1

Introduction

CHAPTER OUTLINE

1.1. Physical and Mathematical Models

Humans have always used models — defined as a simplified picture of reality — as tools to solve problems. The model will never be able to contain all the features of the real system, because then it would be the real system itself, but it is important that the model contains the characteristic features essential in the context of the problem to be solved or described.

The philosophy behind the use of a model is best illustrated by an example. For many years we have used physical models of ships to determine the profile that gives a ship the smallest resistance in water. Such a model has the shape and the relative main dimensions of the real ship, but does not contain all the details such as the instrumentation, the layout of the cabins, and so forth. Such details are irrelevant to the objectives of that model. Other models of the ship serve other purposes: blueprints of the electrical wiring, layout of the various cabins, drawings of pipes, and so forth.

Correspondingly, the ecological model we wish to use must contain the features that will help us solve the management or scientific problem at hand. An ecosystem is a much more complex system than a ship; it is a far more complicated matter to ascertain the main features of importance for an ecological problem. However, intense research during the last three decades has made it possible to set up many workable and applicable ecological models.

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Ecological models may also be compared with geographical maps (which are models, too). Different types of maps serve different purposes. There are maps for airplanes, ships, cars, railways, geologists, archaeologists, and so on. They are all different because they focus on different objects. Maps are also available in different scales according to application and underlying knowledge. Furthermore, a map never contains all of the details for a considered geographical area, because it would be irrelevant and distract from the main purpose of the map. If a map contained every detail, for instance, the positions of all cars at a given moment, then it would be rapidly invalidated as the cars move to new positions. Therefore, a map contains only the knowledge relevant for the user of the map, so there are different maps for different purposes.

An ecological model focuses similarly on the objects of interest for a considered well-defined problem. It would disturb the main objectives of a model to include too many irrelevant details. There are many different ecological models of the same ecosystem, as the model version is selected according to the model goals.

The model might be physical, such as the ship model used for the resistance measurements, which may be called microcosm, or it might be a mathematical model, which describes the main characteristics of the ecosystem and the related problems in mathematical terms.

Physical models will be touched on only briefly in this book, which will instead focus entirely on the construction of mathematical ecological models. The field of ecological modelling has developed rapidly during the last 30 years due essentially to three factors:

1. The development of computer technology, which has enabled us to handle very complex mathematical systems.
2. A general understanding of environmental problems, including that a complete elimination of pollution is not feasible (denoted zero discharge). Instead, a proper pollution control with limited economical resources requires serious consideration of the influence of pollution impacts on ecosystems.
3. Our knowledge of environmental and ecological systems has increased significantly; in particular we have gained more knowledge of the quantitative relations in the ecosystems and between the ecological properties and the environmental factors.

Models may be considered a synthesis of what we know about the ecosystem with reference to the considered problem in contrast to a statistical analysis, which only reveals the relationships between the data. A model is able to include our entire knowledge about the system such as:

1. Which components interact with which other components, for instance, that zooplankton grazes on phytoplankton
2. Our knowledge about the processes often formulated as mathematical equations, which have been shown to be generally valid
3. The importance of the processes with reference to the problem

This is a list of a few examples of knowledge that may often be incorporated in an ecological model. It implies that a model can offer a deeper understanding of the system than a statistical analysis. Therefore, it is a stronger research tool that can result in a better management plan for solving an environmental problem. This does not mean that statistical analytical results are not applied in the development of models. On the contrary, models are built on all available knowledge, including that gained by statistical analyses of data, physical-chemical-ecological knowledge, the laws of nature, common sense, and so on. That is the advantage of modelling.

1.2. Models as a Management Tool

The idea behind the use of ecological management models is demonstrated in Figure 1.1. Urbanization and technological development have had an increasing impact on the environment. Energy and pollutants are released into ecosystems where they can cause more rapid growth of algae or bacteria, damage species, or alter the entire ecological structure. An ecosystem is extremely complex, therefore it is an overwhelming task to predict the environmental effects that such emissions may have. It is here that the model is introduced into the picture. With sound ecological knowledge, it is possible to extract the components and processes of the ecosystem involved in a specific pollution problem to form the basis of the ecological model (see also the discussion in Chapter 2, Section 2.3). As indicated in Figure 1.1, the resulting model can be used to select the environmental technology eliminating the emission most effectively.

