Developments in Environmental Modelling, 4A

Application of Ecological Modelling in Environmental Management, Part A

Edited by

Professor S.E. JØRGENSEN

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Langkaer Vaenge 9, 3500 Vaerløse, Copenhagen, Denmark

ELSEVIER SCIENTIFIC PUBLISHING COMPANY
Amsterdam — Oxford — New York 1983

ELSEVIER SCIENTIFIC PUBLISHING COMPANY
Molenwerf 1
P.O. Box 211, 1000 AE Amsterdam, The Netherlands

ELSEVIER SCIENCE PUBLISHING COMPANY INC.
52 Vanderbilt Avenue, New York, New York 10017

Library of Congress Cataloging in Publication Data
Main entry under title:

Application of ecological modelling in environmental
management.

(Developments in environmental modelling ; 4A)
Bibliography: p.
Includes index.
1. Ecology--Data processing. 2. Pollution--Environmental aspects--Data processing. I. Jørgensen, S. E. (Sven Erik) II. Series.
QH541.15.E45A66 1983 574.5'0724 82-21152
ISBN 0-444-42155-6 (U.S.)

ISBN 0-444-42155-6 (Vol. 4A)
ISBN 0-444-41948-9 (Series)

Printed in The Netherlands

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Chapter 1

INTRODUCTION - ECOLOGICAL MODELLING AND ENVIRONMENTAL MANAGEMENT

BY SVEN ERIK JØRGENSEN

The ever-increasing concern for our environment during the last decade has raised the obvious question: How is it feasible to solve the many environmental problems properly? During this time the cost of raw materials and energy has increased enormously, limiting the economical resources which can be devoted to pollution control. From this an additional question must be raised: Can an economically acceptable solution to environmental problems be found?

The scope of this book, and the second volume planned for publication in 1983, is to present to the readers ecological models which can be used to find a proper solution to the present-day environmental problems. Economical considerations are not treated, but a demonstration of how ecological models can be employed to find ecologically acceptable solutions to environmental issues is given. Among these solutions the economically best suited might be selected, or the economist and ecologist may combine the ecological model with an economic one to find the most acceptable compromise.

The use of ecological models in environmental issues is a rather new field, but their application is the only alternative to zero discharge, if ecologically acceptable solutions to environmental problems are to be provided.

The idea behind the use of ecological models is demonstrated in Fig. 1.1. Urbanization and technological development has had an increasing impact on the environment. Energy and pollutants are released into ecosystems, where they may cause more rapid growth of algae or bacteria, damage species, or alter the entire ecological structure. Now, an ecosystem is extremely complex, and so it is an overwhelming task to predict the environmental effects that such an emission will have. It is here that the model comes into the picture. With sound ecological knowledge it is possible to extract the features of the ecosystem that are involved in the pollution problem under consideration, to form the basis of the ecological model (see also the discussion in chapter 2). As indicated in Fig. 1.1. the model resulting can be used to select the environmental technology best suited for the solution of specific environmental prob-

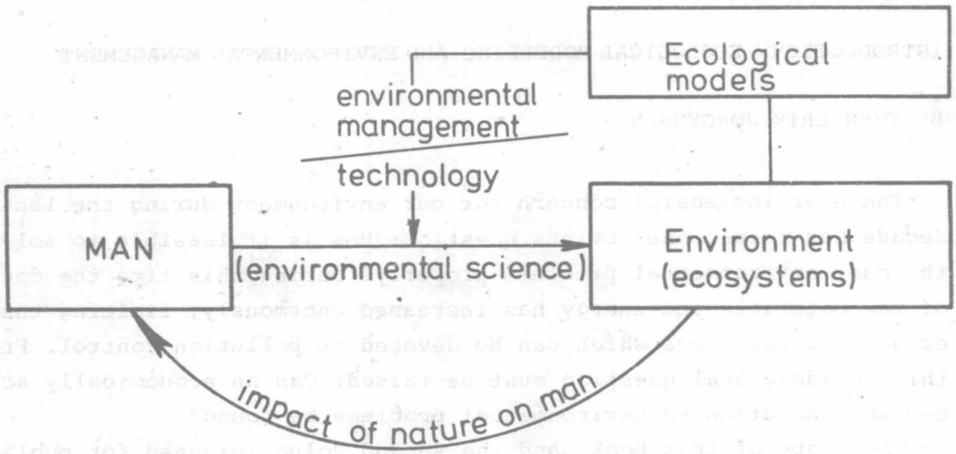

Fig. 1.1. Relations between environmental science, ecology, ecological modelling and environmental management and technology.

lems, or legislation reducing or eliminating the emission can be set up.

