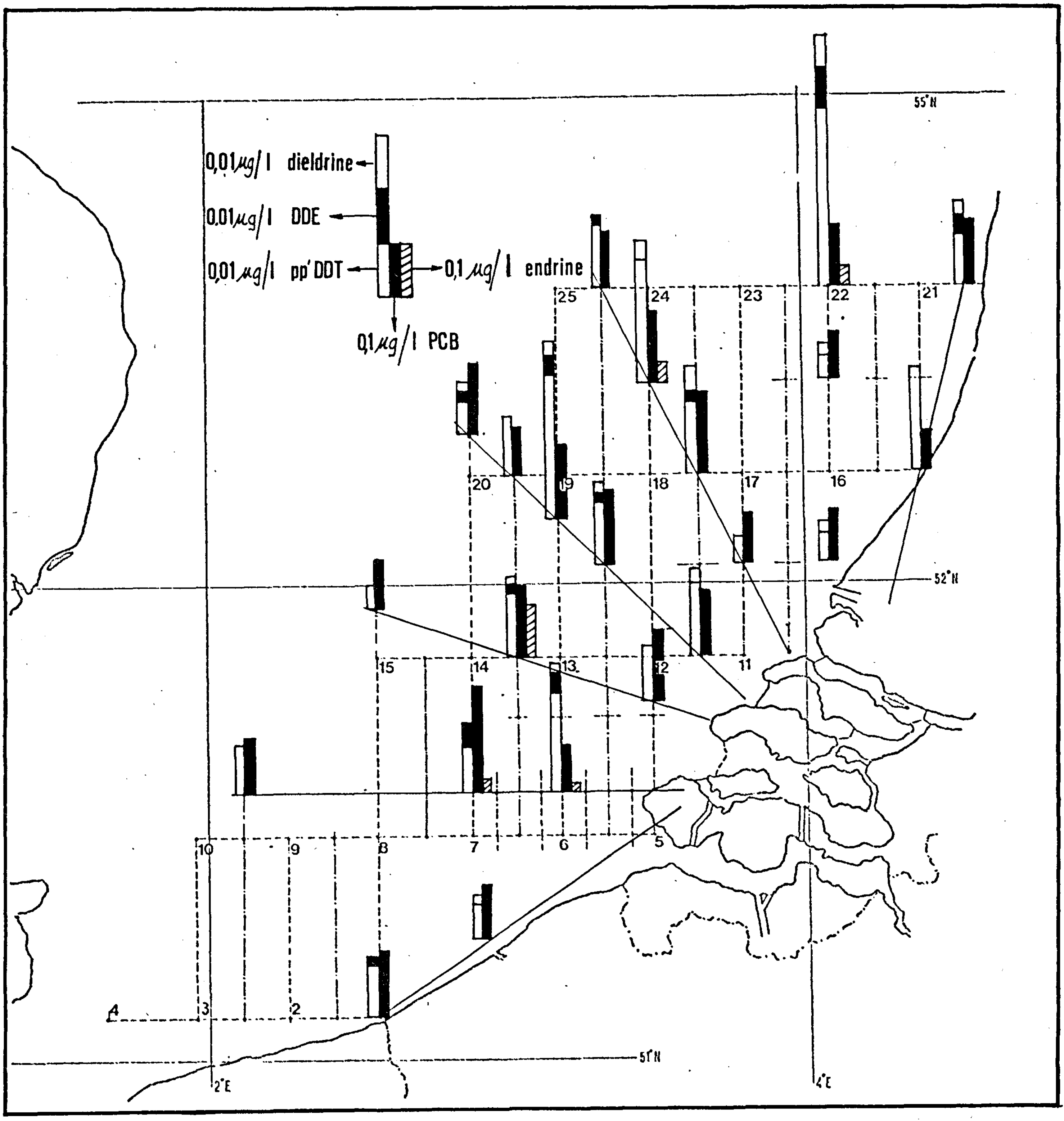

fig. 10.11.- Pesticides in seawater (cruise september 1972).

