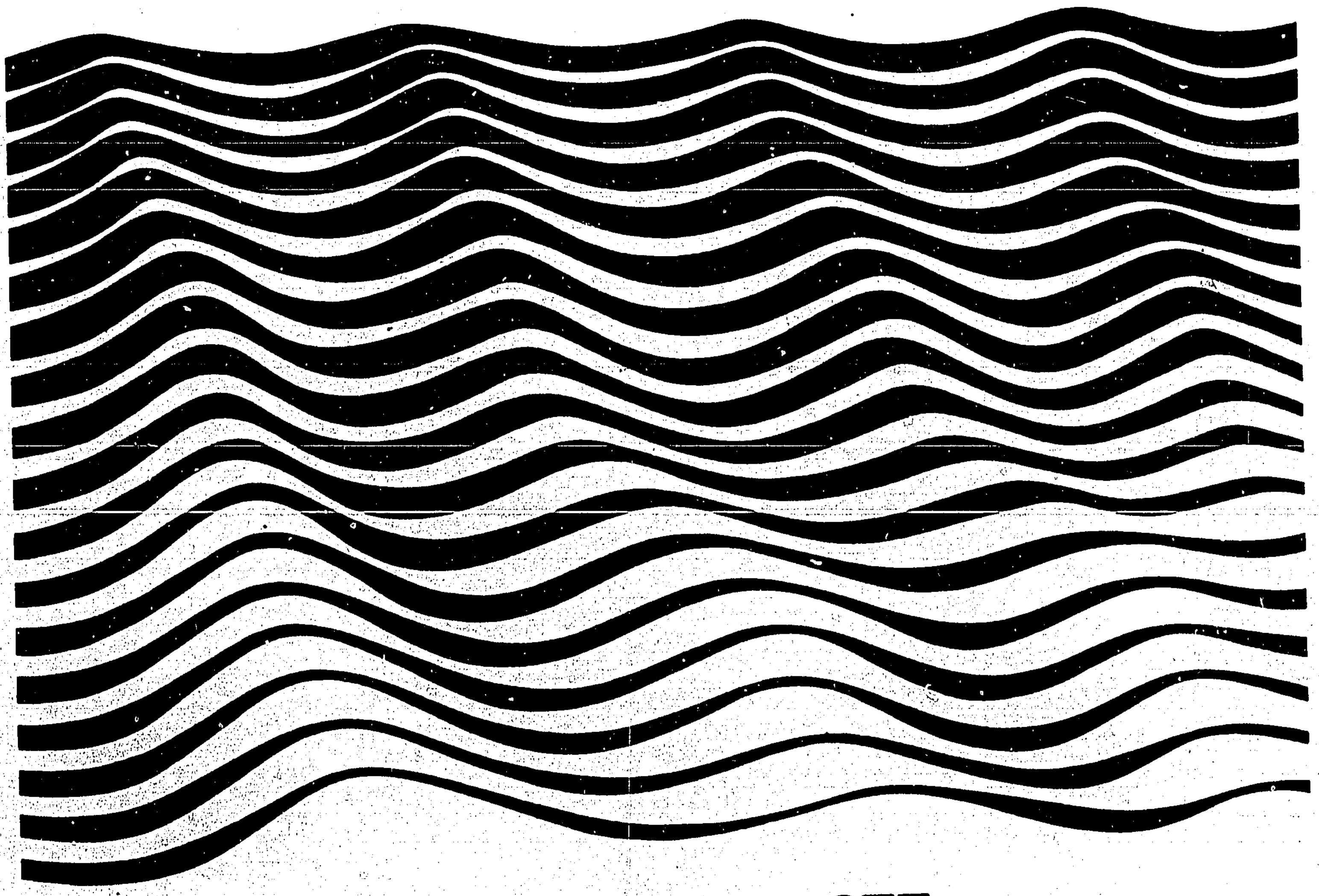
Unesco reports
in marine science 2

Marine ecosystem modelling in the Mediterranean

Report of the Second Unesco Workshop on Marine Ecosystem Modelling



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1. GENERAL REPORT OF THE WORKSHOP

1.1. Summary

The second subregional workshop on marine ecosystem modelling of the Eastern Mediterranean, was held at the Inter-University Centre in Dubrovnik from October 18 to 22, 1976. The first workshop was convened by Unesco in Alexandria, Egypt in December 1974, following the recommendations of the IBP/Unesco[1/] Symposium on the Eastern Mediterranean which was held in Malta in September 1973. During the symposium the scientists from the Eastern Mediterranean countries expressed interest in developing the concept of ecosystem modelling in the Eastern Mediterranean Sea, a sea which is considered to present a unique opportunity for the evaluation of the impact of human activity and technological development on the marine environment.

The participants at the Dubrovnik workshop were welcomed by Dr. B. Kustrin on behalf of the Yugoslav National Commission for Unesco, and by Prof. P. Strohal on behalf of the Centre for Marine Research of the "Rudjer Bošković" Institute, Zagreb, Yugoslavia. Dr. S. Morcos (Unesco) welcomed the participants on behalf of Unesco and invited Prof. J.M. Peres (Station Marine d'Endoume, Marseille, France) and Prof. Strohal to act as Chairman and Co-chairman, respectively. Dr. T. Hopkins (Bigelow Laboratory, Westboothbay Harbour, U.S.A.) was elected Rapporteur. The meeting was attended by 34 participants (see Annex). The participants were briefed by Dr. Morcos on the scope of the meeting and activities of Unesco in the field of ecosystem modelling. Dr. S. Kečkeš (UNEP) described the UNEP-sponsored Action Plan for the Mediterranean, particularly the co-ordinated programme of pollution research and monitoring, and its relation to the workshop. Dr. D. Calamari of FAO(GFCM) spoke on research on the effects of pollutants on organisms, populations and communities of ecosystems within the framework of the FAO(GFCM)/UNEP pilot projects.

A programme of lectures was given to provide the meeting with essential scientific background information. These lectures included :

(i) Introduction to Modelling

- Dr. T. Legović : Principles and Procedure of Modelling of Ecosystems.

(ii) Effects of Modelling in the Mediterranean

- Dr. T. Hopkins : Modelling the Southern Levantine Coastal Ecosystems, Alexandria workshop, December 1974.
- Dr. R. Dugdale : Experience in the Aegean Sea
- Dr. L. Jeftić : Experience in the Adriatic Sea
- Dr. P. Nival : Experience in the Western Mediterranean.

In his briefing to the participants, Dr. Morcos pointed out that since the Malta Symposium, 1973, a major development has taken place in Mediterranean

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1/ See Appendix I, page 101, for list of abbreviations and acronyms used in this Report.

research through the adoption (Barcelona, February 1975) of the UNEP-sponsored Action Plan for the Mediterranean, particularly the Co-ordinated Monitoring and Research Programme, currently consisting of seven pilot projects. Such a major programme could benefit greatly from the development of modelling concepts and methodology among participating marine scientists in the Mediterranean. Because of its relevance to the UNEP Action Plan, this workshop has enjoyed the full support and co-operation of UNEP and FAO. Financial contributions from UNEP and the FAO(GFCM)/UNEP pilot projects provided the means for increasing the number of scientists invited to the workshop. He then indicated that the earlier plans for the workshop had been to focus on the Eastern Mediterranean; but as this strong relevance to the Action Plan emerged, it subsequently was decided to increase the membership and scope of the workshop to encompass the entire Mediterranean Sea. By so doing it was hoped that the discussions and recommendations of the workshop would be of significant importance to the modelling efforts in the entire Mediterranean, and, as such, will represent a new frontier for the Mediterranean Action Plan.

Dr. S. Kečkeš (UNEP) emphasized the relevance and applicability of modelling to the pollution research and monitoring pilot projects that have resulted from the UNEP-sponsored Action Plan for the Mediterranean. He further pointed out the absence of a modelling component in the present pollution research and monitoring pilot projects co-ordinated by UNEP and implemented in close co-operation with a number of UN bodies. These projects were enumerated as follows:

(i) Co-ordinated Mediterranean pollution monitoring and research programme (7 pilot projects):

- Baseline studies and monitoring of oil and petroleum hydrocarbons in marine water (IOC/WMO/UNEP; operational)
- Baseline studies and monitoring of metals, particularly mercury and cadmium, in marine organisms (FAO(GFCM)/UNEP; operational)
- Baseline studies and monitoring of DDT, PCBs and other chlorinated hydrocarbons in marine organisms (FAO(GFCM)/UNEP; operational)
- Research on the effects of pollutants on marine organisms and their populations (FAO(GFCM)/UNEP; operational)
- Research on the effects of pollutants on marine communities and ecosystems (FAO(GFCM)/UNEP; operational)
- Problems of coastal transport of pollutants (IOC/UNEP; operational)
- Coastal water quality control (WHO/UNEP; operational).

(ii) Other projects of the Action Plan for the Mediterranean related to the Co-ordinated Mediterranean Pollution Monitoring and Research Programme:

- Biogeochemical studies of selected pollutants in open waters of the Mediterranean (IAEA/IOC/UNEP; operational)
- Role of sedimentation in the pollution of the Mediterranean Sea (Unesco/UNEP; operational)

- Pollutants from land-based sources in the Mediterranean (WHO/ECE/UNIDO/FAO/Unesco/IAEA/UNEP; operational)
- Transport of pollutants through atmosphere and their input into the Mediterranean (WMO/WHO/UNEP; planned)
- Epidemiology of recreational coastal waters (WHO/UNEP; planned)
- Effects of pollution on Mediterranean fisheries resources and aquaculture (FAO/UNEP; planned)
- Intercalibration of analytical techniques and instrument maintenance services (IAEA/UNEP; operational).

Following the explanations given by Dr. Kečkeš on the scope and output of each project, the workshop decided it could most efficiently direct its discussions on modelling by dividing into three groups that matched participant expertise with those pilot projects which lent themselves most fruitfully to modelling discussions. They were designated as:

- Group 1 : Ecosystems and communities
- Group 2 : Heavy metals in marine ecosystems
- Group 3 : Physical processes.

Individual summaries of these groups are presented in the following paragraphs.

Working group 1, Ecosystems and communities

The working group met under the chairmanship of Dr. B.O. Jansson (Sweden). Dr. P. Nival (France) acted as Rapporteur. After a detailed discussion of the possible use of modelling in the pollution research of the Mediterranean Sea, the group felt that future modelling work should proceed on three levels of complexity, namely : (1) large-scale ecosystems, such as those of the North Adriatic Sea or the Aegean Sea; (2) meso-scale ecosystems, such as those of the Saronikos Bay, Izmir Bay, or Rijeka Bay, and (3) small-scale ecosystems, such as those of *Posidonia* beds or experimental lagoons.

Recalling the fact that the present knowledge of fundamental processes determines the quality and predictive ability of ecosystem models, the group felt that highest priority should be given to studies of small-scale ecosystems. Large-scale models, for the time being, should mainly be used for giving the physical framework (budgets, areas of upwelling, etc.) and inputs to intensively studied smaller scale ecosystems. These should be investigated following the entire set of modelling procedures: building of a conceptual model, field and laboratory measurements of state variables and rates, formulization, calibration, simulation, validation, and sensitivity analysis.

The need was emphasized to generate clear descriptions of stressed ecosystems which would incorporate both their internal dynamic structure and their relationship to the external environment. The *Posidonia* beds were chosen as being an important, stressed subsystem of the coastal areas and which have well defined boundary conditions. Much effort was put into building a conceptual model of the *Posidonia* beds and their place in the total system. A "blow up" of the *Posidonia* plant with epiphytes, nutrients, pollutants and connecting flows and processes were similarly constructed, and the procedures of formulization, calibration, simulation and validation were demonstrated.

A case study of a pollution-stressed deep bay that is dominated by the sea was discussed. A conceptual model was constructed containing a eutrophied subsystem in a sewage plume, connected hydrodynamically to an oligotrophic subsystem mainly sustained by the sea.

A shallow, semi-enclosed bay dominated by land runoff was adopted as another important type of Mediterranean small-scale ecosystem. A conceptual model of such a bay exposed to sizeable agricultural runoff was constructed.

Basic processes such as nutrient uptake dynamics and herbivore grazing were regarded as in urgent need of intensive modelling. In conjunction with the Group 3 on physical processes, a process model of the pelagic primary and secondary production complex under eutrophication was built and discussed.

A benthic organismic assemblage under heavy pollution stress was considered as another serious and widespread Mediterranean problem. The different zones, from the azoic zone close to the sewage outlet, to the areas dominated by only a few pollution species, and to the slightly affected margins were regarded as a complicated benthic sequence to model. Not only the physical dynamics of the sewage plume has to be incorporated into such a benthic complex, but also the processes of immigration, emigration and recolonization.

Working group 2, Heavy metals in marine ecosystems

The working group met under the chairmanship of Dr. M. Bernhard (Italy). Dr. L.J. Saliba (Malta) and Dr. T. Balkas (Turkey) acted as Rapporteurs. In determining the scope of its work, the group took particular cognizance of the relevant FAO(GFCM)/UNEP Mediterranean Pollution Pilot Projects, i.e. :

a. Baseline studies and monitoring of metals, particularly mercury and cadmium in marine organisms,

b. Research on the effects of pollutants on marine organisms, and their populations, and

c. Research on the effects of pollutants on marine communities and ecosystems.

A provisional list of "heavy metals", particularly those with biological functions, was discussed and agreed upon. The relative merits of single-element and multi-element models were considered in terms of practicability. It was decided to adopt a single-element model procedure for the first approach, and to start with mercury. Models for other elements could be constructed in a similar manner, taking into account the necessary adaptations. It was also decided to give particular attention to the biological species agreed on for metal monitoring in the FAO(GFCM)/UNEP pilot projects, e. g. Mytilus galloprovincialis, Mullus barbatus, and Thunnus thynnus thynnus.

The following general scheme of work was adopted:

a. origin (natural and anthropogenic sources) of mercury,

b. distribution and pathways to and within the marine environment,

c. physical and chemical effects (including uptake and loss), and

d. methodology.

It was agreed to adopt the box or compartment type model for conceptual evaluation; several of these were made for illustration and discussion. It was also agreed that body-burden in organisms would be expressed as micrograms of mercury per kilogram freshweight (μg Hg/kg FW), rather than as ppm or ppb.

A conceptual overall model was constructed to illustrate the pathways between the various sources of mercury entering into the marine environment, and the pathways and cycles within the marine environment itself. Generalized sub-models illustrating the interactions in the marine environment, with particular reference to the selected organisms, were similarly constructed.

The relationships between the selected marine organisms and man as the ultimate consumer were discussed. As a guideline for future monitoring, the "safe" body burden for man was taken in terms of an intake of 200 μg total mercury per week (assuming a standard man of 70 kg).

In the selection of geographic areas to model, particular attention should be given to:

a. the presence of natural geochemical anomalies,

b. the availability of information, and

c. the behavioural characteristics of the selected organisms to the presence of endogenic inputs.

Working group 3, Physical processes

The working group met under the chairmanship of Dr. T. Hopkins (USA/Italy), with Drs. V. Diaconu (Romania) and A. Theoharis (Greece) acting as Rapporteurs. The group began its discussions around the topics of:

a. the IOC/UNEP pilot project on the coastal transport of pollutants and their exchange with the open seas, and

b. the problems of interfacing physical and bio-systems models.

As the discussion developed, a rather wide range of topics emerged.

It was decided to emphasize some of the problems arising when quantitative evaluation on the physical transport of pollutants or natural water properties is required. The main points are:

a. that the different pollutants/parameters have an intrinsic time scale determined by their interaction within the marine ecosystem,

b. that these time scales should be determined,

c. that the velocity field also has its energy spread over a wide time scale (or frequency) range,

d. that advective transport involves the spatial change in the product of velocity and concentration, thereby making knowledge of this frequency coupling essential to an assessment of parameter transport, and

e. that point values of concentrations were insufficient for evaluating transports, i.e. spatial gradients must be sampled. A schematic diagram was drawn to illustrate these points.

An understanding of the large-scale transport phenomena was considered essential to the ultimate monitoring of pollutants in the Mediterranean. This is because many pollutants (or their effects) survive long enough to be transported away from the coast, and in particular, to deeper layers. A large-scale conceptual model of the physical processes of the Mediterranean is needed in order to :

a. assess the potential for the transport of surface pollutants to deeper layers for the various coastal discharge points,

b. prescribe high priority monitoring points that would permit the evaluational horizontal exchange between basins, and

c. assist in the dynamic delineation between open and coastal regimes, and thereby the open boundary conditions for coastal models.

An emphasis on the modelling of certain physical processes was felt to be critical to the ultimate success of regional hydrodynamic models. Two of these were discussed specifically, namely:

a. the velocity response to local winds in coastal regions of meso-scale topography. It was recognized that many of the areas receiving pollutants and requiring circulation models in the Mediterranean are often complicated topographically, precluding models of simple bathymetry, and

b. the production of dense surface water through winter atmospheric interaction. This is not only the primary thermohaline mechanism driving the Mediterranean, but also the main transport mechanisms (apart from sinking) by which pollutants enter the deeper layers.

Both of these processes were illustrated with conceptual diagrams. It was felt that complete hydrodynamical models (advective and diffusive) should be encouraged in a limited number of dynamically tractable areas. It was recognized that the advent of a functioning hydrodynamical model useful to ecosystem/pollution modellers is a long, iterative process. Much benefit can be derived en route to this goal through:

a. the evaluation of the supporting sampling programme,

b. a mechanism whereby any approximations used in the model might be improved, and

c. a gradual upgrading of modelling expertise and its methodology.

It was felt that attention should be directed toward identifying those coastal circulations that enhance the transport of pollutant material from one coastal source to another. This should begin as an exercise in quantitative interpretation (of existing information) that would identify circulation situations for specific coastal localities where this kind of pollutant overlap is most probable. The next step should be a quantitative assessment on the basis of coastal circulation models and sampling programmes.

1.2. Recommendations

1. Proposed project formation

The Workshop,
Considering that the modelling of ecosystems, their processes and pathways is an essential component of any overall plan designed to assess the impact of pollution on natural ecosystems and to provide output information for their management;

Considering Unesco's experience in directing attention to modelling in the Mediterranean and the enthusiastic response it has received from marine scientists indicating the need for a Mediterranean modelling programme; and

Being aware that the UNEP-sponsored Mediterranean Action Plan for the Co-ordinated Mediterranean Pollution Monitoring and Research Programme adopted by the Mediterranean governments (Barcelona, 1975) does not include at present a specific project on modelling;

Recommends to Unesco/UNEP:

a) that a project on ecosystem modelling, including processes and pathways with special focus on pollution problems, be established within the framework of the UNEP-sponsored Co-ordinated Mediterranean Pollution Monitoring and Research programme; and

b) that such a project be co-ordinated by Unesco in co-operation with UNEP.

2. Proposed modelling assistance

The Workshop,
Considering the fact that ecosystem modelling is a relatively new approach in marine science, particularly with regard to application in problems of pollution research;

Considering that a number of approaches to modelling are currently being used by marine researchers throughout the world; and

Being aware that most Mediterranean institutions have yet to acquire a sufficient level of competence and experience in this field;

Recommends to Unesco/UNEP:

a) that an educational effort on modelling in Mediterranean countries be promoted and that periodic training programmes in the methodology of modelling be offered;

b) that expert advice to participating institutions on methodology of modelling be provided;

c) that a means to stimulate multidisciplinary working groups of scientists, with the goal of producing some specific models for each ecosystem complexity level, i.e. large-scale, meso-scale and small-scale, be provided; and

d) that the preparation of a suitable guidebook on ecosystem modelling be undertaken. The preparation of this guidebook should be entrusted to competent interdisciplinary teams.

3. Suggested criteria for initial modelling areas

The Workshop,
Considering that certain areas, such as the North Adriatic, Saronikos Bay, etc., are appropriate areas to start the proposed modelling, since they already satisfy certain necessary conditions, namely:

a) physical (they comprise semi-enclosed seas or bays with relatively simple boundary conditions and water movements),

b) data base (initial background data is already available for these areas),

c) initial stage modelling (conceptual models already have been developed for these areas), and

d) expertise (the minimum number of modelling experts already exists);

Recommends to Unesco/UNEP
that support be extended for efforts in explorative modelling to be conducted as soon as possible in one or more areas in the Mediterranean where these conditions exist. The results should be used for designing field experiments of representative ecosystems elsewhere.

1.3. Project Action Plan : The modelling of ecosystems, processes and pathways, with special focus on pollution problems

1.3.1. Outline of the Project

A great need exists to explore the functioning of marine ecosystems in all aspects related to their response to the environmental stresses imposed on them. Modelling is the most comprehensive scientific tool for this purpose. The scientist engaged in modelling is obliged to evaluate and integrate his specialty into the context of the entire marine environment. In its broadest sense of application, the exercise of marine modelling provides a mechanism for the co-ordination, design, and balance of sampling programmes.

A number of pilot projects in the Mediterranean have been initiated within the framework of the UNEP Co-ordinated Mediterranean Pollution Monitoring and Research Programme and are implemented in close collaboration with specialized UN bodies (GFCM of FAO, IOC of Unesco, WHO, IAEA) and a large number of national research institutions. These cover a wide range of sampling required in the search for knowledge of environmental processes and the monitoring of pollutants. The proposed pilot project will provide an excellent scientific method for improved co-ordination and for the assessment of the complex relationship between the effect and cause of marine pollution. It will provide authorities with a continuous assessment of the suite of environmental problems under focus, since it provides a means by which the results of the other individual projects of the Mediterranean Action Plan can be synthesized. The pilot project will be based on the existing experience and national facilities in the Mediterranean countries. Its governing committee will be composed of scientists from each of the participating countries.

1.3.2. Programme of work

Ecosystems to be modelled. To ensure exploitation of the full advantage offered through the development of ecosystems models, a range of models of varying degree of complexity and completion will be developed. The following categorical breakdown illustrates the main classifications of models considered to be appropriate:

- large-scale ecosystem models to deal with the general functioning, the pollutant budgets, and the sampling requirements for the Mediterranean or for its major sub-divisions,

- meso-scale and small-scale ecosystem models to evaluate, in as great a computational detail as is technically possible, the quantitative functioning of certain semi-enclosed bays and smaller marine systems, now under severe environmental stress,

- process or linked-process models to advance the expertise in the mathematical expression of certain vital processes, such as eutrophication, or toxicity, that are occurring in environmentally stressed communities, and

- pathway models to deal with the transfer of selected metals and hydrocarbon concentrations within the main components of Mediterranean ecosystems.

Effects to be studied. The project would focus on evaluating the ultimate fate of pollutants introduced into the Mediterranean, on understanding the nature of the ecosystem modification resulting from exposure to these pollutants, and on assessing the environmental threat caused in cases of irreversible ecosystem modification. The different models would be addressed to different aspects, or combinations of these aspects, depending on their subject matter and scope. Since these aspects of focus are in effect goals, the project will begin in a limited way. For example, first it will deal only with the pathways of mercury among the metal pollutants, and then expand the scope as expertise and priorities evolve.

Methodology. To stimulate a wide variety of approaches to modelling and to accommodate the very diverse scientific backgrounds and facilities found among the Mediterranean countries, the project will not prescribe any standard methodology regarding the modelling process itself. It is felt that methodology is evolving so rapidly that to become fixed on any one set of procedures would ultimately jeopardize the project goals. However, efforts to standardize data formats and evaluate sampling errors in the other projects of the Action Plan will be encouraged.

Areas to be chosen for modelling. Regarding the selection of an area as a subject for modelling, a number of criteria should be applied, namely: the need for environmental assessment, the local facilities for modelling, the historical or on-going sampling programme of the area, and the general relevance to the Mediterranean as a whole or to its major sub-systems. In the event that certain vital areas or processes do not receive modelling attention because of limited local facilities or other reasons, the project will have the responsibility to direct specific working teams of Mediterranean scientists to treat these areas or processes.

Data required. The project will continually review the data collected under the other pilot projects and recommend action to improve their suitability as a modelling input. It will comment on the completeness and suitability of the data with respect to modelling. If necessary, it will initiate special data acquisition programme to fulfil urgent needs; however, whenever possible sampling requirements will be sought through the other project programmes of the Action Plan.

Training. Considerable training in modelling procedures and techniques is anticipated, both to keep those scientists involved in modelling up to date on progress and programmes elsewhere, and to expose new personnel to modelling practices. The project will conduct frequent training exercises, workshops, and expert consultations to participant institutions. That training which addresses specifically modelling inputs and sampling design will be co-ordinated with the appropriate sampling project of the Action Plan.

2. SCIENTIFIC REPORT

2.1. General note

This section of the report comprises an assemblage of scientific contributions emerging out of the workshop discussions. As such, a considerable portion is specifically related to the recommendations and scope of Mediterranean Ecosystem Modelling set out in the first section.

The main objective of this Scientific Report is to provide a printed record of the workshop contributions and discussions, both to serve as a useful reference to participants, and to provide information on the state of modelling consciousness in the Mediterranean to other marine scientists.

The workshop was intended to introduce participants to the concepts of modelling and to discuss preliminary models applicable to the region. The report is not intended to be a comprehensive treatment of modelling. However, it is hoped that each reader may find portions that are of scientific value to him.

2.2. Principles and a procedure of ecosystem modelling

2.2.1. Background

The use of modelling is gaining importance as a suitable activity by which to direct an understanding of the complex behaviour of ecological systems. The rapid development of this approach is due to the practical need for evaluation and prediction of the ecological stress capacity on any given system. System modelling includes a collection of methods, a scientific orientation, and a programme of research based on system theory.

That an ecosystem is complicated can be appreciated from its behaviour as well as from its composition. The two-way complexity caused by the number of functionally different components and their mutual interactions presents a major difficulty. This is a difficulty common to all natural sciences. Some of the complexity is reduced by the causal modelling of separate components within a system. A total ecosystem is then approximated by an assemblage of its component models after accounting for their interactions. A numerical solution of a modelling exercise does not have to have an exact solution in the sense that a differential equation has an exact analytical solution. Instead, the solution is generated through an iterative approximation process that theoretically can approach an exact solution as closely as practical need might require.

Briefly, the purpose of a comprehensive marine ecosystem model is to display :

a. the internal ecosystem dynamics,

b. the causal pathways, processes and mechanisms by which air, water, land and living organisms interact, and

c. the points of potential contact between a marine ecosystem and human endeavours.

Such a dynamic display has many managerial benefits, i.e. administrative, scientific and educational. From the educational point of view, it could be used as a tool to reveal more systematically the way in which different components and subsystems interact with each other. Scientifically, it shows precisely which part of the ecosystem we understand the best, where the "holes" are in our representation of it, and where we should invest more experimental efforts in order to get a more thorough "picture" of ecosystem functioning. Administratively, it serves as a decision-making tool in order to see directly what are the ecological implications of industrial, urban and touristic development. It could serve to find the optimal decision for the development of a particular area. The principles and the procedure explained below emanated from Prof. B.C. Patten's approach (Patten et al., 1976) to the ecosystem analysis. To list the main ideas and thoroughly explain their relevance to a modelling programme is beyond the scope of this brief report, the intention of which is only to give a short, descriptive introduction to modelling of ecosystems.

2.2.2. Principles

The orientation of the approach is to consider ecosystems as a special class of systems. This suggests that one should critically examine the systems theory and adapt or specialize it to a suite of properties characteristic of ecosystems.

We shall here lay down a basis for the approach in the form of several principles. They are the holistic, decomposability, dynamic, optimality, and stability principles.

a. Holistic principle

An ecosystem is viewed as an interrelated, natural entity. As such it has its boundaries, inputs, and outputs. A disturbance initiated on any input propagates throughout the system and finally produces a change on some or all of its outputs. The boundaries are specified either physically by geographical barriers, or by the range of light, temperature, and time interval; chemically, by limiting chemical processes; or biologically, by the presence of a specific assembly of organisms. The inputs to, and the outputs from, an ecosystem are observable quantities that can be measured. A model is then defined as a relation between the set of input symbols and the set of output symbols. The symbols are distinguished from the real quantities in the same way that the model is distinguished from the real system.

b. Decomposability principle

We assume that an ecosystem is a causal entity, that is, for each input (vector) there exists one and only one output (vector) and that an input always precedes the output. In order to represent the causal system one needs to develop a concept of the state of an ecosystem. In systems theory the state is defined as an index set to the family of outputs (vectors) resulting from the specified relation (which was the initial model). The state of an ecosystem has a well defined meaning in terms of mathematics; for a selected ecosystem it represents the behaviour within a reasonable time interval (so-called observation interval).

An ecological entity can be represented as a set of interrelated components, if one assumes that it is a causal entity. An image of an ecosystem can therefore be decomposed into subsystems, and the latter into components. Through the means of existing processes occurring among subsystems or among components, the model is integrated as a functional unit.

From the fact that an ecosystem can be decomposed into subsystems, it does not necessarily follow that these subsystems can be added linearly to resynthesize the original ecosystem. Some scientists (e.g. the Odum-school, or the Patten-school) stress that the system is more than the sum of its parts, and that an adequate picture of its dynamics can not be obtained simply by summing the properties of its subsystems. Still the decomposition approach can be recommended for the understanding of the successive levels of detail within an ecosystem.

c. Dynamic principle

An ecological system is a dynamic entity in the sense that its characteristics change in time and space and both its inputs and processes undergo qualitative and quantitative changes.

It is useful here to distinguish between two different classes of ecosystem states; a nominal state (normal, unstressed) and perturbed (abnormal, stressed) state. Both the nominal and perturbed states are dynamic. The nominal state exists when an ecosystem responds to natural influences. The perturbed state occurs as a result of the influence arising from human activities. Such an influence (vector), depending on the intensity and quality, can change the nominal ecosystem state significantly by means of altering some processes and generating new ones.

d. Stability principle

A system is said to be stable if it returns from the perturbed state to the nominal state after the removal of the perturbation. In those cases when the ecosystem is stable, its subsystems and components are also stable; therefore, an important criterion for correct decomposition is that each of the decomposed components be stable. However, there exist limits that a perturbation should not exceed, otherwise the ecosystem would be destroyed as a unit (see stability analysis 2.2.3., step 5).

e. Optimality principle

Over a long period of time an ecosystem tends to adapt and select a type of behaviour that optimizes some of its internal characteristics. On the basis of this fact, the principles of maximization of the flow of available energy (Odum, 1975) and a maximization of persistent biomass (O'Neill et al., 1975) while constructing ecosystem models were already utilized.

2.2.3. The modelling procedure

A team of experts, in an effort to model an ecosystem, must pass through several modelling steps before the main goal is achieved. They progress gradually from the first qualitative step to the final operational step of the model. Such a building sequence is explained in the following outline.

Step 1 : Ecosystem conceptualization

The objective of this step is to produce a comprehensive qualitative, conceptual model. The necessary inputs to this step are the scientific judgement, existing data and specific objectives of the group of experts that undertake the modelling task.

After working on the qualitative aspects of the model, the products of this step are:

a. definition of the boundaries of the model,
b. submodels and their boundaries,
c. identified relevant components and their description,
d. identified inputs, outputs and external controlling factors, i.e. factors outside the ecosystem which are not modelled but influence processes and transport rates in the ecosystem of interest,
e. binary connectivity matrix between components (a display of processes going on among components of the model)
f. energy circuit diagram, (see Odum, 1975)[1/]
g. feedback dynamic diagrams (see Forrester, 1963)[2/]

Conceptual modelling is the basis for all subsequent steps. As such it can be regarded as the most important step and must be done in a substantial way by the appropriate specialists. Without the initial representation in the form of a conceptual model by the individuals who are closely acquainted with the functioning of the ecosystem components represented in the model, only a superficial or inadequate model can be produced (Patten, 1975). The need for a special knowledge to be built into the conceptual model is the basis for interaction between various specialists, i.e. biologists, chemists, physical oceanographers, etc.

Step 2 : Ecosystem mathematization

The objective of this step is to formulate appropriate mathematical expressions for the conceptual model. Actually in this step one finds mathematical representations to the binary 1's and 0's in the binary connectivity matrix, to the inputs and outputs of the model and to the controlling factors. The input to this step is the conceptual model itself.

The form of the mathematical model may vary with the purpose of the model, the quality of the existing data, computer limitations, etc. If the model is to be used only to analyze the effects of slight perturbations, a linear model might be suitable. If one anticipates that the model will handle higher perturbations, a nonlinear model should be considered before completing this step.

1/ Explanation and examples of binary connectivity matrices and energy circuit diagrams are given in sections 2.3.3., 2.4.1. and 2.3.1., 2.3.2., 2.4.1., respectively. The two formalisms are equivalent.

2/ Examples of Forrester diagrams are given in sections 2.3.3. and 2.4.1.

The components of the binary matrix are selected as dependent variables (X_i) of the model. If a continuous representation is chosen, the model will be represented as a set of differential equations (sometimes called evaluation equations, Nihoul, 1975a).

$$(1) \qquad \dot{X}(t) = f \left[X(t), Z(t), t \right]$$

$$(2) \qquad Y(t) = g \left[X(t), Z(t), t \right]$$

$\dot{X}(t) = \left[X_1(t), \ldots, X_n(t) \right]$ denotes a vector whose components are the components of the model. Z (t) and Y (t) represent the input and output vectors, respectively. Space variations in equations (1) and (2) are omitted because they are implicitly incorporated into an accompanying hydrodynamical model. As it is seen from (1) and (2) the output or a response of the model depends on the state of the model and on the inputs to the model. If the state is represented stochastically, we have a stochastic model. Otherwise we have a deterministic model. Stochasticity in the inputs does not force a model to be a stochastic one, although the responses may make it so appear.

For generating the hydrodynamical part of the model (which includes water circulation, temperature distribution, etc.), various methods are available. For instance, a description of numerical or integral models is given in Nihoul (1975b) Shirazi and Davis (1974), or Dunn, Policastro and Paddock (1975).

The significance of the mathematical step is that it indicates the completeness of the models with respect to their components, processes, inputs and external conditions. In understanding the input requirements to satisfy this completeness, the data necessary to carry out the computation of the model becomes evident.

<u>Step 3</u> : Ecosystem calibration

The mathematical model is, in this step, brought to the point where the actual simulation could begin. Input to this step comes from the output of a step 2 model, e.g. hard data in the form of estimates of turnover rates, numbers for the input function, and representations of processes.

The first output of this is a computer programme. Using averaged functions of inputs over a long period of time and initial quantities for the numerical values of components, one obtains, as a result of a computer run, the transient dynamics of the model. When the steady values are obtained one enters them into the computer programme and the model is ready for the simulation process.

<u>Step 4</u> : Ecosystem simulation

The first goal required in this step is to simulate the nominal state of the modelled components. There are cases for which the nominal state no longer exists in nature. However, if a data set exists that extends historically back to the unperturbed state, the nominal state model can still be verified; and if a historical data set does not exist, then the modelled nominal state can serve as an arbitrary reference state.

At this point, adjustments and iteration processes can proceed quite rapidly with adequate programming and computing facilities. Tests can be made to evaluate the extent of deviations from the reference state occurring as a result of normal or extreme variations in the inputs, or of parameters affecting the internal processes, and thereby to define the limits of the nominal state. Also a comparison between the nominal and present statescan be made to evaluate the ecological deviation of the present state.

Once the model components have successfully been simulated, one can perform various computer trials for a potentially endangered ecosystem. Here, the model is used as a predictive tool. The perturbation experiments with the model are the explorations of the full range of environmental damage, its causes and cures. Now, the model has become an operational tool.