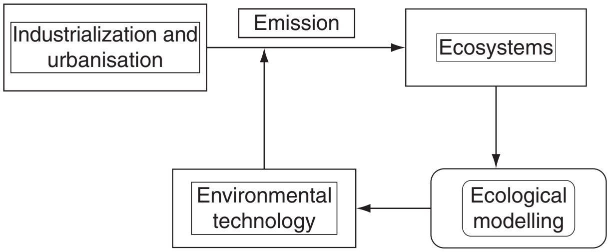

FIGURE 1.1 The environmental problems are rooted in the emissions resulting from industrialization and urbanization. Sound ecological knowledge is used to extract the components and processes of the ecosystem that are particularly involved in a specific pollution problem to form the ecological model applied in environmental management.

Figure 1.1 represents the idea behind the introduction of ecological modelling, which has been a management tool since about 1970. Now environmental management is more complex and is applied to a wider spectrum of tools. Today we have alternatives and supplements to environmental technology such as cleaner technology, ecotechnology, environmental legislation, international agreements, and sustainable management plans. Ecotechnology is mainly applied to solve the problems of nonpoint or diffuse pollution often originated from agriculture. The significance of nonpoint pollution was hardly acknowledged before 1980. Furthermore, the global environmental problems play a more important role today than 20 or 30 years ago; for instance, the reduction of the ozone layer and the climatic changes due to the greenhouse effect. The global problems cannot be solved without international agreements and plans. Figure 1.2 attempts to illustrate the current complex picture of environmental management.

1.3. Models as a Research Tool

Models are widely used instruments in science. Scientists often use physical models to carry out experiments in situ or in the laboratory to eliminate disturbance from processes irrelevant to an investigation: Thermostatic chambers are used to measure algal growth as a function of nutrient concentrations, sediment cores are examined in the laboratory to investigate sediment-water interactions without disturbance from other ecosystems components, reaction chambers are used to find reaction rates for chemical processes, and so on.

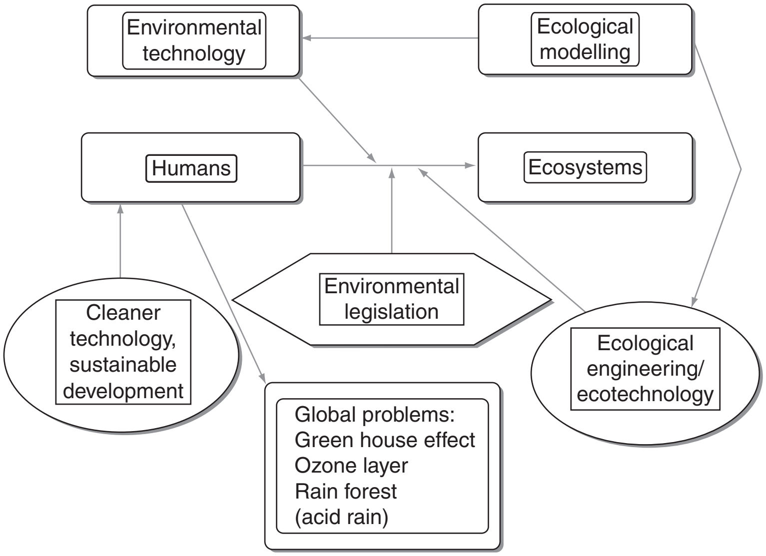

FIGURE 1.2 The idea behind the use of environmental models in environmental management. Environmental management today is very complex and must apply environmental technology, alternative technology, and ecological engineering or ecotechnology. In addition, the global environmental problems play an increasing role. Environmental models are used to select environmental technology, environmental legislation, and ecological engineering.

Mathematical models are widely applied in science as well. For example, Newton's laws are just relatively simple mathematical models of the influence of gravity on bodies, but they do not account for frictional forces, influence of wind, and so forth. Ecological models do not differ essentially from other scientific models except in their complexity, as many models used in nuclear physics may be even more complex than ecological models. The application of models in ecology is almost compulsory if we want to understand the function of such a complex system as an ecosystem. It is simply not possible to survey the many components and their reactions in an ecosystem without the use of a model as holistic tool. The reactions of the system might not necessarily be the sum of all the individual reactions, which implies that the properties of the ecosystem cannot be revealed without the use of a model of the entire system.