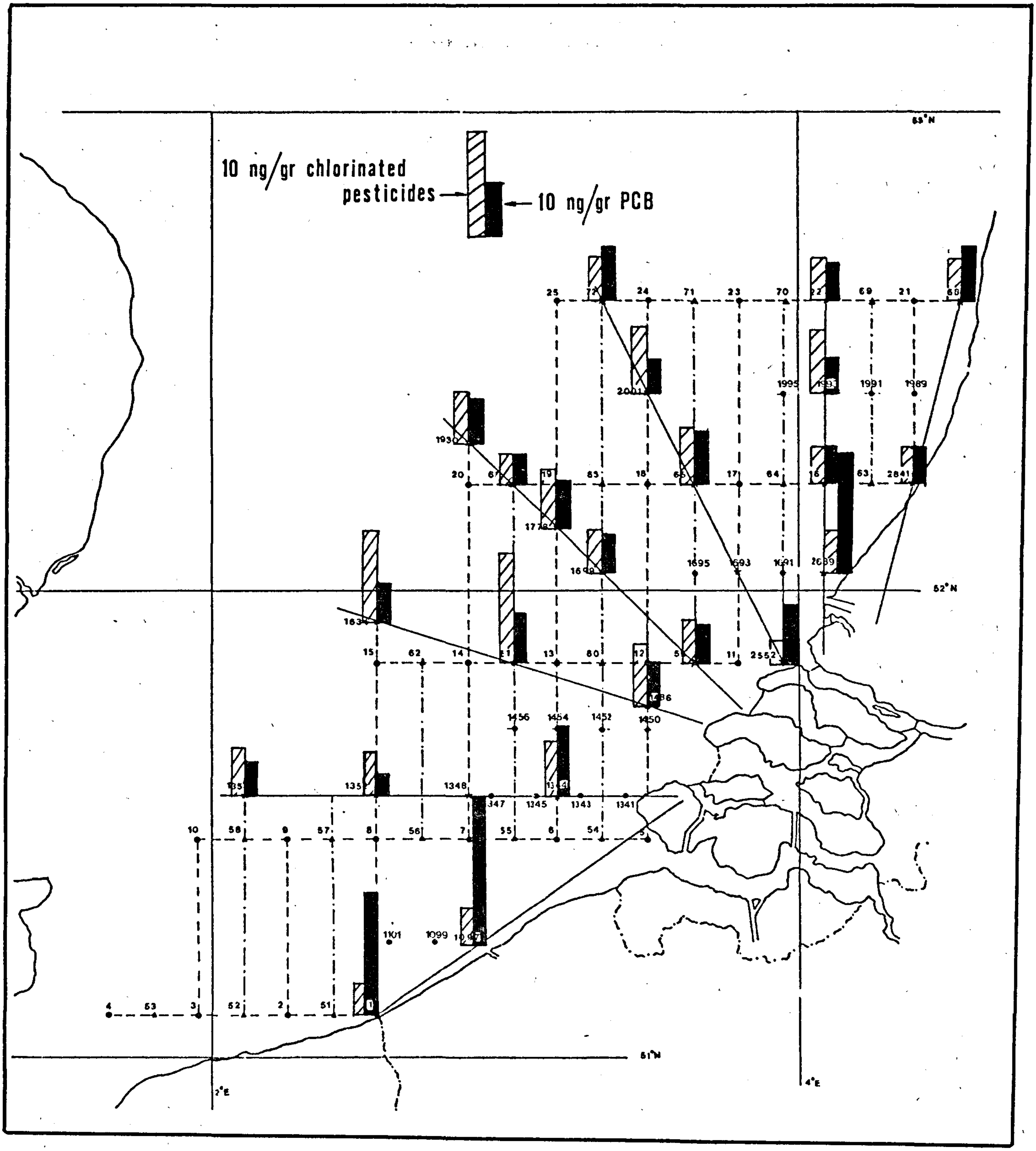

fig. 10.12.- Pesticides in sediments (cruise september 1972).