Step 5 : Ecosystem analysis

The objective of this step is to understand the functioning of the ecosystem, in both the nominal and perturbed states. There are several types of analyses that can be performed on the model depending on the goals of investigators. Three of them are : sensitivity analysis, input-output analysis and stability analysis.

a. Sensitivity analysis. The model represents a dynamically and partially interrelated set of components. It is an "open" model, as the ecosystem itself is an open type of system. By changing one of the forcing functions that drive the model, the change reflected in the quantitative behaviour of each component can be noted. The sensitivity of components or processes can also be investigated in response to multiple changes in forcing functions as they would occur in nature. This sensitivity analysis on complex models can be achieved only on a computer.

b. Input-output analysis. This analysis has been recently developed for treating large-scale ecosystems (Finn, 1976). It answers several important, practical questions. For example, if the flow of Hg through an ecosystem is modelled, this analysis indicates how much of the Hg that entered by e.g. a sewage outflow, passes to (and through) any of the species of fish included in the model. A somewhat opposite example might involve the case where an increase of Hg in the fish, e.g. 50%, is observed; now this analysis is used to answer the question as to which of the inputs contributed the most to this increase.

c. Stability analysis. The next questions to be asked of the model are the following : (1) Will the ecosystem always recover, no matter how strong the stress is ? (2) If it recovers, how long does the recovery take ? The answer to the first question is obviously negative, for if a high enough stress is applied, the ecosystem will either be destroyed or will decompose into smaller units which are capable of resisting such a high stress. When the stress eventually disappears, each of the smaller units will find its optimal strategy of existence and the ecosystem will remain in its new state. For this reason boundaries must be found, i.e. the limits to which the inputs can be changed without inducing a permanent change in the ecosystem.

An answer to the second question involves the "steepness" of the stability region. If the stability region is very steep, the ecosystem will recover very quickly; if it is very slight, it will take the ecosystem a long time to recover. The point is that each forcing function may affect the stability independently, so that for changes in some inputs the ecosystem might recover rapidly while for others the opposite might occur. As an example, consider the input function of solar radiation. As incident radiation decreases, primary productivity declines very fast. If normal radiation values are again used, the phytoplankton productivity responds quickly and returns to the normal value. On the other hand it is easy to find inputs for which this is not the case, that is input changes after which the ecosystem, or some of its components, does not recover or recovers very slowly.

It is not necessary to persuade the reader of the power these analyses offer for the practical purpose of management and decision-making. Management needs precise and comprehensive information on which to base its judgements within the context of a social, economic and political framework. Decision- makers require guidelines for a policy of maximum utilization and minimum permanent alteration for marine ecosystems. Modelling can be very instrumental toward achieving these goals, in addition to the intrinsic scientific merit of the modelling exercise itself.

2.3. Modelling efforts in the Mediterranean. (A map, showing the main geographical divisions of the Mediterranean Sea referred to in this section is shown in Figure 1).

2.3.1. The Southern Levantine subregion, a summary of the Alexandria Workshop

Introductory remarks

The University of Alexandria hosted the first Unesco subregional workshop on Eastern Mediterranean modelling. Attention was focused on utilizing the Egyptian coastal zone as a specific example for the construction of a subsystem model and on formulating priorities and requirements for a general Eastern Mediterranean model.

The workshop began with some general lectures on modelling and its concepts. This was followed by a review of the physical, chemical, biological, and geological oceanographic research carried out in the Eastern Mediterranean, which was presented by Egyptian scientists to familiarize all participants with the area. Likewise, participants from Lebanon, Libya, Malta, Syria and Tunisia reported on the marine science programmes in their respective countries.

In order to facilitate discussion, the workshop was divided by discipline into four topical groups. Each work group was responsible for considering the dominant inputs, outputs, processes, and interactions involved in their subsystem and, from these, preparing a conceptual model. The models were then presented to the entire workshop and interrelated in order to draft an Egyptian coastal model. Then a larger conceptual model of the entire Eastern Mediterranean was constructed using input from all participants. The subsequent presentations and discussions were designed to clarify the various stages of model planning and development, and also to facilitate utilization of modelling as a research tool. The stages of model development, precise data collection and standardization requirements, development of several specific models, and

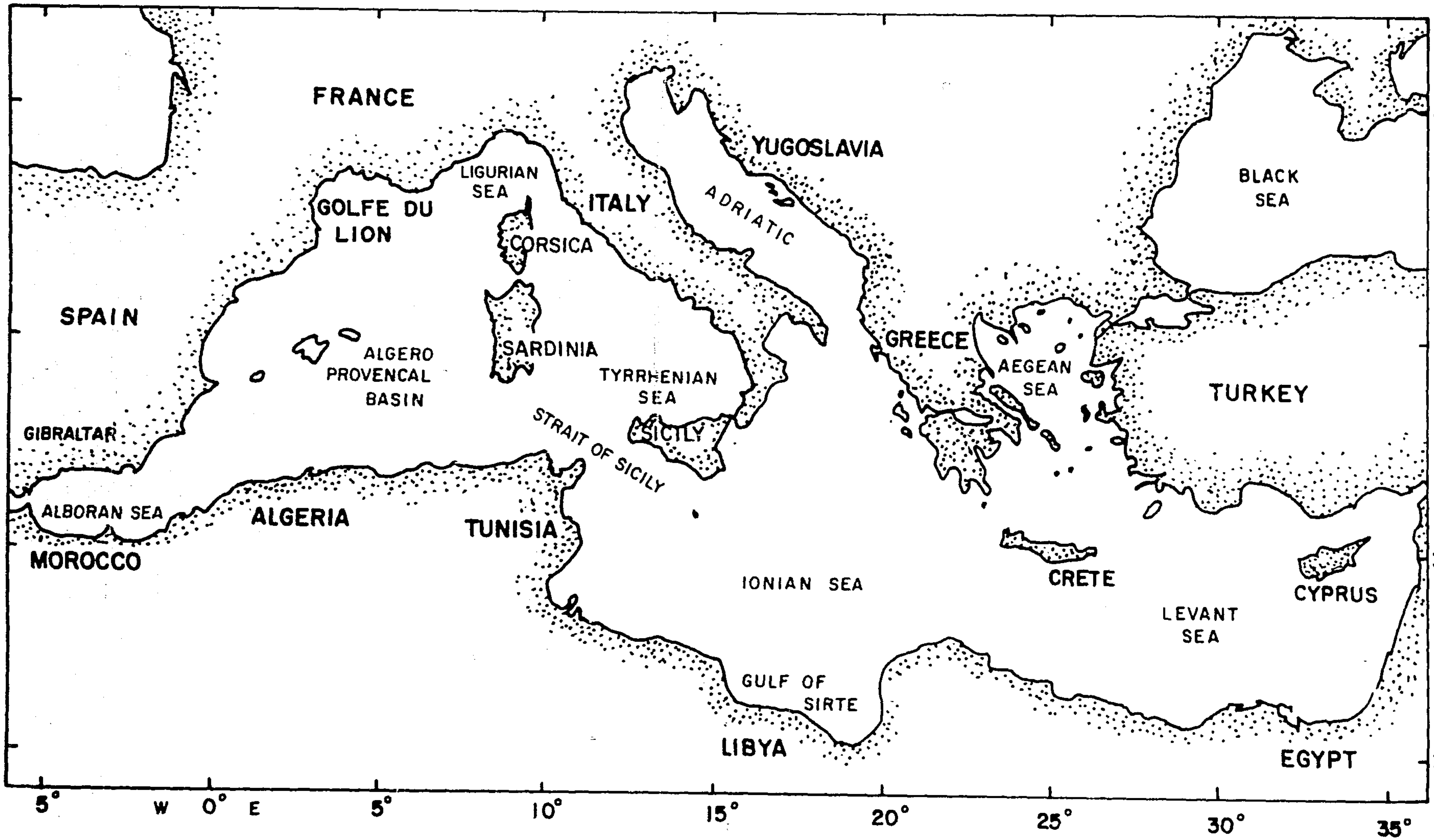

Fig. 1. The Mediterranean.

explanation of model calculations were all components of this session. At the conclusion of the meetings, the workshop was presented with discussions of specific proposals involving future modelling efforts in the Eastern Mediterranean.

Concepts of marine modelling

Recent interest in the alterations of marine ecosystems induced by man-made influences has led to an emphasis on methodologies that can abstractly describe natural systems without regard to their classical disciplinary composition. Traditional research structured along purely biological, physical, chemical or geological lines is being found inadequate in the sense that nature does not necessarily observe these sub-divisions. In addressing ecological problems, marine scientists are finding it more useful to make divisions according to naturally occurring subsystems.

Appropriate subdivision becomes a very important facet of modelling methodology, and since the ultimate natural system extends from the atom to the universe, subdivision also becomes a necessity. Breaks between components are best made where component interaction is the weakest. The criteria for determining such weak interaction may be functional, spatial, or temporal. Functional subdivisions are made on the basis of activity within the system, for example, the distinction between organic and inorganic suspended matter or between producers and consumers. Spatial distinction constitutes another criterion for subdivision. Much of the Eastern Mediterranean's uniqueness stems from its well-defined physical separation from the rest of the marine system. Finally, the inherent time scales of natural processes provide another criterion for subdivision. Processes or components changing slowly can be considered as independent of time with respect to those changing rapidly. For example, phytoplankton biomass turns over within days while that of some consumers requires years.

Once a subsystem is separated, further subdivision may continue as dictated by the resolution required. Thus modelling efforts may involve the entire Eastern Mediterranean, for example, and sacrifice resolution for coverage; or they may deal with smaller subsystems where local effects are of interest. Depending on the resolution, a subsystem is analyzed further into components expressed in terms of inputs, outputs, energy storage and energy consumption, and transfer processes. The procedure for construction then involves exploratory definition of components, comprehension of these components, and finally their reconstruction into a symbolic and qualitative language.

Southern Levantine coastal model

As an example of an ecosystem model, Figure 2 shows a generalized coastal system of the south-eastern Mediterranean, expressed in the energy circuit language developed by H.T. Odum.

In the pelagic and the benthic zone the different organisms are lumped together within the separate symbols. The phytoplankton, mainly consisting of diatoms, is shown by the bullet-shaped symbol for producers. These receive their main energy from the sun. All energy sources outside the system are symbolized by circles.

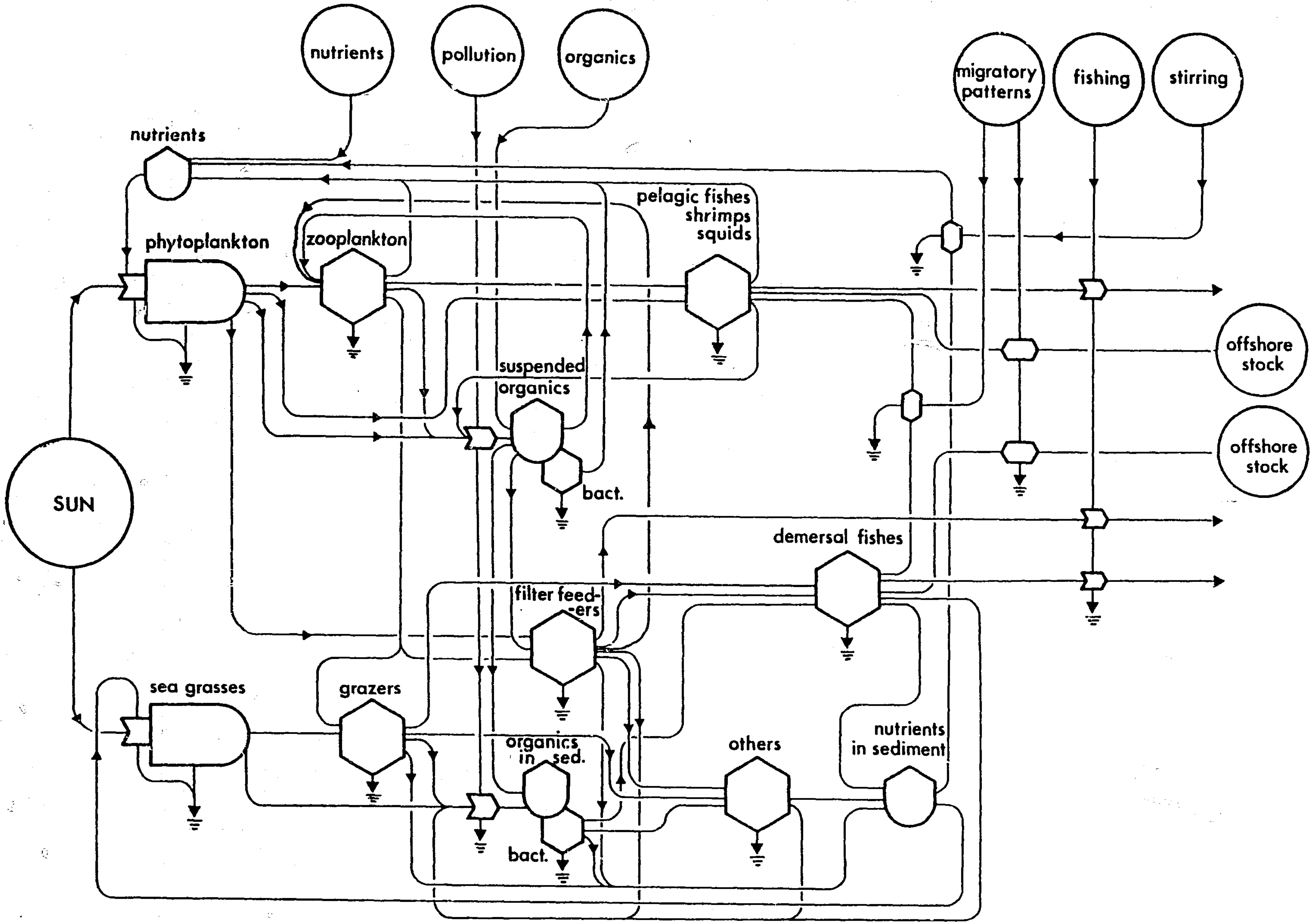

Fig. 2. Ecosystem model of the Mediterranean coastal system.

The storages within the system have a special symbol, "the birdhouse", such as the one used for nutrients, here containing both nitrogen and phosophorus. These are taken up by the producers by photosynthesis. Like all processes, this is shown by a broad arrow, a work-gate. It is also used, e.g. to illustrate the outflow due to "fishing" from the fish compartment at the right border of the model. In the producer symbol the work-gates are joined by a line leading to an arrow which points downwards to a "ground" symbol. This arrow symbolizes the energy lost in any process according to the second law of thermodynamics. It is called a heat sink.

The producers are eaten by the zooplankton, represented by the hexagonal consumer symbol. The zooplankton receives larvae from the benthic animals as shown for the filter feeders by the input to the left side. The settling of larvae is shown by flows in the opposite direction.

In fact both the producer and consumer symbols contain a storage for biomass and a work-gate for the self-maintaining processes, though those are not included here for the sake of clarity. Both phytoplankton and zooplankton are eaten by the pelagic fish, shrimps and squids, another hexagon. When representatives of all these three trophic levels die, they form dead organic material, which is suspended in the water and shown as a storage. The organic matter is immediately attacked by bacteria, which are represented by the hexagon merged into the organic storage to show the close connexion. As a result of the breakdown processes, nutrients are released which, together with excretory products from zooplankton and fish (not drawn here), are transferred to the nutrient storage. This is the important "recycling", a positive feed-back loop which is quite necessary for the proper functioning of the natural system. Both the organic and the nutrient storage are also fed from coastal run-off, especially in polluted areas.

The benthic system has the same main components. The producers consist of seagrasses like Posidonia and epiphytes like sessile diatoms. All these are lumped together into one producer symbol requiring solar energy and taking nutrients, mainly from the sediment. They are grazed by herbivore consumers such as snails. Other consumers are the filter feeders, such as clams and mussels, that live on the suspended organic matter. Some of them use the seagrass leaves as substrate while others live buried in the sediment bottom, and may feed on both suspended as well as deposited organic material.

In the seagrass flats, the filter feeders act to clear the water of detritus providing more sunlight for the plants. The plants in turn grow better and thereby offer more substrate to the filter feeders "as a reward". Nature is built up by such feed-back loops which have been well defined during evolution's trial and error processes.

A third consumer group called "others" includes important detritus eaters and carnivores such as the polychaetes.

Plants, detritus, grazers and filter feeders are all eaten by the demersal fish, subject both to migration and fishing. The migratory process is shown by a two-way gate symbolizing flows in either direction. There is also a migration of fish between the benthic and the pelagic zone.

All the benthic organisms contribute to particulate organic matter, and together with the bacteria, to the bottom nutrients. These are exchanged with the pelagic nutrients through several physical processes such as circulation, and turbulence, represented here simply by a forcing function called "stirring". These physical processes are extremely important to the distribution of all water-borne substances.

This coastal system has worked for thousands and thousands of years running on solar energy and with "natural" nutrients coming in from rivers and surrounding marine waters. The nutrients are concentrated and channeled through food chains and forced by physical factors. Now man has changed the system in many ways, disposing pollutants and constructing dams and canals.

Fishing is an old process whereby man has taken much of his basic food source from the sea. The potential yield of the sea is very much influenced by the man-made changes which influence productivity in the coastal waters. To indicate and warn against these manifold negative effects, pollution has been included in the model as a forcing function, negatively affecting the organisms in the pelagic and benthic zone. Future work will describe clearly both the positive and negative effects of man's activities on marine ecosystems.

2.3.2. The Aegean Sea, Saronikos Gulf example

The Saronikos Gulf has been the field site for studies of the effect of nutrient input on the nature of the phyto-plankton component of the Mediterranean marine ecosystem. The model used is shown in Figure 3a and has the theoretical basis developed by Dugdale (1967). For additional discussion see also Section 2.4., page 78, para e. Basically, this hypothesis states 1) that phytoplankton species that have evolved under chronically poor nutrient conditions will have low K_s values (i.e. high affinity for nutrient) and low V_{max} (maximal uptake rates) Curve B, when compared to species that have evolved under high nutrient conditions, Curve A., and 2) that, as a result, species B has the advantage at low nutrient concentrations while species A has the advantage under high nutrient concentrations. The conceptual model for selection of phytoplankton species on a nutrient basis is shown in Figure 3b. The Saronikos Gulf provides a nearly ideal situation for testing these hypotheses since 1) the circulation pattern is well known and consistently tends to be cyclonic, flowing past the Keratsini sewage outfall, where $4 m^3 sec^{-1}$ of raw effluent is discharged in a manner producing a surface boil at all times, and 2) the nutrient background levels are virtually zero, except for silicate. Verification of the existence of type A and type B kinetics in eutrophic and oligotrophic phytoplankton populations was already available from work in the Mediterranean Sea and in upwelling regions (Mac Isaac and Dugdale, 1969). A cruise, SSP 11 A, was made on the R/V STORMIE SEAS in June 1974, to observe the changes in phytoplankton species composition associated with nutrient input from Keratsini as a test of the model shown in Figure 3b. The results, Fig. 4, showed that in the convergent current along Salamis Island, a phytoplankton assemblage, or functional group, develops that is composed of fast growing diatoms (W. v. Gundenberg and D. Blasco, personal communication). This functional group is shown as Group III in Fig. 4, and is equivalent to type A of Figure 3b. It is indistinguishable from the assemblage of species found in highly productive situations such as coastal upwelling. In Elefsis Bay, where shallow sills severely restrict communication with the surrounding Saronikos Gulf water, nutrients added from industrial and domestic

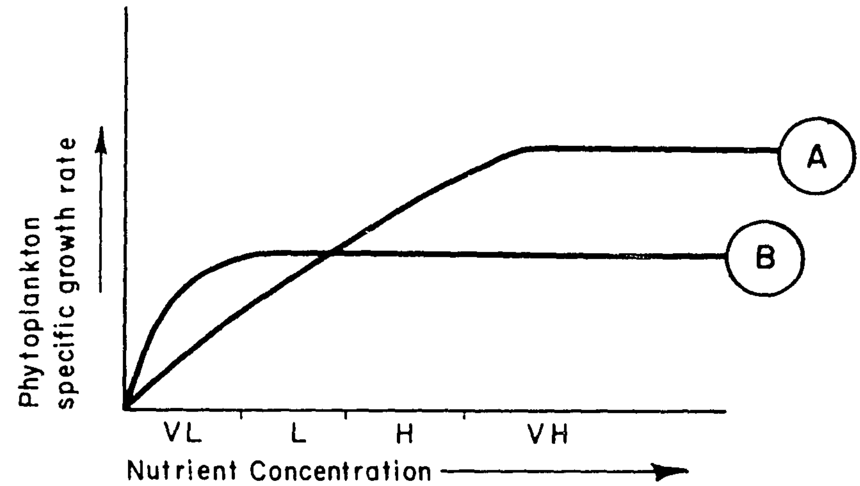

Fig. 3a. A theoretical model for phytoplankton growth rate as a function of nutrient concentration.

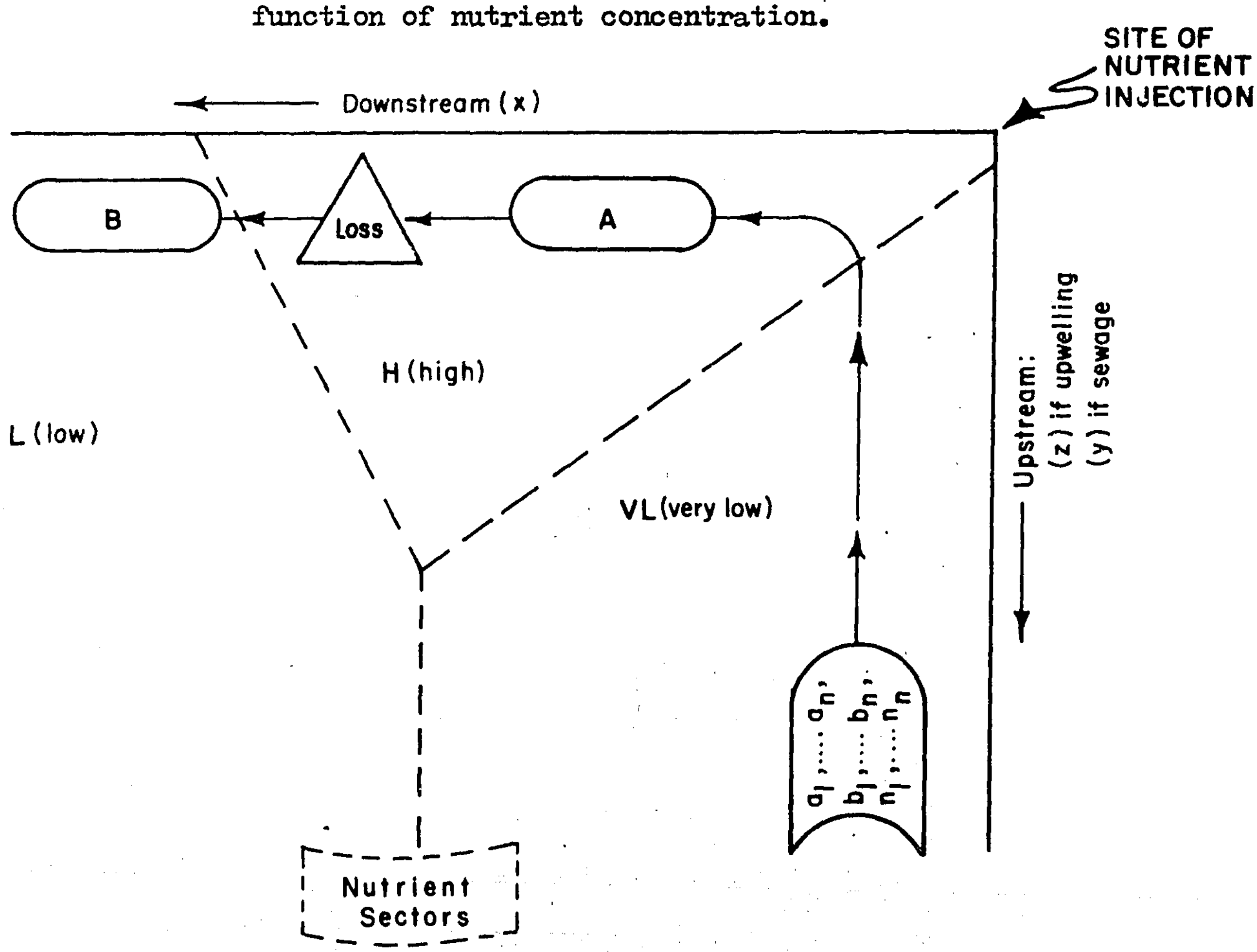

Fig. 3b. A conceptual model of phytoplankton species selection by nutrient injection.

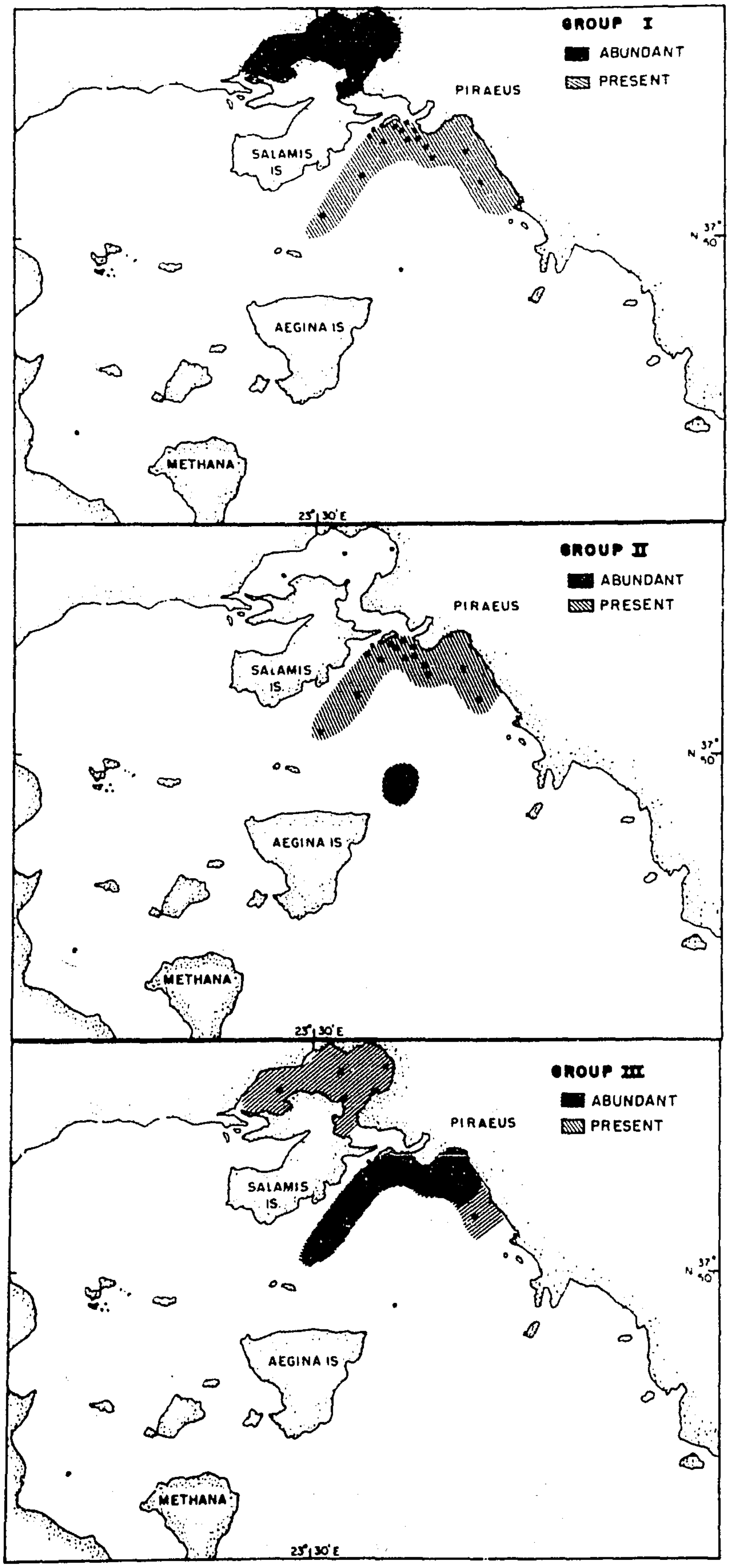

Fig. 4. Phytoplankton functional groups found in the Saronikos Gulf on Cruise SS P 11A on R/V STORMIE SEAS in June 1974.
Group I : dinoflagellates.
Group II : slow growing diatoms.
Group III : fast growing diatoms.

effluents result in a functional group, Group III of Fig. 4, characterized by dinoflagellates. This finding also agrees with the observation that, in upwelling areas, dinoflagellate populations become dominant during periods of weak upwelling. The functional group, characteristic of oligotrophic waters and consisting primarily of slow growing diatoms and coccolitrophores, is shown as Group II in Fig. 4 and is equivalent to type B of Fig. 3b. Its occurrence was detected in the source waters of the Gulf.

The conceptual model for the prediction of phytoplankton functional groups that are formed on the basis of differing nutrient uptake kinetics has been verified in a preliminary way, and numerical modelling has begun. Some fundamental insight into phytoplankton ecology has been obtained from these experiments. The practical outcome should be predictive models that will aid in evaluating and managing eutrophication problems in the Mediterranean Sea and in other oligotrophic seas as well.

2.3.3. The Adriatic Sea, Model of the Adriatic Regional Ecosystem (MARE)

Background

The UNDP assisted project "Protection of the Human Environment in the Yugoslav Adriatic Region" (Adriatic III Project) was begun in 1971. The main purpose of the project has been to acquire a better understanding of the human environment in the Yugoslav Adriatic region in order to assist and influence decision-makers in the further development of the Adriatic coast. From the beginning the project has been divided into the following groups: air, fresh water and soil, marine environment, physical planning and development, nature protection, historical monuments and tourism. Each group had its own programme of research and work.

During early interactions between different groups, it became obvious that a greater effort was needed to improve co-operation and understanding among groups. For that purpose, the work on the Model of the Adriatic Regional Ecosystem (MARE) was started in late 1974 under the leadership of the UNDP expert Prof. Bernard C. Patten. MARE was divided into the following submodels : air, marine, terrestrial, stream, lake and tourism. The main work was done during separate workshops for each group, and during two synthesis workshops in which submodels were linked into MARE. In total, 14 workshops were held in which 98 experts participated.

Conceptually, MARE has been generated in a manner following the principles and procedures outlined in Section 2.2. The model has been constructed so as to follow the mass transfer among physical, chemical and biological components. It was decided that on the conceptual level the space-independent (point) model will be developed, and, that in the computational step the spatial part will be added. The conceptual step, followed by the parameterization, will be applied and calibrated to the particular areas of interest.

The marine conceptual submodel was generated by some 30 scientists from seven institutions during four one-week workshops. In the following paragraphs, this submodel is discussed briefly.

Definition of the submodel boundaries

It was decided that the marine submodel should include processes going on in the sea water, biota, sediment, and the interactions among them. The mass transfer through the air-water interface was treated as input to and output from the system. Light and wind were treated as controlling factors, which were not part of the system, but which influenced the mass transfer among components.

System decomposition

The marine submodel was broken down into 78 components. The choice of components required long discussions about the concept of each component, that is, what should be and what should not be a part of the component. In some cases, a component represents a single chemical element. In other cases single components cover the whole group of complex chemical compounds or various biological systematic groups. The choice of the size of a particular component depended on its importance to the ecosystem and on its capability to be measured. For instance, the nitrogen cycle was divided into three different components (nitrate, nitrite, ammonia). On the other hand, all amino acids or all forms of iodine were considered as one component. Biological components were treated in the same manner.

Some important measurable parameters of the marine ecosystem like pH, salinity, etc., were treated not as components but as controlling factors. As a consequence, for instance, sodium and cloride were not included as components.

Using the above mentioned principles, 78 components were selected for the marine sub-model, divided into 40 chemical, 36 biological and 2 geological elements.

Components definition

All 78 components were defined as precisely as possible and the definition of each component is given in the following list. The numbers refer to the position of each component in the binary matrix (Fig. 5).

A. Description of chemical components:

All chemical components consist of chemical species (according to the specific definition of the component) dissolved in seawater and contained and/or adsorbed on the suspended particles 0.5 μg (passing through a millipore filter-pore size 0.45 μm.).

1-14 Metals (Pb, Cd, Zn, Cu, Hg, Co, Cr, V, Mn, Fe, Sr, Ca, Mg, K). These components comprise free metal cations, metal complexes, and chelates. Defined in this way, the components also represent experimentally measurable (and most often measured) quantities.