Chapter 2 gives a detailed treatment of the modelling procedure and special emphasis has been put on how to assure the proper calibration and validation of the model by use of data from the considered ecosystem. Reliable data and a sound knowledge of natural sciences are needed to set up workable ecological models, but the computer is the fundamental tool. Consequently the third chapter of this book is devoted to its application to ecological modelling. Computer technique improves steadily, and what is up-to-date today is old-fashioned tomorrow. Because of this the chapter focuses on more general aspects and not on the latest techniques.

Chapters 4 and 5 present the biological-chemical-physical unit processes, which are based on natural sciences and used repeatedly as components in ecological models. As demonstrated in chapters 2 and 4 - 14, the models are developed by combining a knowledge of the structure and behavior of the system with quantitative descriptions of the processes that are considered of importance. The two chapters cannot of course, treat all processes relevant to all possible ecological models, but an attempt has been made to include the most general processes, and also those processes which are components in the models presented in the subsequent chapters.

Each one of chapters 6 to 14 treat one specific environmental problem and the related ecological models. The following subjects are included: BOD of rivers and streams, the eutrophication of lakes, how to include non-point sources in management, the significance of sediment-water exchange for water pollution, the control of red tide, the water pollution by toxic compounds, management of fishery resources, the pollution of agricultural land by irrigation waters and rain, and the global climatic consequences of CO_2 pollution.

These ten environmental issues are of great importance; eight are problems of water pollution, one is a case of soil and ground water pollution and the last one deals with air pollution. Several more will be included in the second volume, among them the pollution caused by pesticides, regional air pollution, pest management and forest management.

This first volume details the wide spectrum of issues that can be managed by the use of ecological models, but water pollution problems dominate because more water management difficulties have been solved by the use of models.

We can distinguish between pollution problems caused by emission of energy and release of materials. We can also distinguish between compounds which are emitted, to a certain extent, by living organisms (e.g. biodegradable organic matter and nutrients) and toxic compounds. Finally, we can distinguish between local, regional and global problems. All are represented in this volume.

Each chapter follows approximately the same outline. After the problem has been presented, some of the important processes related to the situation are described quantitatively, with reference to chapters 4 and 5, and followed by a review of the models generally applied to the problem in question. One of these models is presented in detail and a case study is used to demonstrate its applicability. The chapter ends with conclusions and the author's view on needs for further research.

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Chapter 2

THE MODELLING PROCEDURE

BY SVEN ERIK JØRGENSEN

2.1 INTRODUCTION

Models can be defined as formal expressions of the essential elements of a problem in either physical or mathematical terms. The first recognition of the problem is often, and most likely to be, expressed verbally. This can be recognized as an essential preliminary step in the modelling procedure, but the term formal expressions implies that a translation into physical or mathematical terms must take place before we have a model in the sense we are applying throughout this book.

The term, systems analysis, is sometimes used synonymously with modelling, but we do not consider it correct. Systems analysis is defined as the orderly and logical organization of data into models, followed by their rigorous testing to provide validation and improvements.

Most model builders have assembled their own collection of techniques. This chapter presents a particular sequence of modelling, but we do not say that it is the only right procedure. We will embrace a large number of the problems associated with the development of models and demonstrate how they could be solved.