It is therefore not surprising that ecological models have been used increasingly in ecology as an instrument to understand the properties of ecosystems as systems. This application has clearly revealed the advantages of models as a useful tool in ecology, which may be summarized in the following:

1. Models are useful instruments in *survey* of complex systems.
2. Models can be used to reveal *system properties*.
3. Models reveal the weakness in our knowledge and can therefore be used to set up *research priorities*.
4. Models are useful in tests of *scientific hypotheses*, as the model can simulate ecosystem reactions that can be compared with observations.

As it will be illustrated several times throughout this volume, models can used to test the hypothesis of ecosystem behavior such as the principle of maximum power presented by H.T. Odum (1983), the ascendency propositions presented by Ulanowicz (1986), the various proposed thermodynamic principles of ecosystems, and the many hypothesis of ecosystem stability.

The certainty of the hypothesis test by using models is, however, not on the same level as the tests used in the more reductionistic disciplines of science. If a relationship is found between two or more variables by the use of statistics on available data, then the relationship is tested on several additional cases to increase the scientific certainty. If the results are accepted, then the relationship is ready to be used to make predictions, and it is again examined to prove whether the predictions are right or wrong in a new context. If the relationship still holds, then we are satisfied and a wider scientific use of the relationship is made possible.

When we are using models as scientific tools to test hypotheses, we have a "double doubt." We anticipate that the model is correct in the problem context, but the model is a hypothesis of its own. We therefore have four cases instead of two (acceptance/nonacceptance):

1. The model is correct in the problem context, and the hypothesis is correct.
2. The model is not correct, but the hypothesis is correct.
3. The model is correct, but the hypothesis is not correct.
4. The model is not correct and the hypothesis is not correct.

To omit cases 2 and 4, only very well-examined and well-accepted models should be used to test hypotheses on system properties, but, unfortunately, our experience in modelling ecosystems is limited. We do have some well-examined models, but we are not completely certain they are correct in the problem context and a wider range of models is needed. A wider experience in modelling may therefore be the prerequisite for further development in ecosystem research.

The use of models as a scientific tool as described earlier is not only known from ecology; other sciences use the same technique when complex problems and complex systems are under investigation. There are simply no other possibilities when dealing with irreducible systems (Wolfram l984a,b). Nuclear physics has used this procedure to find several new nuclear particles. The behavior of protons and neutrons has inspired models of smaller particles, the so-called quarks. These models have been used to predict the results of planned cyclotron experiments, which have inspired further changes of the model.

The idea behind the use of models as scientific tools may be described as an iterative development of a pattern. Each time we can conclude that case 1 (see the earlier list for the four cases) is valid, that is, both the model and the hypothesis are correct, we can add another "piece to the pattern." That provokes the question: Does the piece fit into the general pattern? This signifies an additional test of the hypothesis. If not, we can go back and change the model and/or the hypothesis, or we may be forced to change the pattern, which will require more comprehensive investigations. If the answer is "yes," then we can use the piece at least temporarily in the pattern — which is then used to explain other observations, improve our models, and make other predictions — for further testing. This procedure is used repeatedly to proceed stepwise toward a better understanding of nature on the system level. Figure 1.3 is a conceptual diagram of the procedure applied to test hypotheses by using models.

The application of this procedure in ecosystem theory is still relatively new. We need, as already mentioned, much more modelling experience. We also need a more comprehensive application of our ecological models in this direction and context.

1.4. Models and Holism

Biology (ecology) and physics developed in different directions until about 30 to 50 years ago, when there was more parallel development, which has its roots in the more general trends in science that have been observed in the last 20 years.