15. Iodine-dissolved I^-, IO_3^- and I_2, as well as its associates with metalic cations.

16. Bromine-bromide Br^-, free as well as its complexes and associates with metals.

17. Carbonate-HCO_3^- and CO_3^{2-} and soluble metal complexes and associates.

18. Sulfate-SO_4^{2-} and soluble metal complexes and associates.

ADRIATIC REGIONAL ECOSYSTEM MODEL

MARINE SUBMODEL - BINARY CONNECTIVITY MATRIX

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                         PCZCHCCVMESCMKIBCSBOCHNNNSPOMPAHCELPVEDDCHPTMCDOACCBTCSPCSAGBBEBPPMRC 3PBEFSSDO
                         BDNUGOR NFPAG  RO0020200HIORIH  A IIINIIO HIIOESMLOEUHIONPRAINCNLLADNKHA UEEER
                                       343 2S32404GHEAARAPGTZANCFYNCPCTPAPNHAPLIOTSV I   N   ACCNSDTG
                                                2  NCCBCIMAYTOCLTTREARHDE IEHYDNHTACNFFCMAAANTOCTIE
                                                  COOIIOIDEMMOFOAONOPPAIOLLCTOCAGRRLEOIIEALLLEELIOMRP
                                                  AILDDHDSNIEMLLGPNZOOCPCTAAO HREPPVPDSSPLGGGRRI NNGO
                                                  RLSSSYS TN SGTELDODDDDRSRTG TASDDAHMHHHSAAAGA   TTL
                         000000000111111111122222222223333333333444444444455555555556666666666777777777
                         123456789012345678901234567890123456789012345678901234567890123456789012345678

LEAD                  1  X000000000000000000000000000000000000011111111111111111111111111111111111111100
CADMIUM               2  0X00000000000000000000000000000000000011111111111111111111111111111111111111100
ZINC                  3  00X0000000000000000000000000000000000011111111111111111111111111111111111111100
COPPER                4  000X000000000000000000000000000000000011111111111111111111111111111111111111100
MERCURY               5  0000X00000000000000000000000000000000011111111111111111111111111111111111111100
COBALT                6  00000X0000000000000000000000000000000011111111111111111111111111111111111111100
CHROMIUM              7  000000X000000000000000000000000000000011111111111111111111111111111111111111100
VANADIUM              8  0000000X00000000000000000000000000000011111111111111111111111111111111111111100
MANGANESE             9  00000000X0000000000000000000000000000011111111111111111111111111111111111111100
IRON                 10  000000000X000000000100000000000000000011111111111111111111111111111111111111100
STRONTIUM            11  0000000000X00000000000000000000000000011111111111111111111111111111111111111100
CALCIUM              12  00000000000X0000000000000000000000000011111111111111111111111111111111111111100
MAGNESIUM            13  000000000000X000000000000000000000000011111111111111111111111111111111111111100
POTASSIUM            14  0000000000000X00000000000000000000000011111111111111111111111111111111111111100
IODINE               15  00000000000000X0000100000000000000000011111111111111111111111111111111111111100
BROMINE              16  000000000000000X000000000000000000000011111111111111111111111111111111111111100
CARBONATE            17  0000000000000000X00000000000000000000011111111111111111111111111111111111111100
SULFATE              18  00000000000000000X000100000000000000001111111111111111111111111111111111111100
BORATE               19  000000000000000000X000000000000000000011111111111111111111111111111111111111100
OXYGEN               20  00000000000000100000X0010000000000000001101100000000000000000000000011111111100
CARBON DIOXIDE       21  0000000000000000100 0X00000000000000000 1111111111111111111111111111111111111100
HYD. SULFIDE         22  0000000000000010000 10X0000000000000000 0000000000000000000000000000000000101100
NITRATE              23  0000000000000000000100X10000000000000000000011111111111111111101111000000101100
NITRITE              24  00000000000000100000001X0000000000000000000011111111111111111101111000000101100
AMMONIUM             25  0000000000000000000100 00X0000000000000000000111111111111111111011110000001011 00
SILICON DIOXIDE      26  0000000000000000000000000X0000000000000000000000000000000000000000000000101100
PHOSPHATE            27  00000000000100000000000000X00000000000000011111111111111111101111000000101100
DISS.ORG.CARB.       28  000000000000000000000000000X0000000000111111111111111111111111111111111111111100
MINERAL OILS         29  0000000000000000000000000000X000000000000001111111111111111111111110000010 1100
PHENOLS              30  00000000000000000000000000000X00000000000000000000000000000000000000000000101100
AMINO ACIDS          31  000000000000000000000000000000X0000000000001111111111111111111111110000000000 0
HUMIC ACIDS          32  0000000000000000000000000000000X00000000000111111111111111111111111111111111100
CARBOHYDRATES        33  00000000000000000000000000000000X000000000011111111111111111111111100000101100
FATTY ACIDS          34  000000000000000000000000000000000X00000000011111111111111111111111100000101100
LIPIDS               35  0000000000000000000000000000000000X0000000011111111111111111111111100000101100
PIGMENTS             36  0000000000000000000000000000000 1000X00000001111111111111111111111110000 1101100
VITAMINS             37  000000000000000000000000000000000000X0000001111111111111111111111110000 1101100
ENZYMES              38  0000000000000000000000000000000000000X000001111111111111111111111110000 1101100
DIATOMS              39  11111111111111111011011110111111000011X000000000000000000000000000000001110011
DINOFLAGELLATA       40  111111111111111110010111101111110000110X00000000000000000000000000000001110000
COCCOLITHOPHORID     41  1111111111111111101101111011111100001100X00000000000000000000000000000000000 11
N. FLAGELLATA        42  11111111111111111011010110111111000011000X000000000000000000000000000001111011
OTHER PHYTOPLAN.     43  111111111111111110110111101111110000110000X00000000000000000000000000001111011
TINTINNID            44  1111111111111111101001010000011110000011111X0000000000000000000000000001111011
OTHER MICRO ZOOPL.   45  11111111111111111010010100000111100000111110X000000000000000000000000001111011
COPEPODA             46  111111111111111110000101000001111000000111111X00011100000000000000000001001011
DECAPODA             47  1111111111111111101001010000011110000001111111X1111000000000000000000001111001
OSTRACODA            48  11111111111111111010010100000111100000011111101X101100000000000000000001111011
AMPHIPODA            49  111111111111111110000101000001111000000111111000X11100000000000000000001111011
CLADOCERA            50  1111111111111111100001010000011110000001111110101X1100000000000000000001111011
COPELATUS            51  11111111111111111000010100000111100000011111100000X100000000000000000001111011
BENTHIC LARVAE       52  111111111111111110100101000001111000000111111000011X00000000000000000001111011
TUNICATE             53  1111111111111111100001010000011110000001111110111111X0000000000000000001111011
CHAETOGNATHA         54  11111111111111111000010100000111100000000000010111110X000000000000000001111000
SIPHO/MED.           55  111111111111111110000101000001111000000000000011111100X00000000000000000001011
POLYCHETA            56  1111111111111111100001010000011110000000000000000000000X0000000000000000000111
BENTHIC CINDARIA     57  11111111111111111010010100000111100000000000000000000000X000000000000001110011
SPONGES              58  111111111111111110100101000001111000000111111000000000000X00000000000001111111
ARTHROPODA           59  1111111111111111101001010000011110000000000000000000000100X1101001011100000111
GASTROPODA           60  11111111111111111010010101110111000000000000000000000001110X100000011110000111
BIVALVIA             61  111111111111111110100101000001110000000111110111111000000000X00000000001111011
BENTHIC CEP.PODA     62  1111111111111111100001010000011100000000000000000000000100111X0100000000000011
ECHINODERMATA        63  11111111111111111010010100000111000000000000000000000001010110X000011110000111
BENTHIC FISHES       64  111111111111111110000101000001110000000000000000000000010011111X01011100000111
PELAGIC FISHES       65  1111111111111111100001010000011100000111111010000000000000000000X0000000000011
PELAGIC CEP.PODA     66  11111111111111111000010100000111000001000001010000000000000000001X000000000011
MAMMALS              67  111111111111111110100101000001110000000000000000000000000000000011X00000000011
RED ALGAE            68  1111111111111111101101111011111101000000000000000000000000000000011X0000000111
GREEN ALGAE          69  11111111111111111011011110111111010000000000000000000000000000000000X000000111
BROWN ALGAE          70  111111111111111110110111101111110100000000000000000000000000000000000X00000111
PHANEROGAMS          71  1111111111111111101101111011111101000000000000000000000000000000000000X0000111
BACTERIA             72  11111111111111111011011111111111111111000000000000000000000000000000000X111111
E. COLI              73  111111111111111110110111111111111111110000000000000000000000000000000000X00011
FUNGI                74  1111111111111111011011101111011110010000000000000000000000000000000000011X1111
SESTON               75  11111111111111111111111111111111111111111111111111111111100000000111000111X011
SEDIMENT             76  111111111111111111111111111111111111111100000000000000001111111111111111111X11
DETERGENTS           77  00000000000000000000000000000000000000000000000000000000000000000000000000011X0
ORGANIC POLLUT.      78  0000000000000000000000000000000000000011111111111111111111111111111111000011 0X
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Fig. 5. A binary connectivity matrix for the marine submodel of MARE (Model of the Adriatic Regional Ecosystem). Note that the top nine lines are to be read vertically, e.g. $\frac{P}{B}$ = LEAD).

19. Boron-total borate.

20. Oxygen-dissolved molecular oxygen, and its reduced forms, (except H_2O and OH^-).

21. Carbon dioxide-dissolved molecular CO_2.

22. Hydrogen-sulfide-H_2S and sulfides.

23. Nitrate.

24. Nitrite.

25. Ammonium.

26. SiO_2-silicates.

27. Phosphate-inorganic phosphates.

28. TOC-total organic carbon-empiric quantity that comprises all organic compounds expressed in mg C/1 (overlaps components 19-38).

29. Mineral oils-soluble, dispersed, adsorbed, adsorbed at sea surface (slicks included).

30. Phenols-free acids.

31. Amino acids-free acids and chelated to metals.

32. Humic acids-free acids and chelated to metals.

33. Carbohydrates.

34. Fatty acids
35. Lipids
36. Pigments
37. Vitamins
38. Enzymes

(34–38:) dissolved, dispersed, adsorbed at sea surface; free acids and its salts (or complexes)

77. Detergents-cations, anions, and neutral detergents.

78. Organic pollutants-organic chemical components (not included in components 29-38) which are effluents of industrial, urban and touristic activities.

B. Description of biological components:

39-43 Phytoplankton. Phytoplanktonic forms that spend all their life cycle in free sea water. Primary producers of organic matter and oxygen. They are defined by the systematic groups.

44. Tintinnids. The most common group among the microzooplankton. Included are all forms which are collected by any method of sampling.

45. Other microzooplankton. Includes all organisms up to 125 μm that spend part of their life in free water.

46. Copepoda. Copepods are the most common group of net zooplankton. Included are adult and advanced larval forms. 125-500 μm.

47. Decapoda. Includes all the taxonomic groups, although some benthic decapod larvae are found also in the zooplankton community.

48. Ostracoda. The group of net zooplankton with shell-like integument. Included are adult and advanced larval stages.

49. Amphipoda, planktonic crustacea. During some period of the year they are very abundant. Included are adult and advanced larval stages.

50. Cladocera, neritic planktonic crustacea. During some periods of the year they are very abundant.

51. Copelatus. Planktonic forms mostly found along the coastal waters, including adult and advanced larval forms.

52. Benthic larva. Larval forms of benthic animals that spend part of their life cycle in the zooplankton (decapods excluded).

53. Tunicata. Adult forms of salps and Doliolids appearing in aggregated and solitary forms, mostly neritic.

54. Chaetognatha. Predator planktonic organisms; neritic juvenile and adult forms are included.

55. Siphono-medusae. Planktonic forms of Cnidaria.

56. Polychaeta. Sedentary and motile forms; sedentary types feed on seston and plankton; motile types are carnivores and scavengers.

57. Benthic cnidaria. Colonial and solitary forms that feed on seston and plankton; some are carnivores.

58. Sponges. Colonial benthic forms that feed by filtering seston and plankton.

59. Arthropoda, benthic crustacea. Includes carnivores, herbivores and scavengers.

60. Gastropoda, benthic forms. Includes carnivores, herbivores and scavengers.

61. Bivalvia. Typical benthic, filter feeders.

62. Benthic cephalopoda. Includes juvenile and adult benthic types as well as the juvenile stages of the pelagic forms.

63. Echinodermata. Includes all adult benthic forms, carnivores, herbivores and scavengers.

64. Benthic fishes. Adult boney fishes and selachia, living and feeding on animals or plants distributed in, on or very close to the bottom.

65. Pelagic fishes. Adult boney fishes living and feeding on phytoplankton, zooplankton and nekton.

66. Pelagic cephalopoda. Adult nektonic squids feeding on pelagic fish.

67. Mammalia. Dolphins and porpoises feeding on pelagic fish or squids.

68–70 Macroalgae. Benthic macroalgae defined by the listed systematic groups.

71. Phanerogams. Benthic greengrass (flowering plants).

72. Bacteria, except E. coli. Coliform bacteria.

73. E. coli. Coliform bacteria.

74. Fungi. Marine fungi of various systematic groups.

C. Description of geological components :

75. Seston-suspended particles $< \mu$ 0.5 m.

76. Sediment-surface layer (10 cm deep) of sea bottom excluding the living organisms.

Binary connectivity matrix

In order to construct the binary connectivity matrix, an understanding of processes with the mass transfer (binary 1) or without it (binary 0) must be achieved. For biologists this approach is convenient because it relates to the marine food web. However, for chemists this was not always the case since not all interactions involve direct mass transfer. For this purpose conventions for modelling of chemical processes were prepared. Examples of such processes are given in Figures 6 and 7.

Figure 6 shows the nitrate to nitrite reversible redox reaction. In one direction (oxidation of nitrite to nitrate) nitrite and oxygen combine into nitrate. Accordingly, there exist mass transfer (1) from nitrite to nitrate as well as from oxygen to nitrate (1). On the other hand there is neither transfer from nitrite to oxygen (0) nor transfer from oxygen to nitrite (0). In the reduction of nitrate to nitrite there is mass transfer from nitrate to both nitrite and oxygen.

Figure 7 explains the precipitation and dissolution of MnO_4. The rationale for denoting these interactions follows the previous example.

a) $NO_2^- + O_2 \rightleftharpoons NO_3^- + OH^-$

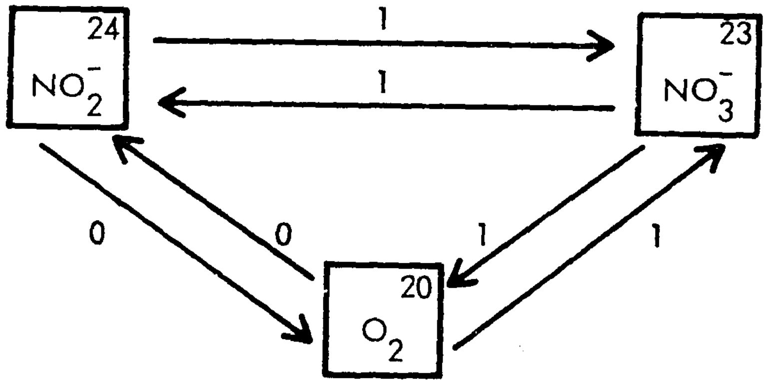


Fig. 6. An example of binary connectivity conventions. Nitrate-nitrite redox process.

b) $Mn^{2+} + O_2 \rightleftharpoons MnO_4$

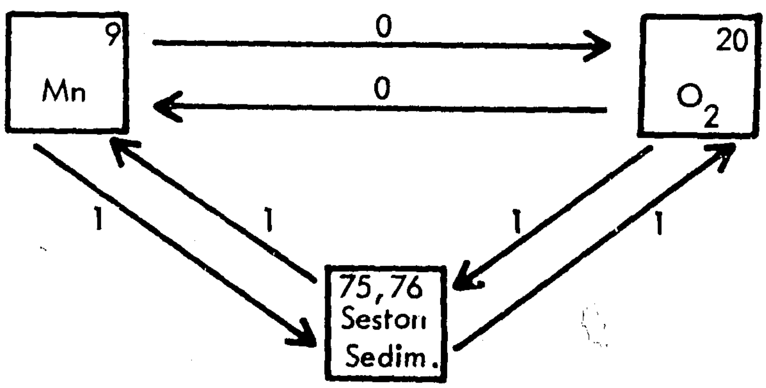


Fig. 7. An example of binary connectivity conventions. Magnesium oxide precipitation - dissolution process.

In the same way as in the above examples, the total matrix was constructed (Fig. 5). It should be read from the column (vertical) to the row (horizontal). For instance, the example of Figure 6 is presented in the binary matrix in such a way that "1" could be found in the intersections of column 24-row 23; column 23-row 24; column 20-row 23; column 23-row 20. On the other hand, lack of mass transfer is shown as "0" in the following intersections : column 24-row 20; column 20-row 24.

Feedback dynamics (Forrester Diagrams)

The binary connectivity matrix expresses only the presence of an interaction between any two components. All connexions of one component to all others can be presented using feedback dynamics diagrams (Forrester, 1963; Patten, 1975). In such a diagram, besides all component connexions, the inputs and the external factors which influence the mass transfer between components are presented.

The example of a feedback dynamics diagram for Pb is shown in Figure 8. Indicated inputs to this component are from the atmosphere, land, streams, suspended and marine sediments, living plants, and animals. Hence the model accommodates movement of lead into marine environment, where it is taken up by the living plants and animals (components 39-74), by the seston (75), and by the sediment (76). The feedback dynamics diagram of marine Pb concentrations also indicates that temperature, pH, light, chemical equilibria, and salinity influence the transfer of Pb in the sea; and it indicates that halogens and amino acids control the input dynamics into organisms. Its own presence, the density of living plants and animals, the temperature, and the equilibria condition control its output dynamics.

Turnover rates for the components

In order to produce a quantiative, mathematical model from the conceptual one, a preliminary evaluation of turnover rates was carried out using the Delphi method. The rates were determined for all 78 components. The maximum rate was recorded for E. coli (component No. 73) at $7x10^{2}$ mo^{-1}, and the minimum rate was recorded for potassium (component No. 14) at $2x10^{-4}$ mo^{-1}. These values correspond to 1 hour and 500 years turnover times, respectively.

Future perspectives

With the completion of the first five points, the conceptual model of the marine Adriatic Regional Ecosystem has been produced. In the preceding section the mathematization step was mentioned briefly. In order to prepare the mathematical model (i.e. an operational model that could be used for decision-making) from the conceptual one, a marine area that fulfils certain requirements must be chosen. The special requirements are the following:

a. a geographical area with well defined boundary conditions (a semi-enclosed bay with simple coastline and sea bottom topography),

b. a reasonable amount of background data, and an ongoing research project for data collection with defined frequency of sampling and spatial distribution of sampling stations,

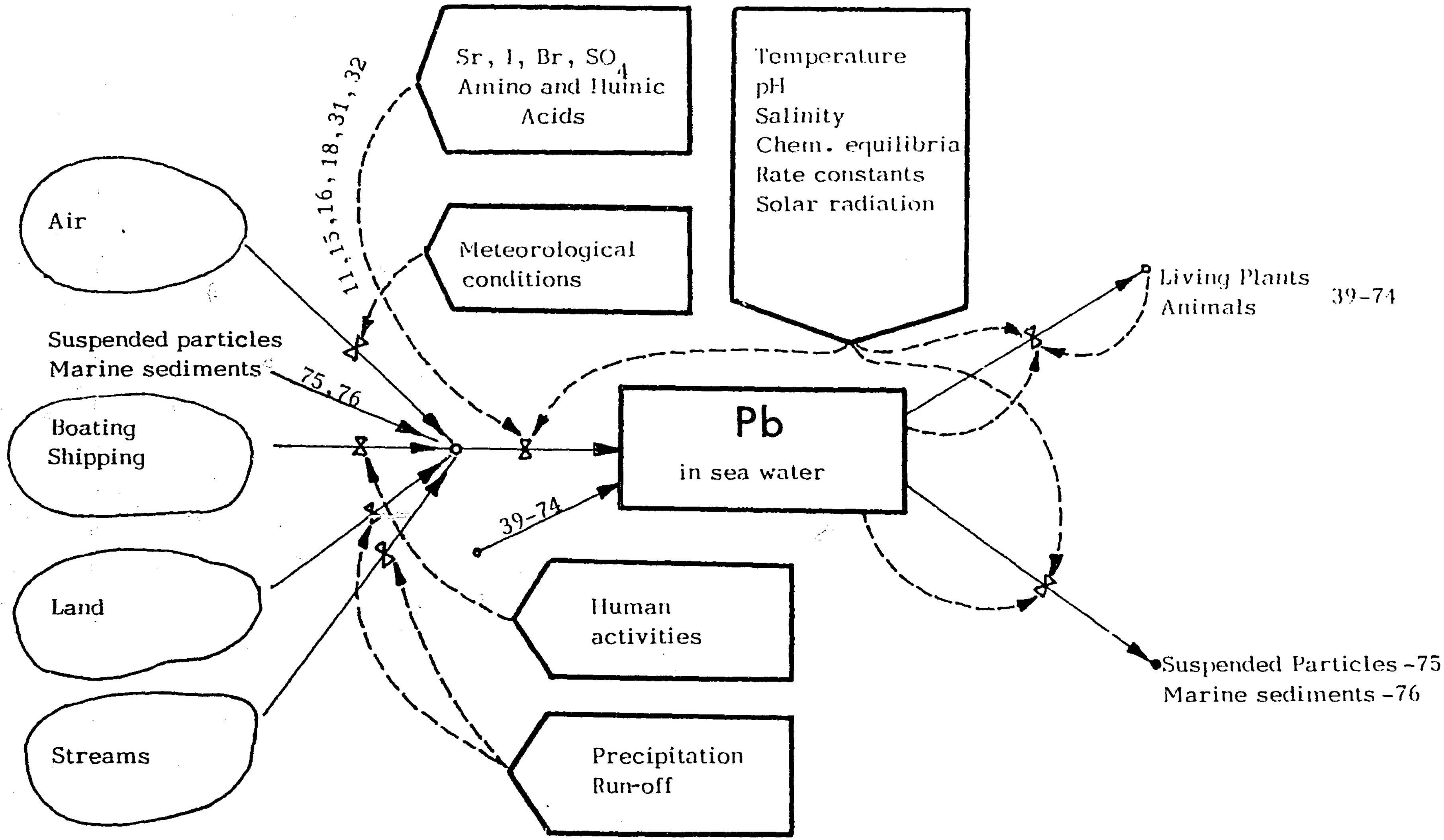


Fig. 8. Feedback dynamics (Forrester) diagrams of lead in the sea.

c. a minimum number of experts (physical and chemical oceanographers, marine biologists and modellers), and

d. computational facilities.

If these requirements are met, an area could qualify for development of the mathematical modelling stage. The preliminary assessment of the results from Rijeka Bay shows that it would be a good choice for mathematical modelling.

2.3.4. Western Mediterranean ecosystem

Large-scale features of the Western Basin

Research in the Western Mediterranean has been mainly concentrated in coastal areas. An exception is the northern part, where many offshore investigations have been conducted. This Section is based on the results of different cruises in this part of the basin.

The Mediterranean is a three-layered body of water:

1. a surface layer, where the conditions vary throughout the year, but in which there is enough light to allow phytoplankton growth.

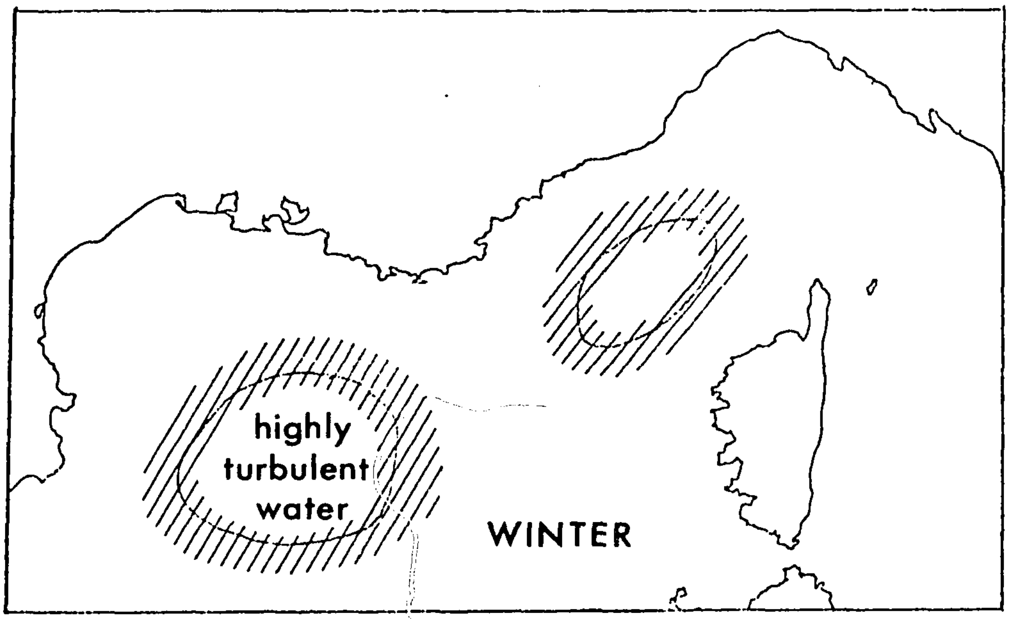
2. an intermediate layer derived from a Levantine origin and situated between 400 and 600 m.

3. a deep layer, found between the intermediate layer and the bottom. The last two layers are nutrient rich. Some mixing mechanism must be operative so that these nutrients can upwell into the surface layer, and foster a phytoplankton bloom. This enrichment appears on different time and space scales (e.g. it takes place either during some period of the year, or at some place in the sea).

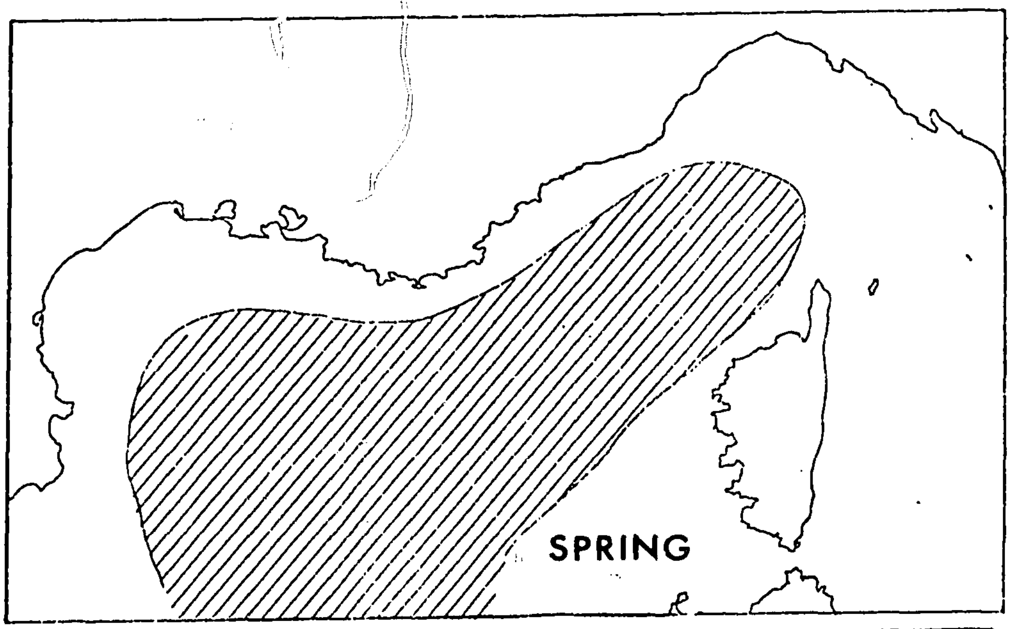
On an annual basis the important phenomena in the ecosystem of the northern part of the basin are:

a. In winter (Fig. 9a). Under the effect of strong winds and cold air masses coming from the north and north-east over the offshore waters, dense water is produced at the surface. The instability that follows induces a strong mixing between surface and deeper waters. By this phenomenon nutrients are brought into the illuminated layer, but the mixing is so strong as to inhibit the phytoplankton growth by mixing the phytoplankton down to aphotic depths (the mixed layer can reach 1000 m or even 2500 m (bottom) as in March 1963). When this occurs the phytoplankton develops on the margin of the two turbulent areas, where it can find enough nutrients diffusing from the offshore water and a moderate stability in the vicinity of coastal water.

b. In spring (Fig. 9b). The heating of the surface water allows the development of a thermocline. These conditions produce a bloom of phytoplankton, and, at the same time, a zooplankton bloom. The surface layer is rapidly depleted of a : In winter, high concentrations of phytoplankton are found around patches of turbulent water.



b : Spring bloom in the entire off-shore water.



c : In summer, the phytoplankton is abundant only in the divergence zones.

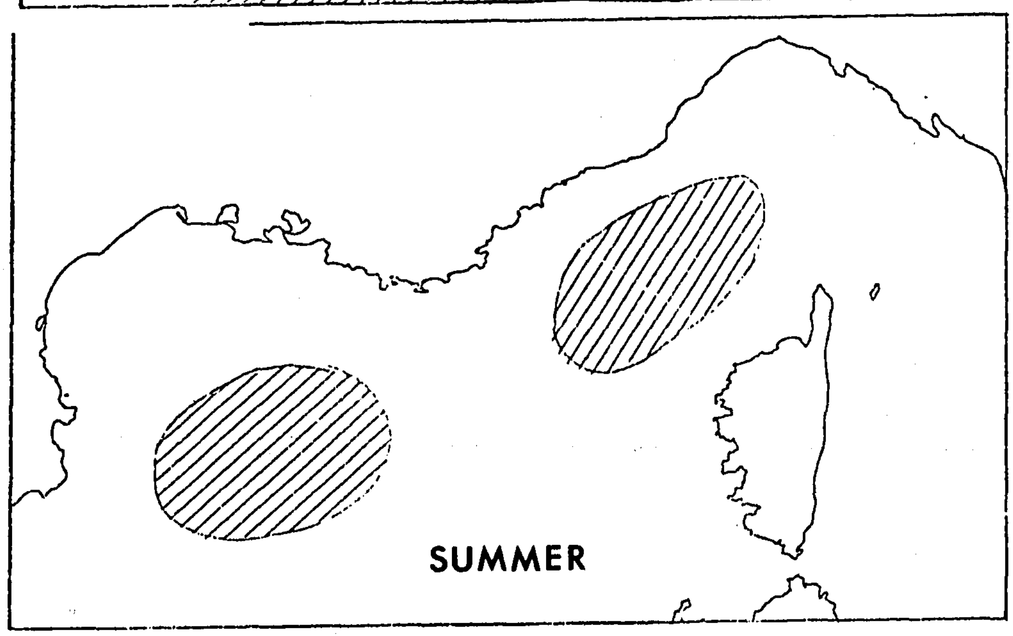


Fig. 9. Areas of high phytoplankton biomass in the north-western basin of the Mediterranean.

nutrients, and the plankton begins to decline. At the beginning of the summer the surface layer is nutrient deficient, and the phytoplankton population is diminished.

c. In summer (Fig. 9c). An enrichment process can be found at nearly the same place as the strong turbulent mixing in winter. The cyclonic circulation in the northern part of the basin produces divergences in the offshore water in the Ligurian Sea and in the Golfe du Lion, south of Marseille. Such a divergence produces a doming of the nutrient rich layers (intermediate waters) into the euphotic zone. In such places where nutrients and light occur, a phytoplankton bloom takes place. In the Mediterranean it is always a moderate bloom because of the relatively low concentrations of nutrients, even in the upwelling water.

The two transects of the Ligurian Sea between Nice and Calvi (Fig. 10) show the region where phytoplankton grows in winter, on the margin of the strongly mixed water, and in summer : on top of the intermediate water in the offshore water. As we have seen, the two important enrichment processes (in winter and in summer) are occurring in the offshore water, so this part of the basin can be divided into two main spatial regions : the coastal waters (where the enrichment is negligible) and the offshore ones. The coastal circulation, which can be strong (maximum of 35 $cm\text{-}sec^{-1}$ 15 miles off Nice), certainly plays an important rôle in this segregation of coastal waters.

We can illustrate the differences in the annual cycle of plankton by a graph (Fig. 11). A relatively high level of phytoplankton and zooplankton occurs during spring in the offshore water and a low level during summer. In contrast, only a small bloom of phytoplankton and zooplankton occurs in the coastal waters. Although the enrichment processes are taking place in the offshore waters, we suggest that the small peak in the coastal waters is related to this offshore enrichment. The coupling of the two regions can occur through lateral eddy diffusion across the westward current and through the assumed meandering of the front separating the offshore and coastal systems (Fig. 12).

There are two other large scale processes occurring in the coastal region of this basin :

1. Coastal upwelling. Coastal enrichment of the surface layer through the process of coastal upwelling of nutrients is inhibited by the prevailing downwelling situation, which is driven by the offshore divergence piling up surface water against the coast. Occasionally upwelling does occur, but it is ineffective in supporting phytoplankton blooms. On the Spanish coast it occurs more frequently and is considered to be a major factor in coastal phytoplankton blooms.

2. River outflows. Two rivers are important in this part of the basin : the Rhône, which has an important effect in the Golfe du Lion and the Ebro which influences strongly the evolution and the distribution of plankton on the Spanish coast.

Meso-scale processes

Up to this point, only some important large scale phenomena which take place in this part of the Mediterranean have been summarized. Some meso-scale processes

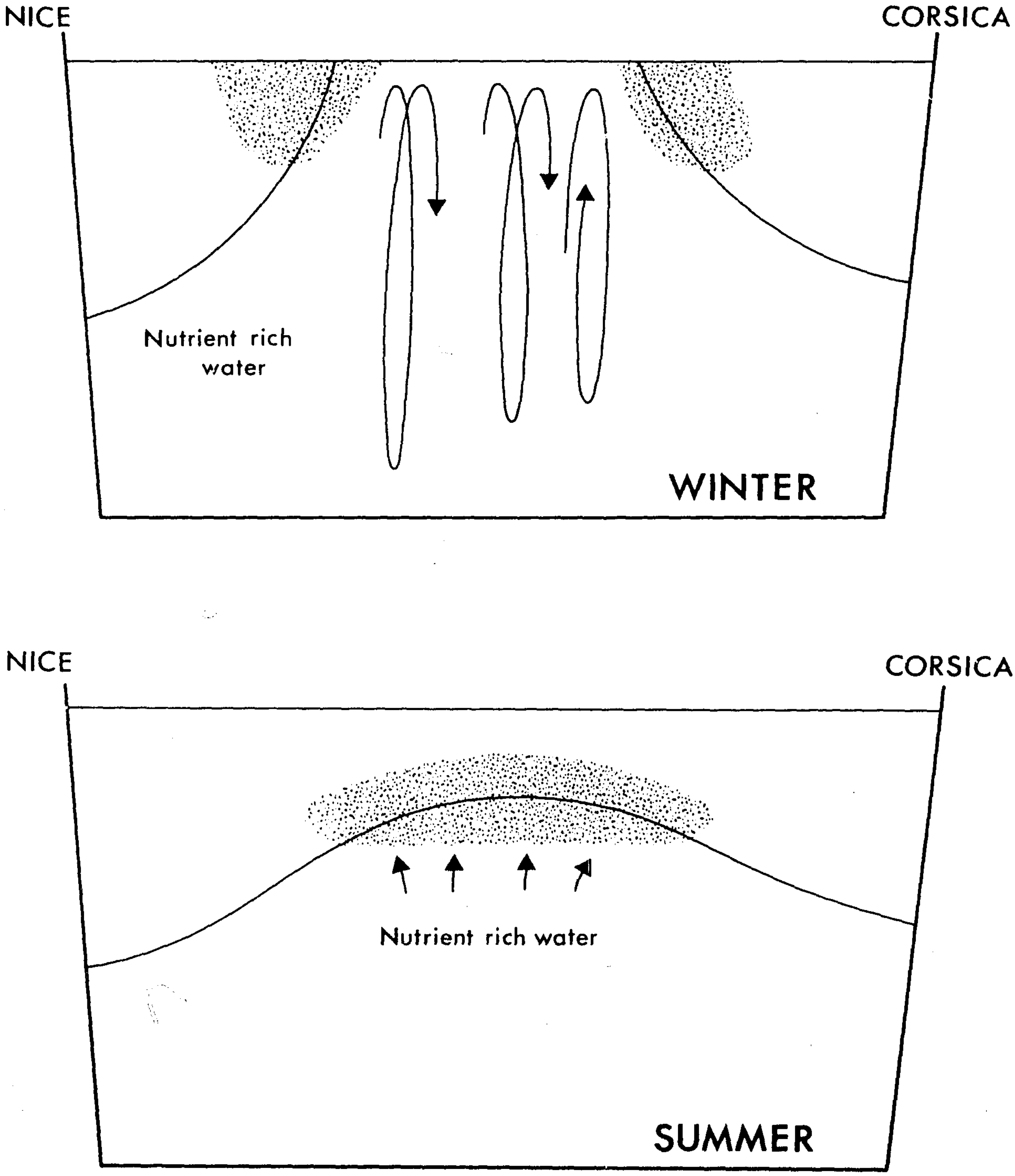


Fig. 10. Transect in the Ligurian Sea between Nice and Calvi (Corsica).

Upper : In winter, the phytoplankton grows on the margin of the turbulent water where the upper layer is stable.

Lower : In summer, the phytoplankton grows at a depth where the nutrient rich water is upwelled into the euphotic layer by the divergence.

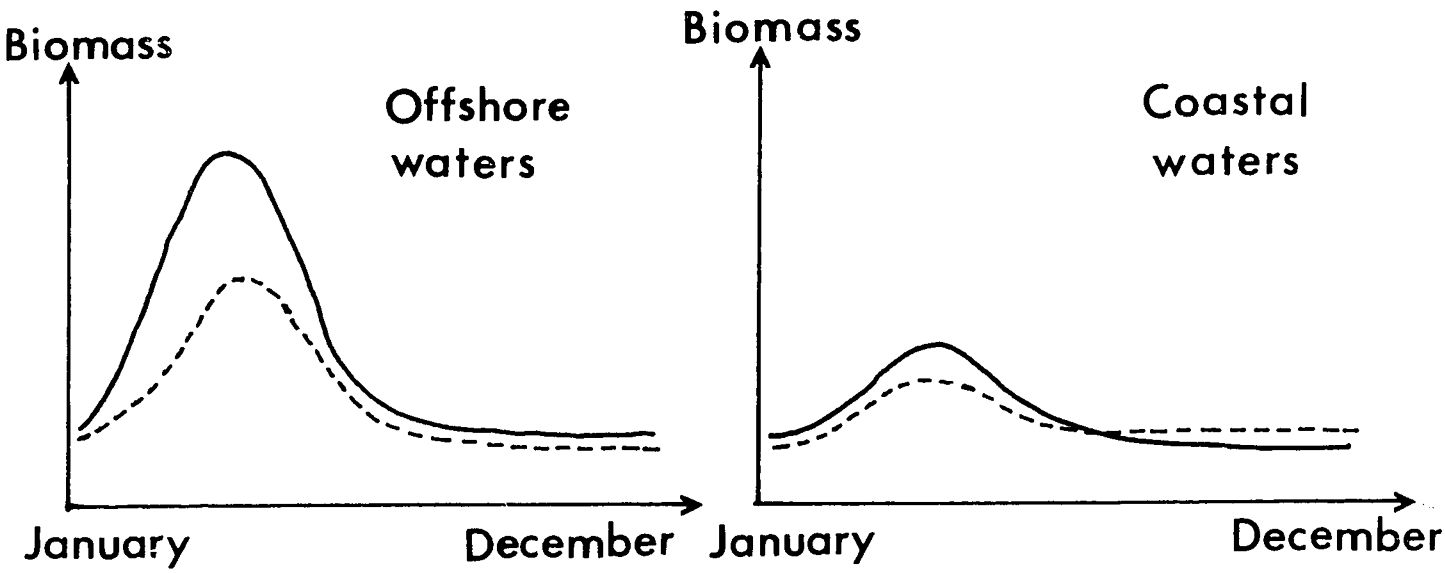


Fig. 11. Annual cycle of plankton (in relative units). The spring bloom of phytoplankton and zooplankton is more important in offshore waters than in coastal waters.