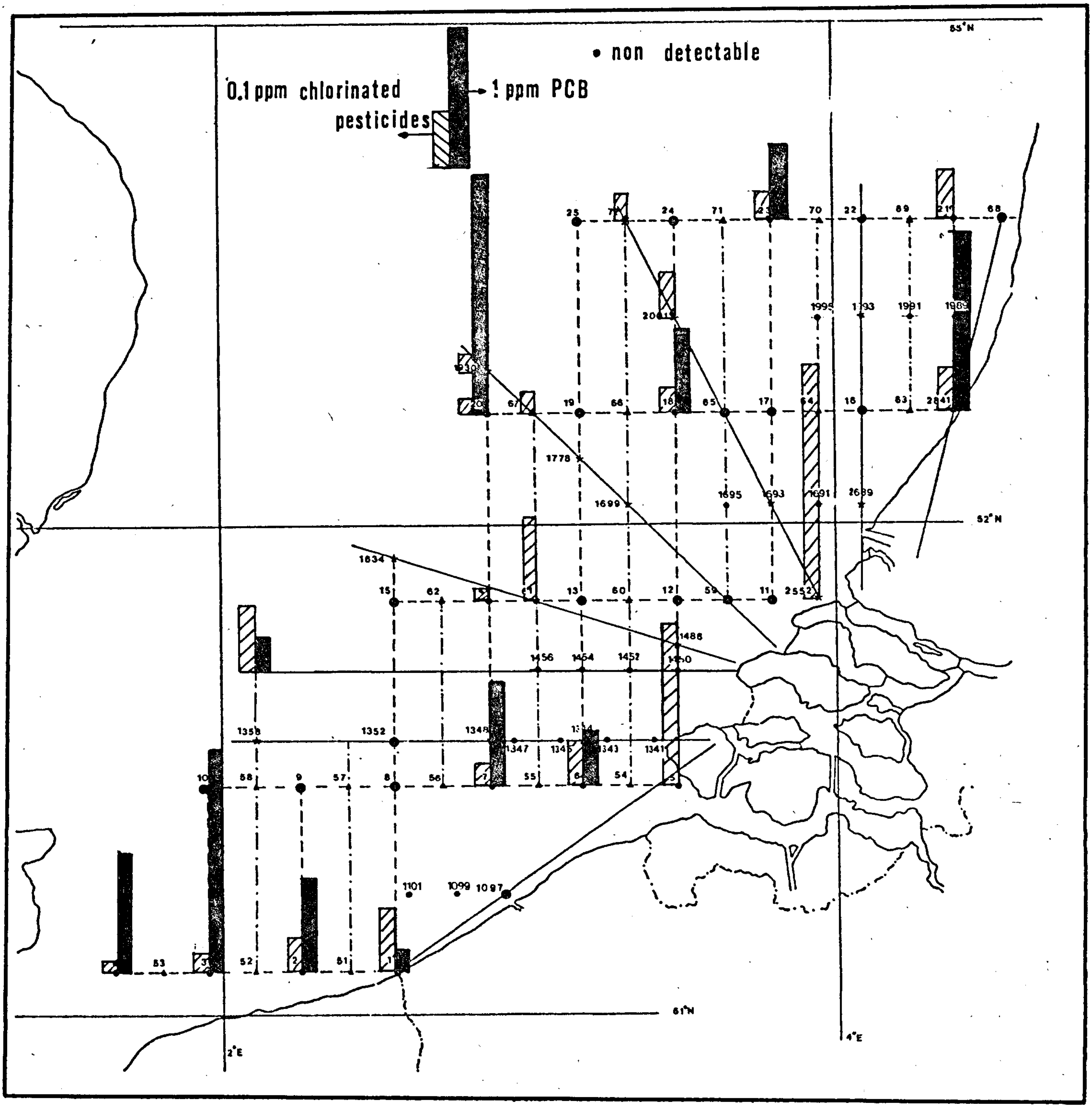

fig. 10.13.- Pesticides in plankton (samples taken during 1972 and 1973).

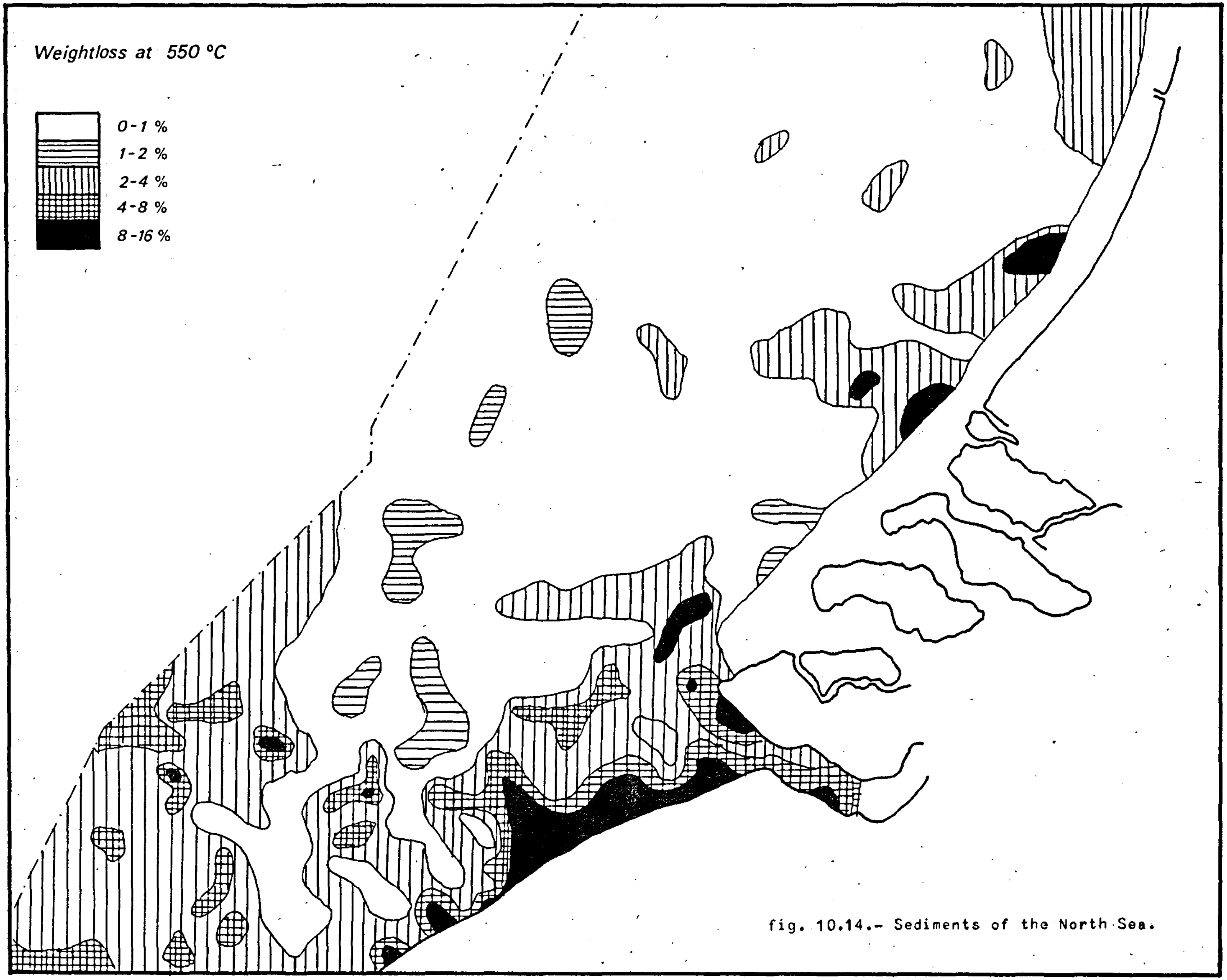

fig. 10.14.- Sediments of the North Sea.

