Ralf Seppelt

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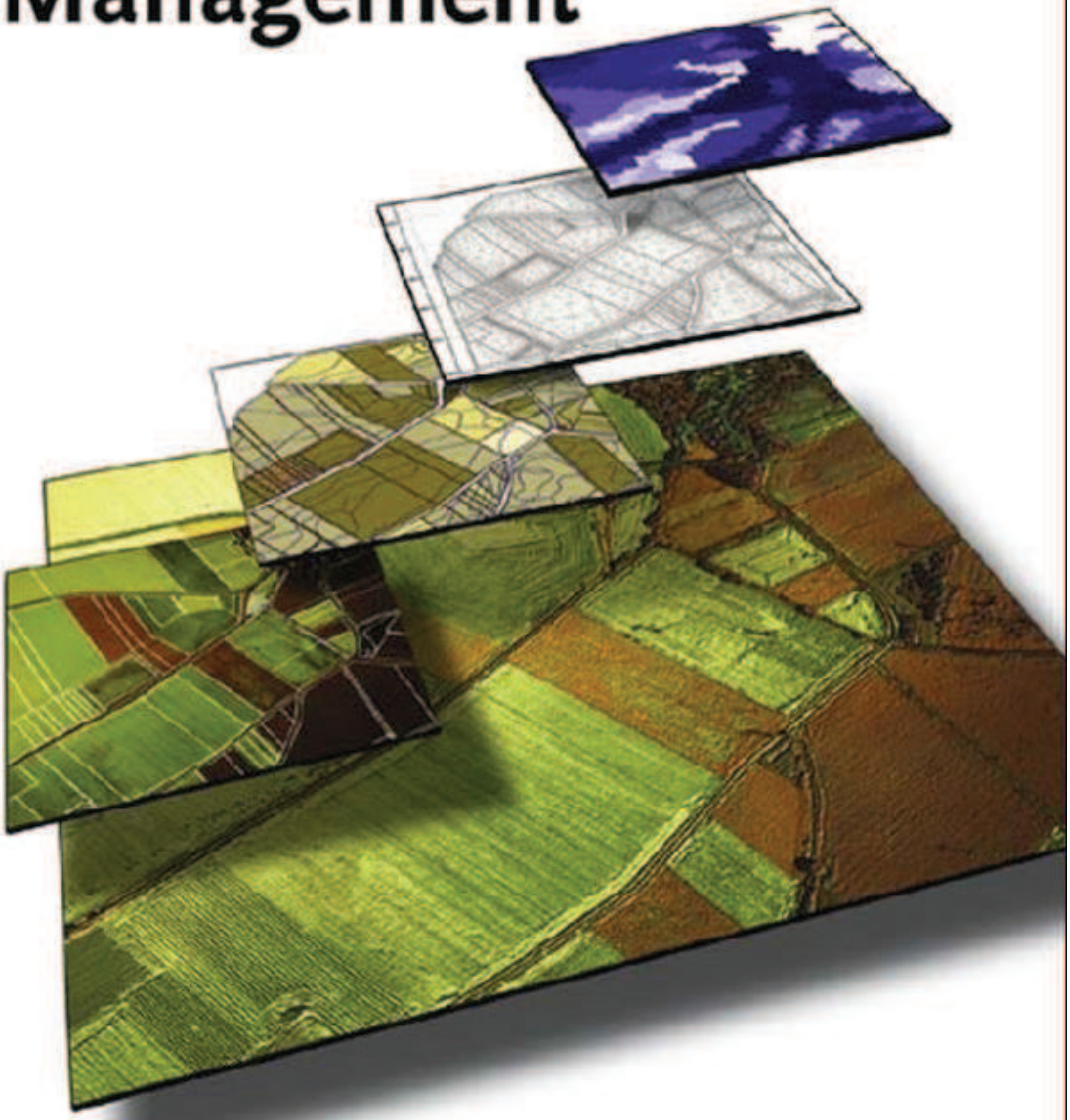
Computer-Based Environmental Management



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Foreword

As an active designer, user, and teacher of models and modeling, I'm always on the lookout for better tools. Ralf Seppelt's book is a unique and welcome addition to that toolbox. It is unique in its comprehensive integration of the theory and practice of environmental modeling and management.

Because of this integration, the book will appeal to three broad audiences and be useful:

(1) as an upper level or graduate course text in environmental modeling and management;

(2) as a guide for practitioners to get up to speed on the latest developments in computer modeling of the environment;

(3) as a guide for environmental managers to get a good handle on the latest developments in modeling and how they could be useful in making better environmental decisions.