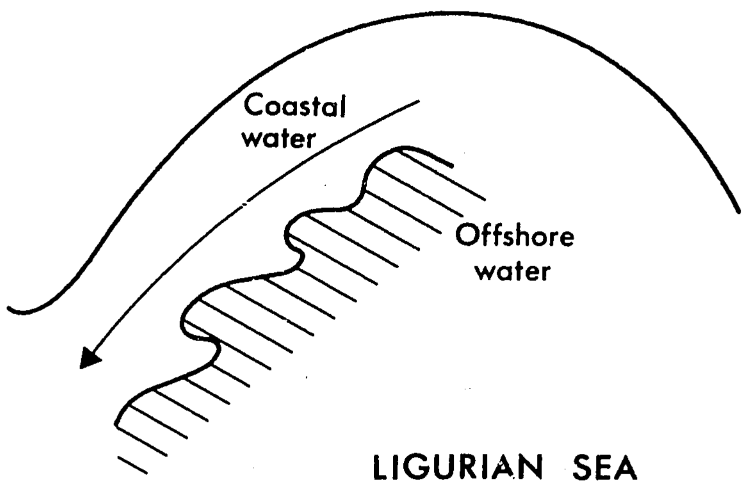


Fig. 12. Meandering boundary between offshore and coastal waters, which can explain a moderate enrichment of the latter.

can also be important in determining the distribution of either physical properties or living biomasses.

The illustration given in Fig. 13 summarizes a meso-scale process that has been observed in the divergent zone south of Marseille. In the southern part of the divergence zone, the boundary between the inner cold water and the southern, warmer water can undulate. Meanders develop which can induce slow vertical movements of descending cold water and upwelling intermediate water rising. These movements are similar to what happens in the atmosphere when cold and hot fronts evolve. At the tip of the meander of the fronts, a baroclinic instability develops. In this small spot a violent vertical mixing can occur, inducing a cyclonic pattern of flow which has been verified with neutrally buoyant floats and explains the high vertical currents occasionally observed.

It appears that the region of winter enrichment consists of eddies of different sizes (related to dissipation of kinetic energy) that have different effects on plankton growth. The measurements of nutrients and chlorophyll made by the R/V T.G. THOMPSON between Sardinia and Barcelona showed that the patchiness has different characteristics in the turbulent water from those in the marginal water where phytoplankton is more abundant.

Indications are that an overall model for precise management purposes of the Western Mediterranean basin is not yet possible, mainly duo to the incomplete knowledge of the basic processes taking place at the different levels of the system. Modelling is still restricted to bays or to small scale events.

Function analysis

System analysis in the modelling procedure involves the partitioning of the system, and an estimation of important processes. It is possible to list all the basic processes that take place in the ecosystem, e.g. :

(i) nutrient assimilation (primary production and growth, herbivore feeding),

(ii) bacterial regeneration (dissolved organic matter production and decay),

(iii) zooplankton physiology (benthic animal filtration, etc.).

They can be represented by sub-models, the output of which can be compared with experiments at the laboratory or in enclosed water masses. These processes are general and are not restricted to the Mediterranean Sea, as they are common components to any marine ecosystem. The process parameters certainly must be optimized, however, in order to fit the peculiarities of Mediterranean communities or species.

These modelling efforts can demonstrate to the scientist in what way he must introduce new concepts in order to obtain a good fit between the sub-model and the experimental data (saturation of assimilation of nutrients, internal pool of inorganic nutrients, resource partitioning in zooplankton feeding ...).

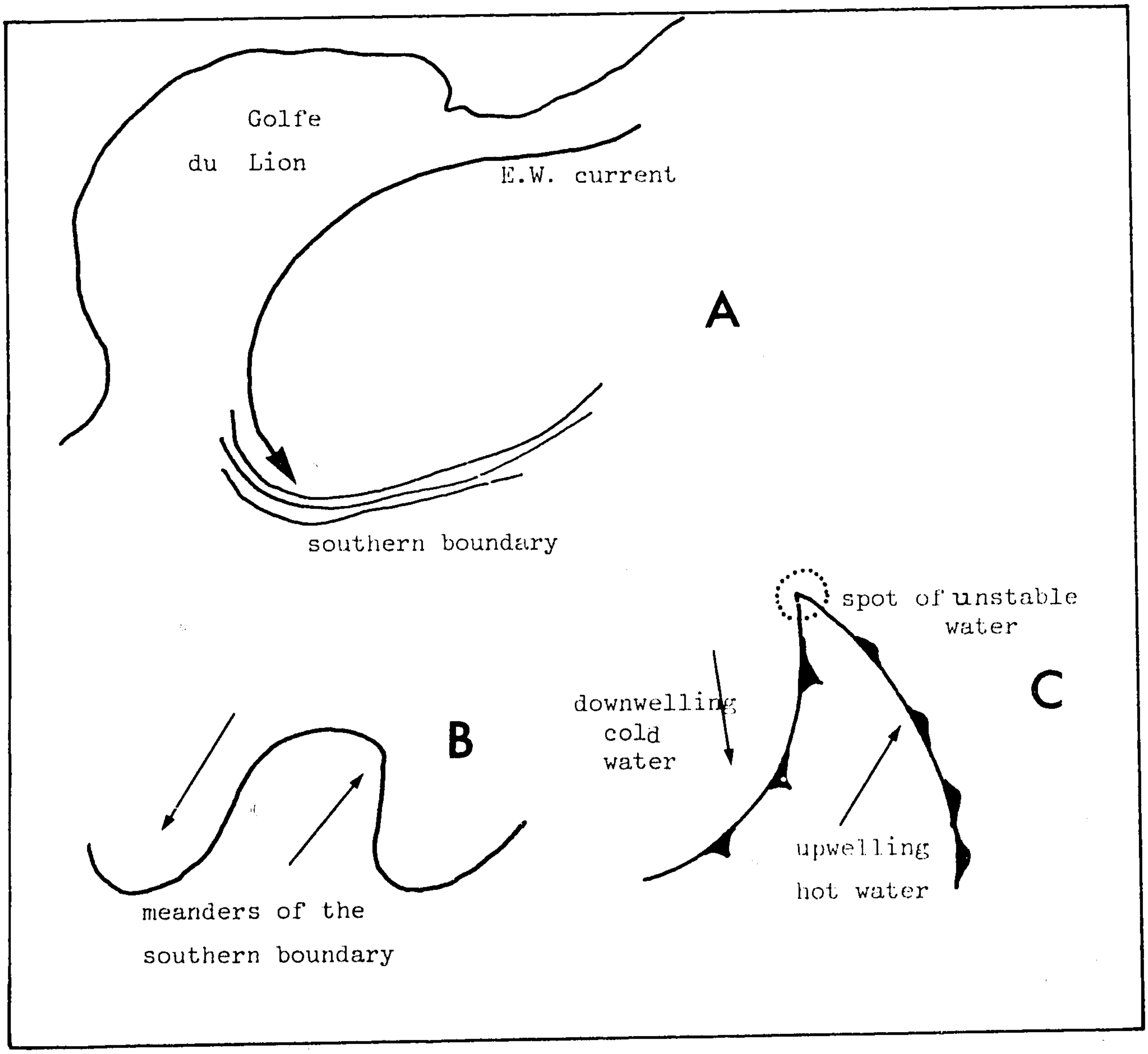


Fig. 13. A meso-scale process observed in the divergent zone south of Marseille.

A : Geographical position of the southern boundary between the divergence zone and the warm water mass in the south.

B : Meso-scale observations of the boundary, showing meanders, with opposite circulation of the two water masses.

C : Meteorological analogy and position of baroclinic instability, producing a very strong vertical mixing.

A sub-model example of herbivorous zooplankton feeding

One of the most important features of the evolution of an ecosystem is the species succession (with time or in space) : replacement of species by others when the ecosystem evolves from a young to a mature state. The feeding sub-models must take into account the fact that phytoplankton biomass is distributed between the different species or different size classes of particles. Fig. 14 shows the two different conceptions of the phytoplankton - herbivore trophic relation. The distribution of biomass (or volume) of particles in the sea within each size class now can be measured. For every sample of water, it is possible to know the biomass spectrum (Fig. 15).

The data that usually are collected at sea to test a model requires the modeller to use the biomass of a trophic level instead of individual species numbers of biomasses, i.e. by grouping together, by species : phytoplankton, zooplankton, herbivores, carnivores, and fish.

A study of the anatomy of species belonging to the most important group of zooplankton (the copepods, crustacea) has suggested that their feeding is strongly dependent on the shape of the biomass spectrum. A copepod is an ovoid animal which has two long antennules in its forehead. At the rear end, it possesses a pair of antennae which are thought to produce a local inward current. A series of thoracic limbs, that play a role in the feeding, ends with one pair of maxillae and one pair of maxillipeds. These act as a net or a scoop, to collect the particles carried by the water current. In detail these last appendages appear as some sort of plankton net. They bear a limited number of setae which in turn are fitted with two rows of setules (Fig. 16). The spaces between the setules are not homogeneous on each seta. The probability that a particle of a given diameter can be collected by an appendage depends on whether or not its surface contains smaller meshes. By measuring the distance between setules one can calculate the probability for different particle sizes to be collected, thus making it possible to relate the filtration efficiency (probability of capture) to the particle size, and to draw the filtration efficiency spectrum (Fig. 17). The study of the appendage anatomy permits better definition of the ascendant part of the spectrum. Some experiments have suggested that the efficiency of filtration decreases when the particles are too large. The copepods are less efficient in removing the small particles from the water than the large ones, but for a given size range, some species are more efficient than others. It is easy to see that if some pollutants or toxic substances are carried by small particles, the species Temora stylifera will collect them in a very small quantity compared to the speices Euterpina acutifrons. This observation has many implications on the pathways of such substances in the food web.

We have constructed a simple sub-model to test this concept. The basic expression relates the variation of biomass of particles in a size class per unit time to the growth and grazing rates:

$$\frac{dB}{dt} = \text{growth grazing, or}$$

$$\frac{dBi}{dt} = kB_i - g \cdot E_i \cdot B_i \cdot H$$

where B_i is the biomass of the particles in size class i, H is the number of copepods in a unit volume of water, and Ei mean filtration efficiency in size class i. Sixteen such equations have been used to model the evolution of sixteen size classes of particles submitted to grazing (the number 16 is due to the number of size classes of the apparatus used to establish the biomass spectrum).

One more expression is needed to relate the filtration coefficient g to the biomass. The relation can be expressed as:

$$g = \frac{R_{max}}{\Sigma B_i}$$

where ΣB_i is the total biomass of the particles, R_{max} is a constant. We have assumed that all particles are plant cells and that there is no nutrient limitation to their growth, so that the growth rate k is constant. The comparison between experimental results (Fig. 15) and the output of the model shows that this concept is able to explain the modification of the biomass spectrum by the activity of the herbivores.

This simple model can only simulate what happens during a short period of time. In order to explain the phenomena occurring over a longer time period, it would be necessary to introduce more equations into the model and to include new factors operating during a short time period. The shema below shows a time axis on which are indicated the phenomena that cannot be neglected as the time scale of the model increases. A similar reasoning is applicable to a space scale.

Duration of experiment	0	1 hour	1 day	1 month → time
Important processes for each time scale	- grazing	- grazing - phytoplankton growth	- grazing - phytoplankton growth - zooplankton growth	

This process of selection of the particles in the environment can explain some part of the species succession; it is concurrent to the differential assimilation rate of nutrients by the phytoplankton species.

A simple model of plankton evolution in the Bay of Villefranche-sur-Mer

In summer a phytoplankton patch can be observed in the northern part of the bay of Villefranche-sur-Mer (Fig. 18). The patch is a result of the discharge of urban sewage along the north-eastern coast. The zooplankton biomass is more abundant on the margin of the patch than inside. The effect of zooplankton grazing on the evolution of the phytoplankton patch becomes an important question.

In May and June 1971, an intensive study of the northern part of the bay, was conducted (sampling every two days, day and night, in three stations).

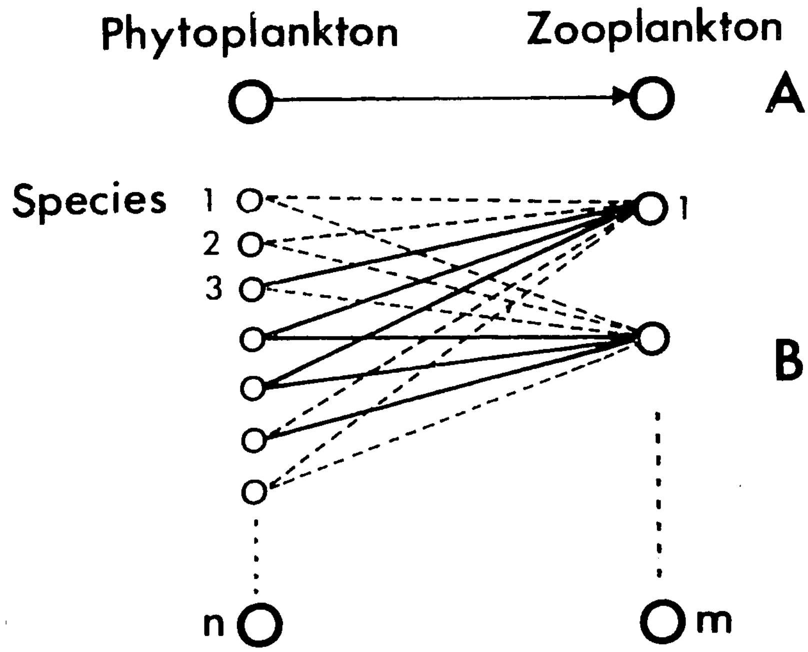


Fig. 14. Two concepts of trophic relations in the plankton :
A : A simple conception of a food chain.
B : Model of a food web : some species are more strongly related (heavy lines).

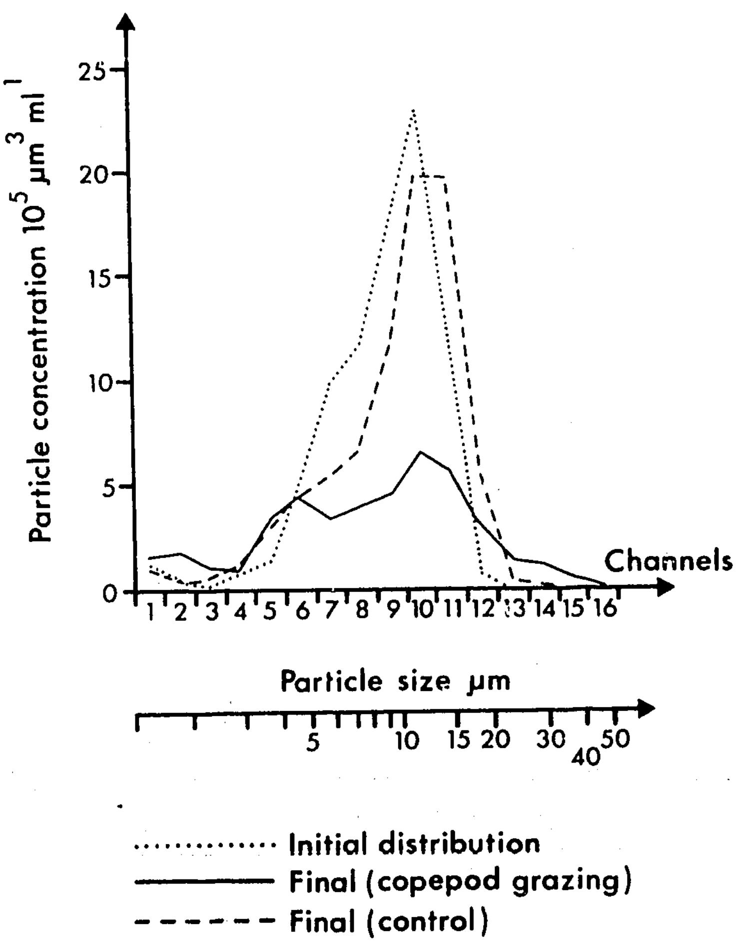


Fig. 15. Biomass spectra (particle concentration versus size of particles) in water containing phytoplankton (mainly the diatom Skeletonema costatum).

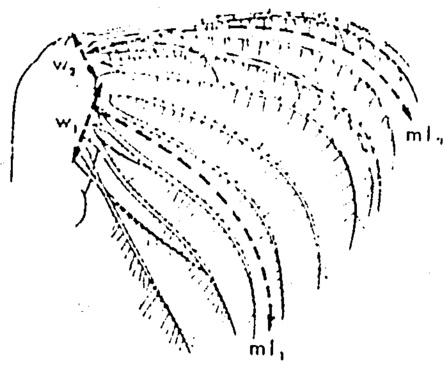


Fig. 16. Drawing of one of the feeding appendages of a copepod (Acartia clausi), showing the long setea fitted with setules. This appendage is similar to a plankton net with different mesh sizes.
(After Nival and Nival, 1976).

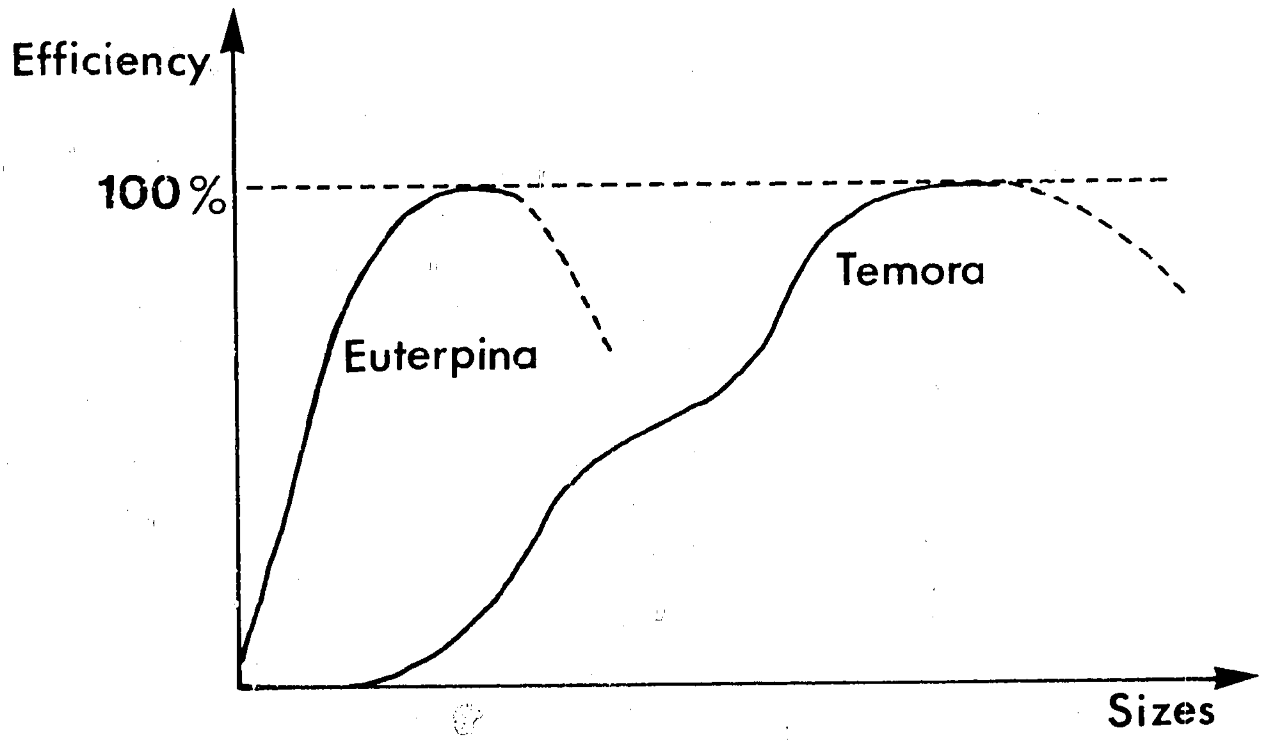


Fig. 17. Spectrum of filtration efficiency (efficiency versus particle size) for two species of copepods. Euterpina sp. can collect small particles more efficiently than Temora.

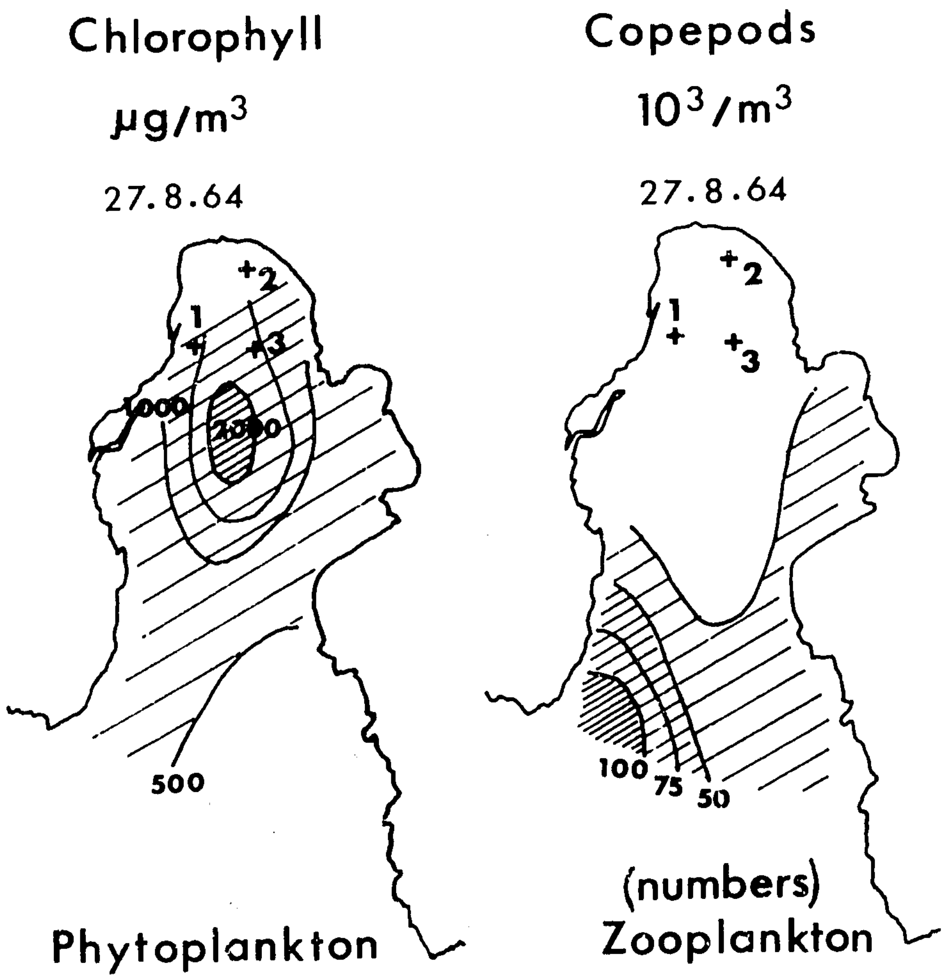


Fig. 18. Phytoplankton and zooplankton distributions in the Bay of Villefranche-sur-Mer (+ sampling stations where the data for the model have been taken).

During this period three peaks of phytoplankton were observed. The zooplankton biomass shows a similar oscillation but of smaller amplitude. Nevertheless, the variations are significant, as shown by the similar evolution at the three stations.

We have designed a simple model to simulate the variation of biomasses and to explain the effect of grazing and water currents during the observed planktonic evolution. A grazing function which is less powerful than the previous sub-model was used due to the lack of specific information on the parameters of the different species found in the sea. It was assumed, as a preliminary hypothesis, that all the phytoplankton and all the zooplankton species behave similarly. This assumption allows use of the conventional measurements of biomass, i.e. chlorophyll or carbon concentration for the phytoplankton, and dry weight or carbon concentration for the zooplankton. The design of a realistic model is often impossible due to the lack of knowledge of basic processes or of experimental estimation of the parameters.

The graphs in Fig. 19 suggests that some trophic relationship between phytoplankton and zooplankton must exist. This can be modelled as a predator-prey system using the well-known predator-prey equations.

The expressions for the variation per unit time of biomass are:

phytoplankton: $$\frac{dB}{dt} = a_1 B - b_1 H B \quad = \text{growth} - \text{grazing}$$

zooplankton : $$\frac{dH}{dt} = -a_2 H + b_2 B H \quad = \text{death rate} + \text{growth related to grazing}$$

The most abundant zooplankters are crustaceans (copepods). A modification taking into account the fact that, at least 4 steps are necessary to go from the egg to the adult (egg ⟶ nauplius ⟶ copepodite ⟶ adult) must be introduced into the system. The first stages of the nauplii do not feed significantly; it is assumed that only the copepodite and the adult are able to graze significantly on the phytoplankton. This phenomenon introduces a time-lag between food grazing by the animals and their growth. The system is improved by introducing $H(t-\tau)$ in the second equation in place of H, which means that the growth rate at time t depends on the population at time $t-\tau$ (τ being time-lag taken as 6 days). The simulation output of the model is a typical predator-prey cycle with some damping due to τ, that can be represented as variations in time of the two components as on Fig. 19, or on a graph of prey-predator relationship (Fig. 20). Beginning with small biomass conditions (lower left of the graph) the prey (phytoplankton) increase until they are reduced by the growing predators. When the latter have reached some concentration, their grazing reduces the concentration of prey, but they go on growing. When the food is reduced below a minimal level, the predators begin to decline and the whole system returns to low values.

A comparison of the output of the model to the data has shown that the mean value for phytoplankton around which the system oscillates (ordinate of point M) is too high. It became evident that some limiting effects on the phytoplankton growth existed (nutrients or other substances).

A simple way to introduce the limiting effect is to assume that the phytoplankton have a "logistic growth". If isolated from grazing pressure, their growth reaches a maximum biomass after the limited resources are consumed.

We can improve the model by adding a term ($-c_1 B^2$) which takes into account this limitation. It appears as a self limitation of phytoplankton, or a competition between the phytoplankton cells for the same resource. A new run of the programme which translates the model into computer language, gives a new simulation for which the mean values are the same as those from the data. Unfortunately, the model cannot explain an important feature of the evolution of the data which is that the data plotted on a predator - prey graph, (as Fig. 20) show the point representing the state of the system as cycling in the opposite way to that predicted by the model (Fig. 21). This conclusion demonstrates that the physical effect of dilution of the water mass and its population, or translation of water masses, might be more important than the grazing effect.

Some features of the circulation in the bay must be explained. When the wind blows from the east, it increases the speed of the general cyclonic current that enters the bay at the surface and it induces a countercurrent in the deeper layer (if the water column is stable). If the wind coming from the west is strong enough, it can produce a reversal of this pattern, i.e. the water enters the bay at depth and goes out at the surface (producing a moderate upwelling). In both cases the water which enters the bay is nutrient poor, and has a low concentration in phytoplankton. The plankton hauls usually made in the Bay of Villefranche have shown that the zooplankters increase in abundance to the south and with depth. The meteorological data taken during the study show that strong winds (either from east or west) were occurring during the phytoplankton declines. It is assumed that they induce the washing out of the phytoplankton patch. When the wind slows down the phytoplankters are able to grow but are influenced by the grazing by zooplankton. The regularity of the occurrence of wind impulses during this period of the year allow us to model the conservative part of the system (the physical part) with a sinusoidal function. The final state of the system adopted to simulate the events in the Bay of Villefranche is:

$$\text{phytoplankton} : \frac{dB}{dt} = a_1 B - c_1 B^2 - b_1 H B + \alpha_1 . B . \sin (kt + \phi_1)$$

$$\text{zooplankton} : \frac{dH}{dt} = a_2 H + b_2 B H (t - \tau) + \alpha_2 H . \sin (kt - \phi_2).$$

The values of the parameters a_1, b_2, c_1, a_2, b_2 have been estimated from experimentation, but the values of the physical ones have been calculated by an optimization procedure. This procedure gives the parameters values which minimize the sum of distance between the model output and the data. Fig. 22 shows, on the same graphs, the best simulation and the data. We can see that the model fits quite well the values measured in the field.

Nevertheless the model must be improved to be of general use. A better model might include a sub-model of nutrient assimilation, implying a new set of equations for nutrients, and a sub-model of water circulation in the Bay of

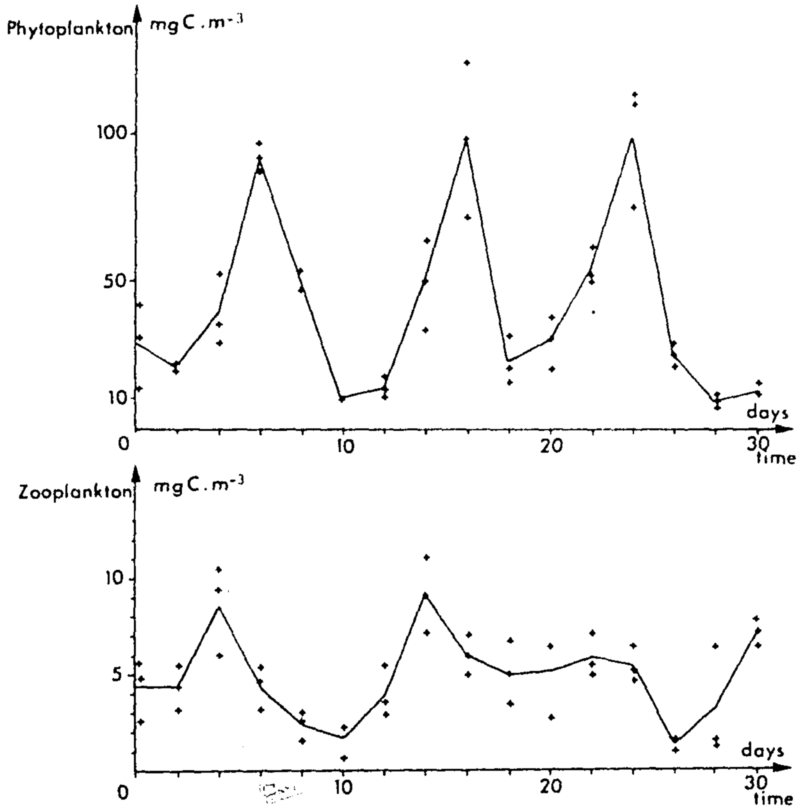


Fig. 19. The variations in biomass of phytoplankton and zooplankton at the end of spring in the Bay of Villefranche-sur-Mer.

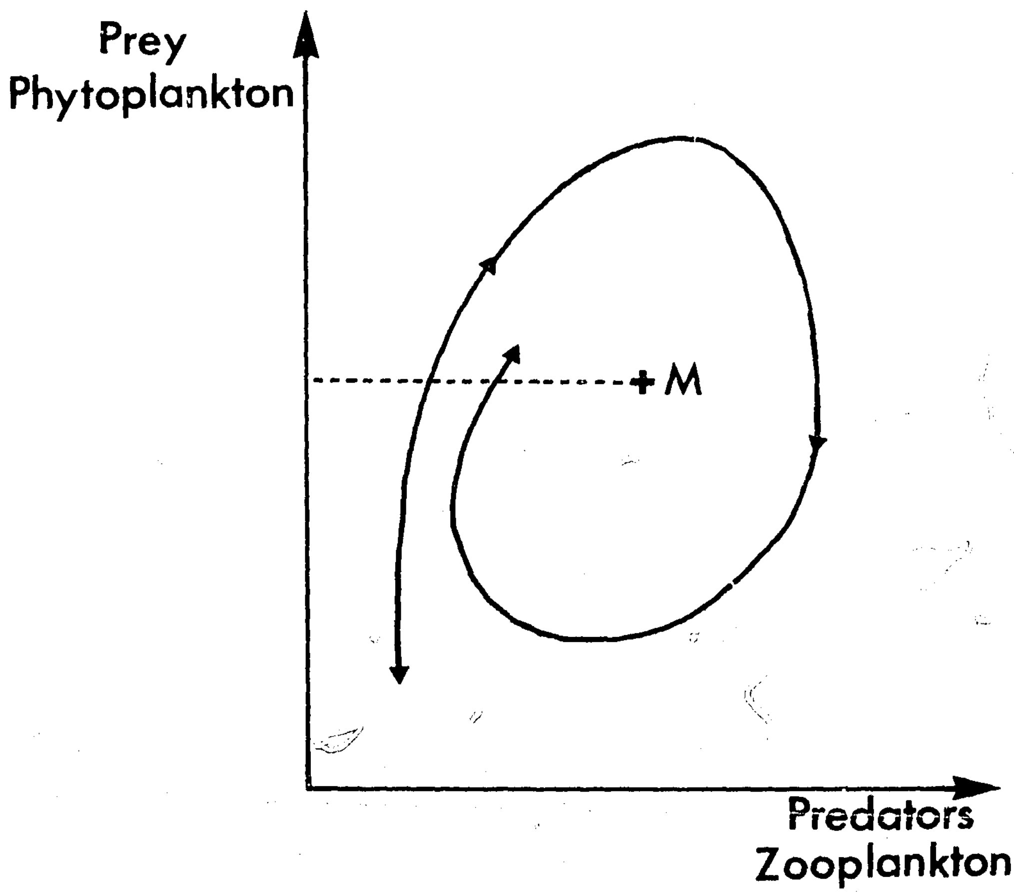


Fig. 20. Graphic illustration of the prey-predator relationship between phytoplankton and zooplankton.

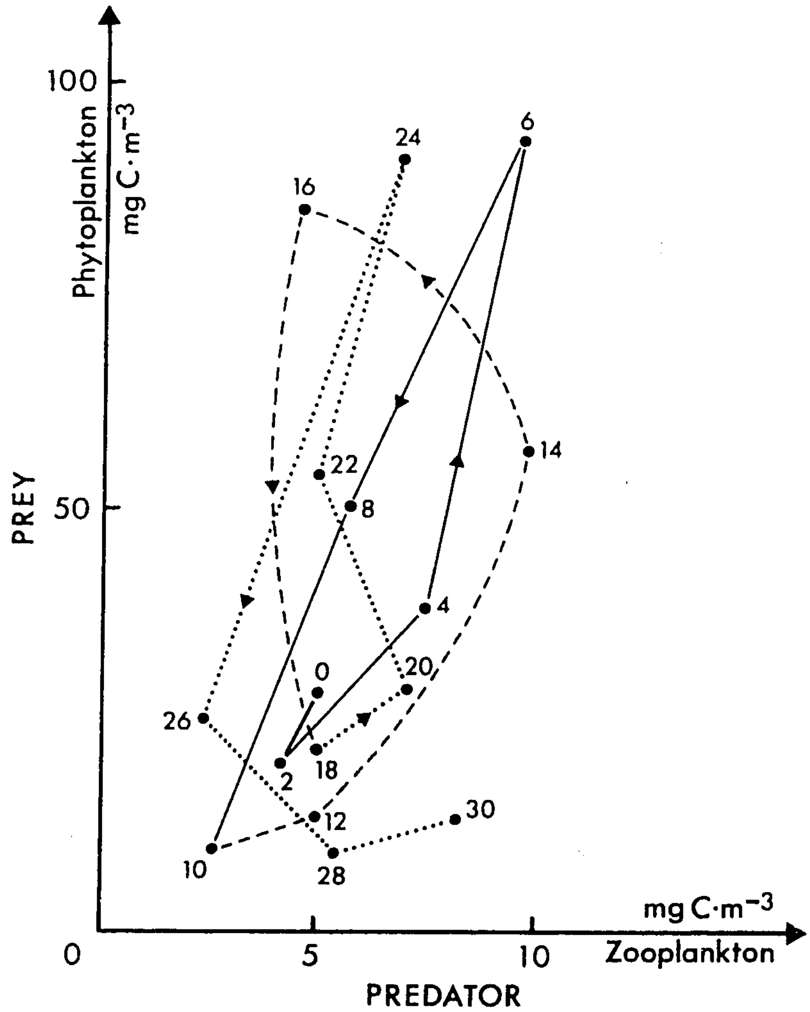


Fig. 21. Time variation of the natural system in the phase plan (prey-predator: phytoplankton-zooplankton).