We are mainly concerned here with mathematical models, and physical models will only be mentioned as an alternative solution. The strength of mathematics lies in their ability to provide a symbolic logic which is capable of expressing ideas and relationships of very great complexity but at the same time retaining its simplicity of expression. The use of mathematical notation in the modelling of complex systems is an attempt to provide a representational symbolic logic which simplifies but does not markedly distort the underlying relationships. The various mathematical operations enable us to make predictions of the changes which we expect to occur in ecological systems as external variables are changed. The adequacy of the model can be tested by comparing our results (predictions) and the real systems that that the model is intended to represent.

Some researchers in the field distinguish between models and simulations. They regard a mathematical description, with a practical purpose and which includes as many relevant details as possible, as a simulation, and restrict the use of the term model to the description of general ideas which include as few details as possible. This distinction will not be used in this book.

2.2 CLASSES OF MATHEMATICAL MODELS

It is impossible in this brief introduction to include all possible classes of models, and so our examination is confined to those which the user of the models is most likely to meet. It is often useful to distinguish between various pairs of model types, as shown in Table 2.1. Models may also be classified in accordance with the model pattern as indicated in Table 2.2.

The lists are far from exhaustive but at least provide us with illustrations of the basic ideas.

As indicated by the title of the book, most models presented in this text are management tools, although almost all the models also can be used in the research context to find new relations or to point to research needs. The eutrophication model presented in Chapter 7 has, for example, been widely used as a research instrument in addition to its use for management. The carbon dioxide climate model in Chapter 13 is at present more useful to indicate further research needs than to make reliable predictions.

Most models in the book are deterministic. Our experience in the field of ecological modelling is not advanced enough to allow the use of stochastic elements, although some stochastic ecological models have been developed. In some of the chapters this possibility will be mentioned.

Compartment models are widely used in the field of ecological modelling, but many biodemographic models are using matrix in the mathematical formulation.

Limited attempts have been made to use holistic models in ecology, but up to now the reductionistic models have been dominant. The difference between the two approaches is best illustrated in Chapter 11 (modelling the distribution and effect of toxic substances in an aquatic ecosystem). Here reductionistic models, as well as a more holistic modelling approach, are presented.

Steady state models cannot, in most cases, be used for management as they do not generate any predictions. In Chapter 7 a simple steady-state eutrophication model (the so-called Vollenweider Model) is mentioned which exemplifies the application of such a model in the management context.

TABLE 2.1

Classification of models (pairs of model types).

Types of models	Characterization
Research models	used as a research tool
Management models	used as a management tool
Deterministic models	the predicted values are computed exactly.
Stochastic models	the predicted values depend on probability distribution
Compartment models	the variables defining the system are quantified by means of time-dependent differential equations
Matrix models	use matrix in the mathematical formulation
Reductionistic models	include as many relevant details as possible
Holistic models	use general principles
Steady state models	the variables defining the system is not dependent on time (or space)
Dynamic models	the variables defining the system are a function of time (or perhaps space)
Distributed models	the parameters are considered functions of time and space
Lumped models	the parameters are within certain prescribed spatial locations and/or time, considered as constants
Linear models	first-order equations are consecutively used
Non-linear models	one or more of the equations are not of the first order
Causal models	the inputs, the states and the outputs are interrelated
Black-box models	the input disturbances affect only the output responses

Distributed models are most often used when large ecosystems have to be modelled. When a hydrodynamic and an ecological model for a large waterbody are combined it is often necessary to use distributed models. This type of model will not be touched on in this book, as the problems involved are related to the hydrodynamic models. In other words, all models presented in this book will be lumped models.

TABLE 2.2

Identification of models

Type of models	Organization	Pattern	Measurements
Biodemographic	Conservation of species and/or genetic information	Life cycles	Number of individuals or species
Bioenergetic	Conservation of energy	Energy flow	Energy
Biogeochemical	Conservation of mass	Element cycles	Mass or concentrations

In principle there is no difference between linear and nonlinear models, although the linear type has a simpler mathematical formulation. Most ecological models contain nonlinear expressions such as for instance hyperbolic or exponential expressions. With modern computer techniques there seems to be no reason to force such models into linearity for the sake of saving some milliseconds of computer time.

Black-box models can never be used generally, as they do not contain any understanding of the system constituents and their relations. Therefore, causal models have been preferred in ecological modelling, as an understanding of the ecosystem is required in most case studies.

