Simulation of Bioecological and Water Quality Processes in Enclosed Coastal Seas

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This paper discusses recently developed numerical models which have been used as tools in the management of marine ecosystems. A brief description of the models is given, together with the way in which they can be coupled to extend the scope of the modelled system. The hardware requirements for implementing the models on a low-budget microcomputer system are given.

In enclosed marine waters, eutrophication (a term more often applied to lakes), often leads to prolific growth of algae, an accumulation of sediments and the onset of anaerobic conditions following the death and decay of particular plant species. If anaerobic conditions exist for extended periods there is a high risk of water discolouration, the release of sulphurous gases and death of marine animal life.

A restoration program may have to run over many years, so any mathematical model capable to providing reliable long term predictions must run in a fraction of real-time. On the other hand, short term water quality changes are also of interest, such as they decay of bacteria discharged from a sewage outfall. Modelling this type of situation may require a different approach. The multi-disciplinary nature of environmental studies often acts to confound attempts to isolate the basic spatial and temporal scales of the processes of interest. However, identification of the underlying scales can provide the key to developing successful predictive models.

Management Considerations

The types of problem with which an environmental manager is likely to be confronted can be split into the following categories:

(i) Short term phenomena (lasting a few days), such as algal blooms and accidental releases of toxic chemicals.

(ii) Longer term phenomena (lasting several years), such as in the Mediterranean and Adriatic Seas, where there has been a steady accumulation of pollutants over many centuries. Indeed, many large enclosed water bodies are showing symptoms of eutrophication (Pain 1990).

(iii) Circumstances in which a combination of both (i) and (ii) occur. Examples of this in Europe are lagoons bordering the Mediterranean.

To assess the cost benefit of using a numerical model, the manager has to appreciate the ramifications of all its inherent assumptions. Ideally the model will have been calibrated against good quality data, tested in real situations, run in substantially less than real-time and require inputs that are easy and cheap to

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measure or estimate. Validated numerical models which simulate both the short and long term aspects of water quality are now available (Brown et al 1989, 1990), (Reeve et al 1990).

Model Parameter Identification

The role of the modeller is crucial. Not only must he/she appreciate the use to which the manager will put the model but also the conclusions that will be drawn from the output. The modeller must draw on the knowledge of experts in many fields and be able to extract the salient points to include in the model. The most important step is the choice of approximations which simplify the model while keeping it sufficiently general to that it does not have to be rewritten for each new application.

For instance, the computational load of the hydrodynamical calculations can be reduced greatly if flow in two rather than three dimensions is considered. Using depth average equations is a reasonable approximation if stratification is not strong, implying that the water column is 'well mixed'. Also, in ecological models, it may suffice to model only the most populous species while including any important aspects of competition between biological species/groups.

Finally, the equations describing the ecological processes may exhibit various numerical problems (such as instability, poor accuracy, undue sensitivity to initial conditions) which must be overcome. To be useful the model must run in less than real-time on inexpensive hardware.

Description of the Models

The ecological/water quality modelling suite contains two fundamental components: a hydrodynamic/solute transport model and an ecological process model. The former is used for tidal and contaminant dispersal predictions over periods of days and weeks. The latter model is designed for use as a long term predictive tool, and may be used to assess inter-annual variations in marine flora, dissolved chemical levels and sediment nutrient pools.

The hydrodynamic model is based on the momentum and continuity equations:

$$\underline{v}_t + \underline{v}.\nabla \underline{v} + 2\underline{\Omega} \times \underline{v} = -\underline{g} + \underline{F} \qquad (1)$$

$$\nabla.\underline{v} = 0 \qquad (2)$$

where $\underline{v}$ is the velocity field, $\underline{g}$ the Earth's gravitational force, and $\underline{\Omega}$ the vector angular velocity of the Earth. Depth-averaged forms of (1) and (2) are used. The equations are fully nonlinear and the term $\underline{F}$ includes pressure gradient, wind stress, bed shear resistance and turbulence induced shear force effects. The Coriolis effect, due to the earth's rotation, is included using the f-plane approximation (see e.g. Gill (1982)). Over the geographical area normally considered in coastal studies the atmospheric pressure gradient is generally negligible in comparison to the water surface slope, and is therefore omitted from the momentum equations.

The hydrodynamic equations are solved using a central implicit finite difference scheme in conjunction with the alternating direction algorithm (see e.g. Ames (1977)). The model is designed to use nested grids of varying spatial resolution where such an approach is necessary to describe the circulations in the modelled area adequately.