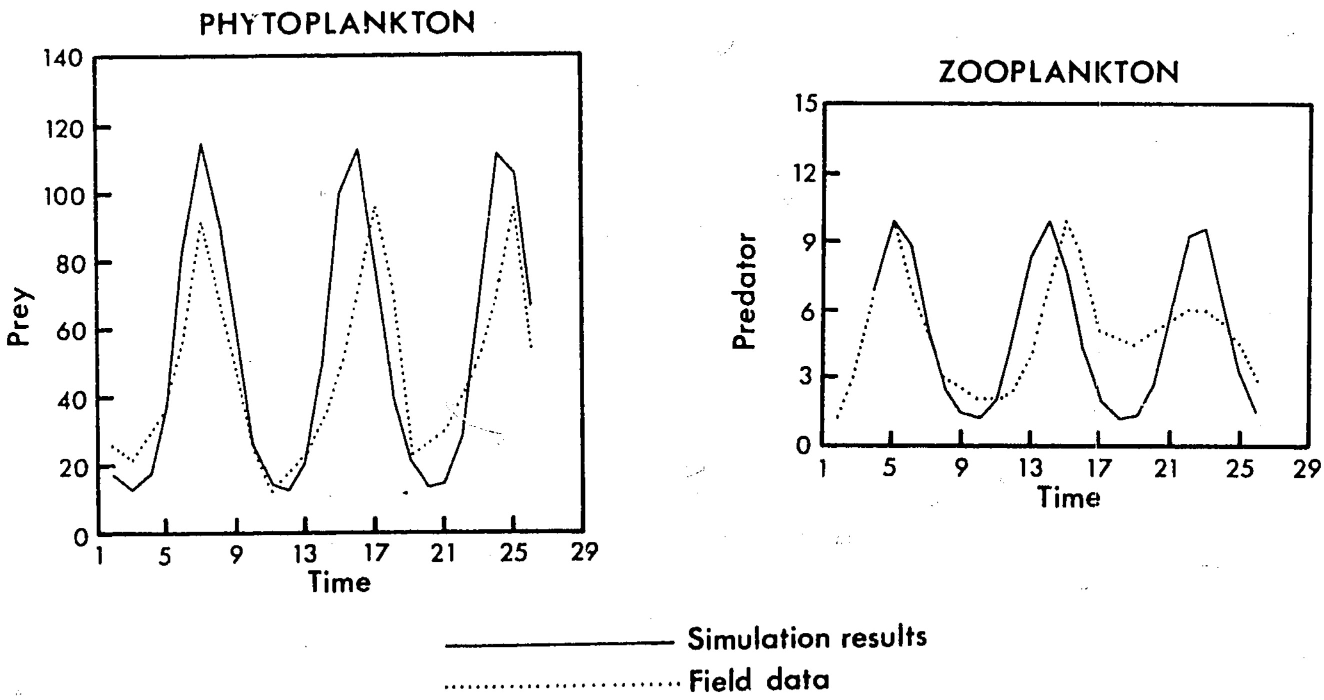


Fig. 22. Time variation of the prey (phytoplankton) and the predators (zooplankton) biomass.
(After Ross and Nival, 1976).

Villefranche. As with every model it is applicable only within a defined range of space and time. The values for other periods in the year, or other bays, must be checked with new sets of data.

These examples have shown the procedure and the limits of modelling of a natural process and the limits of this technique. They have shown that modelling is an iterative procedure that implies a constant exchange of information between experimentation and field observations.

2.4. Modelling exercises

2.4.1. Ecosystems and communities

Introduction

The coastal Mediterranean does not have a unique ecosystem, that is, one that might be called typically Mediterranean and studied as such. This is in contrast to the deep benthic or pelagic systems of the open Mediterranean that are relatively uniform for a sea of its size, owing to the more homogenous conditions found in the bulk of its waters. The conditions along the shores vary significantly due to changes in substrata or water properties. The occurrence of waste disposal has superimposed an additional variety to the coastal environments by introducing concentrations of substances foreign to any of the normal set of environments. Therefore, the coastal Mediterranean ecosystem must be considered rather as a set of distinct subsystems linked only by the coastal transport processes carrying water-borne substances between them.

This dramatic change in physical scale between the pelagic and neritic must be reflected in any comprehensive attempt to study Mediterranean ecosystems. In terms of modelling it is convenient to make distinctions according to the degree of complexity, since any model is limited in the detail it can express. Complexity per unit length governs the spatial extent of a model; however, this criterion is customarily expressed in the reverse, that is, that the spatial scale governs the complexity, and hence, the resolution of the model. Equally relevant to the discussions that follow is the fact that the value of a model is not a strong function of its resolution, since the different scale models answer different types of questions. These distinctions are made elsewhere (e.g. the Alexandria Workshop Report).

With regard to the Mediterranean, three spatial distinctions are immediately obvious and, since much of the following discussion is predicated on such scale divisions, they are listed as follows:

Level	Example
a. large-scale	the Aegean, Tyrrhenian, Adriatic or Levantine Sea
b. meso-scale	the Saronikos Gulf, or Izmir, Rijeka and Abu Qir Bays
c. small-scale	brackish water lagoons, small coastal subsystems with well defined boundaries e.g. *Posidonia* beds or anoxic benthic regimes in the vicinity of a sewage outfall.

The large-scale models are essential to provide balance and control to a modelling effort. The small-scale and meso-scale models are the most accurate and effective for quantitative comment on local problems. They contribute to increase the resolution of large-scale models. A few typical cases of pollution stressed well-defined small-scale models were therefore discussed and subjected to modelling exercises by the workshop. Examples of process or linked-process models were also discussed. These permit the modeller to focus on certain vital functions within an ecosystem, without regard to scale.

Examples of small-scale ecosystems models

Posidonia beds. The incidence of *Posidonia* benthic systems is widely spread along Mediterranean coastal regions, and strongly correlated with the local fish yield. The physical dimension of *Posidonia* beds is easily defined, as the dense vegetation has definite boundaries. They are restricted in the offshore direction to distances corresponding to specific light levels at the bottom, and alongshore by the proper substrate. The fluid boundary conditions dictated by the hydrodynamical processes governing the transport of nutrients, dissolved matter, and detrital matter (pollutants included) are more difficult to specify realistically. Therefore the approximation of a homogeneous exposure to the state variables within the boundaries was made, and a conceptual model of the *Posidonia* sub-system was constructed (Fig.23). The physical system is here represented as a black box with connection to the state variables within the ecosystem.

The forcing functions provide input from outside the system. The state variables (dependent variables) represent the responses to the energy and mass flow through the system. Their response is governed by certain vital processes. A list of these characteristic features was made as follows:

Forcing functions	State variables	Processes
Fishes	Posidonia	Phytosynthesis
Wave action	Nutrients in water	Self-shading
Solar energy	Nutrients in sediments	Growth
Nutrients	Suspended solids (organic)	Grazing
Temperature	Suspended solids (inorganic)	Boring
Salinity	Transparency	Death-rate
pH	Sediments	Decomposition
Toxic substances	Toxic substances	Sedimentation
Turbulence	Epiphytes	Nitrogen fixation
Suspended solids	Microfauna } vagile fauna	
Growth promoting substances	Meiofauna } vagile fauna	
Chemical reactions	Macrofauna } vagile fauna	
	Infauna	
	Microbenthos	
	Meiobenthos	
	Macrobenthos	
	Dissolved organic matter (D.O.M.)	
	Bacteria	
	Calcareous Algae	
	Sessile diatoms	
	Blue-green algae	

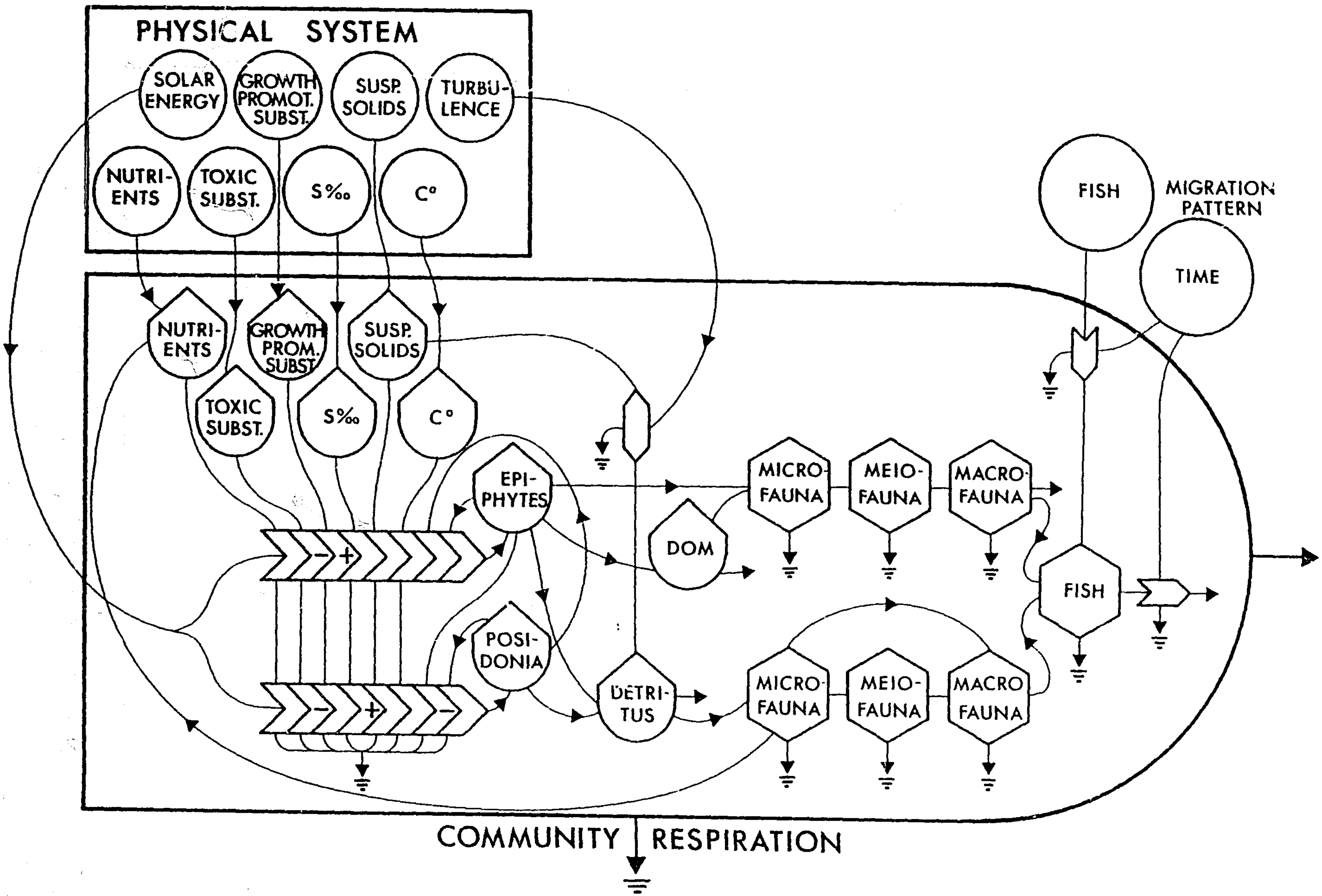


Fig. 23. A conceptual model of the <u>Posidonia</u> sub-system.

The main variables and processes were put together to formulate a conceptual model using the energy circuit language (Odum, 1972). This procedure is described in more detail in the Alexandria Report (Unesco Reports in Marine Sciences, No. 1). Fig. 23 shows the Posidonia sub-system as a producer component (the dark bullet-shaped contour represents a producer symbol) using the assumption that the total production of the sub-system is greater than its respiration. The inputs are solar energy, nutrients, pollutants such as toxic substances and growth promoting substances. These are brought into the system by the work of the physical system, which is represented here simply by a box containing the forcing functions. The salinity and temperature of the inflowing water will also affect the living organisms in the system. Here these are represented by Posidonia with connecting epiphytes such as diatoms, blue-greens, calcareous algae, that partially shade the Posidonia leaves. This is shown by a line from epiphytes to a negative workgate connected to the Posidonia component. The same set of processes (workgates) that affect the Posidonia and epiphytes will also affect the animals. For the sake of clarity this is not indicated in the picture. The different animals have simply been lumped together according to size and thus represent the two types of food-webs in an ecosystem: the herbivore chain starting with the epiphytes, and the detritus chain starting with the dying plants and sedimenting suspended solids. The fish in the system migrate in and out to some extent, generated from an energy pool outside the syutem. The main exports from the sub-system are dissolved organic matter (DOM), detritus, some invertebrates, and fish.

In order to keep the conceptual model of the Posidonia sub-system as understandable as possible, the chemical reactions were kept out of the system (state variables) and treated as forcing functions. As an alternative their connexion to the state variables was presented as the binary connectivity matrix that is shown in Fig. 24 . This matrix shows the existence of mass transfer between any of the two components. The sign "1" signifies that there is a mass transfer, and "0" signifies that there is not. A more detailed explanation of the use of binary connectivity matrix in conceptual modelling is given in "Principles and a procedure of ecosystem modelling" and in the model of the Adriatic Regional Ecosystem (Sections 2.2. and 2.3.3., respectively, of this report).

The binary connectivity matrix expresses only the presence of an interaction between each two components. All connexions of one component to all others can be presented using feedback dynamics diagrams. In such a diagram, besides all component connexions, the inputs and external factors which influence the mass transfer between components are presented. Therefore, in addition to the binary connectivity matrix in order to explain connexions of the chemical reactions to the Posidonia sub-system, the feedback dynamics (Forrester diagrams) is also illustrated in Fig. 25. For a more detailed explanation see Sections 2.2. and the paragraph :"Feedback and dynamics", page 34.

In order to demonstrate the use of modelling procedures, the Posidonia sub-system model is elaborated in the following paragraphs according to the modelling procedures outlined in Section 2.2.

Conceptualization. The structure of the model is shown in Fig. 26. Only the Posidonia plant with epiphytes is considered and is divided into three functionally different parts (Fig. 27). The effects of the different potential variables are not shown explicitly here, as the purpose is more to exemplify a procedure than to present a detailed model.

TO	FROM 1	2	3	4	5	6	7	8	9
1. MICROCONSTITUENTS		1	0	0	1	1	1	0	1
2. MACROCONSTITUENTS	1		0	0	1	1	1	0	1
3. NUTRIENTS	0	0		1	1	1	1	0	1
4. DISSOLVED GASES	0	0	1		1	1	1	0	1
5. DISSOLVED ORGANIC MATTER	0	0	0	0		1	1	0	1
6. ORGANIC POLLUTANTS	0	0	0	0	0		0	0	1
7. SESTON	0	0	0	0	0	0		1	1
8. POSIDONIA	1	1	1	1	1	1	0		0
9. SEDIMENT	1	1	1	1	1	1	1	1	

Fig. 24. Binary connectivity matrix showing connection of *Posidonia* sub-system to the chemical components.

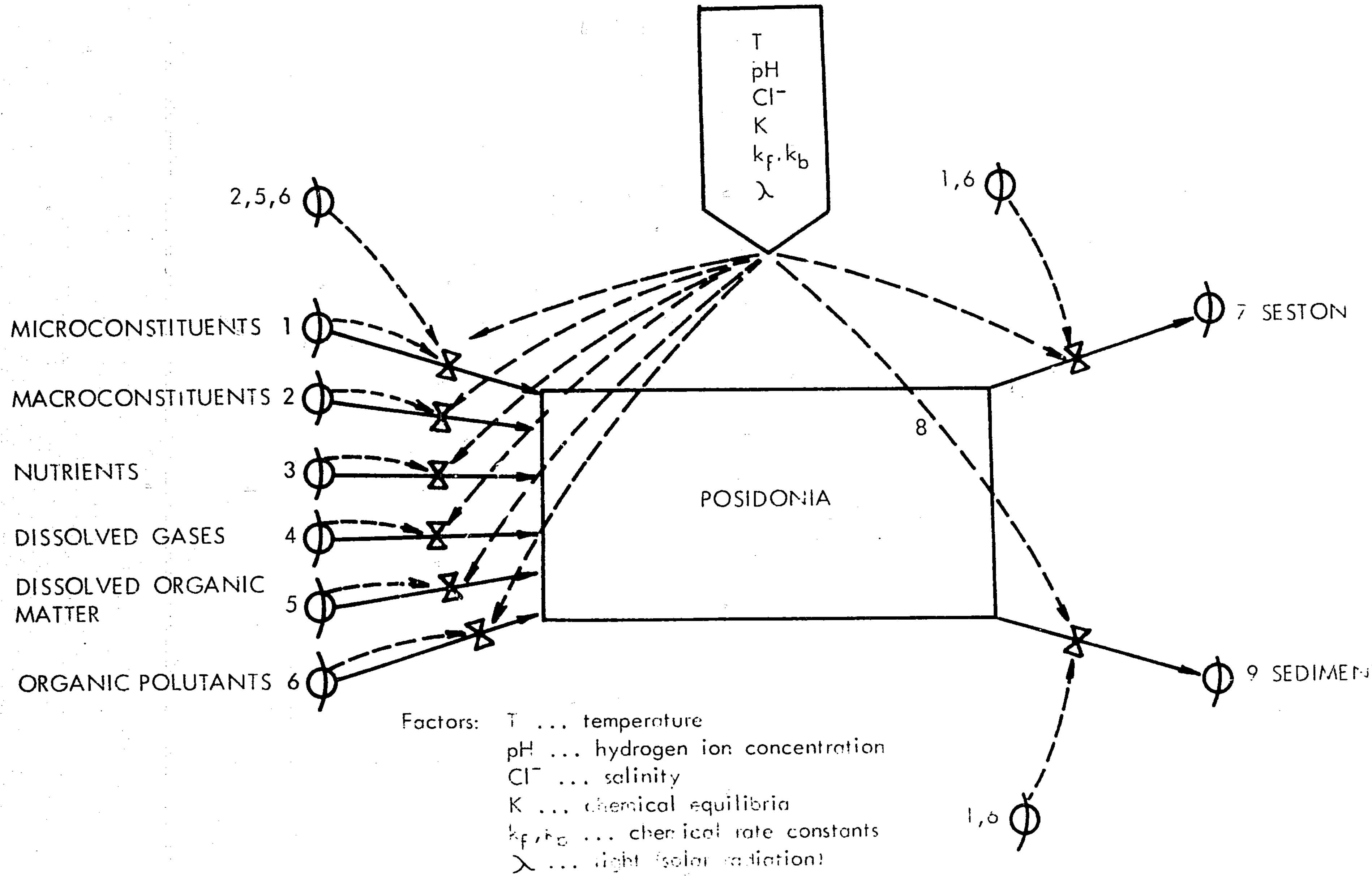


Fig. 25. Feedback dynamics (Forrester) diagram for the connectivity of chemical components with *Posidonia* sub-system.

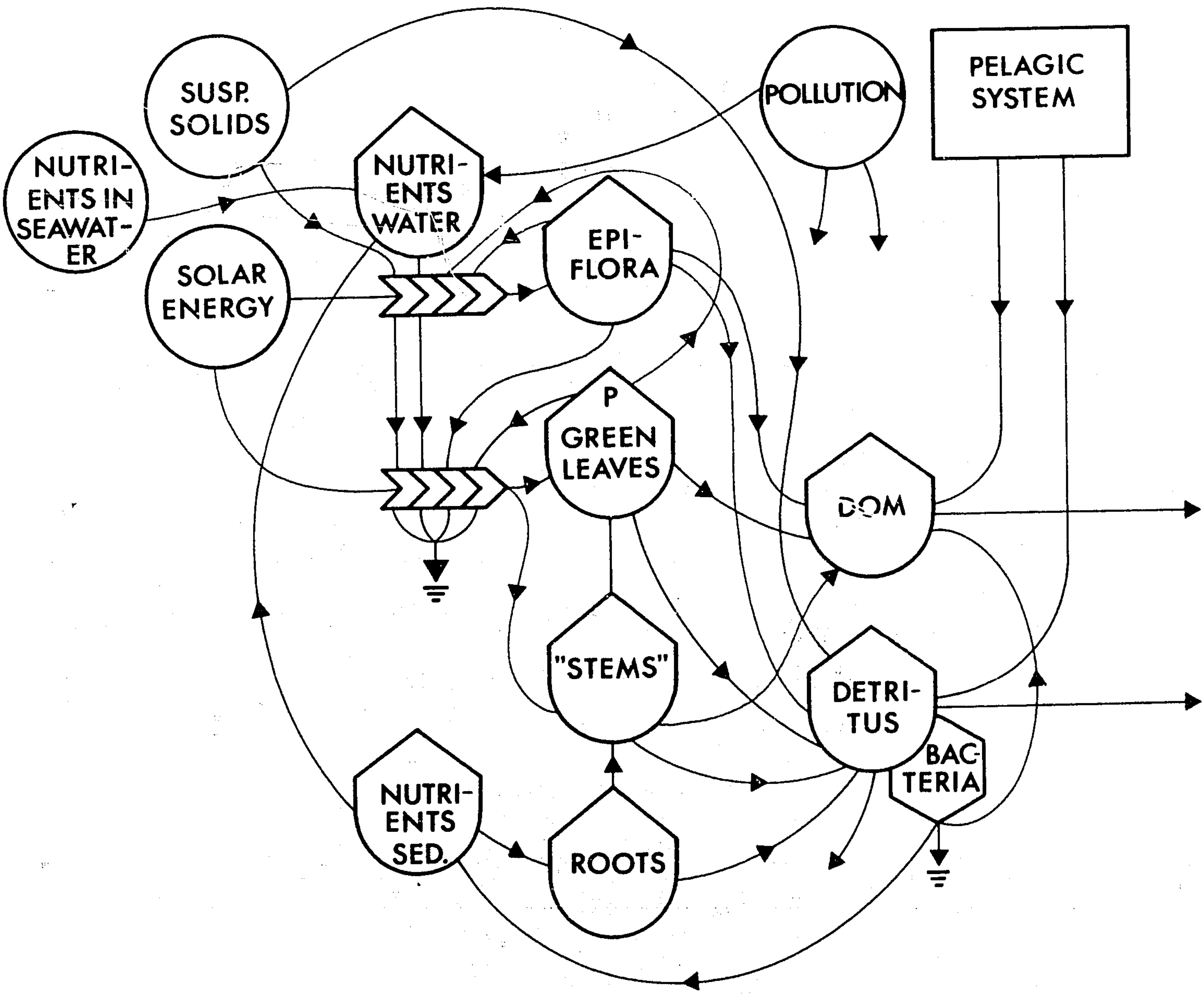


Fig. 26. Structure of model of *Posidonia* sub-system.

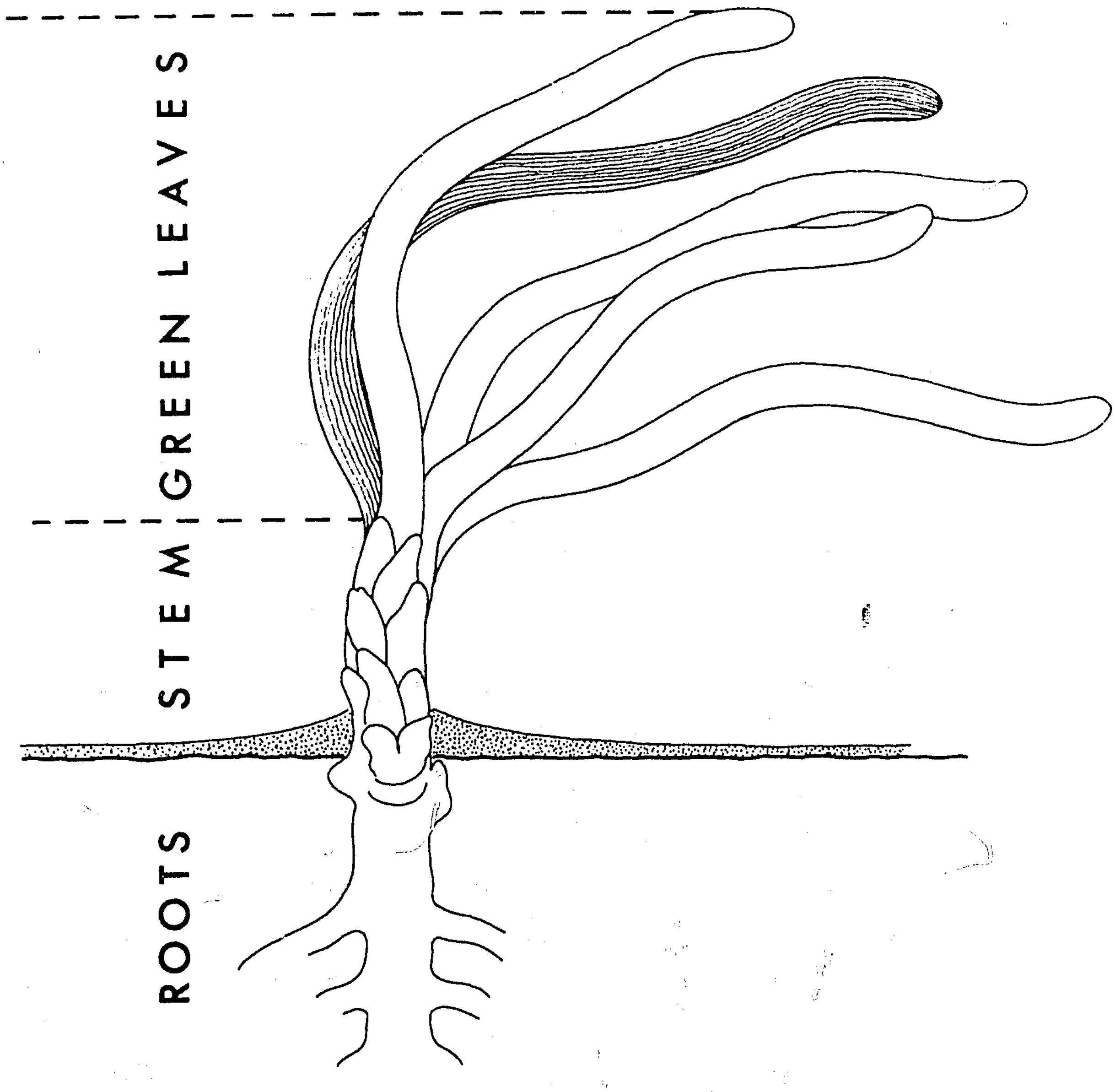


Fig. 27. <u>Posidonia</u> plant

Mathematization. The conceptual model is useful for recognizing all the variables and processes known to be important in the natural system. The next step in the modelling procedure is to translate into mathematical expressions the state variables in terms of the inputs controlling the internal processes. Depending on the amount of data available and on the associated spatial and temporal scales, different techniques can be used, e.g. either a stochastic or deterministic treatment.

The mathematization may be written as a set of differential equations (one for each state variable), that corresponds to transfer rates (the variation of biomass over a short period of time), as for example:

$$\frac{\Delta \text{ Biomass of epiphytes}}{\Delta t} \quad \text{or more simply} \quad \frac{\Delta E}{\Delta t} \quad \text{or } \dot{E}$$

where the dimensions are mg carbon per day or mg dry weight per month. In other words, $\dot{E}$ expresses the difference between those positive processes generating epiphyte mass and the negative ones destroying it, or

$$\dot{E} \equiv \text{growth rate} - \text{death rate} - \text{rate of loss to DOM.}$$

The model assumes that the overall process of growth is controlled either by forcing functions or by state variables, consequently,

growth = f (light, nutrients, suspended solids, biomass of upper part of Posidonia, biomass of epiphytes)

In the same way the other rates can be related to forcing functions or state variables (Table 1, page 61).

The only difficulty at this point is to define the right mathematical formula for f (...) to represent accurately the natural process. One of the most important ways to obtain this information is through experimentation in the field and the laboratory. A sub-model of each elementary process can then be prepared and included in the total model in place of the function f (...). Initially, the process may be understood empirically only, but the ultimate goal is to understand it exactly in an analytic or deterministic way.

This procedure can be illustrated for the first term of the function, i.e. light. If laboratory experiments provide the response curve of net photosynthesis as a function of higher intensity, as in Fig. 28, then the dependence can be translated into mathematical terms by the following formula:

$$P_{net} = \frac{P_m \cdot L}{K + L} - R$$ where P_m, and K are coefficients, L = light, R = respiration.

This formula expresses the net photosynthetic growth rate as proportional to light in the range of small light intensity values, and as independent of light for high light intensity values. In some cases, an input of large values of light causes photoinhibition, and consequently the net photosynthesis declines. It is possible to include this effect by a modification of the mathematical expression. In this form the expression can be used to simulate the growth of Posidonia leaves.

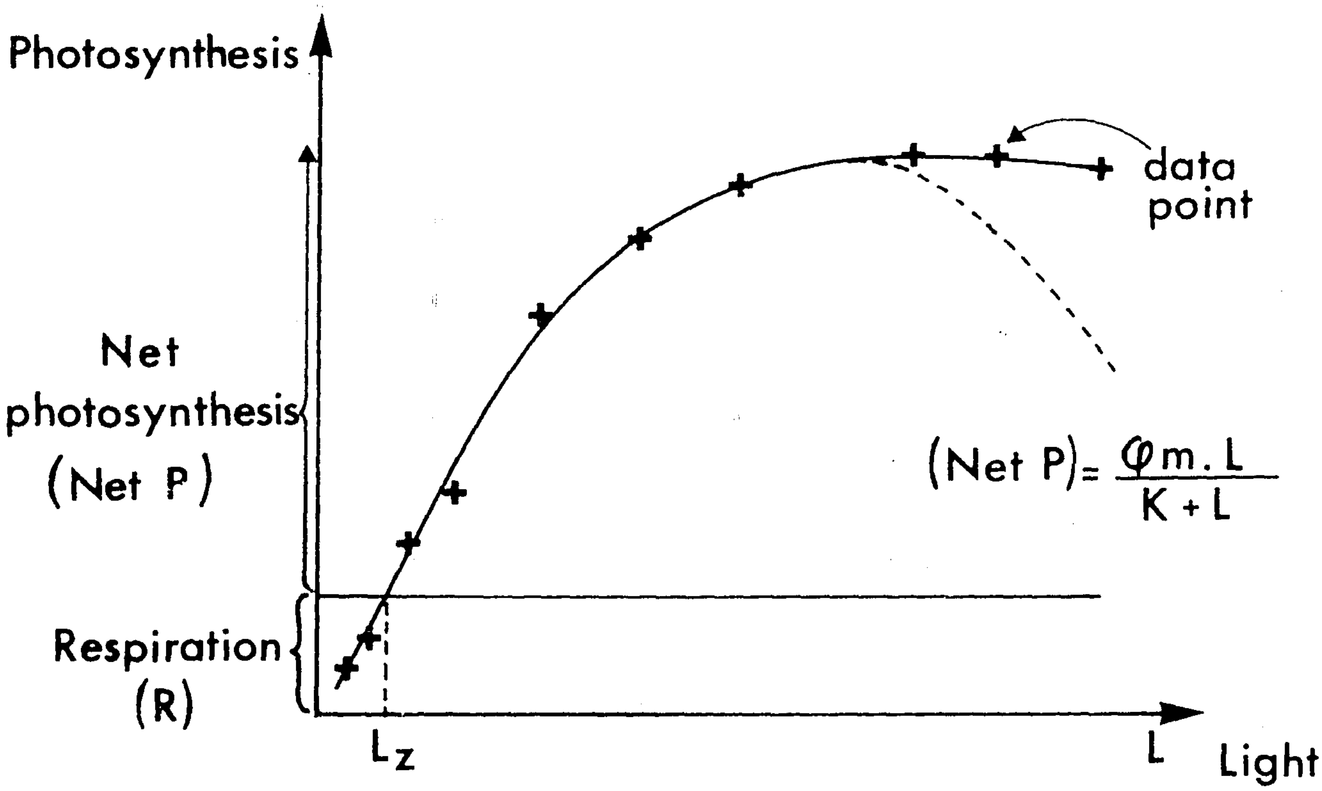


Fig. 28. Assumed variation of gross production and respiration versus the light. The formula on the right is a mathematical expression of the kind of relation shown by the data points. Other formulas can take into account the decrease of photosynthesis at high light intensity.

Table 1. Symbols and Equations

SYMBOLS

Symbols	Meaning
E	Epiflora
G	*Posidonia* : green leaves
S	*Posidonia* : stems
R_t	*Posidonia* : roots
N_w	Nutrients in water
N_s	Nutrients in sediment
D	Detritus
B	Bacteria
D_o	Dissolved organic matter

Footnote : to express the variation of e.g. E, $\dot{E}$ is used instead of $\frac{\delta E}{\delta t}$

EQUATIONS

$\dot{E}$ = f (E, N_w , suspended solids, solar energy, pollution) − (loss to D_o) − (death rate to D)

$\dot{G}$ = f (G, N_w, S, suspended solids, solar energy, E, pollution) − f(loss to D_o) − (death rate to D)

$\dot{S}$ = f (G, N_w, R, suspended solids, solar energy, E, pollution) − f(loss to D_o) − (death rate to D) − f (loss to G)

$\dot{R}_t$ = f (N_s) − f (loss to S) − f (loss to D)

$\dot{N}_w$ = f (pollution, N_s) − f (E,G)

$\dot{N}_s$ = f (B) − f (loss to N_w) − f (loss to R)

$\dot{D}$ = f (suspended solids, E, G, S, R) − f (B) − export + (input from pelagic system)

$\dot{B}$ = f (detritus) − f (loss to N_w + loss to D_o) − export

$\dot{D}_o$ = f (E, G, S, R, B + pelagic input) − export

This kind of empirical mathematical expression is a way to ignore the more detailed processes of photosynthesis (light reactions, dark reactions) that are thought not to be critical processes in such a model. It might be necessary to refine the model from this point of view, depending on the accuracy that is needed to explain the natural phenomenon.

The light energy (L) at the depth of the Posidonia leaves depends on the transparency of the water above it. This can be related to the solar energy outside the water by the usual formula:

$$L = L_o \cdot e^{-kz}$$

where L_o = light at surface and k = extinction coefficient. The coefficient k, can be related to the total amount of suspended solids, in the water column, expressed by $k = \alpha S$. This relation could be more complicated when taking into account the various extinction coefficients from the water itself, the dissolved substances, the amount of phytoplankton, etc.

The effect of a tar or oil film at the surface also can be introduced. The amount of light just under the surface (L'_o) is reduced, expressed as :

$$L'_o = L_o - L_T$$

where L_T is the amount of light absorbed by oil or tar which is related to the thickness of the film.

The net photosynthesis expression now becomes:

$$P_{net} = \frac{P_m \cdot L_o \cdot e^{-\alpha S \cdot z}}{K + L_o \cdot e^{-\alpha S \cdot z}} - R$$

Experiments show that R is affected by the temperature (T) of the water. This can be expressed as: $R = a. b^T$. We must estimate the value of the 6 coefficients : L_o (α ,Pm, K, a, b) that we have used. This is done on an individual, experimental or analytical basis. Finally, the same procedure, as we have just explained for the dependence on light, must be followed for all the processes that are in the equations.