As a teacher of environmental modeling, I've been searching for many years for the perfect text to use in courses. There are several books out there that are each very good in their own way, but which cover only some of the issues needed to get a good, comprehensive grasp of modeling and the uses of modeling in environmental management. It's also hard to find a text that is at just the right level — not so general as to be useless yet not so technical as to be useful only to a small, specialized audience. My search has ended with the publication of Ralf Seppelt's book and I intend to use it as a core text in modeling courses.

As a practitioner of modeling as a method to achieve an integrated understanding of complex systems, I can appreciate the range of applications covered in the book. Ralf spent a sabbatical year at our Institute when were still at the University of Maryland and jointly developed several of the applications discussed in the book. That year was extremely productive for all of us, and helped to expand the envelope of spatially explicit environmental modeling, as reported in the book. I intend to use the book to make researchers in our Institute fully conversant with the theory and latest applications in environmental modeling so they can take the next steps forward.

As someone who interacts with environmental managers and tries to help them to use modeling effectively in their decision-making, I can see that the book will be very useful. Managers need a single source that can show them both how models work and how they can be useful in decision-making. By integrating theory and applications, this book can quickly bring environmental managers up to speed and help them to use existing models more effectively, to commission better models in the future, and to actively participate in the modeling process themselves. I intend to recommend this book to environmental managers as the best way to familiarize themselves with the latest theory and uses of environmental modeling.

Finally, as Ralf Seppelt makes clear in this book, modeling is an activity, and this activity is itself at least as important and valuable as the models themselves. Modeling as an activity can be seen as the essence of the scientific method. The unique integration that this book represents is thus also a good platform for talking about what science is at a very fundamental level. The links between science and policy are so tenuous today precisely because of some fundamental confusions about what science is, and how it can best inform decision-making. Science is *not* certainty, as it is often mischaracterized in the media. Science is about understanding *un*certainty, and modern science recognizes that complex systems can never be understood with certainty. Computer modeling is the best tool we currently have to describe and understand uncertainty in complex systems. By clarifying these confusions, this book will be a valuable and important tool at a very fundamental level, and will help to create a better link between science and policy in general.

July 2003

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Acknowledgments

Ecological modeling is a fast developing area in the field of environmental science in which substantial progress has been achieved in recent years. User-friendly software packages, including high performance numerical tools, enable environmental scientists to code complex systems and thus study environmental processes in a systematic fashion. Modeling has become an important part of environmental research. Redundancy and a confusing diversity, however, have been a frequent result of this development. In this book, the recent state of environmental modeling is presented in a concise manner, and model applications in environmental management are studied.

This project would have been impossible without the support of several colleagues and friends whom I would like to thank especially now that this project has been completed.

First of all, I would like to thank Otto Richter for his support and inspiring ideas. Special thanks go to the good humor of Dagmar Söndgerath and Boris Schröder for many fruitful discussions, suggestions and critical remarks, and — much more important — the resulting motivation.

The ideas and results presented in this publication are the outcome of numerous co-operations and projects. I appreciate having worked together closely with the following people (in alphabetic order): Robert Costanza, Michael Flake, Claudia Hiepe, Olaf Jensen, Verena Korr, Matthias Kuhnert, Tom Maxwell, Florian Stange, Christian Thiel, Christine Vogel, and Alexey Voinov. I gratefully appreciate their suggestions, inspiring discussions and ideas.

My thanks are due to Klaus-Jürgen Schmalstieg for his support related to GIS analysis and data management, to Wolfgang Max for his unfailing technical support as well as to Kerstin Schulze for technical assistance with figures, tables, bibliography and several simulation runs. Marko-Michael Temme and Conrad Hoffmann spent much of their spare time in programming and tweaking the software presented in this book.

I am very grateful to Wolfgang Pittroff, Leland J. Jackson and Charles A.S. Hall for their remarks and suggestions for this book in a very early stage of the project. Mary Korndorffer has carefully edited the final manuscript. Very special thanks to her, as well as to Carsten Dormann who provided many valuable comments on the final manuscript.

Finally, not only does environmental science make progress, so too did the situation of my private life. Since my first projects in environmental science several years ago Tim, Anika, and Moritz were born and changed our life fundamentally. Thus, most of all I owe a deep sense of gratitude to my wonderful family and especially to my wife Martina who supported me all these years.

R. S.

Contents

Introduction

"and what is the use of a book," thought Alice,
"without pictures or conversations?"