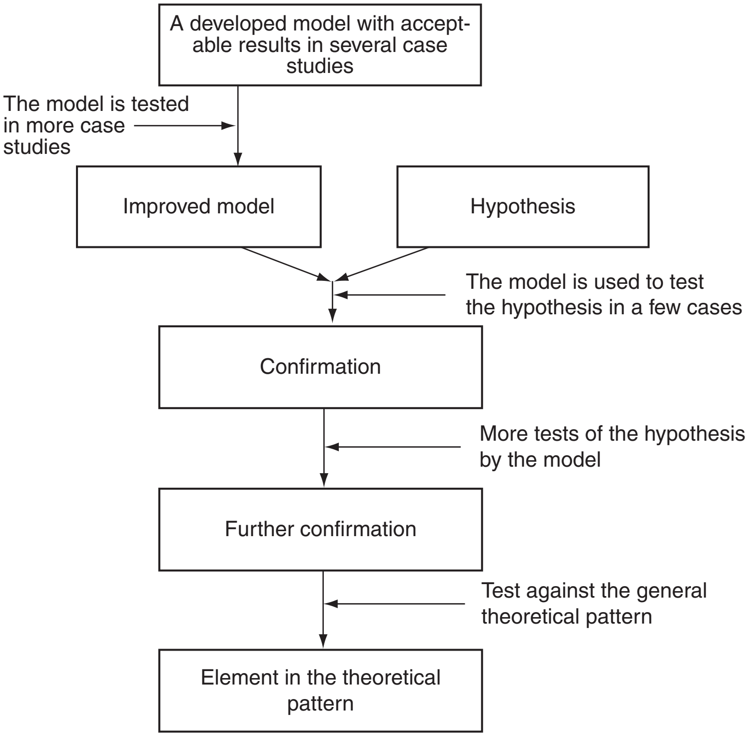

FIGURE 1.3 This diagram shows how it is required to use several test steps, if a model is used to test a hypothesis about ecosystems, as a model may be considered a hypothesis of its own.

The basic philosophy or thinking regarding science is currently changing with other facets of our culture such as the arts and fashion. The driving forces behind such developments are often very complex and are very difficult to explain in detail, but we will attempt to show at least some of tendencies in the development.

1. The sciences have realized that the world is more complex than previously thought. In nuclear physics several new particles have been found. In ecology we have seen new environmental problems. Now we realize how complex nature is and how much more difficult it is to cope with problems occurring in nature than in laboratories. Computations in sciences were often based on the assumption of so many simplifications that they became unrealistic.

2. Ecosystem ecology — we call it the science of (the very complex) ecosystems or systems ecology — has developed very rapidly and has evidently shown the need for systems sciences as well as interpretations, understandings, and implications of the results obtained in other sciences.
3. In the sciences, many systems are so complex that it is impossible to know all the details of every system. In nuclear physics there is always an uncertainty in our observations as expressed by Heisenberg's uncertainty relations. This uncertainty is caused by the influence of our observations on the nuclear particles. We have a similar uncertainty relation in ecology and environmental sciences caused by the complexity of the systems (Jørgensen & Fath, 2006). A further presentation of these ideas is given in Chapter 2, Section 2.6, where the complexity of ecosystems is discussed in more detail.
   In addition, many relatively simple physical systems such as the atmosphere show chaotic behavior, which makes long-term predictions impossible. The conclusion is unambiguous: We cannot and will not be able to know the world with complete accuracy and in complete detail. We have to acknowledge that these are the conditions for modern sciences.
4. Many systems in nature are irreducible systems (Wolfram 1984a,b); that is, it is impossible to reduce observations on system behavior to a law of nature, because the system has so many interacting elements that the reaction of the system cannot be surveyed without using models. For such systems other experimental methods must be applied. It is necessary to construct a model and compare the reactions of the model with our observations to test its reliability and get ideas for model improvements, construct an improved model, compare its reactions with the observations again to get new ideas for further improvements, and so forth. By such an iterative method we may be able to develop a satisfactory model that can describe our observation properly. These observations have not resulted in a new law of nature but in a new model of a piece of nature. As seen by the description of the details in the model development, the model should be constructed based on causalities, which inherit basic laws.

5. As a result of previous tendencies 1–4, modelling as a tool in science and research has developed and expanded. Ecological or environmental modelling has become a scientific discipline of its own — a discipline that has experienced rapid growth during the last decades. The core scientific journal in ecological modelling, *Ecological Modelling*, now publishes more than 4000 pages per year, while it published 320 pages in 1975. Developments in computer science and ecology have also favored this rapid growth in modelling, as they are the components on which modelling is founded.
6. The scientific analytical method has always been a very powerful tool in research. Yet, there has been an increasing need for scientific synthesis, that is, for combining the analytical results to form a holistic picture of natural systems. Due to the extremely high complexity of natural systems, it is impossible to obtain a complete and comprehensive picture of natural systems by analysis alone; it is necessary to synthesize important analytical results to get system properties. Synthesis and analysis must work hand-in-hand. The synthesis (e.g., in the form of a model) will show that further analytical results are needed to improve the synthesis and new analytical results may be used as components in better syntheses. The recent tendency in sciences is to give synthesis a higher priority than previously, but this does not imply that the analyses should be given a lower priority. Analytical results are needed to provide components for the synthesis, and the synthesis must be used to give priorities for the needed analytical results. No science exists without observations, but no science can be developed without the digestions of the observations to form a “picture” or “pattern” of nature either. Analyses and syntheses should be considered as two sides of the same coin.
7. A few decades ago, the sciences were more optimistic than they are today, because it was expected that a complete description of nature would soon be a reality. Einstein even talked about a “world equation” as the basis for all physics of nature. Today, we realize that nature is far more complex than a single world equation, and complex systems are nonlinear and sometimes chaotic. The sciences have a