Computation. If all the equations have been written and the values for all the coefficients have been found, the next step is to make a computer programme using one of the specialized languages (FORTRAN, BASIC, FOCAL, PL1...) and to run the programme to get a simulation of the evolution of the modelled system. In this way an output of the masses for each of the elements in each storage compartment and of the values of the elementary processes ("pointed blocks") at each time will be generated. For instance, a curve of the evolution in the epiphyte biomass (Fig. 29a) will be generated.

Validation. In order to check whether the model is representative of the natural system, it is necessary to compare the output of simulation to field data from the natural system (Fig. 29b).

There are two extreme possibilities :

a. The simulation fits the data quite satisfactorily (Fig. 30a), the criteria being that the sum of squared distances between data points and calculated values is a minimum. In this case the modelling has been successful, and the set of equations gives a good picture of the natural system at the level of accuracy of the measurements in the field.

b. The simulation does not fit the data at all (Fig. 30b). Either the parameters have been badly evaluated (biased experiments, ...) or the structure of the conceptual model is wrong (some important state variable or forcing function or process has been forgotten, e.g. decomposition is not carried out successfully). This conclusion requires a feedback procedure to model conceptualization or model parameterization. A review of the steps in the model construction and a quality check on the input data must be made.

<u>Sensitivity analysis</u>. In the case of a good fit of the simulation to the data a further step can be made to determine which of the parameters are the most important ones. That is, which variables, when changed, generate the largest variations in the model output. This procedure is known as sensitivity analysis.

Suppose one equation of the system is:

$$\dot{E} = a_1 A - b_1 A B - c_1 D^{\alpha}$$

Simulations are now made in which different values are used, of a_1, then of b_1, and so forth. Each time fixed deviations are used, for example 20% of the original value. These changes then induce changes in the output (Fig. 31a), which again fall into two categories : a) If the simulated curve of E is not very different from the original one (Fig. 31b) then E is not sensitive to variations in b_1. b) If the simulated curve of E is very different from the originally simulated one (Fig. 31c), the biomass of epiphytes is considered to be sensitive to variations in the c_1 coefficient.

Of course this presentation of the steps of modelling an ecosystem is only a simple illustration of the basic principles. The different steps in this process must be done by a multidisciplinary working group.

<u>Shallow semi-enclosed bays dominated by land</u>

This type of bay occurs frequently along Mediterranean coasts. Because of their relative isolation from the open waters, they are commonly the sites of harbours and urban development, and consequently are subject to environmental stresses. Some of them are on their way to becoming azoic, and virtually all of them are endangered by increased discharges of domestic or other wastes. These areas are often essential breeding and feeding grounds for several economic fish, molluscs and crustaceans. Management of such areas is urgent and imperative. Three examples will be given.

<u>The Gulf of Syrte</u>, on the Libyan-Tunisian coast, is a relatively shallow and open gulf. Extensive <u>Posidonia</u> beds occur on its sandy bottom. The gulf is also an important breeding and feeding ground for fish and shrimps, in particular for <u>Penaeus kerathurus</u>. The gulf is increasingly exposed to heavy oil pollution from tankers, and oil terminals.

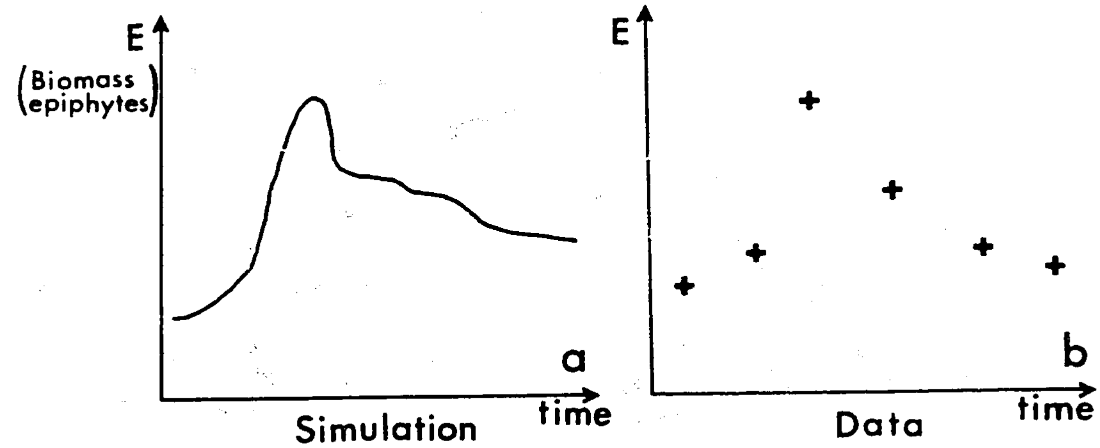


Fig. 29. Assumed results of computation of the time variation of the system. The curve in (a) is a simulation of the evolution of e.g., epiphyte biomass, to be compared to the field data in (b).

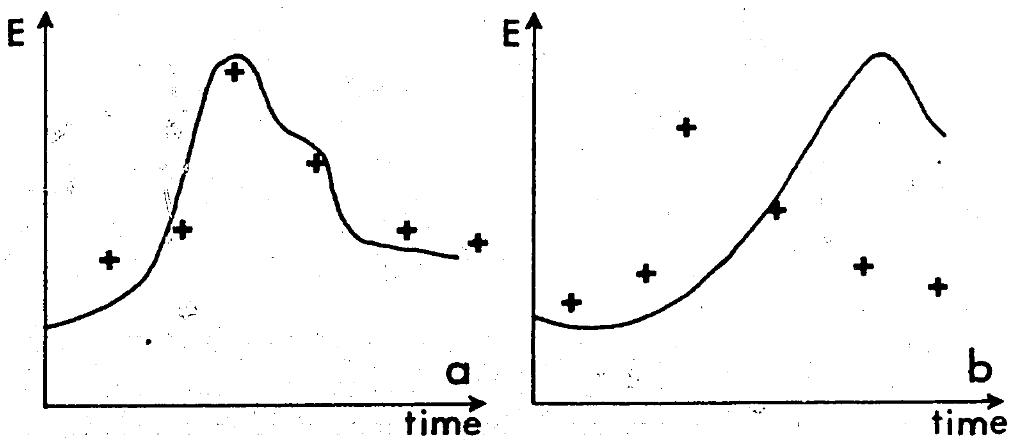


Fig. 30. Two extreme cases in the validation step:
(a) good fit of the simulation of the data,
(b) bad fit.

A good fit gives a minimum value to the sum of squared difference between the data and the calculated values.

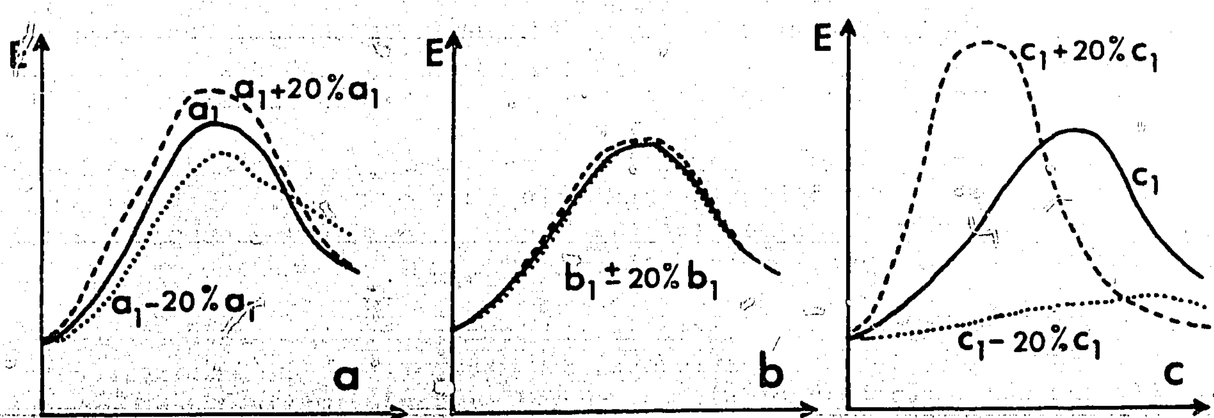


Fig. 31. Sensitivity analysis :
a : Variation of the parameter value induces a modification in the output.
b : The system output is <u>not very</u> sensitive to variations of the parameter.
c : The system is <u>very</u> sensitive to the variation of the parameter c_1. It will be necessary to pay special attention to the factors causing its variations.

The Bay of Izmir, on the Aegean coast of Turkey, is 90 km in length and about 20 m in average depth. Alluvial deposits from the river Gediz have gradually raised the sill at the bay outlet to a few meters depth. Posidonia beds occur on the soft bottom in the region just outside the mouth of the bay. Salinity values of 38‰ are typically lower than that of the open sea. Red tide blooms in the bay result in fish mortality. The waters below the sill are anoxic during stratified conditions. Winter mixing reintroduces anoxic sediments into the water column.

The bay is exposed to a wide range of pollutants. Heavy metals, mercury, lead and copper are washed down from mines located on the mountainous southern coast. Paper mills, textile and tanning factories on the northern and eastern coasts discharge their wastes into the bay. It also receives the domestic wastes and solid wastes from the town of Izmir. The bay is deteriorating at such a rate as to alter permanently its own ecosystem and to create a threat to the adjacent Aegean Sea coastal waters.

The four Nile Delta lakes of Egypt have a high fish production that supports a large fisheries industry. Tilapia and the migratory Mugil are the major fish species. The lakes are endangered by the organic load caused by eutrophication and by the toxic wastes derived from an increasing use of agricultural pesticides. These lakes are wide and shallow coastal basins which receive large volumes of land runoff that ultimately reach the sea through the lake-sea connexions. Circulation is determined by the drainage inflow from land canals, the wind pattern, and water exchange induced by a small difference in tidal elevation at the lake sea connexions.

Drainage water and lake water are quite low in salinity, with values of about 1‰ and 2-3‰, respectively. Drainage water is rich in POM (particulate organic matter), DOM and humid material but very low in dissolved oxygen. High concentrations of chemical fertilizers, soil silicates, and pesticides are periodically washed down to the lakes through the drainage canals.

Dense blooms of blue-green algae, diatoms, dinoflagellates, and green algae are present continuously. Planktonic filter feeders comprise mainly rotifers, cladocerans and copepods. The vegetation also includes floating macrophytes such as Potamogeton and rooted plants such as Phragmites. Dense belts of Potamogeton, covered with Navicula diatoms, and harbouring a variety of sedentary or vagile animals (Gammarus, Corophium, gastropods, vorticellids) cover wide areas. They provide food and shelter for fish and fish fry, and raise the level of dissolved oxygen to supersaturation.

The persistent pesticide derivatives are absorbed on the suspended material, taken up by the phytoplankton and by the macrophytes. They are transferred through the food chain to higher trophic levels, gradually accumulating in all fish, whether they are herbivores, detrital feeders, or carnivores.

The flushing time of the lakes is not known, but the drainage rates are recorded. Since drainage is continuous, the outflow of the lake water to the sea, and therefore its load of dissolved and suspended matter together with plankton, is continuous. The accumulation of persistent pesticide derivatives and other foreign substances of the lakes are transported to the sea also by migratory fish (mullets) breeding in the sea. The Delta lakes provide another example of an ecosystem alternation. Here the technique of modelling would be extremely useful in its management and in assessing its effect on the adjacent coastal waters.

Fig. 32 shows a simplified model of a Delta lake. The producers are the macrophytes, the phytoplankton affected by the nutrients and contributing through their decomposition to the sediment pool, and the seston (suspended solids). The living plants are important for the formation of oxygen. The latter can be critical in the shallow basins, creating problems for zooplankton, benthos and fish. The system is driven by the waterflow of the effluent land runoff whose pattern will greatly affect the residence time of the lake water. The wind which will force the water in or out of the lake is also of critical importance. For simplicity the effects of land runoff and wind are shown as combined mechanisms in the model. The expressed flows between bay and sea are therefore net flows.

Deep semi-enclosed bays dominated by the sea

This type of bay is usually found where the continental shelf is narrow and/or where the coasts are steep and without major sedimentary features. Also, these bays are not restricted by shallow sills, so that flushing by outside sea water is facilitated. The relative deepness of the bays increases the ratio of planktonic to benthic production over that of the shallower bays. The increased exposure to flushing from open sea water makes the occurrence of pelagic, oligotrophic planktonic populations close inshore more common than in the case of the restricted, shallow bays.

Domestic waste discharge into these bays induces major changes, the most important of which is that of planktonic eutrophication. Distinct spatial distributions, or plumes, of plankton are commonly observed, because the outside water is circulated in and eutrophied water out faster than the net production in the bay. The waters transported in contain oligotrophic populations, and contrast markedly with the eutrophied populations of the contaminated waters. Strong biochemical gradients or a mixed zone can exist between the two water masses. Two examples of these kinds of bays were given in the sections 2.3.2. and 2.3.4.

The conditions in the sewage outfall plume (eutrophic system) are so different from those found in the uncontaminated outside water (oligotrophic system) that they must be considered separately. Fig. 33 shows the two systems. A more complicated set of state variables is shown in the outfall ecosystem to emphasize its greater exposure to toxic substances, growth promoting substances, dissolved organic matter, etc. than to the oligotrophic ecosystem. The regeneration process is considered to be of greater relative importance in the oligotrophic than in the eutrophic system and is indicated by a return arrow to the nutrient storage from bacteria.

The two systems are linked by a process dependent on a physical model that would specify the supply and the mixing of the two water masses associated with each system. The physical model is essential to explain the spatial variations. For example, a high inflow rate will result in a flushing out of the

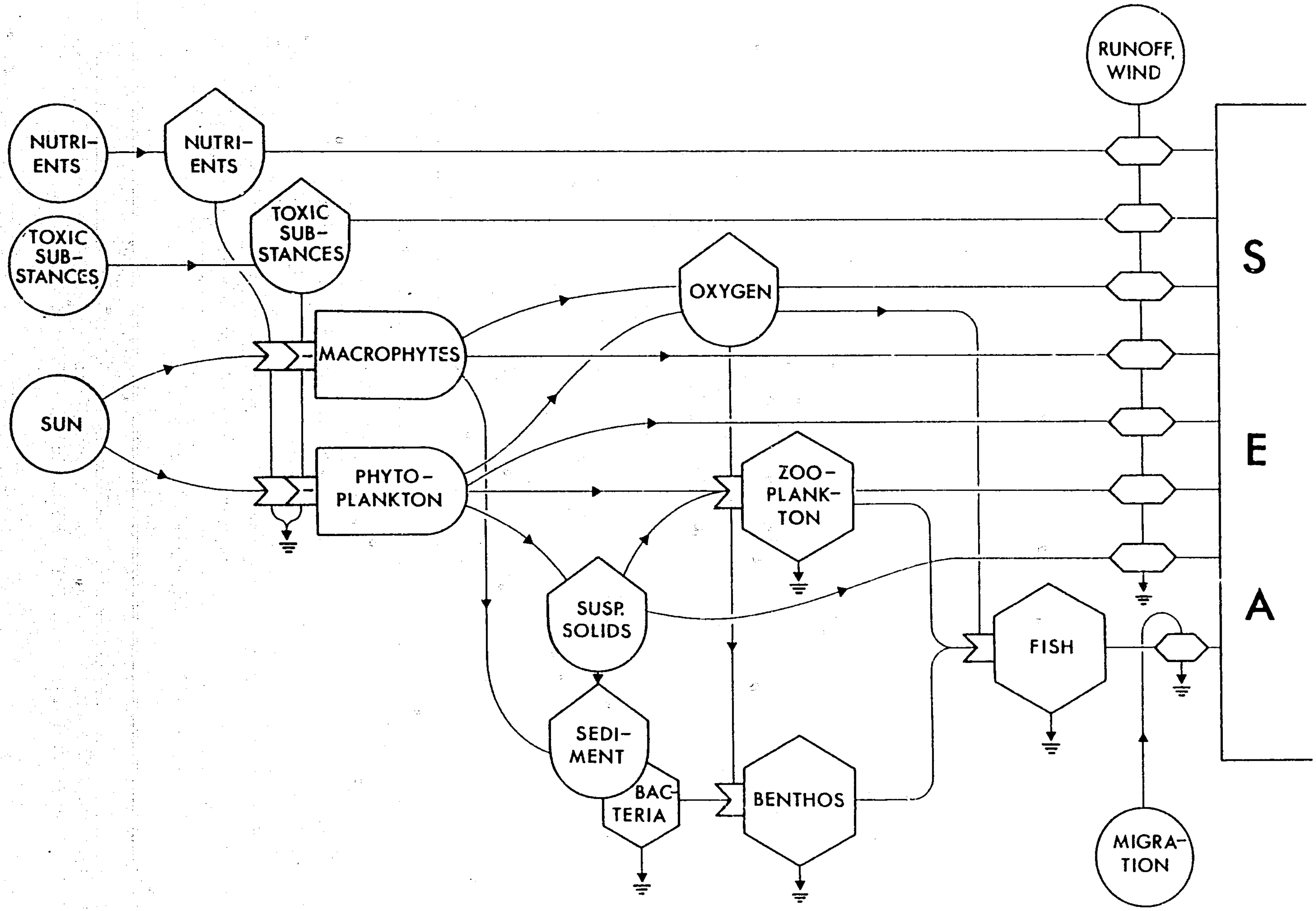


Fig. 32. Simplified model of a Delta lake.

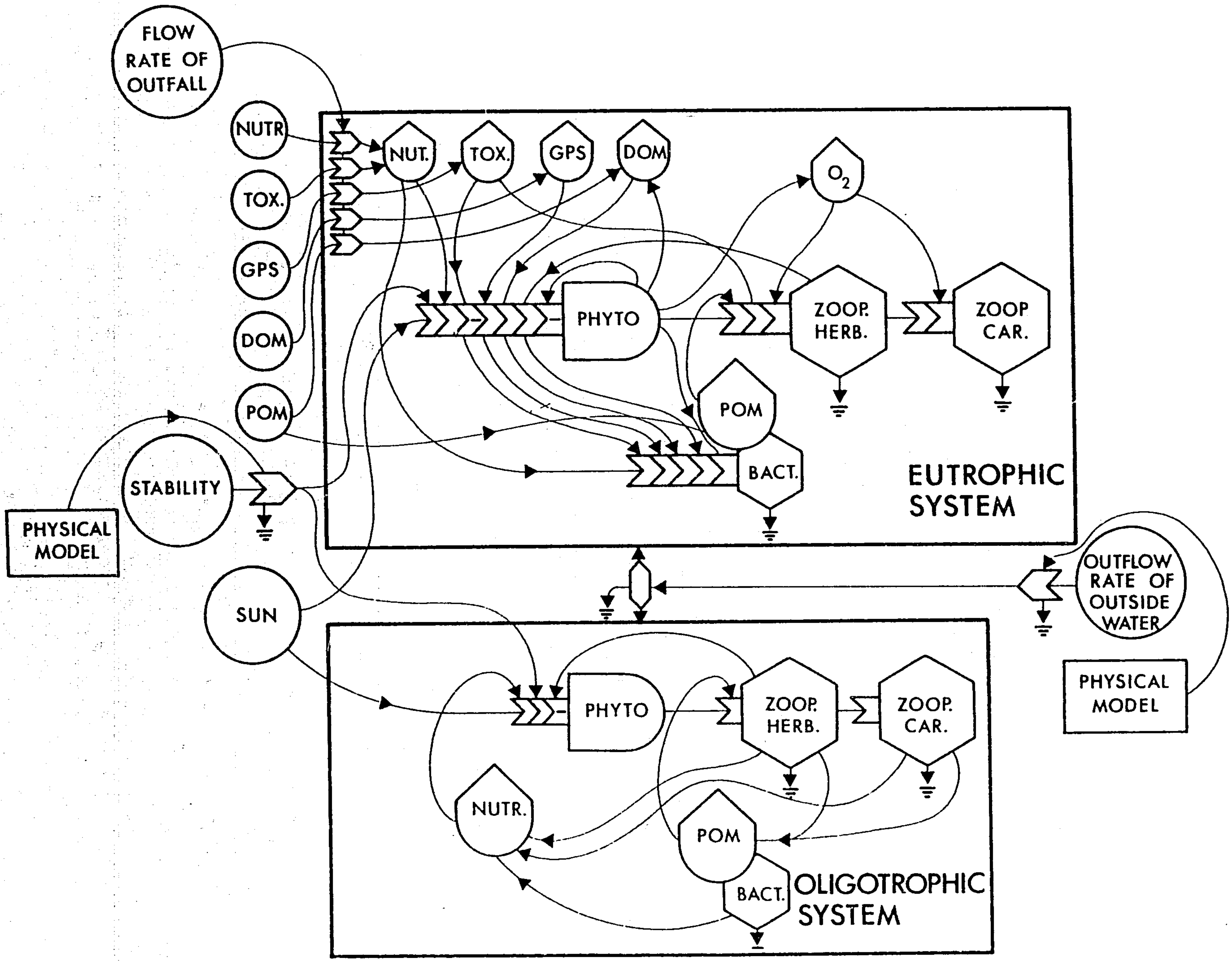


Fig. 33. Model of eutrophic and oligotrophic systems.

eutrophic system and, on the contrary, a low inflow rate will result in an increasing dominance of the eutrophic system. It must be emphasized that the circulation will affect differently the phytoplankton and zooplankton, because of their different growth rates, and because of their different vertical distributions.

Eutrophication models can be looked on as subsets of ecosystem models, being simply models with the input of nutrients as one set of forcing functions. Eutrophication models are usually desired to assess certain undesirable features of a nutrient enriched ecosystem, e.g. decreased transparency, change in species composition, increase in inorganic loading and consequent decrease in oxygen levels. In the marine environment such models must be embedded in a local circulation, which may be either measured or developed from a hydrodynamical sub-model. With respect to linked-process models, a sub-model must also be incorporated for each ecosystem process involved. In turn, a phytoplankton sub-model requires the incorporation of a photosynthesis process model, a nutrient uptake process model, a sinking rate process model, trace organic and inorganic assimilation process models, and so forth. These process sub-models must be synthesized into linked-process models with the appropriate feedback and interaction connexions.

The major factors influencing the phytoplankton response to eutrophication are :

1. nutrient kinetic responses of three functional groups of phytoplankton:
   a. oligotrophic diatoms and cocolithophorids (slow growing),
   b. diatoms (fast growing), and
   c. dinoflagellates (more or less fast growing).

   These groups are discussed in Section 2.3.2.
2. light and nutrient availability to plankton;
3. loss rates of the various groups, including advection, sinking and grazing;
4. light kinetics;
5. temperature; and
6. response to contaminant substances which may affect the competition between functional groups.

In one study of an enriched semi-enclosed bay, it was found that the major forcing function for selection between group b and c (between diatoms and dinoflagellates) was the advective loss term. When this term is high, fast growing diatom populations are dominant. When it is low, large populations of dinoflagellates occur. These results are in accord with the observations of species composition variability in oceanic upwelling areas. These processes may be visualized in a series of workgates as indicated in Fig.34 where the nutrient gate influences the tendency of group b and c to predominate and the advective gate provides the selection mechanism between group b and group c.

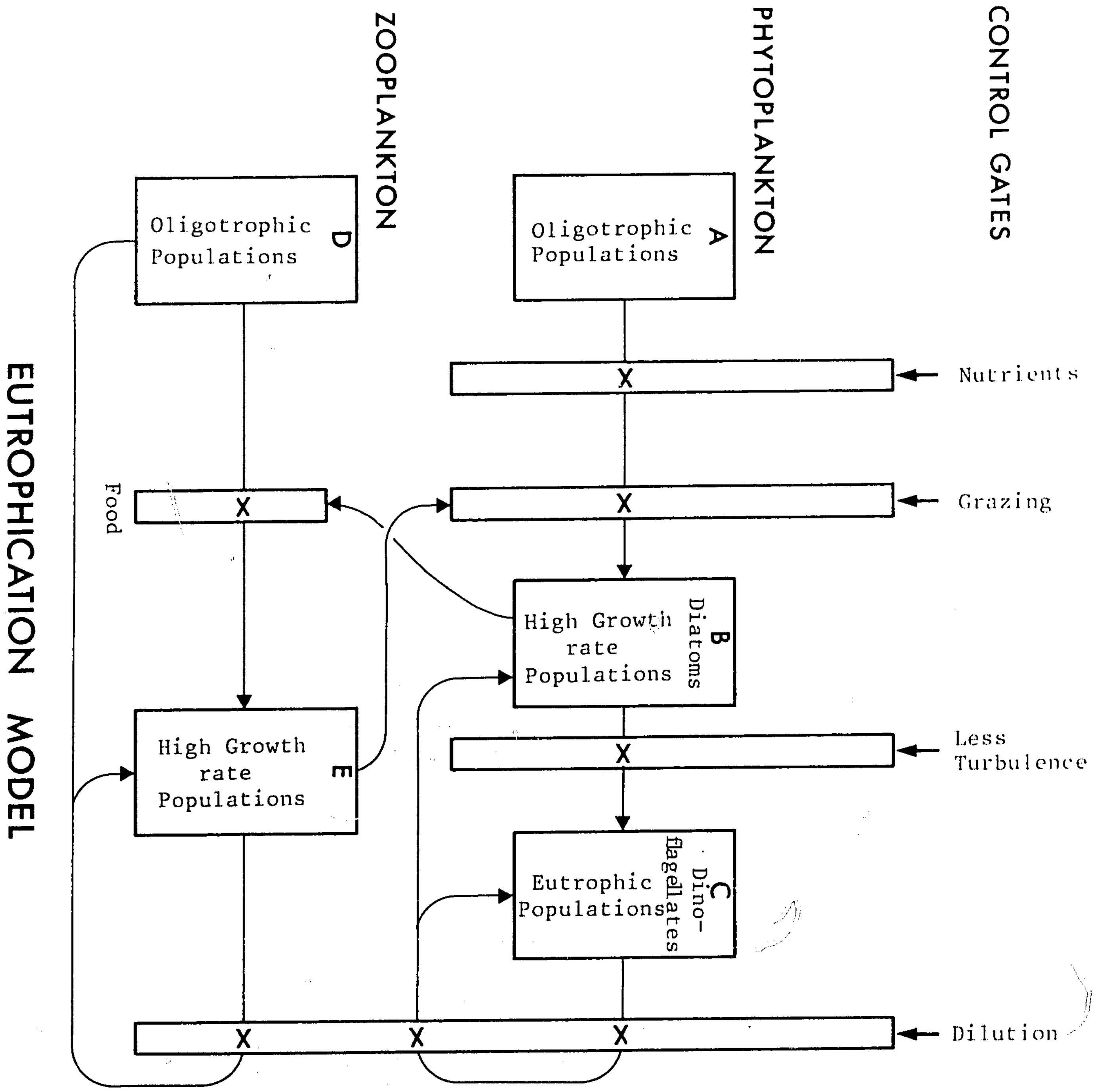


Fig. 34. A eutrophication model for phytoplankton species prediction.

Dilution levels can be expected to influence primarily the rapidity of the response to point sources of nutrients and the ability of a group to persist or disappear from its most favourable region. A low dilution rate of outside water will favour the growth of group c ; an intermediate dilution rate will result in a mixture of b and c groups and a high dilution rate will result in dominance of group b. Eutrophication results in a higher biomass of phytoplankton (groups b and c) near the nutrient source and the plume than in the outside oligotrophic water.

The zooplankton are affected through two processes :

1. increase in the food concentration, and
2. change in the species composition of phytoplankton group.

This results in a change in species composition of zooplankton from group D to E. Fast growing species are favoured (Acartia community group E). As the growth of the animals is slower than that of plants[4/], the dilution rate of the bay water by outside water affects them differently and helps explain the spatial distribution of their species. A low dilution rate will allow the fast growing population (E) to stay near the point source. A large dilution rate will result in a washing out of this community and a spreading of the oligotrophic one (D) all over the bay.

Eutrophication models could be made and tested within the semi-enclosed bay or open coastal models. Areas selected for emphasis should include as simple hydrographic conditions as possible and a secure point of high-nutrient effluents of known composition.

Perhaps the most critical need for the development of useful eutrophication models for the Mediterranean Sea is to design and test the phytoplankton and zooplankton process models. It is widely recognized that the application of biological sciences to ecosystem modelling is so far behind that of the physical sciences that a serious imbalance exists between the two approaches. The development and validation of biological process models is a necessary first step before serious ecosystem modelling can proceed.

4/ Phytoplankton regneration time is 1 day, and zooplankton regeneration time is about 6 to 15 days.

2.4.2. Transport of "heavy metals" in marine ecosystems

A. Introduction

"Heavy metals", in various forms, enter the marine environment from a number of sources. Their distribution and eventual fate depend on a variety of factors, including: a) the characteristics of the element itself, b) the form of the element, c) the physico-chemical oceanographic conditions, both in the area of release, and in the area of ultimate disposition, d) the uptake by marine organisms, including transfer through food-chains, and e) the presence of other materials in sea water (including other pollutants) which may react with the metal ion to cause modification of its form either in the sea water or within the bodies of living organisms.

A project on the modelling of "heavy metal" transport in Mediterranean ecosystems would be particularly relevant to three pilot projects already operational on Mediterranean pollution, namely:

1. baseline studies and monitoring of metals (particularly mercury and cadmium) in marine organisms,

2. research on the effects of pollutants on marine organisms and their populations, and

3. research on the effects of pollutants on marine communities and ecosystems.

B. General scheme and approach

There are several important aspects that must be treated in any attempt at the modelling of "heavy metal" transport. These include the following: a) origin (natural and anthropogenic sources) of the metal, b) distribution and pathways within the marine environment, c) physical and chemical effects (including uptake and loss) and d) methodology.

The box (or compartment) type of model appears to be the most suitable for the modelling of "heavy metal" transport in the marine environment. Several conceptual models can be constructed using this type. Metals can also be grouped into two categories : those with and those without biological functions. Consideration of the first obviously deserves a higher priority.

Two types of box models are possible : single-element and multi-element. Both have their relative merits. It is considered, however, that in the initial approach to metal pollution modelling in the Mediterranean, a single element model would be more desirable. Mercury can be taken as the best example, because of its significance, and because of the attention already being devoted to it in other Mediterranean pollution pilot projects. The Hg-model could, at a later stage, be used for or adapted to other metals.

In modelling pathways within any marine ecosystem, "end-species" must be selected, and the food-chain corresponding to each of these "end-species" must be studied, both individually and integrally. It would appear that the species already being monitored for mercury content in the UNEP/FAO(GFCM) pilot projects, i.e. Mytilus galloprovincialis, Mullus barbatus, and Thunnus thynnus thynnus would be the most appropriate.

The general scheme would therefore be the initial construction of an overall conceptual model giving the relationships between the three principal components of a marine ecosystem, and the different metal inputs into the system. This would be followed, at a later stage, by the consideration of conceptual sub-models for the more important sub-systems.

In order to avoid confusion between different weight units, all concentrations could be expressed in weight of element per weight of biomass, e.g. $\mu g\ Hg_T/kg$ FW (fresh weight) or volume (e.g. $\mu g\ Hg_T/l$), rather than ppm (mg Hg/kg FW) or ppb (μ g Hg/kg FW).

C. Examples

1. Overall model of a marine ecosystem. The ecosystem chosen consists of only three compartments or boxes (Fig. 35): seawater, sediments, and marine organisms. Inputs have been divided into those of anthropogenic and those of natural origins. Anthropogenic inputs of "heavy metals" originated from direct discharge of "heavy metals" through marine outfalls and indirectly as inputs through atmosphere and runoffs (rivers, streams etc...). The natural sources include "heavy metals" from the atmosphere, from runoff, and from submarine volcanos. Terrestrial vulcanoes and geochemical anomalies are indirect inputs through the runoff of vulcanic volatiles and the atmospheric weathering of sediments. The model outputs are the losses to the atmosphere and to the sediments. The losses to the sediments are distinguished between those not in interaction with the ecosystem, and those exploited for their food resource and their industrial application. Possible inputs and outputs to and from the three compartments to other adjacent marine systems are not considered in Fig. 35.

2. Conceptional model of the sub-system seawater. Fig. 36 shows a scheme of the different physico-chemical forms of "heavy metal" speciation with some indication of size, techniques of separation, and transformation rates. Hg species are given as examples. The number of compartments can be reduced if the transformation between species is fast, relative to inputs and outputs of the sub-system. For example, if the transformation rate between free ions, ion pairs, and inorganic and organic complexes is fast compared to their absorption rate by marine organisms or sediments, then these forms could be considered in one model compartment instead of three. At the other end of the size spectrum, compartments could be used to differentiate between the preferential uptake by size of inorganic or organic particles. The uptake of unicellular algae by filter feeders such as mussels and copepods would be a specific example.

3. Conceptional model of food chain transfer. The several routes of transfer within the marine food chains are depicted in Fig. 37 . They include direct uptake from the water and indirect uptake by phytoplankton, by heterotrophic microorganisms, and by marine plants. Recycling can occur through the pool or inorga-

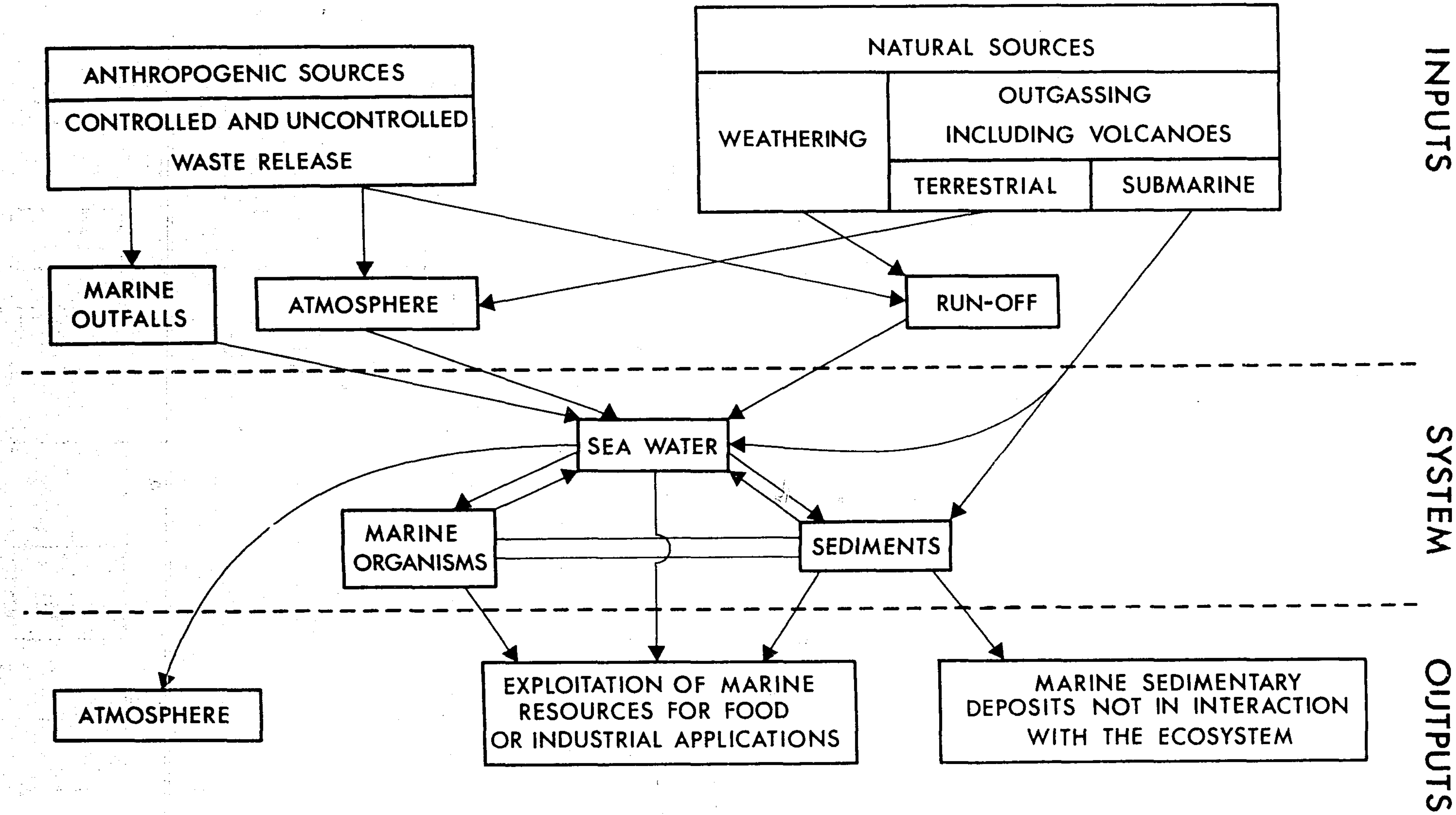


Fig. 35. Overall model of "heavy metal" transport in a marine ecosystem.