—Lewis Carroll[1]

Modeling, ...

Our environment with its dynamic and spatial processes is recognized as complex, highly interacting and spatially distributed. These properties make analyzing, describing, modeling and even simulating our environment a challenging task. A framework that enables us to study, for example, the consequences of human influences on ecological systems without even disturbing these is a valuable and important tool for environmental management. Models are therefore identified as important and necessary tools for studying and understanding ecological processes, testing hypotheses of the functioning of ecosystems in a systematic manner and for investigating environmental response to human impact.

This makes modeling an important part of the interdisciplinary research field of environmental science. Ecological modeling however is done less and less by mathematicians and more and more by practicing ecologists and environmental scientists.

[1] see p. 280 for references of quotations.

The present state of environmental modeling is characterized by a number of model developments. Several authors state that a general concept is missing in ecological or environmental modeling. Recent development of environmental models has shown that a multitude of possible approaches and theories have been developed. Some authors complain that *we have produced an enormous redundancy*. This multitude of different approaches refers to the considered temporal scale, the considered mathematical languages — such as differential equations (partial or ordinary), matrix models, fuzzy systems etc. — and the chosen concept of regionalization and spatial extent. The incorporation of spatial attributes into the modeling process causes a mismatch between the scale at which attributes are obtained, and the scale at which the processes occur.

The first part of the book (Chapters 1 to 3) gives a synthesis of model development concepts. Compiling mathematical equations and setting up simulation models is a complex and challenging task. Setting up ecological models requires a detailed system analysis of the processes of interest. A systematic way to achieve a concise and valid simulation model is to start with a conceptual model, which every scientist usually has in mind when investigating a process. Chapter 1 traces the path from conceptual models to validated regionalized environmental simulation models. The step of translating conceptual models into computer models is assisted by several development platforms. These platforms translate conceptual models into mathematical equations of a certain mathematical "dialect".

Focusing on processes of the abiotic environment as well as the first two trophic levels of the biotic environment, several different translations of conceptual diagrams into mathematical models are studied in Chapters 2 and 3. The first focuses on the dynamic patterns on different temporal scales such as nutrient flow, water transport, growth of crops and weed, population dynamics, competition, etc. Migration of species, vertical and horizontal fluxes of matter and information through a landscape are the characteristic properties of ecosystems. In Chapter 3 spatial interactions are discussed and the possible mathematical modeling concepts are presented, starting from highly aggregated mathematical models given by partial differential equation systems, we end up with with a discussion of cellular automata. For comparison, different mathematical "dialects" are used for modeling the same process to analyze and compare different methodologies.

Integration, . . .

Although there is consensus on a general methodology of model development, one needs to consider that environmental modeling is a diverse field of research. First of all because it is an interdisciplinary issue. Biologists, ecologists, computer scientists, mathematicians, physicists have to work together and to integrate their methodology to solve ecological problems of the 21st century. This diversity leads to a multitude of approaches solving similar or even identical tasks. Several scientists complain of a lack of theoretical foundation of environmental modeling.

For example, conceptual difficulties stem from the fact that processes of different dynamic quality interact. The dynamics of technical systems are mostly time discrete and their dynamics are closely related to discrete spatial structures, whereas many environmental processes are continuous in time and space. The whole system can be characterized as structured time discrete and time continuous. One is faced with a problem that can be summarized as mathematical heterogeneity. It is not feasible to model integrated systems in the framework of one mathematical "dialect".

An environmental model requires the integration of all these approaches. This requires a general theoretical framework. The subject of Part II of the book is to bring together modern mathematical methodologies to solve the task of integration. These concepts are used to assess the anthropogenic impacts of production and the use of goods and services on the environment. This life cycle impact assessment methodology comprises a system-wide analysis of mass- and energy flows, performed within the step of life cycle inventory. Distributions of emissions are estimated within an environmental fate model including dispersion–reaction modeling and impact assessment has to be performed for different impact categories. The product is a hybrid model which integrates different environmental techniques and demonstrates how these effects can be addressed in environmental assessment.