long way to go and it is not expected that the secret of nature can be revealed by a few equations. It may work in controlled laboratory conditions where the results usually can be described by using simple equations, but when we turn to natural systems, it will be necessary to apply many and complex models to describe our observations.

1.5. The Ecosystem as an Object for Research

Ecologists generally recognize ecosystems as a specific level of organization, but what is the appropriate selection of time and space scales? Any size area could be selected, but in the context of ecological modelling, the following definition presented by Morowitz (1968) will be used: "An ecosystem sustains life under present-day conditions, which is considered a property of ecosystems rather than a single organism or species." This means that a few square meters may seem adequate for microbiologists, while 100 km^2 may be insufficient if large carnivores are considered (Hutchinson, 1970, 1978). Population-community ecologists tend to view ecosystems as networks of interacting organisms and populations. Tansley (1935) claimed that an ecosystem includes both organisms and chemical-physical components. It inspired Lindeman (1942) to use the following definition: "An ecosystem is composed of physical-chemical-biological processes active within a space-time unit." E.P. Odum (1953, 1959, 1969, 1971) followed these lines and is largely responsible for developing the process-functional approach, which has dominated ecosystem ecology for the last 50 years.

This does not mean that different views cannot be a point of entry. Hutchinson (1978) used a cyclic causal approach, which is often invisible in population-community problems. Measurement of inputs and outputs of total landscape units was the emphasis in the functional approaches by Bormann and Likens (1967). O' Neill (1976) emphasized energy capture, nutrient retention, and rate regulations. H.T. Odum (1957) underlined the importance of energy transfer rates. Quilin (1975) argued that cybernetic views of ecosystems are appropriate, and Prigogine (1947), Mauersberger (1983), and Jørgensen (1981, 1982, 1986) all emphasized the need for a thermodynamic approach for a proper holistic description of ecosystems.

For some ecologists ecosystems are either biotic assemblages or functional systems; the two views are separate. It is, however, important in the context of ecosystem theory to adopt both views and integrate them. Because an ecosystem cannot be described in detail, it cannot be defined according to Morowitz's (1968) definition before the objectives of our study are presented. Therefore, the definition of an ecosystem used in the context of system ecology and ecological modelling, becomes:

> An ecosystem is a biotic and functional system or unit, which is able to sustain life and includes all biotic and abiotic variables in that unit. Spatial and temporal scales are not specified *a priori*, but are entirely based upon the objectives of the ecosystem study.

Currently there are several approaches (Likens, 1985) used to study ecosystems:

1. Empirical studies — Bits of information are collected, and an attempt is made to integrate and assemble these into a complete picture.
2. Comparative studies — Structural and functional components are compared for a range of ecosystem types.
3. Experimental studies — Manipulation of a whole ecosystem is used to identify and elucidate mechanisms.
4. Modelling or computer simulation studies.

The motivation (Likens, 1985) in all of these approaches is to achieve an understanding of the entire ecosystem, giving more insight than the sum of knowledge about its parts relative to the structure, metabolism, and biogeochemistry of the landscape.

Likens (1985) presented an excellent ecosystem approach to Mirror Lake and its environment. The research contains all the previously mentioned studies, although the modelling part is less developed than the others. The study clearly demonstrates that it is necessary to use all four approaches simultaneously to achieve a good representation of the system properties of an ecosystem. An ecosystem is so complex that you cannot capture all the system properties by one approach.

Ecosystem studies widely use the notions of order, complexity, randomness, and organization. They are often interchangeably applied in the literature, which causes much confusion. As the terms are used in relation to ecosystems throughout the volume, it is necessary to give a clear definition of these concepts in this introductory chapter.