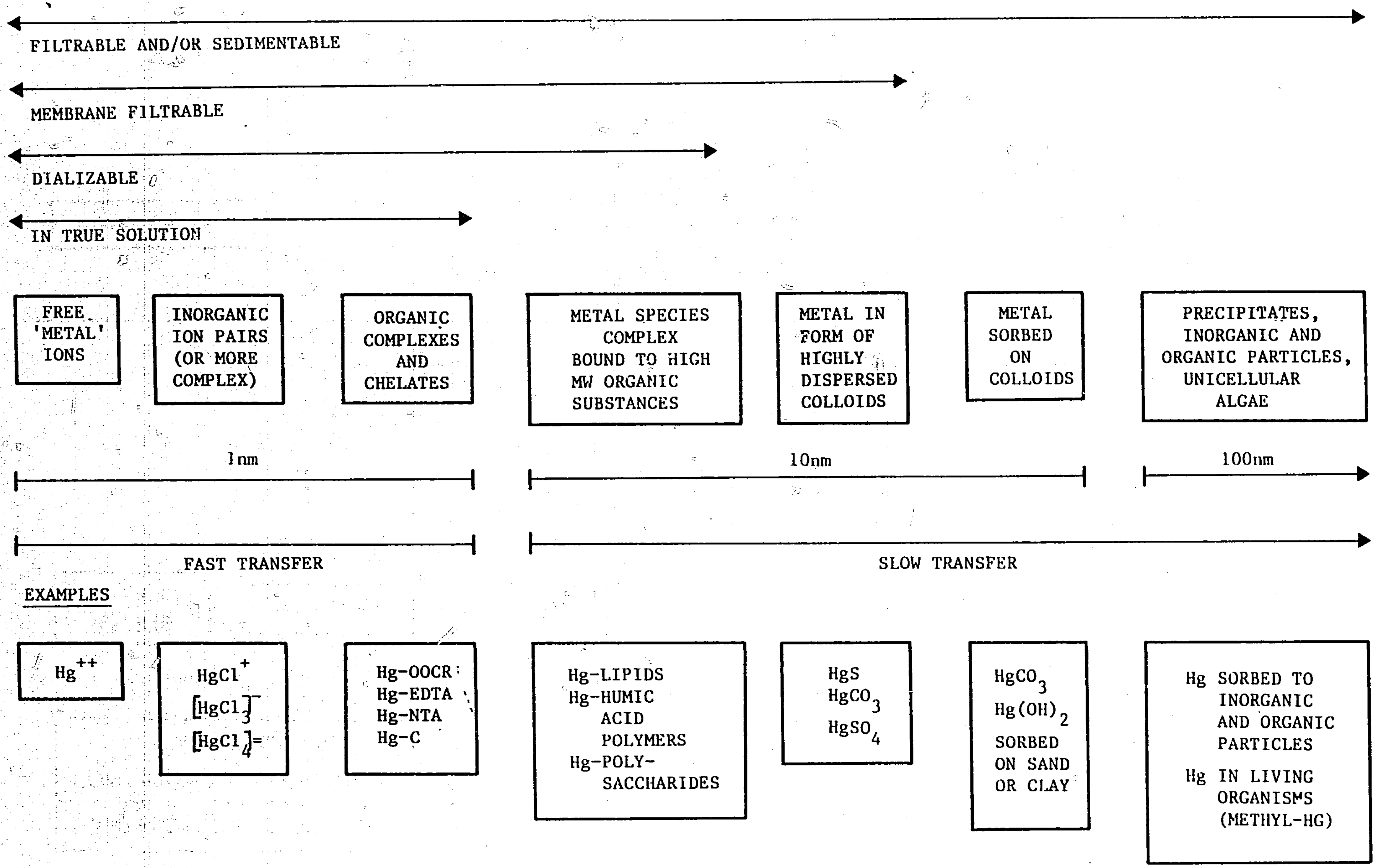


Fig. 36. Scheme of "heavy metal" species in a seawater sub-system.

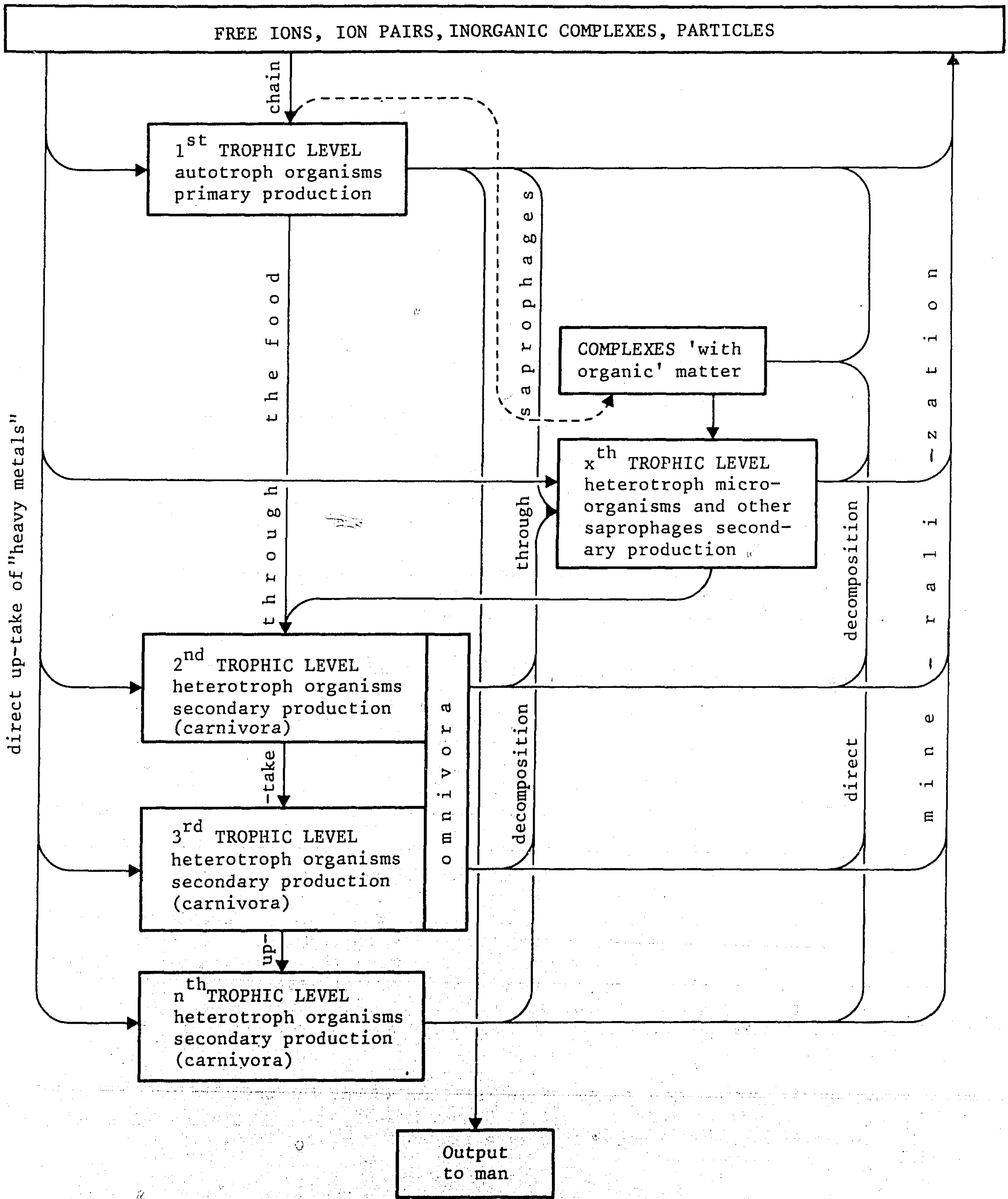


Fig. 37. Scheme of the possible paths of "heavy metals" in a marine food chain.

nic "heavy metals", or through ingestion by saprophytes. It is realized that organisms change their position in the food chain during their life cycle and many feed on organisms that belong to different trophic levels. Therefore the trophic model is only a rough approximation of the real prey/predator interrelationship in the ecosystem. With regard to "heavy metal" contamination, the output in such edible forms as seaweeds, molluscs, crustaceans, fish and marine mammals are of special importance. The maximum tolerable intake of "heavy metals" by humans (as recommended by WHO/FAO panels), the body burden (concentration of a metal in a marine organism), and the consumption of fishery products by the general public and by critical populations may serve as one of several criteria for determining the relative importance of a specific metal in the marine environment and hence the necessity to monitor it.

4. Conceptual models of the prey/predator relationships of organisms mentioned in the FAO(GFCM)/UNEP "heavy metal" monitoring pilot programme.

Conceptual models for Mytilus, Mullus and Thunnus can be constructed to illustrate the pathways of mercury (and other metals) through the relevant food-chains. Sufficient information on possible food sources necessary for growth and reproduction under laboratory conditions is available only for Mytilus. However, the selection of these animals for study does not necessarily imply that they are the important or the major food-sources in the natural environment.

D. Discussion on the significance of body burden of "heavy metals" in marine organisms and effects of toxicants on marine organisms and ecosystems.

In discussing the significance of the monitoring of "heavy metals" in marine organisms in relation to their effects on marine organisms and ecosystems, it should be recalled that different marine organisms possess different sensitivities. Body burden itself may have no effect on the organisms but may effect its predator. On the other hand, seawater concentrations may effect membrane permeability and enzyme activity in peripherical metabolic systems directly exposed to the seawater while body burden of toxicants affects internal metabolic systems.

Regulations of "heavy metal" concentrations, especially of the so-called essential elements, influence the body burden of tissues differently. Concentrations in organs that actuate and control the uptake and loss of "heavy metals" can be markedly different from the concentration in their body tissues, therefore, making it necessary to consider additional compartments for any sub-model including metal concentrations internal to an organism.

The relation between the ambient seawater "heavy metal" concentration and the body burden of the organism is shown in Fig. 38 . Three different phases in the reaction of the organism can be distinguished: deficiency, regulation, and toxicity. The relationships between body burden and environment become much more complicated when the food consumption also contributes significantly to the "heavy metal" intake. Therefore, the modelling of the effects on individual marine organisms, populations or communities must consider body burden, pollutant concentration in the food organisms, and the pollutant concentration in seawater and sediments.

E. Concluding remarks. Considering all the above, the workshop noted that the relevant operational pilot project on "heavy metal" monitoring was restricted to determination of metal content in only a few specific organisms. It was

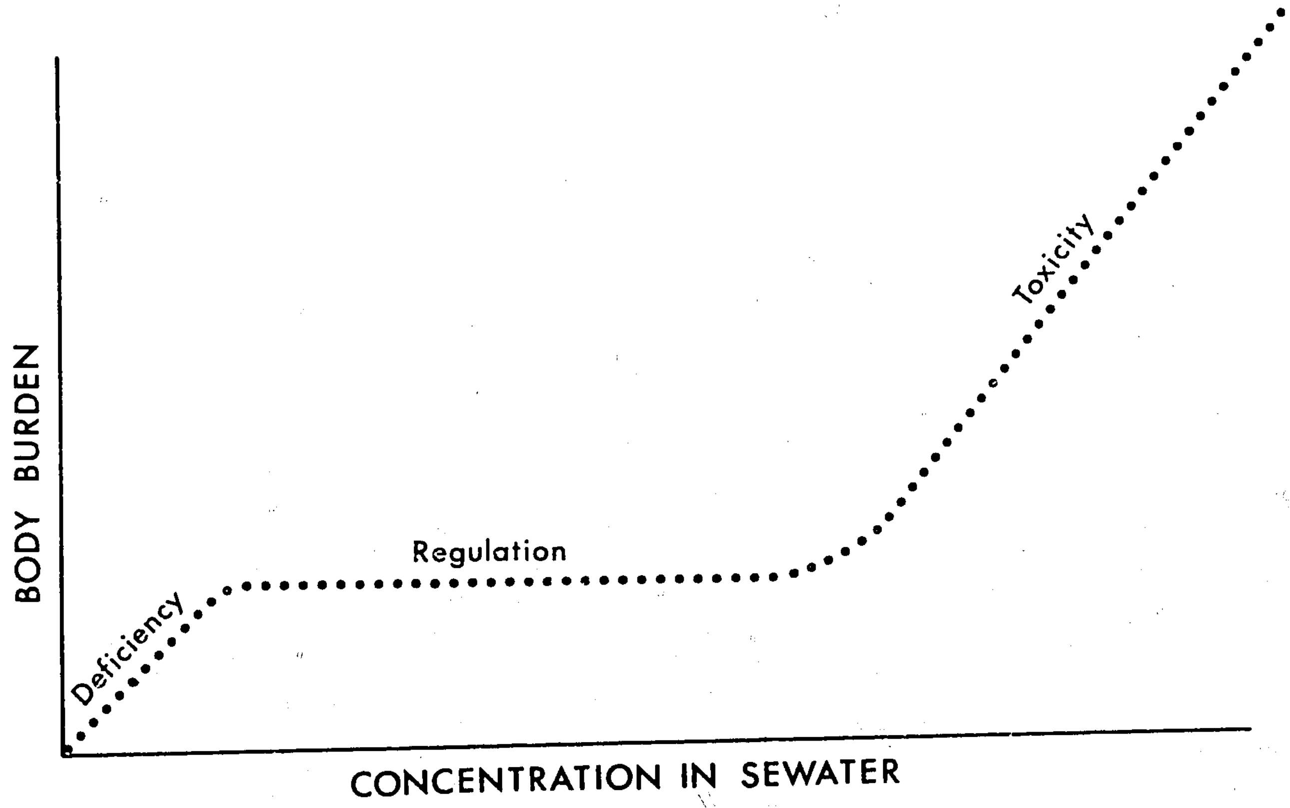


Fig. 38. Scheme of body burden versus concentration of a regulated "essential element.

considered very important that this pilot project be allowed to expand, at the earliest appropriate date, to include other components of ecosystems, principally seawater and sediments.

2.4.3. Physical processes

A. Introduction

The Mediterranean Sea is virtually severed from the oceanic dynamics of the Atlantic Ocean. The dynamics within the Sea are driven by local meteorological forcing. The land-locked location of the Mediterranean causes it to experience a greater exposure to continental air masses than an oceanic water body at a similar latitude. This exposure increases eastward due to an increased isolation from westward-moving North Atlantic weather systems. A significant result of the dynamic separation of the Mediterranean from the Atlantic, or of its smaller basins from its larger ones, is the existence of low-scale cutoffs in the energy spectrum, a fact that simplifies the advective boundary conditions and hence dynamic modelling.

The Mediterranean Sea, however, is not separated from a low frequency thermohaline dependence on the Atlantic. The water mass exchange with the Atlantic is important to the Mediterranean. Consequently, the same bathymetric restrictions that damp the dynamic coupling are the ones that facilitate the definition of the thermohaline boundary conditions. The lateral heat and salt exchanges are confined to the well defined cross-sections above the sills. The same arguments hold for the internal basins within the Mediterranean.

In the following brief discussions, emphasis is placed on transport processes, especially those resulting in an exaggeration of the role of pollutants. It was implied in the first two paragraphs above that the Mediterranean presents physical conditions favourable to modelling, due to some scale limitations in its dynamics, and due to the ease in monitoring its inputs. A division in scale, similar to that suggested elsewhere in this report, is valid also in terms of physical processes.

The coastal processes are coupled to offshore processes but must be described on a smaller scale in the offshore direction because they constitute a dynamic boundary layer for the interior dynamics. The alongshore scale for this boundary layer is reduced and complicated by the very uneven shoreline. A smaller scale treatment also is imposed by the sharp environmental gradients existing in coastal regions where pollutants are discharged.

B. Transport of water-borne properties

The transport of water-borne properties, particularly that of pollutants, is of critical importance to stressed ecosystems. In describing their distribution and interaction with a geographically defined ecosystem, the main difficulty lies in the fact that the movement of the fluid environment cannot be defined geographically in the same manner as the ecosystem itself, since the fluid and its properties are moving with respect to a geographically fixed point. Even in the cases where a mean flow is prescribed, the transport of a property can not be specified completely, because the higher frequency diffusion processes are still effective wherever gradients occur.

The change-over time of a given parameter (Q) at a geographic location is a combination of the effects of internal sources and sinks, of diffusion changes, and of advective changes wrought by the movement of water transporting varying amounts of the property, Q. This combination of changes is commonly expressed as

$$\underset{\text{time change}}{\frac{\delta Q}{\delta t}} = \underset{\text{advective change}}{-\frac{\delta(UQ)}{\delta X}} \underset{\text{diffusion change}}{+K\frac{\delta^2 Q}{\delta X^2}} \underset{\text{source or sink change}}{\pm R}$$

Where K is a diffusion coefficient, U the velocity in the X direction and R the source/sink term.

The link between the circulation of water and its substances, transported through a geographically defined ecosystem, is found in the advective change. This represents a change in the flux of a property between entering and leaving a geographically fixed region. For example, the mean flux of nitrate (NO_3 gatm/cm^2-sec) brought in on one side of a Posidonia bed would not equal that existing from the other side in cases where either the flow or the nitrate concentration changes over the bed. Another change occurs in the vertical. For example, if the NO_3 had been uniform in the vertical on the upstream side, it would not exit so on the downstream side because a nitrate sink is along the bottom, which then generates a vertical gradient. The strength of this gradient depends on the success that the vertical fluxes might have in redistributing the nitrate in the vertical direction, a fact which in turn depends on the amount of vertical kinetic energy gained from the horizontal kinetic energy as the water flows over the bed.

This example has intended to show briefly how a biological system can introduce spatial gradients into the distribution of a water property. The resulting vertical and horizontal gradients will vary in scale. It must be pointed out that the circulation also may generate gradients in water properties. For example, any non-steady and/or dispersive circulation past a sewage outfall will generate spatial gradients in the distributions of the effluent.

When the advective change term is small compared to the source/sink term, then the bio-system is less sensitive to circulation transports than when the term is large. For example, in the Posidonia bed the concentration of nitrate might be determined mostly by that taken up by the plants and epiphytes and by that regenerated due to bacterial action in organics.

The problem in evaluating the advective change term is that the temporal variability of both the water property and the velocity must be known, in addition to their spatial variability. A strong coupling between the circulation and a geographically fixed ecosystem occurs only when the relative values of the source/sink term and the advective change term are approximately equivalent. If a substance, e.g. NH_4^+, is highly reactive within a bio-system, then low frequency variations of ammonia flux will be immaterial; and vice-versa, if a substance is relatively inert, e.g. fine suspended inorganics, then high frequency variations in their flux into an area will be immaterial. The result is that different circulations are important for the transport of different substances. The following table is presented to illustrate better this point:

Time Scale	Survival of water property in ecosystem	Length Scale	Transport Processes
Hours to		cm	diffusion small scale advection
	short	to	
Days to		10 m.	coastal summer upwelling coastal winter convection
	meso	to 50 km	summer offshore frontal upwelling winter offshore convection
			meso-scale advection (local coastal flows) (summer offshore gyres) (winter offshore gyres)
Weeks to			
	long	to	
years		5,000 km	water mass exchange between basins

It is obvious that good sampling detail is required to provide information on the transport of substances by local circulations. Certainly, data representing the seasonal means of velocity and of substance concentration at some geographically fixed point, would be inadequate in all cases except for an inert substance far (in space) from any source. Fig. 39 illustrates in a schematic way the complexity of the relationships between the forcing functions, the velocity, and the water property transports. The observed velocity field must be considered stochastic, over a period usually much longer than that of the sampling interval, unless the forcing functions are adequately sampled, the transfer functions known, and the non-linear internal interactions known. Finally, the spatial and temporal fields of the state variables (water properties) must also be known to evaluate their interaction with the velocity field, and hence their transports.

A very important aspect of the pollutant-transport problem concerns the transport between systems, regardless of scale. For example, contaminants may be carried from the bay in which they originated to an adjacent bay along the coast, to a large scale offshore circulation, or to another regime in the vertical having quite a different scale of motion. The joining of different systems of different scales is not an easy task. With reference to Fig. 39 it is quite probable that the forcing functions, the boundary conditions, the transfer functions, the consequent frictional interactions, and the interactive time scale of a water property all may change from one system to another. For example, eutrophic phytoplankton of a nearshore sewage outfall plume may, with a change in the local wind-driven circulation, find themselves downwelled and transported offshore to a region below the photic zone and driven mainly by large scale

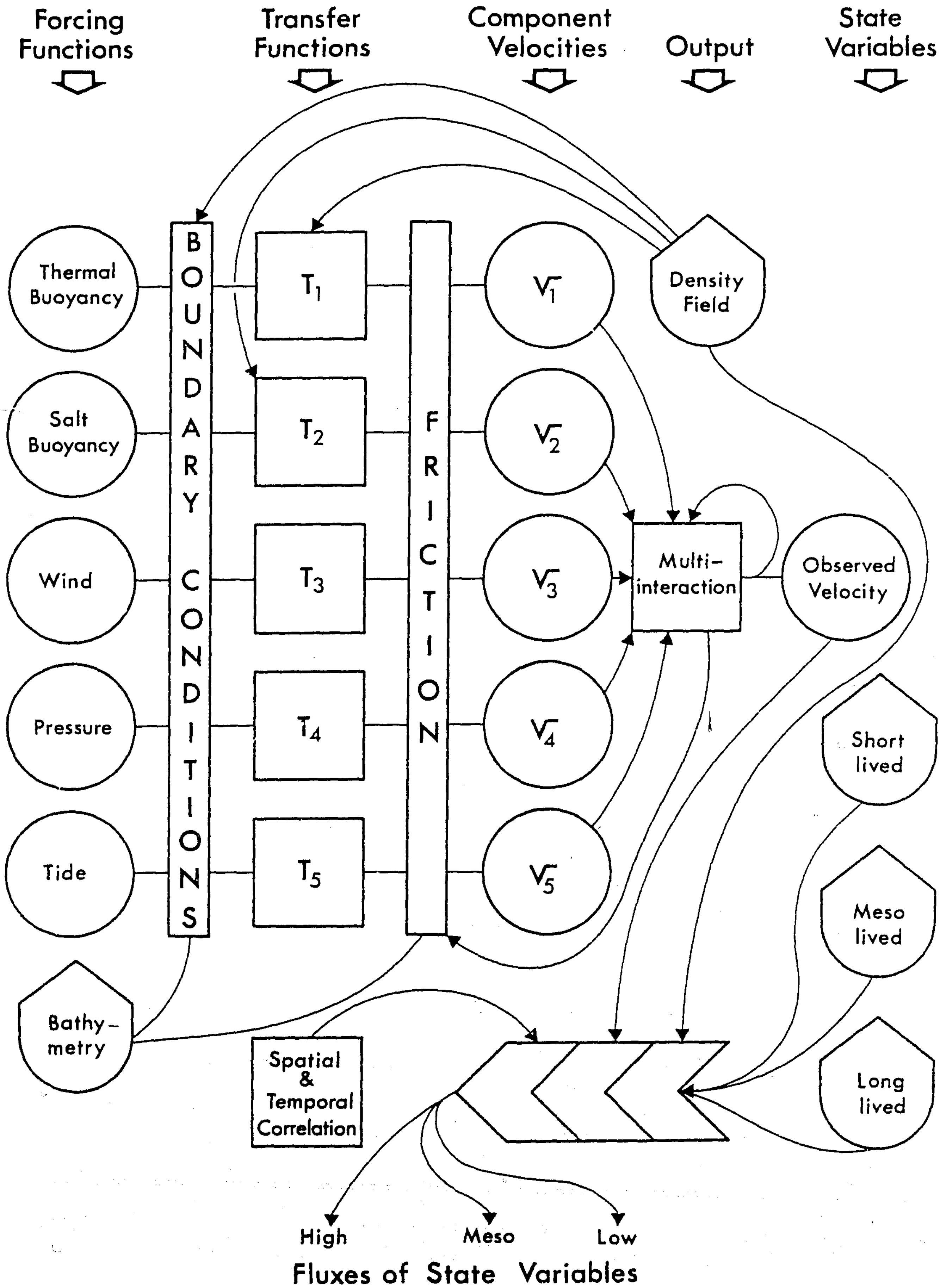


Fig. 39. Scheme of the relationships between physical forcing functions, velocity field and state variables.

thermohaline circulation. In this case, the distribution and transport of the phytoplankton was changed from one of small spatial scale and rapid time changes to one of large spatial scale and slow time changes. The fact that the different scale systems are inter-dependent is an unavoidable complexity in modelling the transport and disposition of pollutants.

C. Large-scale transport phenomena

The Mediterranean waters basically move in response to a three-layer thermohaline circulation, the surface layer of which is also wind-driven. Information on large-scale structure and circulation has come from numerous oceanographic expeditions transiting the deep basins; and thermohaline additional information has come from detailed sampling of sills, particularly those of Gibraltar and the Bosporus. Published works on the general physical features of the Mediterranean can be found, for example in the following works : Nielsen (1912), Schott (1915), Sverdrup et al. (1942), Lacombe and Tchernia (1960 and 1972), Wüst (1961), Miller (1963), Gerges (1974), Ovchinnikov (1966 and 1974), Hopkins (1976) and others. It is clear from these works that sufficient information, either in the form of hard data or in the form of interpretative assessment, is not available for the evaluation of transport and exchange processes throughout the Mediterranean system of basins in sufficient quantitative detail to answer questions concerning the residence and fate of pollutants introduced into the sea.

As suggested elsewhere in this report, attempts to generate complete quantitative models of the large-scale dynamics may not yet be technically feasible, and more importantly may be out of priority. Given the limitation of resources, efforts engaged in complete quantitative models should address the smaller scale coastal circulation problems. However, the importance of proceeding with large scale models of a more limited stage of completion (conceptual) or of major processes (convection, property budgets, etc.) must be emphasized.

The data base required to delve further into the large scale processes is in some ways made difficult by the international and extensive nature of the sampling efforts required, and in some ways made easy by the level of data coverage needed to support conceptual or limited process models. A great deal of important information can be obtained if data collecting exercises are well designed; the MEDOC experiments are an excellent example (MEDOC, 1970). One of the advantages of operational conceptual models is that they can update field experiment designs to increase the efficiency of information retrieval.

An outline of important large scale phenomena and their consequences is presented below, as the first steps required to address them in an integrated, conceptual way.

Horizontal exchange

a. Transports

(i) The fluxes of heat and salt between basins. This is absolutely essential information to calculate inter-basin exchange, to estimate air-sea mass and heat exchanges, and to determine the thermohaline sensitivity of the basin systems to variations in their forcing functions. This important boundary condition could be easily measured by continuous monitoring at the important sills, e.g. Gibraltar, Sicily, and Otranto.

(ii) The fluxes of other water properties between basins. Many bio-chemical substances change form (are reactive) within a system. The form and amount of a substance leaving a basin is highly desirable information; for example, it would be desirable to know the extent to which the Adriatic is a sink for its own pollutants, and the biochemical form of these pollutants that eventually are exported out of its basin. This represents not only an important boundary condition for the Adriatic but also for the deep water of the Eastern Mediterranean. Nutrient concentrations and particulates could be sampled frequently over at least a year.

(iii) The flow of the intermediate water. The route of the Levantine intermediate water is critical to understanding the Mediterranean transport dynamics. Pollutants entering this water during the winter in the eastern Levant have the possibility to re-enter the deep water system in the Adriatic and the Golfe du Lion. In addition to sill monitoring at Sicily and Gibraltar, this layer should be mapped at other critical points.

(iv) The flow of the deep water. The deep water masses of the Eastern and Western Mediterranean are distinct in origin and have no direct connexion to each other nor to the Atlantic. This makes them potential reservoirs for long-lived contaminants. It also places importance on their flow patterns and points of maximum diffusive exchange upwards to the intermediate water.

b. Processes

(i) Sill dynamics. The cross-sill pressure gradients, their flow response, and the frictional interaction between layers and the bottom need to be further investigated and verified, e.g. Assaf and Hecht (1974). Estimates of flow variations occurring at frequencies higher than seasonal are critical to evaluating sampling errors likely by short-time observations.

(ii) Mid-basin gyres. It is often stated that the various basins of the Mediterranean are occupied by gyres (mostly cyclonic). In most cases, their existence and extent need better definition, along with their seasonal permanence and generating mechanisms. The residence time of surface water (possibly carrying pollutants) must be estimated.

(iii) Boundary flow connexions. The task of dynamically coupling an interior flow regime to a boundary layer is by no means simple, and the Mediterranean coastal flows are the exception. However, to allow comment on the disposition of pollutants in the coastal zone the horizontal water mass exchange must be understood to some degree or the progress of coastal modelling will suffer as a consequence. Certain helpful semi-quantitative information would be most useful, such as the dynamic width of the boundary layer as a function of local forcing and season.

a. Transports

(i) The fluxes of heat and salt. Continued attempts to monitor the heat and salt exchange within the typical three-layered stratification are vital to the understanding of the thermohaline forcing and the residence times for the deeper layers.

(ii) The fluxes of other water properties. To assess the environmental impact on the total Mediterranean, the amount of organics and pollution related material being actively convected either down or up must be understood. The dynamics are such as to make quite possible the input of contaminants at one point, their subsequent submergence, and their upwelling at another point.

b. Processes

(i) Evaporation. The predominance of continental air flows over the Mediterranean waters makes the process of evaporation (and sensible heat exchange in the winter) relatively much more important than if the sea were exposed to marine air flows. The offshore dependence of the evaporation process on wind speed, relative humidity, and atmospheric stability need further study (e.g. Bunker, 1972) to integrate spatially evaporation over large areas of the sea.

(ii) Circulations important to the surface formation of dense water. The causal mechanisms for the cyclonic gyres associated with deep water formation are not completely understood (e.g. Saint-Guilly, 1963).

(iii) Mechanisms of convective mixing. Anati (1971) has provided plausible evidence for the existence of non-penetrative mixing during the MEDOC experiment (dense water formation off the Golfe du Lion). This has important ecological consequences since it requires that new deep water be formed by the atmospheric heat extraction from a mixture of intermediate and surface water, as opposed to intermediate and deep water which would be the case for a penetrative type of mixing process. With the non penetrative process the deep water is more vulnerable to surface pollution. The process and the roles of the various water masses need further study.

(iv) Circulations important to upwelling. Throughout the Mediterranean substantial increases in nutrient values rarely occur before several hundreds of meters or into the intermediate water. This means that for upwelling to be important for biological enrichment significant movements must occur. Increased chlorophyll along frontal divergences and in the centre of divergent gyres has been noted (e.g. Section 2.3.4.). Even if these vertical movements do not result in surface enrichment of primary production due to nutrient transport, they still are important in terms of other water property transport between vertical layers.

In Fig. 40 some of the critical areas, where these processes and transports might be evaluated, are indicated on a chart of the Mediterranean.

D. Meso-scale wind-driven transport.

The unevenness of the Mediterranean shoreline tends to increase the dominance of discrete meso-scale circulations along the coasts. The alongshore distance without curvature of the shoreline and the offshore distance to deep water, the shelf width, are critical dimensions in regard to allowing, for topographic reasons, meso-scale circulations. The alongshore distance is the more critical. A glance at a Mediterranean chart shows the northern shores to be more topographically uneven than the southern shores. Because of the correlation between natural harbours and urban development most of the coastal pollution problems occur in areas of complicated coastal topography.

Meso-scale circulations are stimulated also by spatial wind variability along the coasts, particularly, as in the Mediterranean when other types of forcing are not dominating over local wind forcing. Local sea breeze systems, found during strong solar heating, are quite common and introduce considerable local variability at the meso-scale. This variability is compounded by the frequently steep coasts that generate terrestrial boundary layer effects strong enough to superimpose appreciable spatial dependence into the marine wind field.

The importance of coastal circulations has already been emphasized. The fact that strong environmental gradients (of equal or smaller scale) increases this importance also has been emphasized. There are a number of typical coastal circulation problems:

a. Buoyant effluent. Although rivers are not a common Mediterranean feature they are inevitably located, coincident with important marine areas; the Po River is an excellent example. The resulting thermal plumes are usually located in areas where the circulation is of interest. They are limited in scale, essentially by their discharge volume. Buoyant effluents, either for reasons of low salinity or high temperature, represent a form of dynamic contamination because the effect of the buoyancy is to cause a secondary circulation that must be considered along with the primary one.

b. Straight coast. If indeed the coast is without alongshore variation, then the shelf width determines the importance of a distinct meso-scale circulation. Narrow-shelved coasts are exposed to a higher incidence of off-shelf flow regimes, and therefore have a lower incidence of meso-scale circulations.

c. Semi-enclosed coast. There are a number of factors obviously related to the shoreline configuration and size of embayments that affect the circulation. It must be noted that the depth is very important. Shallow bays are responsive to wind forcing and more likely to have less stratification, and more thermohaline variability, than deeper bays.