. . . and Management

Quantitative and qualitative analysis of environmental processes by computer models is one aspect of ecosystem modeling. Additionally, a very frequent application of ecological models is to study the consequences of anthropogenic impact on the ecosystem with respect to the environmental fate of substances, habitat suitability of species, persistence of populations etc. In this way different management strategies can be compared. The question of the degree of impact which nature can sustain without harm to the environment has already been posed. Ideas like most sustainable yield were introduced in the late 1960s. Ecosystem management has become now an important discipline of scientific research and is an important branch in the political decision-making process. Because ecological models are complex and highly interacting, as stated above, this decision making process requires methodological support. The third part of the book deals with applications of ecological models in the decision-making process: either by the use of scenario analysis technique or by the application of optimum control theory to an ecosystem model. Problems of ecosystem management are solved by the use of numerical optimization. This can be interpreted as the follow up of the most sustainable yield concept by the use of scientific computing.

With increasing complexity of ecosystem models, one becomes aware, that scenario analysis may not be the appropriate tool to vary all required control parameters. Systematically sorting through all possible combinations of control variables yields a desired optimal scenario. This is achieved by the optimization or optimum control approach. Chapter 8 introduces this third part of the book, offers an overview of the approaches "scenario analysis" versus "optimization" and defines the tasks to be solved for optimum control of environmental systems.

Complexity of environmental models leads to an enormous computational effort, if these models are to be used in optimum control theory. Introducing certain hierarchies is one concept which can deal with increasing complexity. In Chapter 9 a framework is proposed for an application of environmental models in optimum control theory. This development focuses on spatially explicit models as well as models with a broad range of temporal patterns and dynamics. The generic code can cope with hybrid models. It requires appropriate numerical procedures, too. This is achieved by a hierarchical approach to the optimization problem and this decreases numerical effort.

Applications of this concept are presented in Chapters 10 to 12. Chapter 10 focuses on optimum temporal patterns of management strategies of an agroecosystem. Different results of optimum fertilizer input, pest management, weed control and crop rotation schemes are presented. Several scenarios of environmental assessment are compared using the tool of optimization. These results are then studied within a regionalized model. Beside the dynamic solution, Chapter 11 focuses on the regionalization of the optimum control problem. The task is solved by the identification of homogeneous units in the observed region by a geographic information system. The second innovative topic, which enables a regionalized solution of the optimum control problem, is the estimation of families of optimum solutions parameterized by spatial properties. The proposed methodology supports the step of decision support in site-specific farming.

In Chapter 12 all these concepts are applied to solve management problems of land use with a spatially explicit model on a landscape scale. Spatially explicit ecosystem models allow the calculation of water and matter dynamics in a landscape as functions of spatial localization of habitat structures and matter input. For a mainly agricultural region the nutrient balance as a function of different management schemes is studied in this chapter. The results are tested using Monte Carlo simulations which are based on different stochastic generators for the independent control variables. Gradient free optimization procedures are used to verify the simplifying assumptions. The framework offers tools for optimization with the computational effort independent of the size of the study area. As a result, important areas with high retention capabilities are identified and fertilizer maps are set up depending on soil properties. This shows that optimization methods can be a useful tool even in complex simulation models for systematic analysis of management strategies for ecosystem use.

Summary: How this Book is structured

Aspects of ecological modeling are of increasing importance in any branch of ecology, biology, landscape ecology, and environmental management. The book focuses on two main issues: the integration of different modeling approaches, together with applications in optimization and optimum control theory. It aims at supporting problems of environmental management and tries to bring together modern mathematical methods with environmental ecological research. The concept of the book is to offer a theoretical and methodological platform for environmental modeling, that can provide a starting point for every environmental scientist to solve a particular modeling problem. This is achieved by using the level of conceptual models as a starting point for model development and explanes the types of models that can be derived from one conceptual diagram.

Recent progress in ecological modeling is presented in a concise way showing results of high standard mathematical methods, such as the use of numerical solutions of partial differential equations for modeling water and matter transport, as well as population dynamics and migration in real landscapes. This provides a foundation for aggregated spatially explicit models using geographic information systems. Finally these high standard mathematics are used to develop concepts of solving optimization and optimum control problems for environmental management.

This structure of the book follows these objectives. Chapter 1 introduces terms and methodologies and presents an overview of environmental modeling concepts. Chapters 2 and 3 can be understood as a toolbox for translating conceptual models into equations. These chapters provide the necessary functions and equations used in most ecological models. It must be noted that all equations presented are illustrated with examples and applications. Chapter 4 discusses the results obtained in the context of meta modeling and scientific theory. Further applications of hybrid models in biology as well as in environmental assessment are reported in Chapters 6 and 7. The focus in Chapters 5 and 9 is on the mathematical foundation of the integrating modeling concept as well as the application of environmental models in optimization. Applications of concepts are presented in Chapters 10 through 12, which are understandable without reading Chapters 5 or 9 in detail.