same situation likely occurs at the exit of the Rhine estuary and along the dutch coast between "Hoek van Holland" and Katwijk.

The weight loss chart between 550° and 1000° corresponding to the $CaCO_3$ contents (fig. 10.15) shows the carbonate-rich sediments to be mainly within the southern part of the network. In these sediments, a large part of the carbonates consists of shell-fish debris. In the south-western part of the network, one must moreover consider a contribution of chalk sediments erosion from the Pas de Calais.

As for the heavy metals[1], iron (fig. 10.16), manganese (fig. 10.17), copper (fig. 10.18) and zinc (fig. 10.19), the distributions follow those of the silts, in accord with the previously established relations [Wollast (1972)].

Lead, on the other hand (fig. 10.20), is distributed as previously, erratically, asides from the dutch and belgian coastal zone where one finds a systematically higher lead content. There are other spots, distributed on the whole network area, where the concentrations are abnormaly high. It must, however, be noted that lead content is never very high, contrarily to that of the other heavy metals.

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[1] Chlorinated pesticides and P.C.B. 's are specifically discussed in § 3.

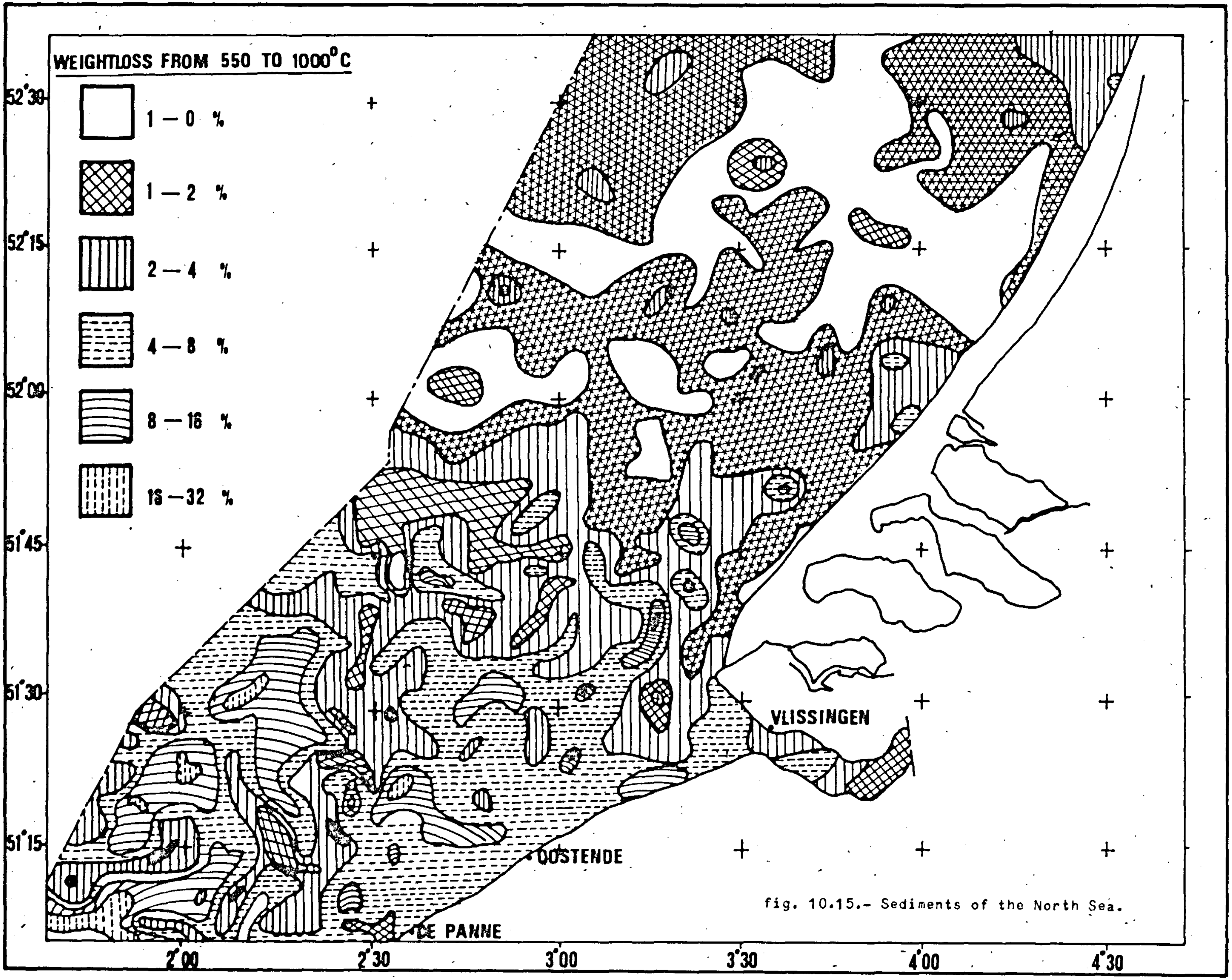

fig. 10.15.- Sediments of the North Sea.