According to the Third Law of Thermodynamics about entropy at 0 K (Jørgensen, 2008a), randomness and order are the antithesis of each other and may be considered as relative terms. Randomness measures the amount of information required to describe a system. The more information required to describe the system, the more random it is.

Organized systems are to be carefully distinguished from ordered systems. Neither kind of system is random; whereas ordered systems are generated according to simple algorithms and may therefore lack complexity, an organized system must be assembled element by element according to an external wiring diagram with a high level of information. Organization is a functional complexity and carries functional information. It is nonrandom by design or by selection, rather than by *a priori* necessity. Complexity is a relative concept dependent on the observer (Jørgensen & Svirezhev, 2004). We may distinguish between structural complexity, which is defined as the number of interconnections between components in the system and functional complexity and defined as the number of distinct functions carried out by the system.

1.6. The Development of Ecological and Environmental Models

This section attempts to present briefly the history of ecological and environmental modelling. From the history we can learn why it is essential to draw upon the previously gained experience and what goes wrong when we do not follow the recommendations set up to avoid previous flaws.

Figure 1.4 gives an overview of the development in ecological modelling. The nonlinear time axis gives approximate information on the year

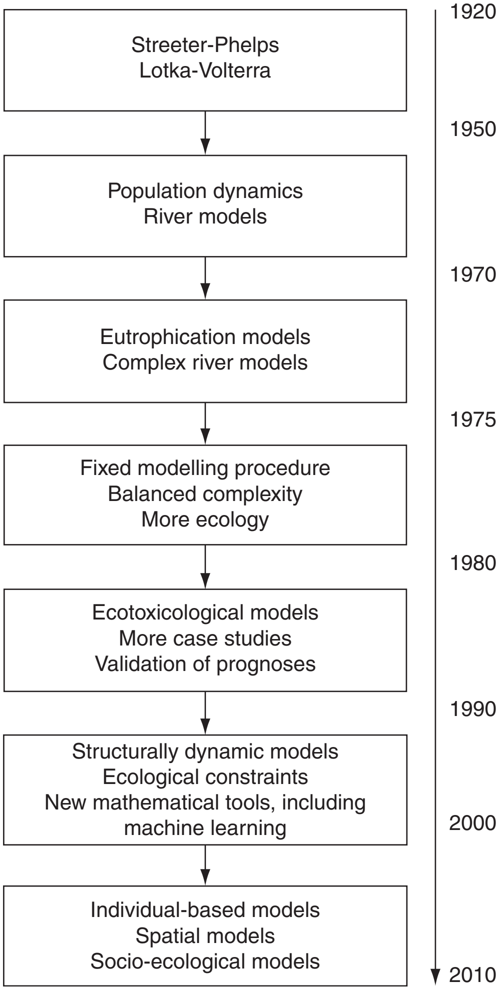

FIGURE 1.4 The development of ecological and environmental models is shown schematically.

when the various development steps took place. The first models of the oxygen balance in a stream (the Streeter-Phelps model, presented in Chapter 7) and of the prey–predator relationship (the Lotka-Volterra model, presented in Chapter 5) were developed back in the early 1920s. In the 1950s and 1960s, further development of population dynamic models took place. More complex river models were also developed in the 1960s. These developments could be named the second generation of models.

The wide use of ecological models in environmental management started around 1970, when the first eutrophication models emerged and very complex river models were developed. These models could be named the third generation of models. They are characterized by often being too complex, because it was so easy to write computer programs that could handle rather complex models. To a certain extent it was the revolution in computer technology that created this model generation. However, it became clear in the mid-1970s that the limitations in modelling were not from the computer and the mathematics, but from the available data and our knowledge about ecosystems and ecological processes. So, the modellers became more critical in their acceptance of models. They realized that a profound knowledge of the ecosystem — the problems and the ecological components — was the basis for development of sound ecological models. This period resulted in recommendations that are given in the Chapter 2:

- Strictly follow all steps of the procedure, such as conceptualization, selection of parameters, verification, calibration, examination of sensitivity, validation, and so forth.
- Find a balance between data, problem, ecosystem, and knowledge.
- A wide use of sensitivity analyses is recommended in the selection of model components and model complexity.
- Make parameter estimations by using all the methods, such as literature review, determination by measurement in laboratory or in situ, use of intensive measurements, calibration of submodels and the entire model, theoretical system ecological considerations, and various estimation methods based on allometric principles and chemical structure of the considered chemical compounds.