This model is also able to predict the distribution of up to ten water quality determinants, using the nonlinear advection-diffusion equation (Rinaldi et al 1979):

$$C_t + \underline{v}.\nabla C = \nabla.(D\nabla C) + G \qquad (3)$$

where C is the constituent concentration, D a dispersion tensor, G a source/sink term and $\underline{v}$ is the vector velocity field. The depth averaged form of (3) is solved using the explicit approach of (Cheng et at 1989). Determinants such as BOD (biochemical oxygen demand), nitrogen and dissolved oxygen are 'built-in' to the program. Other, independent parameters (such as coliforms or metals) may be selected by the user.

The ecological process model can run independently of the hydrodynamic model but requires water flow rates as input. The area of interest is considered as a set of rectangular boxes. Water, solutes and marine organisms are exchanged between adjacent boxes according to the specified flow rates. However, within each box conditions are assumed to be uniform. The exchange of material between boxes is determined by an equation which expresses the conservation of mass, and is solved explicitly.

The ecological processes are described by a set of coupled differential equations which are solved using an adaptive time step algorithm. One 'time-step' involves advancing the set of ecological variables by one day in each box, the mass conservation equation is then solved to determine the exchange of material between the boxes.

The form and number of equations used in the model depends on the type of ecosystem being modelled. As an illustration, Figure 1 shows a schematic representation of a model used for a recent application in the Mediterranean (Reeve et al 1990). The various interactions between marine flora, fauna and chemical solutes are represented by a set of coupled ordinary differential equations. See, for example, (Canale & Auer 1982), (Evans & Parslow 1985) and (Orlob 1983). Closure of the system was achieved by parameterising the consumption of zooplankton by fish as a nonlinear zooplankton death rate term.

Both the hydrodynamic and ecological models are written in modular form and can easily be implemented for new applications.

Discussion

Both models, together with a menu driven graphics post processing suite, have been installed on an IBM-compatible 386 microcomputer equipped with a 110 MByte hard disc and 8 MBytes of Random Access Memory. Using a maths coprocessor the hydrodynamic model, with a full suite of water quality determinands, runs in less than real-time. A one year prediction using the ecological process model takes approximately 7 minutes per box.

Figures 2 and 3 show examples of time series generated by the ecological model. Dissolved oxygen and available nitrogen in the sediment in various boxes within the ecological model from an integration covering a period of several years are shown. Intervals in which the dissolved oxygen falls below about 2 g/m^3 coincide with widespread death of marine flora due mainly to heat stress, and indicate near anaerobic conditions.

For this particular ecosystem in regions where macrophytes dominate the plankton, substantial reductions in the nutrient pools in the sediments occur over the integration period. The converse is true in areas where plankton dominate. This case illustrates that macrophyte growth, coupled with harvesting, can be used to counteract eutrophication.

Both models have been validated against extensive experimental data sets, and have been used in coastal management projects. Further developments and extensions of the models are currently being considered and will be presented in future papers.