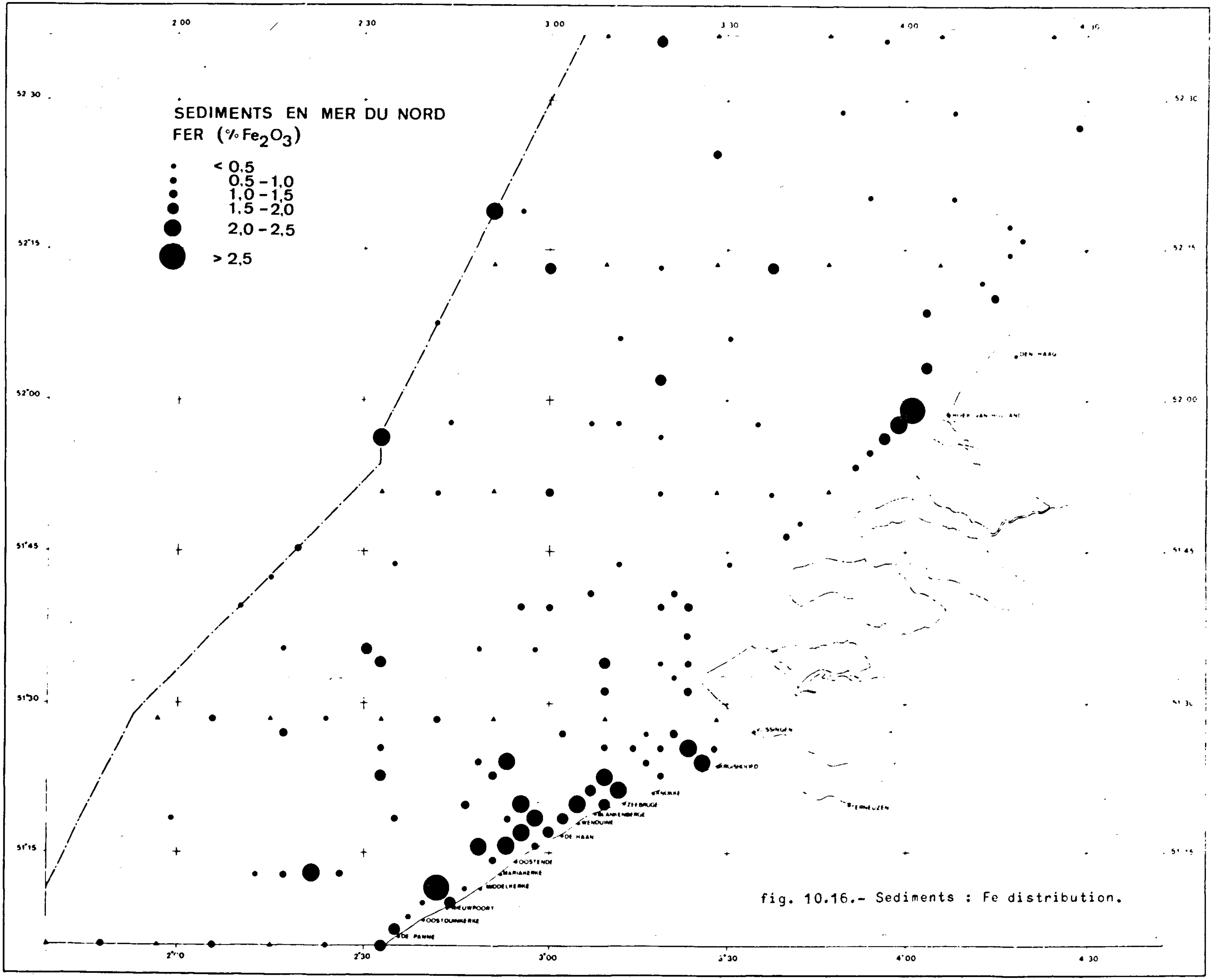

fig. 10.16.- Sediments : Fe distribution.