Parallel to this development, ecologists became more quantitative in their approach to environmental and ecological problems, probably because of the needs formulated by environmental management. The quantitative research results from the late 1960s onward have been of enormous importance for the quality of ecological models. They are probably just as important as the developments in computer technology.

The models from this period, going from the mid-1970s to the mid-1980s, could be called the fourth generation of models. The models from this period are characterized by a relatively sound ecological basis, along with an emphasis on realism and simplicity. Many models were validated in this period with an acceptable result and for some (few) it was even possible to validate the prognosis.

The conclusions from this period may be summarized in the following three points:

1. Provided that the previously listed recommendations are followed and the underlying database is of good quality, it is possible to develop models used as prognostic tools.
2. Models based upon a database of less than acceptable quality should not be used as a prognostic tool, but they could give an insight into the mechanisms behind the environmental management problem, which is valuable in most cases. Simple models are often of particular value in this context.
3. Ecologically sound models, that is, models based upon ecological knowledge, are powerful tools in understanding ecosystem behavior and as tools for setting up research priorities. The understanding may be qualitative or semiquantitative, but has in any case proved to be of importance for ecosystem theories and a better environmental management.

1.7. State of the Art in the Application of Models

The shortcomings of modelling have also been revealed. It became clear that the models were rigid in comparison with the enormous flexibility, which is characteristic of ecosystems. The hierarchy of feedback mechanisms that ecosystems possess was not accounted for in the models, which made them incapable of predicting adaptation and structural dynamic changes. Since the mid-1980s, modellers have proposed many new approaches such as (1) fuzzy modelling, (2) examinations of catastrophic and chaotic behavior of models, and (3) application of goal functions to account for adaptation and structural changes. Application of objective and individual modelling, expert knowledge, and artificial intelligence offers some new additional advantages in modelling. This will discussed in Chapter 3 of this volume as well as when it is advantageous to apply these approaches and what can be gained by their application.

Table 1.1 Biogeochemical Models of Ecosystems

Ecosystem	Modelling Effort
Rivers	5
Lakes, reservoirs, ponds	5
Estuaries	5
Coastal zone	4
Open sea	3
Wetlands	5
Grassland	4
Desert	1
Forests	5
Agriculture land	5
Savanna	2
Mountain lands (above timberline)	1
Arctic ecosystems	2
Coral reef	3
Waste water systems	5

All these recent developments could be named the fifth generation of modelling, which is covered in Chapters 3, 9, 10 and 11.

Table 1.1 reviews types of ecosystems, which have been modelled by biogeochemical models up to the year 2000. An attempt has been made to indicate the modelling effort by using a scale from 0–5 where 5 means very intense modelling effort, more than 50 different modelling approaches can be found in the literature; 4 means intense modelling effort with 20 to 50 different modelling approaches found in the literature; 4–5 may be translated to class 4 but on the edge of an upgrading to class 5; 3 means some modelling effort with 6 to 19 different modelling approaches published; 2, few (2 to 5) different models have been well studied and published; 1, one good study and/or a few insufficiently well-calibrated and validated models; and 0, almost no modelling efforts have been published with no well-studied models. Notice that the classification is based on the number of different models, not on the

Table 1.2 Models of Environmental Problems

Problem	**Modelling Effort**
Oxygen balance	5
Eutrophication	5
Heavy metal pollution, all types of ecosystems	4
Pesticide pollution of terrestrial ecosystems	4–5
Other toxic compounds include ecological risk assessment (ERA)	5
Regional distribution of toxic compounds	5
Protection of national parks	3
Management of populations in national parks	3
Endangered species (includes population dynamic models)	3
Groundwater pollution	5
Carbon dioxide/greenhouse effect	5
Acid rain	5
Total or regional distribution of air pollutants	5
Change in microclimate	3
As ecological indicator	4
Decomposition of the ozone layer	4
Relationships health-pollution	3
Consequences of climate changes	4

number of case studies where these models have been applied. In most cases, the same models have been used in several case studies.

Table 1.2 similarly reviews environmental problems that have been modelled through the years. The same scale is applied to show the modelling effort seen in Table 1.1. Table 1.2 covers biogeochemical models, as well as models used for management of population dynamics in national parks and steady-state models applied as ecological indicators. It is advantageous to apply goal functions in conjunction with a steady-state model to obtain good ecological indication, as proposed by Christensen (1991, 1992).