All the three types of models listed in Table 2.2 are used in ecological modelling, although the biogeochemical models are employed most widely. The biodemographic type is represented in Chapter 10 and the bioenergetic models are touched on in 7.6 and in Chapter 13.

2.3 COMPONENTS OF MODELS

An ecological model consists, in its mathematical formulation, of five components:

(1) Forcing functions or external variables, which are functions or variables of an external nature that influence the state of the ecosystem. In a management context the problem to solve can often be reformulated as follows: if certain forcing functions are varied, what will be the influence on the state of the ecosystem? The model is, in other words, used to predict what will change in the ecosystem when forcing functions are varied with the time. Examples

of forcing functions are the input of pollutants to the ecosystem, the consumption of fossil fuel, a fishery policy, but temperature, solar radiation, and precipitation are also forcing functions (which, however, we cannot at present manipulate).

(2) State variables described, as the name indicates, the state of the ecosystem. The selection of the variables is crucial for the model structure, but in most cases the choice is obvious. If, for instance, we want to model the eutrophication of a lake it is natural to include the phytoplankton concentration and the concentrations of nutrients. When the model is used in a management context the values of the state variables predicted by changing the forcing functions can be considered as the result of the model, because the model will contain relations between the forcing functions and the state variables. Most models will contain more state variables than are directly required for purpose of management, because the relations are so complex that they require the introduction of additional state variables. For instance, it would be sufficient in many eutrophication models to relate the input of one nutrient with the phytoplankton concentration, but as this state variable is influenced by more than one nutrient (it is influenced by other nutrient concentrations, temperature, hydrology of the water body, zooplankton concentration, solar radiation, transparency of the water etc.) a eutrophication model will most often contain a number of state variables.

(3) The biological, chemical and physical processes in the ecosystem are represented in the model by means of mathematical equations. They are the relations between two or more state variables and between forcing functions and state variables. The same types of processes can be found in many ecosystems, which implies that the same equations can be used in different models. Two chapters, 4 and 5, have therefore been devoted to summarizing the mathematical representations of these unit processes. It is, however, not possible today to have one equation that represents a given process in all ecological contexts. Most of the processes have several mathematical representations which are equally valid either because the process is too complex to be understood in sufficient detail at present, or because some specified circumstances allow us to use simplifications.

(4) The mathematical representation of processes in the ecosystem contains coefficients or parameters. They can be considered con-

stant for a specific ecosystem or part of ecosystem (see however the discussion of distributed models and lumped models in 15.3). In the causal models the parameters will have a scientific definition, e.g. the maximal growth rate of phytoplankton. Many parameter values are known within limits. In Jørgensen et al. (1979) can be found a comprehensive collection of ecological parameters. However, only a few parameters are known exactly and so it is necessary to calibrate the others, for reasons summarized below:

a) As indicated above the parameters are in most cases known only within limits.

b) Different species of animals and plants have different parameters, which can be found in the literature (see Jørgensen et al. 1979). However, most ecological models do not consider species, but trophic levels: many eutrophication models do not distinguish between different species of phytoplankton, but consider them as one state variable. In this case it is possible to find limits for the phytoplankton parameters, but as the composition of the phytoplankton varies throughout the year an exact average value cannot be found.

c) The influence of the ecological processes which are of minor importance to the state variables under consideration, and therefore not included in the model, can to a certain extent be considered by the calibration, where the results of the model are compared with the observations from the ecosystem. This might also explain why the parameters have different values in the same model when used for different ecosystems. The calibration can, in other words, take the site differences and the ecological processes of minor importance into account, but obviously it is essential to reduce the use of calibration for this purpose. The calibration must never be used to force the model to fit observations if this implies that unrealistic parameters are obtained. If a reasonable fit cannot be achieved with realistic parameters the entire model should be questioned. It is therefore extremely important to have realistic ranges for all parameters or at least for the most sensitive.

(5) Most models will also contain universal constants such as the gas constant, molecular weights etc. Such constants are of course not subject to a calibration.