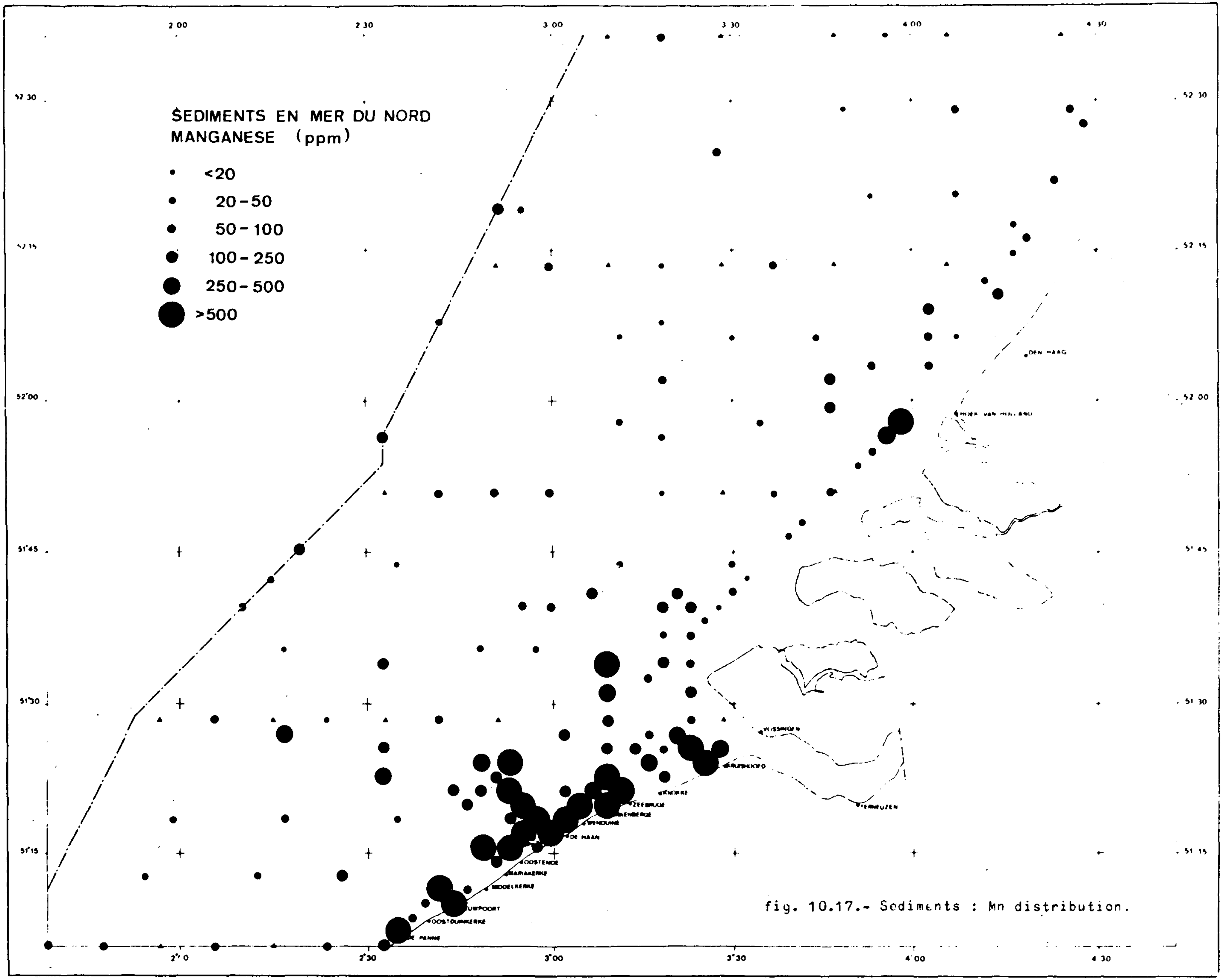

fig. 10.17.- Sediments : Mn distribution.