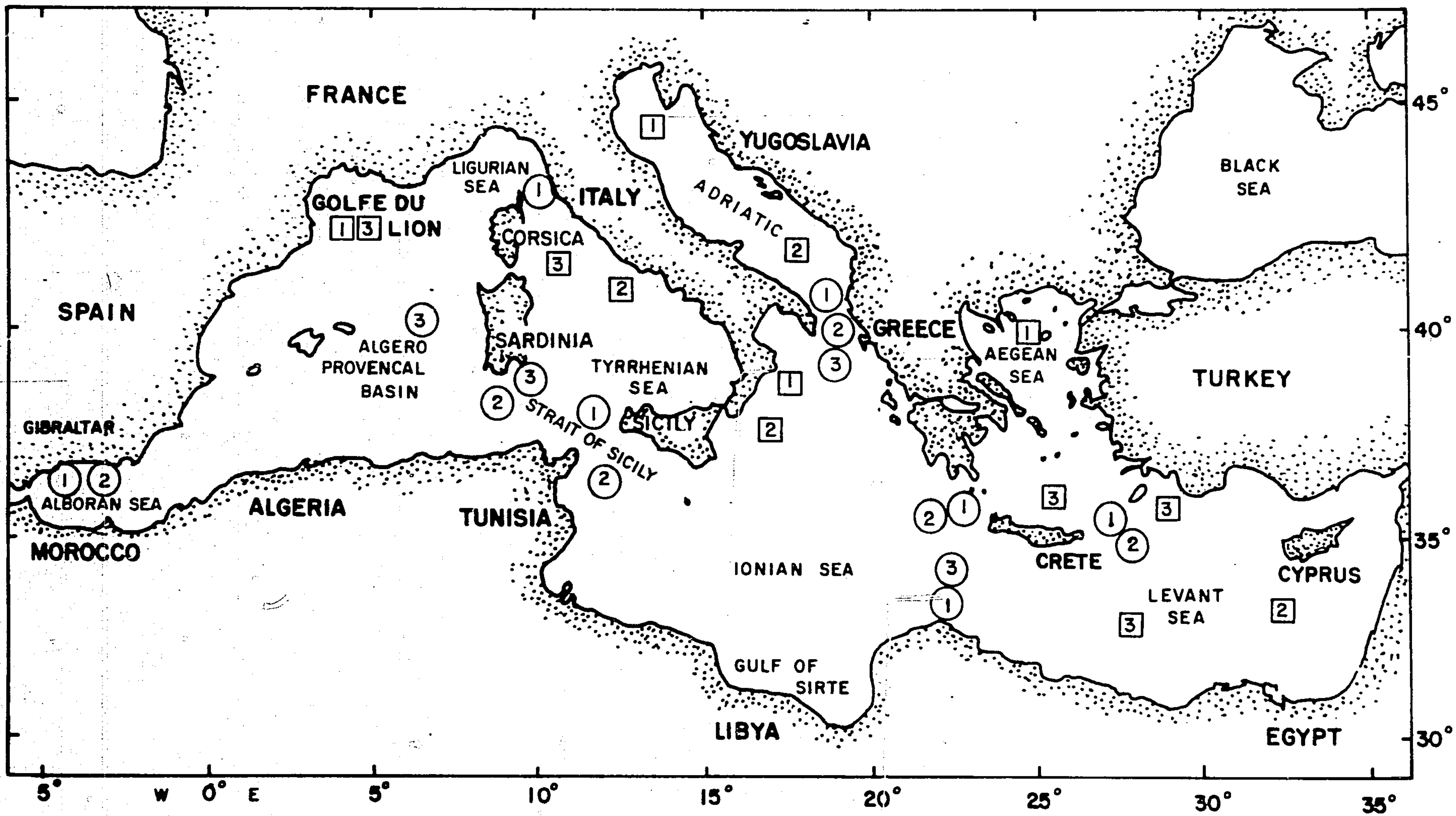


Fig. 40. Primary areas critical to horizontal transport between basins:
(1) surface (2) intermediate (3) deep.
Primary areas critical to vertical exchange : [1] surface to deep
[2] surface to intermediate [3] intermediate to surface.

d. Around islands. Islands are a considerable topographic complication, particularly for modelling. They distort the sea level configuration and block larger scale flows. Often they are located at the seaward boundary of what is being considered as a coastal system.

E. A conceptual discussion of meso-scale wind-driven circulation

Each of these circulations should be examined in terms of the different forcing functions; however, such a discussion is clearly beyond the scope of this report. Instead, and by way of illustration, some conceptual treatment of a wind-driven/semi-enclosed case is presented in the following paragraphs.

Consider a semi-enclosed bay of depth d, a function of x and y, the horizontal co-ordinates. The vertical direction is taken as positive downwards. A simplified equation of motion in the x direction is:

$$(1) \qquad \underset{A}{\rho \frac{\delta u}{\delta t}} - \underset{B}{\rho f v} = \underset{C}{-g \frac{\delta e}{\delta x}} \quad \underset{D}{-g \frac{\delta \rho}{\delta x} z} \quad - \underset{E}{\frac{\delta \tau^{x}}{\delta z}}$$

where ρ is the density, u the x velocity, f the Coriolis parameter, g the gravitational parameter, τ^x a stress in the x direction. The non-linear portions of the equation have been removed or included in the stress term. A similar equation exists for v, the y velocity component :

$$(2) \qquad \underset{F}{\rho \frac{\delta v}{\delta t}} + \underset{G}{\rho f u} = \underset{H}{-g \frac{\delta e}{\delta y}} \quad \underset{I}{- g \frac{\delta \rho}{\delta x} z} - \underset{J}{\frac{\delta \tau^{y}}{\delta z}}$$

As they are written, the right hand sides represent the active forcing of surface slope (barotropic), respectively, wind, and mass field (baroclinic). The left hand sides represent the net force and the Coriolis force.

A final equation is needed to begin the discussion, i.e. the continuity equation,

$$(3) \qquad \underbrace{\frac{\delta u}{\delta x} + \frac{\delta v}{\delta y} + \frac{\delta w}{\delta z}}_{K} = 0$$

where w is the vertical velocity component. This equation merely states that water cannot be compressed, so that movements in one direction are compensated by movements in another.

Intrinsic to the response are several important time scales that determine the relative importance of these terms. A and F contain the free and forced response times. A seiche would be a free wave response, not generally important for water transport. The forced response results from a mapping of the time dependence of the forcing function into the water regime. B and G contain the inertial response frequency corresponding to the Coriolis parameter. For wind-driven circulations, C and H are secondary forcing functions, not primary forcing functions as they would be in the case of tidal circulations. However, when they are coupled with A and F they provide the barotropic response, which is independent of depth. D and I are complicated terms. They carry the frequency information from surface wind forcing and the frictional damping time constants for interior movements. The terms E and J, similar to C and H are not primary forcing functions for wind-driven circulations, and when coupled with A and F they establish the baroclinic response of the system.

Fig. 39 has indicated that the velocity that is actually measured is the result of a non-linear interaction between a set of velocity components, each of which results from a linear transfer from some forcing function. In a linear model the final interaction is omitted, or at best linearized somehow in a frictional approximation.

To illustrate the sequence of momentum flow through a locally wind-driven, circulation system, consider a linear interaction in which the observed velocity is the sum of a surface frictional component 1, a bottom frictional component 2, a barotropic component 3, and a baroclinic component 4. Consider an identification code based on equations 1, 2 and 3 that identifies the term by letter and the component by number, thus the code G3 would indicate ρ f u for the barotropic component.

For an initial condition of wind blowing in the x direction, the sequence of momentum is shown in Fig. 41 using the code given for equations 1, 2 and 3.

In the non-linear case, any time momentum is put into one velocity component, it can spread (or leak) to the other components without going through this linear sequence. It should be noted that the baroclinic response depends on the stratification and that it is directional, i.e. normal to the pycnoclinal interface.

Fig. 42 summarizes these relationships more diagramatically, but without the specific time sequence information. The flow of energy is described briefly as follows : the kinetic energy of the wind is transferred to the surface layer through a surface stress (SF KE). The surface transport feels the boundary through continuity changes the surface slope (Bt PE). The surface slope drives first a barotropic wave and later a geostrophic motion (Bt KE). Continuously the barotropic transport and the surface frictional transport are compared through continuity, the difference being the bottom frictional transport (Bf KE). Internally the frictional kinetic energy (IF KE) is transmitted in the vertical by a non-linear transfer process which is shown here to be a function of the vertical shear and the vertical density gradient. The kinetic energy transfered to the bottom figure (BF KE) experiences frictional dissipation in a non-linear process dependent on the bottom roughness (R). The combined frictional and barotropic transports through continuity (and boundaries) reorient the field of mass and establish a baroclinic potential energy (Bc PE), which in turn transfers energy to baroclinic waves and geostrophic baroclinic flow (Bc KE). Several other forcing functions are shown also. Heat transfers, evaporation, and precipitation affect the baroclinic potential energy directly. Precipitation and vertical atmospheric momentum affect the barotropic potential energy.

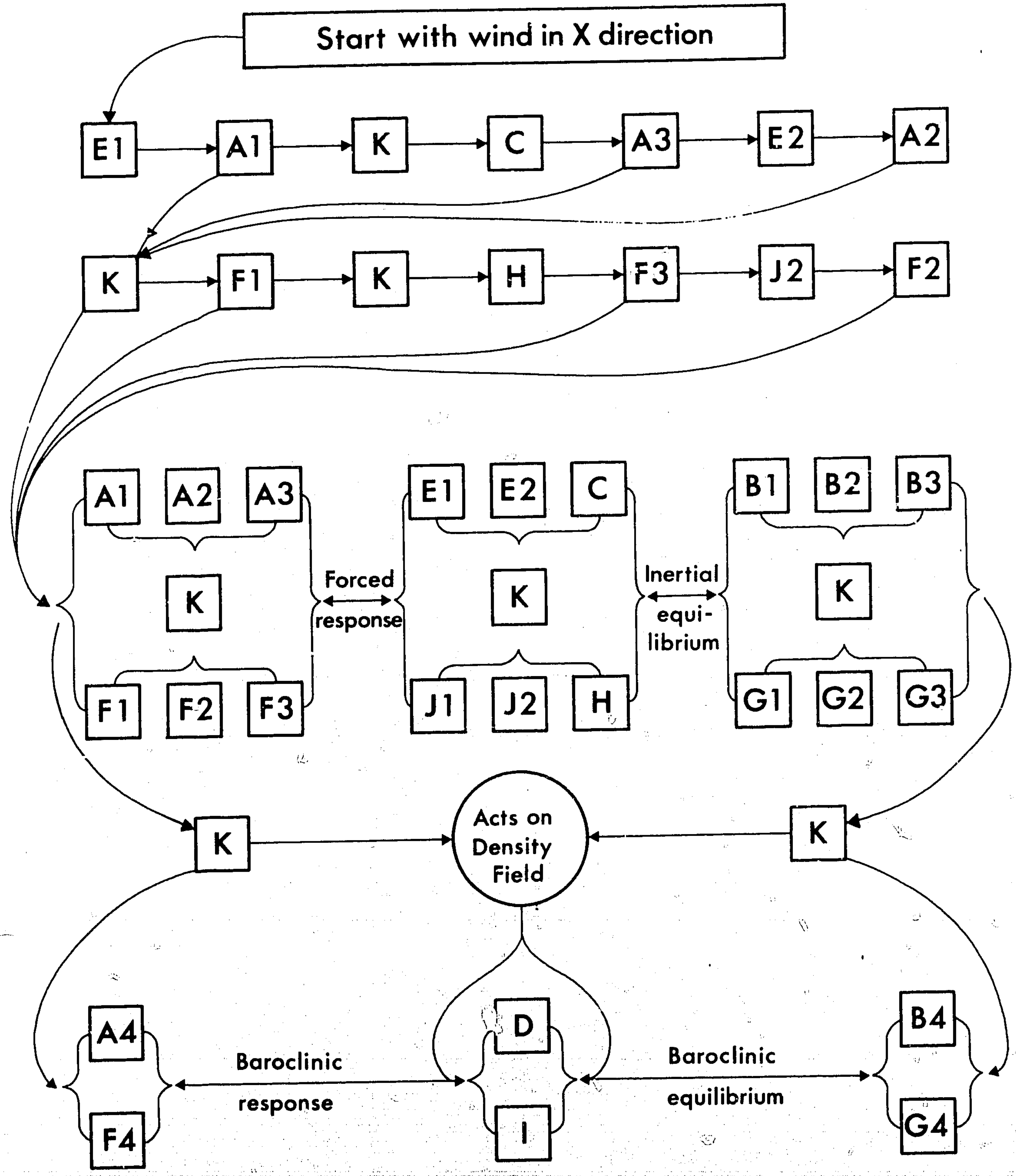


Fig. 41. Time sequence of momentum through the equations of motion starting with a wind stress in X direction near a coastal boundary.

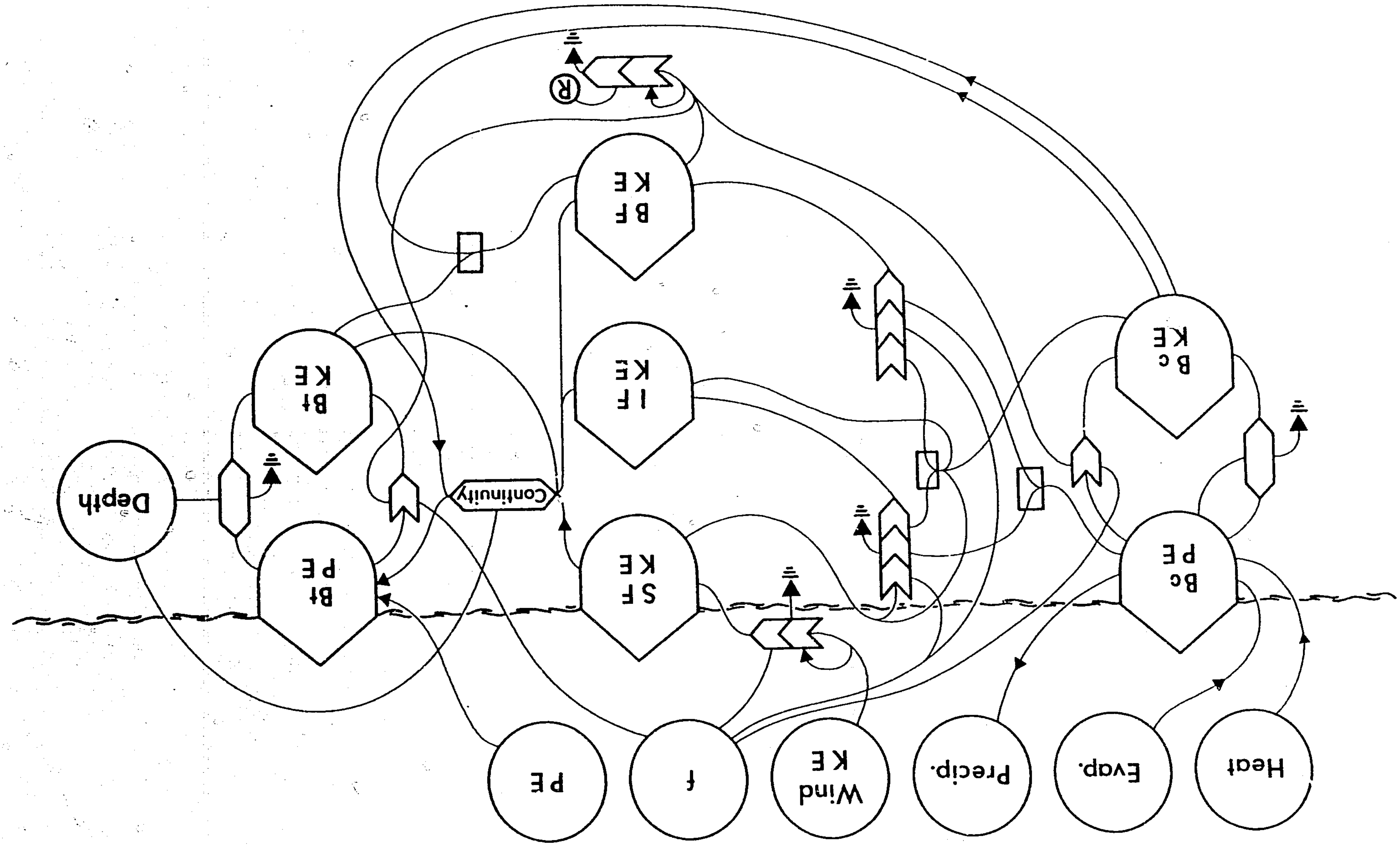


Fig. 42. Flow of energy in a locally wind driven circulation system (see page 90).

F. A specific model of a meso-scale wind driven circulation:

As an example of a solution to only the barotropic and frictional components, a model from Hopkins (1974) for the flow in the Gulf of Petalion, Greece, is summarized below.

Consider a homogenous semi-enclosed bay of depth d. Using Cartesian coordinates the x, y, z axes are positive in the east, north, and down directions, respectively. The Coriolis parameter is constant. The equations of motion, as specialized from equations (1) and (2), become:

(4) $$\partial u/\partial t - fv + \varkappa u - A(\partial^2 u/\partial z^2) = -\partial\varphi/\partial x$$

(5) $$\partial v/\partial t + fu + \varkappa v - A(\partial^2 v/\partial z^2) = -\partial\varphi/\partial y$$

where φ is the barotropic body force. The eddy viscosity coefficient, A, is a constant. The horizontal frictional term $\varkappa u$ is made as simple as possible to avoid imposing unrealistic or unknown boundary conditions at the lateral boundaries. Since the term customarily enters the equations of motion in the form

$$(\partial/\partial x)A_h(\partial/\partial x)$$

with the dimensions of T^{-1}, it can be regarded as a frictional decay factor.

A complex velocity can be formed by setting q = u + iv; the result is

(6) $$\{\partial/\partial t + \varkappa + if - A(\partial^2/\partial z^2)\}q = -\nabla\varphi$$

where $\nabla\varphi = \partial\varphi^x/\partial x + i(\partial\varphi^y/\partial y)$. Taking the Laplace transform of (6), observing the initial condition of $q(z,0) = 0$ and using the notation

(7) $$\bar{q} \text{ or } q(z,s) = \int_0^\infty e^{-st}q(z,t)dt$$

gives

(8) $$A\{(\partial^2/\partial z^2 - \alpha^2\}\,\bar{q} = \nabla\bar{\varphi}$$

where $\alpha^2 = (s + if + \varkappa)/A$.

The solution in transformed time, after imposing the boundary conditions, will involve the product of the characteristic transfer function and a forcing function. The transformation to real time can be made by the convolution technique.

The wind stress is represented as:

(9) $$g(\tau_l) = -\sum_{i=0}^{l}(\Delta T_i/A)$$

where $\Delta T_i = T(t_i) - T(t_{i-1})$, and which considers the wind stress function to be a series of step functions in time approximating the continuous function. Thus, a series of data points can be used directly to generate the response, and in fact assumptions on wind values several steps beyond the present permit a predictive capability.

The problem of connecting the surface and bottom Ekman layers amounts to determining the relationship between the sea surface slope and the wind forcing function. Integration in x and y is necessary to include the effects of topography and the responses to the boundaries. A simple approximation is considered here, by assuming that the boundaries are always felt and that the transport always integrates to zero. A solution is obtained first for the case where the velocity goes to zero at the bottom (depth equal d') then the solution is iterated to obtain a bottom stress correction and a non-zero bottom velocity.

Using equation (8) and the boundary conditions,

(10) $$\partial q(o,s)/\partial z = g(s) \qquad q(d',s) = 0,$$

the solution

(11) $$q(z,s) = g(s)H(z,\alpha) + \frac{\nabla\bar{\varphi}}{A}K(z,\alpha)$$

follows, where H and K are the transfer functions for the surface and bottom layers, respectively. They are

$$q(z,s) = g(s)\,H(z,\alpha);$$

$$q(z,s) = \nabla\bar{\varphi}K(z,\alpha)/A,$$

Assuming the bottom stress and the integrated transport to be negligible, vertical integration from the surface to the bottom $(z = d')$ in (6) gives

(12) $$\nabla\varphi = T/d'$$

where T is the surface wind stress. Pollard and Millard (1970) used this representation to model wind generated currents in a surface mixed layer.

Now consider the problem at a depth d, and with a bottom boundary condition of

(13) $$q(d,s) = q_d(s);$$

where $d < d'$ and q_d is given by (10) at z = d. The bottom stress is given by

(14) $$T_d = -C_d|q_d|q_d,$$

where C_d is a drag coefficient.

The barotropic slope gradient is now

(15) $$\nabla\varphi = (1/d)\{T - T_d\}$$

The transformed solution to (8) using (13), (14), and (15) is

$$q(z, s) = g(s)H(z, x) + \bar{q}_d L(z, x) + (\bar{T}/d)K(z, x) - (\bar{T}_d/d)K(z, x). \qquad (16)$$

where $L(z, x) = \cosh az/\cosh ad$. The first and third terms on the right of (16) are the same as in (11) computed at a new depth d, and the second term is the correction for the bottom slip velocity and the fourth term is the correction for the bottom stress.

The behaviour of the solution under various conditions can be illustrated by permuting some of the constant parameters. The solution without the correction for bottom slip is shown in Fig. 43a. After the onset of a constant wind to the north, the velocities approach steady values within 24 hrs. The surface velocity is 24° to the right of the wind. The velocity vector rotates clockwise with depth, rapidly through the surface layer, and less rapidly in the bottom layer. The bottom water is moving approximately 180° from the surface layer. If the eddy viscosity were decreased or the depth increased, the rotation within the column would increase, that is, the surface and bottom Ekman layers would have less overlap.

If slip is allowed at the bottom (Fig.43b), flow in the bottom layer is larger than without slip. The solution converges at the bottom to a finite value rather than to zero. In this case it is assumed that the velocity ultimately goes to zero logarithmically through a thin bottom boundary layer. The bottom stress arising from a bottom velocity provides a correction to the slope current. Thus if slip is allowed, the bottom flow is increased over the no slip case.

By comparing Figure 43b with Figure 43c the results of decreasing the eddy coefficient can be seen. The bottom velocities are rotated farther clockwise with respect to the surface velocities than was the case with the higher eddy coefficient. More vertical shear exists with the lower coefficient causing the surface layer to be slightly shallower.

Finally, if the bottom drag coefficient is increased, the bottom stress becomes more important. The result can be seen in Figure 43d compared to Figure 43c. The velocity in the surface layer experiences more rotation, because the opposing bottom stress reduces the slope current allowing the surface Ekman structure to be more dominant.

Results

This solution approximates the wind-driven circulation in the Petalion Gulf, Greece, a small gulf, 17km by 37 km and enclosed on three sides. Time records of wind and water velocity were recorded during March 1970. Details concerning measurement are given in Hopkins, Pillsbury, Dugdale and Smith (1973). The water was almost completely homogeneous. Baroclinic, tidal, and estuarine currents were considered insignificant.

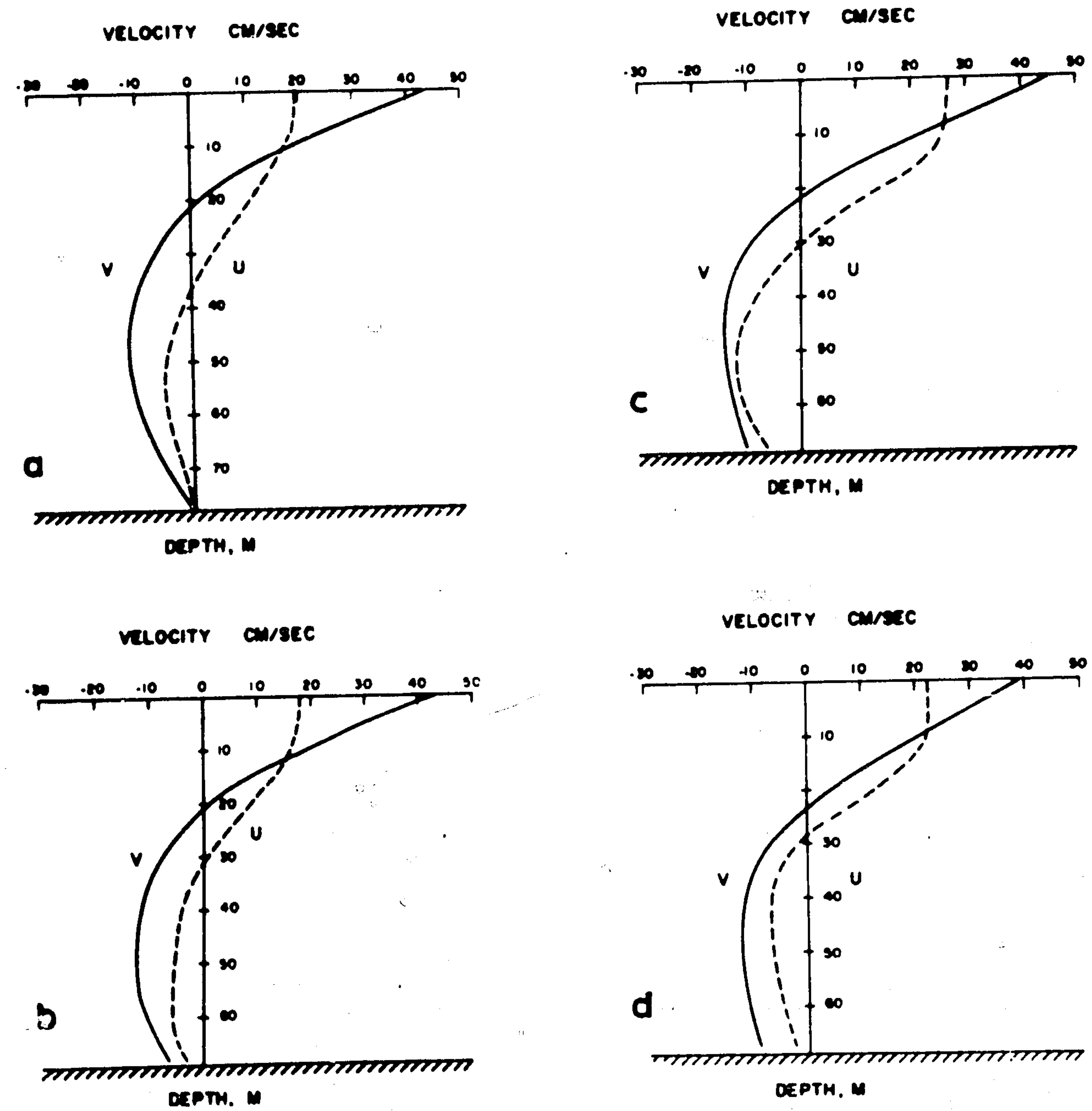


Fig. 43. Various solutions to the enclosed system when acted on by a constant wind stress. a. $T^y = 3{\cdot}5$, $A = 300$, $\varkappa = 2 \cdot 10^{-5}$, $f = 8{\cdot}79 \cdot 10^{-5}$, $C_d = 2{\cdot}6 \cdot 10^{-3}$, $d = 7{\cdot}8 \cdot 10^3$ cgs units. b. $d' = 7{\cdot}8 \cdot 10^3$, $d = 6{\cdot}8 \cdot 10^3$ cgs units. c. $A = 200$ cgs units. d. $C_d = 2{\cdot}6 \cdot 10^{-2}$.

(After Hopkins, 1974).

The wind was measured with a portable Woelfe-type anemometer placed on top of a small island 3.9km from a taut-wire instrument moor. At the moor three Braincon-type current meters were placed at depth of 5m, 32m, and 59m in 69m of water. The wind amplitudes were contaminated by island boundary effects that differed from those over the water. The 5m and 59m current records are good. The directions in the 32m record were less reliable, many had to be estimated due to insufficient film exposure. A seven-day period between the second and ninth of March was chosen for comparison between observed and computed currents (Figs. 44a, b and c).

During the initial computations the computed currents were smaller than the observed values, particularly during periods of weak or variable winds. It appeared that the drag coefficients used to compute the wind stress should have been higher for low wind speeds. Also the boundary effects over to the island tended to decrease the magnitude of the wind compared to values over the water. For computational purposes the wind speed was doubled and a drag coefficient suggested by Neumann (1956) was used, $c(W) = 9 \cdot 10^{-3} W^{-1/2}$ where W is in m/sec. This drag coefficient equals $2{\cdot}6 \cdot 10^{-3}$ at $W = 12$; it increases for lighter winds, and decreases for stronger winds.

The observed and computed currents show much better agreement during steady winds than at other times, as occurred during a northerly storm from day 5.5 to 7. During the less steady winds the agreement is poorer. The 5m record has much more noise than those at the greater depths. The surface waters respond more directly to the wind stress, whereas the deeper waters, preferentially respond to the surface slope which is an integrated effect of the wind stress. Increased turbulence during variable winds may be explained qualitatively by poor coupling between wind and water, and by the likelihood of increased spatial variability.

The 5m current velocities were approximately 60° clockwise from the wind direction. Reducing the eddy viscosity to match this rotation resulted in too much shear in the water column between the depths at which the two shallow records were obtained. On the other hand, increasing the bottom stress and thus changing the total slope gradient preferentially increased the rotation in the surface layers but not the shear. The slope current has no shear in the surface layer. The slope current and surface Ekman are generally in opposition in the surface layer so that changing the amplitude and direction of the slope current seriously affects the total current.

With a larger eddy coefficient, there is less shear, amplitude and rotation throughout the column. The observed velocities at 59m exhibited considerable amplitude and tended to be out of phase in direction with those at 5m. Increasing the slip velocity, the bottom layer velocities preferentially increased and the rotation decreased.

The velocities at mid-depth are the most difficult to match because of the inflection point in the vertical. Velocity components computed at slightly different depths can be of opposite sign. If the physical parameters such as the eddy coefficient change with time, the inflection point will move up and down in the vertical. The computed velocities at the 32m depth give the poorest agreement; for example, the component at 3 days is completely out of phase (Fig. 44b).

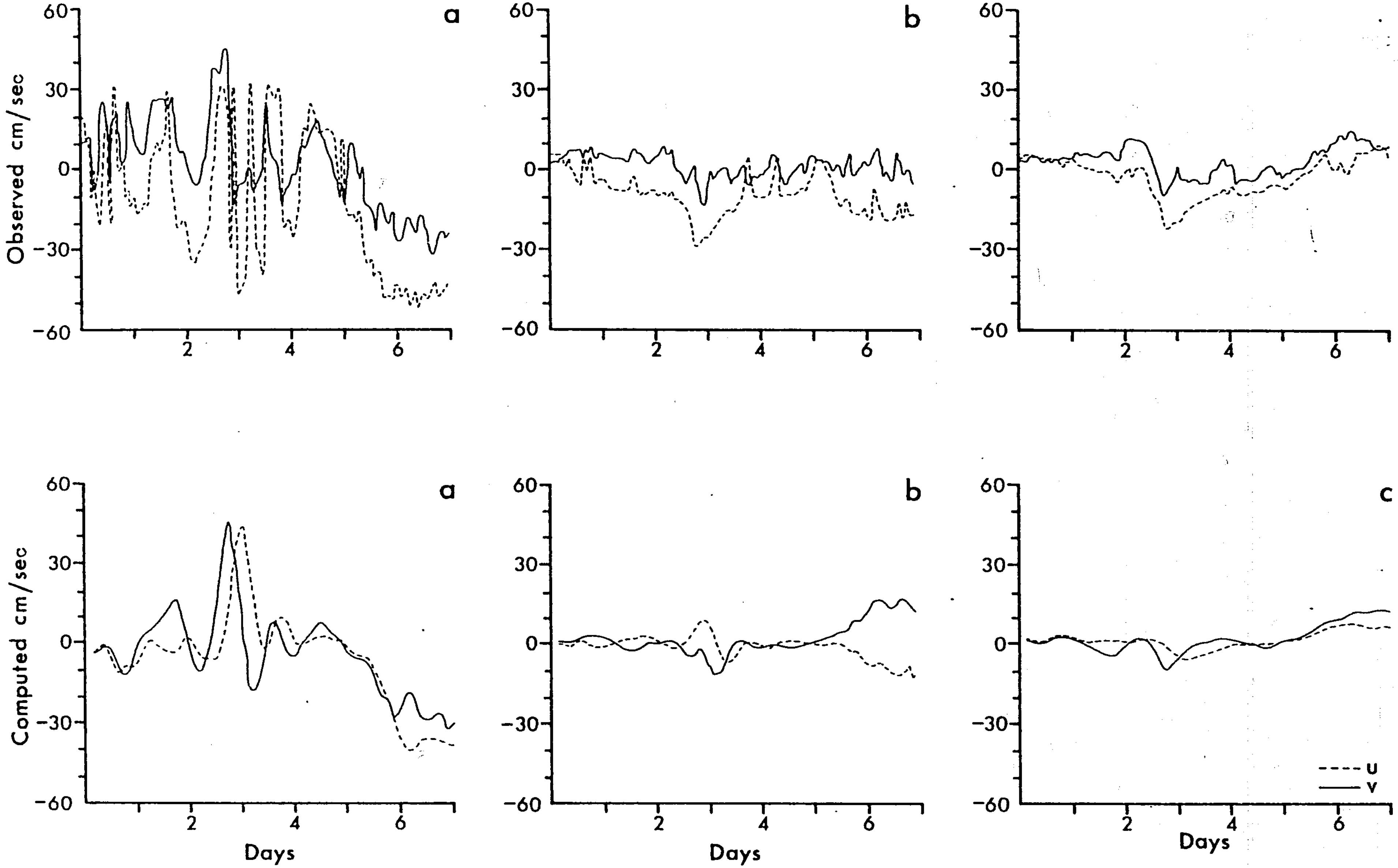


Fig. 44. The observed and computed velocities at the depths of:
(a) 5 m (b) 32 m (c) 59 m
in the Gulf of Petalion, Greece. (After Hopkins, 1974).

The Gulf of Petalion opens to the south, which may explain the better agreement in the v component compared to the u component. The wind-to-slope relation is less definite in the case of winds producing transport out of the Gulf than that associated with winds giving cross-gulf transport.

Other deviations could be caused by characteristic horizontal flow. For example, even though the water was nearly homogeneous, horizontal replacement of water cannot be excluded and hence a violation of the assumption of no integrated transport. The uneven topography could produce a velocity field differing from a gulf of simple topography.

No definitive conclusions can be made on the values of any of the physical parameters as there may be other combinations that could produce some agreement with the observations. The values used to compute the velocities shown were:

$$f = 8{\cdot}7 \cdot 10^{-5}\,\mathrm{sec}^{-1},\ A = 250\,\mathrm{cm}^2\ \mathrm{sec}^{-1},\ \varkappa = 2 \cdot 10^{-5}\mathrm{sec}^{-1},\ C_d = 5 \cdot 10^{-2},\ d = 69\ \mathrm{m, and}\ d' = 85\ \mathrm{m.}$$

2.4.4. Conclusion

A few of the concepts related to transport problems in the Mediterranean have been sketched in this section. Much remains undiscussed. Comparatively speaking, the Mediterranean represents a wealth of dynamical modelling experiments, primarily because of the diversity of its meso-scale subsystems and their relatively simple energy spectrum of their forcing functions.

2.5. General remarks

The existing knowledge of the physical and biological processes in the sea does not enable scientists to design a single model which would simulate the entire Mediterranean ecosystem. An infinity of models can be designed depending on the time and space scale of the phenomenon to be modelled. At either extreme of the range of possibilities one can design:

1. a large-scale overall model which will be of low precision, or

2. small-scale models of restricted areas or specific processes with relatively higher precision but lower generality.

The latter can be useful for local decision making.

Good modelling strategy requires scientists to attempt to achieve a proper balance between these two approaches. Both types of models are necessary and should be developed. The first type will be useful for studying general trends of the entire area or large sub-areas while the second, i.e. small-scale models, will help to illustrate and evaluate local problems of special concern and scientific interest. It should also be realized that the small-scale models can be considered as sub-models of the general or large-scale model.

The knowledge of biological processes is far behind that of the physical ones due to the large complexities of organisms and communities. As a result, biological and chemical models are less advanced than physical models. It is therefore desirable to stimulate the efforts for biological and chemical modelling to bring them to a higher level of sophistication. Process sub-models can be elaborated and then combined to produce, with the addition of appropriate links and feedback relations, a more general model.

Data acquisition is necessary in two steps of the modelling process:

1. Parameter evaluation. Experimental or field data are needed to calculate the most appropriate values of the parameters.

2. Validation of model. Here again a new set of data are required to test the model.

In the future, it would seem advisable to encourage research on the most important biological, chemical, or physical processes and models. It would also seem necessary to plan a sampling programme, restricted in space and time, for which an intensive modelling effort would be made. Priority should be given to problems of public concern, such as the pollutant impact on marine ecosystems and resources, as well as the possible routes of pollutants to man and the terrestrial environment. Efficient overall large-scale models and small-scale or process models are urgently needed to assist in ocean management and decision making. They would be of great value in the development of sound strategies for the conservation of the marine environment, such as in the control and abatement of pollutants, alterations in the marine ecosystems and climatic changes.

APPENDIX I

Abbreviations and acronyms

DDT	dichloro-diphenyl-trichloro-ethane
DOM	dissolved organic matter
ECE (of UN)	Economic Commission for Europe
FAO	Food and Agriculture Organization of the United Nations
GFCM (of FAO)	General Fisheries Council for the Mediterranean
IAEA	International Atomic Energy Agency
IBP	International Biological Programme
IOC	Intergovernmental Oceanographic Commission
MARE	Model of the Adriatic Regional Ecosystem
MEDOC	Mediterranean Occidental Survey
PCB	polychlorinated-biphenyls
POM	particulate organic matter
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
Unesco	United Nations Educational, Scientific and Cultural Organization
UNIDO	United Nations Industrial Development Organization
WMO	World Meteorological Organization

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APPENDIX III

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APPENDIX IV

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