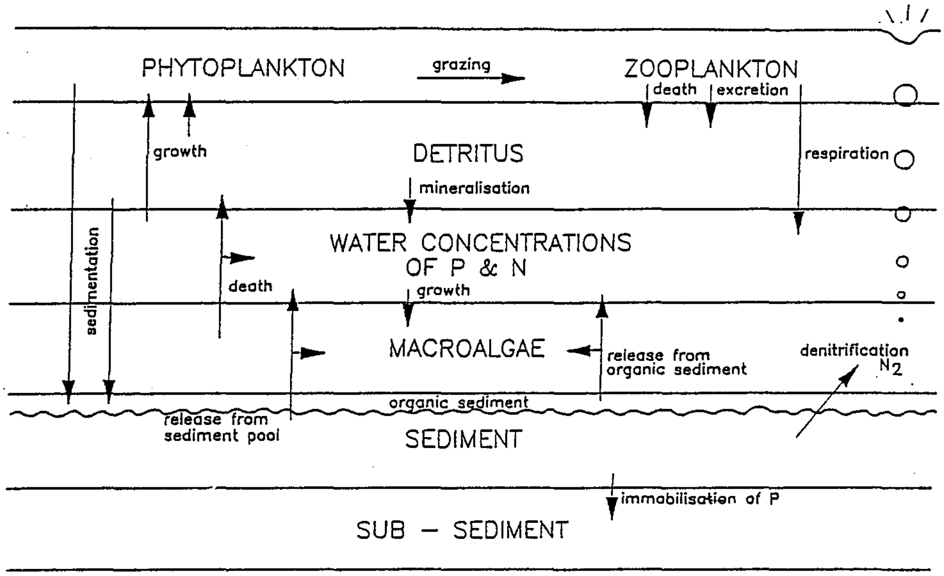

Figure 1 - Schematic of Ecological Process Model

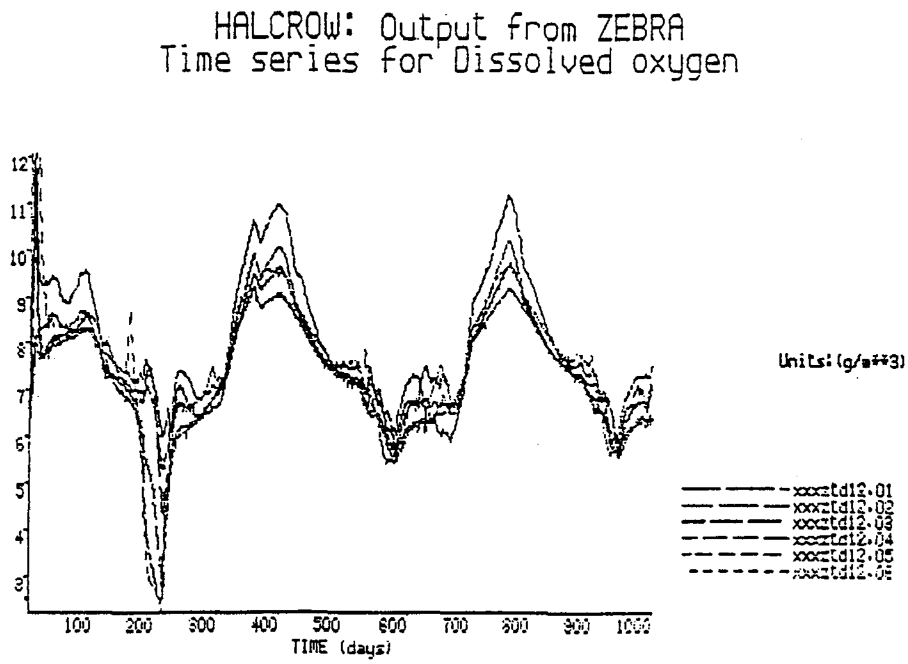

Figure 2 - Simulated Levels of Dissolved Oxygen (g/m^3) in different boxes as a function of time

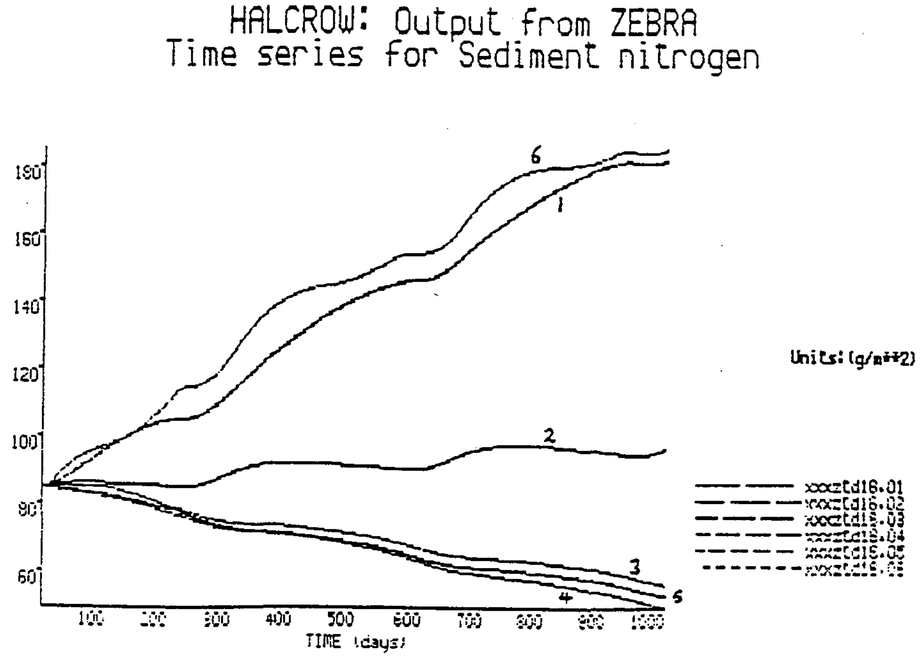

Figure 3 - Simulated Levels of Nitrogen in the Sediment (g/m^2) in different boxes as a function of time

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