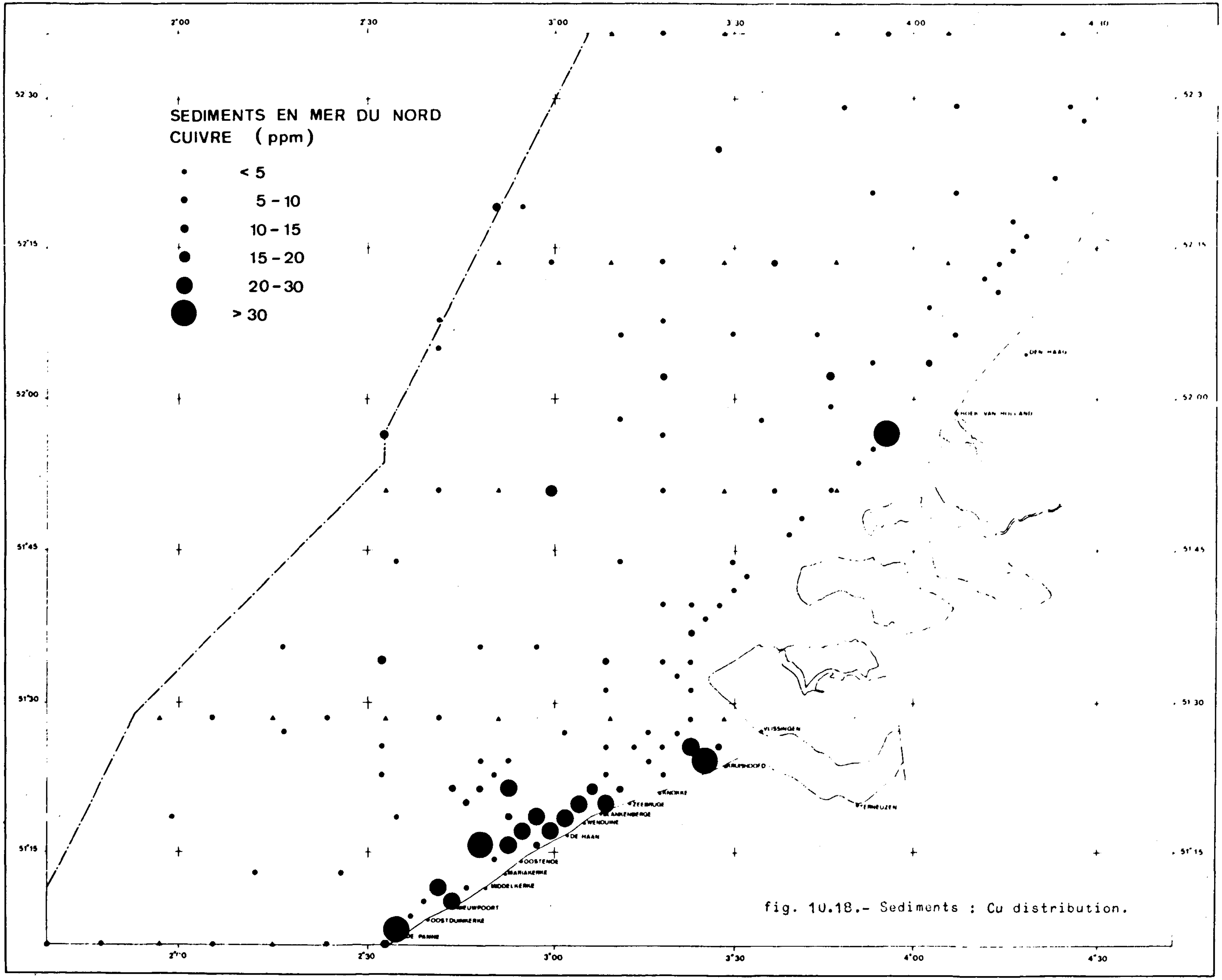

fig. 10.18.- Sediments : Cu distribution.

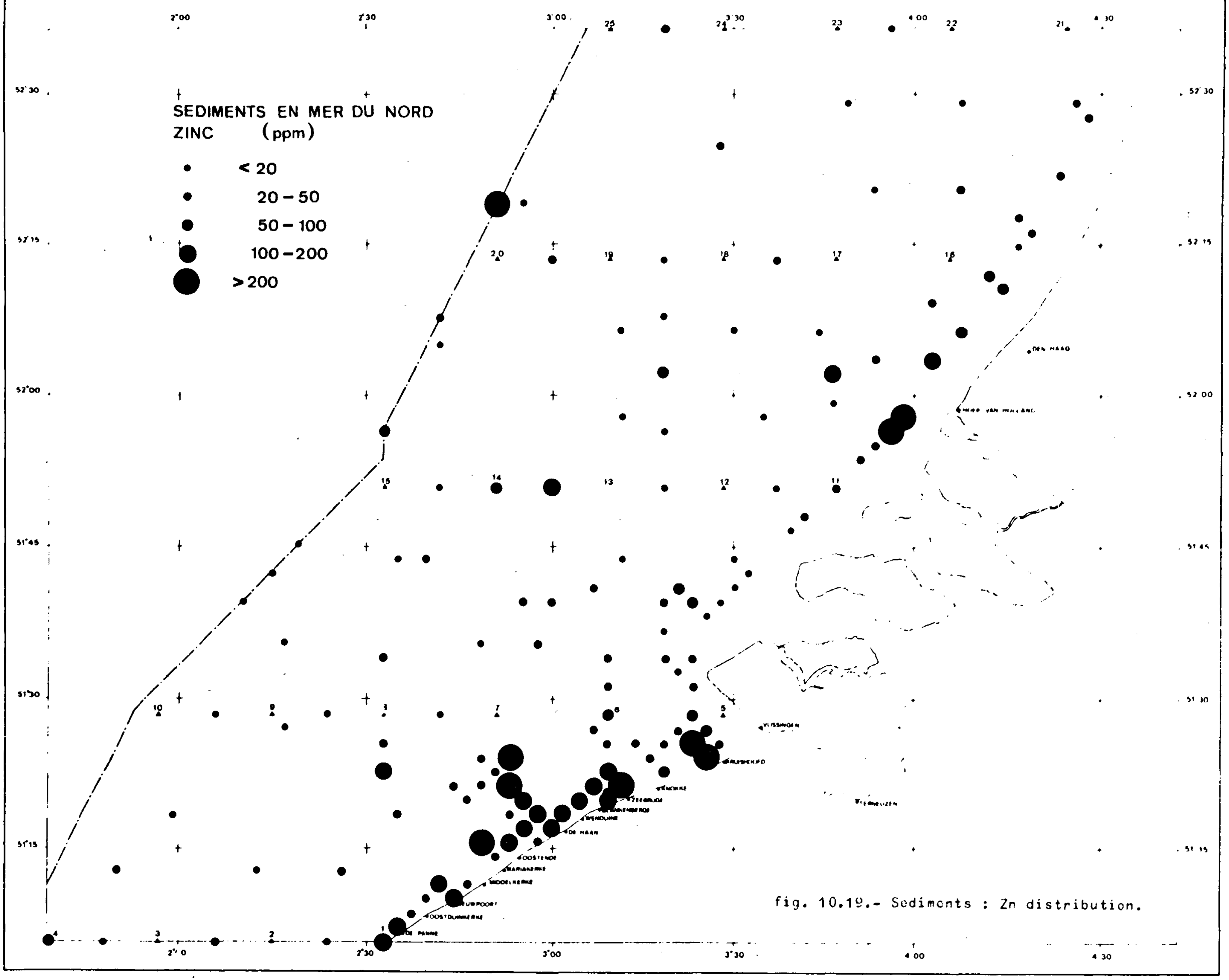

fig. 10.19.- Sediments : Zn distribution.

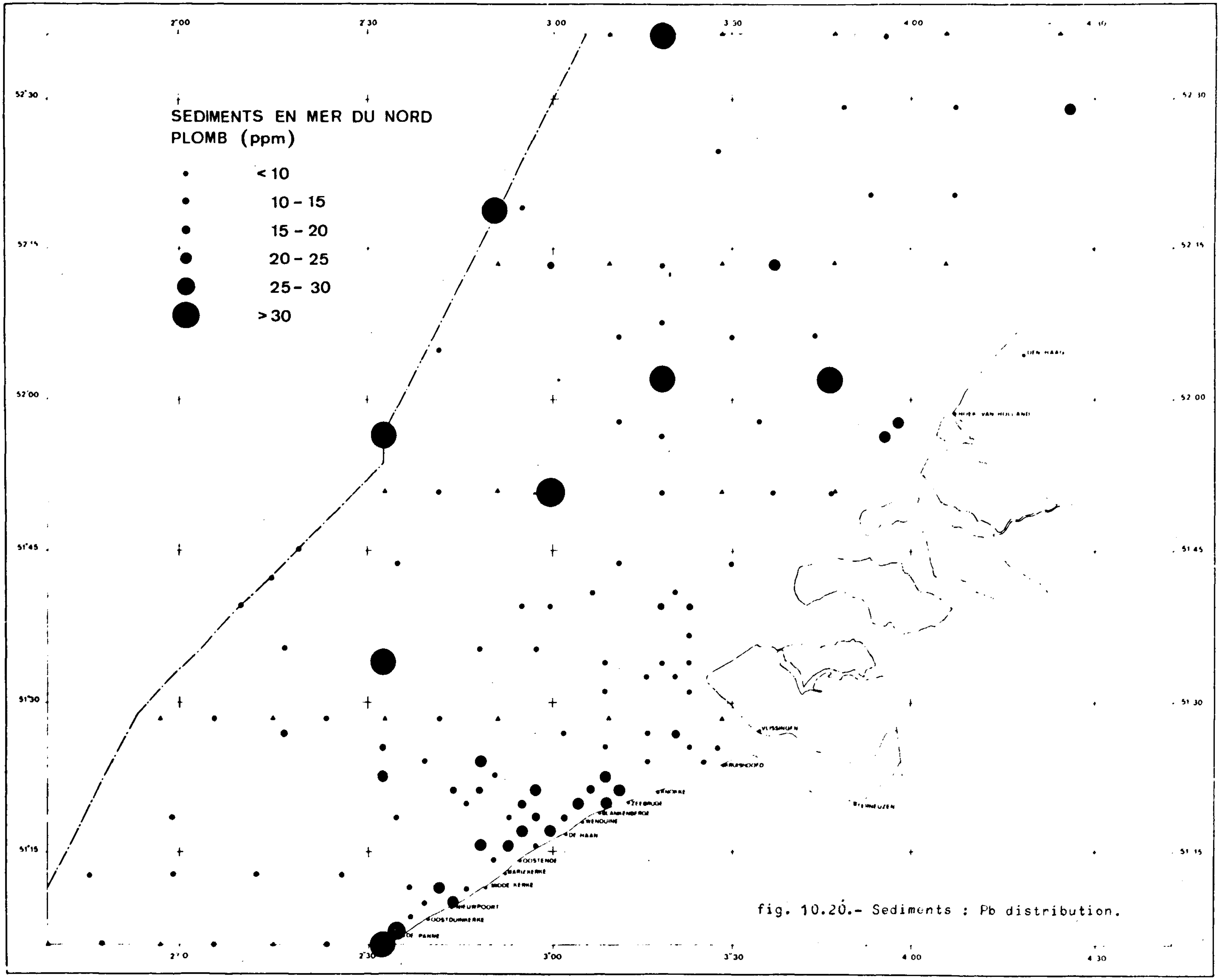

fig. 10.20.- Sediments : Pb distribution.

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