3

An Overview of Different Model Types

CHAPTER OUTLINE

3.1. Introduction

In Chapter 2, a modelling procedure was presented and how to select close to optimum complexity was discussed. In the 1970s, when ecological models started to be applied in environmental management and as a scientific tool in systems ecology, most of the applied models were of three types: population dynamic, bioenergetic, and biogeochemical. For the first type, conservation of the number of individuals in a population was applied to set up the equations. For the second and third types, the conservation of energy and/or mass was the key principle applied for the development of the equations (see Table 2.3). For all three types, there can be both a dynamic version using the differential equations and a steady-state version using algebraic equations. The steady-state versions are used when the problem can be solved by presentation of an average situation or a worst-case situation, presuming both situations are steady state. In data-poor situations, it is often beneficial to apply the steady-state versions, because the quality and the quantity of the data are not sufficient to develop a dynamic model. For all three types, the development of a conceptual model is the first step to visualizing how the state variables are connected by processes. Sometimes the conceptual model is considered an independent model type when it is developed only to get

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an overview of the model components and how they are connected through processes such as transfer of mass, energy, and/or information. This does not prevent the conceptual model from being used to further develop the model. Section 3.3 presents conceptual models that can be visualized by several different methods.

In the last 20 to 30 years, several new types of models have emerged to solve a wide spectrum of problems that cannot be solved by the application of bioenergetic models, biogeochemical models, population dynamic models, or even conceptual models. This makes the selection of model type even more complicated. It is therefore crucial to have a good overview of all the available model types and their characteristics to be able to choose the model type that best meets the model objectives. In this chapter, the information needed to be able to make the best selection of model type will be presented.

3.2. Model Types — An Overview

The new model types, developed during the last couple of decades, have been created to answer a number of relevant modelling problems or questions that arose as a result of the increasing use of ecological models in the 1970s. Seven relevant modelling questions formulated around 1980 as a result of this model experience are listed below:

1. How can we describe the spatial distribution that is often crucial to understand ecosystem reactions and to select the best environmental strategy?
2. Ecosystems are middle number systems (Jørgensen, 2002). Since all of the components are different, what is the proper description of the ecosystem reactions when considering the differences in properties among individuals?
3. The species are adaptable and may change their properties to meet the changes in the prevailing conditions, which means forcing functions. Furthermore, the initial species may be replaced by other species better fitted to the combinations of forcing functions. How should we account for these changes? Even the networks may change if more biological components with very different properties are replaced by other species. How should we account for these structural changes?

4. Can we model a system that has a poor database — a few data of only low quality?
5. The forcing functions and several ecological processes are in reality stochastic. How do we account for the stochasticity?
6. Can we develop a model when our knowledge is mainly based on a number of rules, properties, and propositions?
7. Can we develop a model based on data from a wide spectrum of different ecosystems, which means that we have only a very heterogeneous database?

These problems could not be solved by the three "old" model types mentioned in Section 3.1, but they have all found a solution with the new model types.

Spatial models often based on the use of Geographical Information System (GIS) have been developed to answer question 1. Individual-based models (IBMs) are able to answer question 2. Software that can be used to develop IBMs is even available to facilitate IBM development. This software can also be utilized to cover spatial distribution (see question 1). Structurally dynamic models (SDM) have been developed to solve the problem expressed in question 3. Fuzzy models can be used to make models based on a poor or semiquantitative database. Stochastic models were not often applied in the 1970s, but they are still used today. The application remains infrequent, probably because an urgent need to include stochastic processes in ecological models does not happen often. IBMs can often meet the demands expressed in question 6. Artificial neural networks (ANN) are a good solution to the problem formulated in question 7.

Ecotoxicological models, discussed in Chapter 8, are sometimes considered a special model type. They are developed similar to other biogeochemical models, and have been widely used, particularly the last 10–15 years, because they are needed for environmental risk assessment of chemicals. It is therefore relevant to devote a special chapter to ecotoxicological models.

This book presents the development of biogeochemical models (both dynamic and steady-state types are discussed), population dynamic models, spatial models, ecotoxicological models, structurally dynamic models, IBMs, fuzzy models, and application of ANN. These types are the most common types (see Jørgensen, 2008b; Jørgensen, Chon, & Recknagel, 2009). Different methods used to present conceptual models considered as the first model step for any of the nine types of models will be presented in the next section.

Table 3.1 gives a summary of model statistics based on the number of publications in the journal *Ecological Modelling*. The percentage application of most general model types from the 1975 to 1980 are compared to the period from 2001 to 2006. Ecotoxicological models are included as a model type, although they are constructed similar to biogeochemical models. In Table 3.1, we have distinguished between nine types of models:

1. Dynamic biogeochemical
2. Steady-state biogeochemical
3. Population dynamics
4. Spatial
5. Structurally dynamic
6. Individual-based
7. Ecotoxicological
8. Fuzzy
9. Artificial Neural Networks

Table 3.1 Application of the Most General Model Types From 1975 to 1980 with the Model Types from 2001 to 2006

	% Application 1975–1980	% Application 2001–2006
Dynamic biogeochemical models	62.5	32.0
Steady state biogeochemical models	0	1.8
Population dynamic models	31.0	24.9
Spatial models	0	19.1
Structurally dynamic models	1.5	8.0
Individual-based and cellular automata	0	5.2
Artificial Neural Networks and use of artificial intelligence	0	4.9
Fuzzy models	0.5	1.8
Ecotoxicological models	0	2.2

The data in Table 3.1 are shown graphically in Figures 3.1 and 3.2 and are reproduced from Jørgensen (2008b).

The number of papers published from 2001 to 2006 is about nine times the number of papers published from 1975 to 1980. This means that the number of dynamic biogeochemical model papers published recently is more than 4.5 times the number published during the late 1970s, and that the number of papers on structurally dynamic modelling has increased by a factor of almost 50 during the last 35 years. A comparison of Figures 3.1 and 3.2 also shows that the spectrum of model types applied today is much wider than applied about 30 years ago. This is not surprising as the new types of models were developed because there was an urgent need to answer the seven modelling problems previously listed.

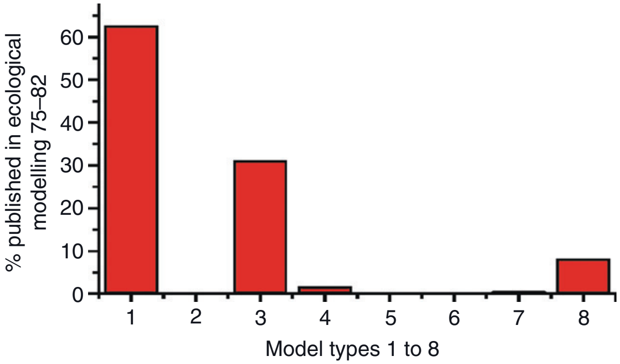

FIGURE 3.1 Percentage of papers published about the eight model types in *Ecological Modelling* from 1975 to 1982 previously listed and in Table 3.1.

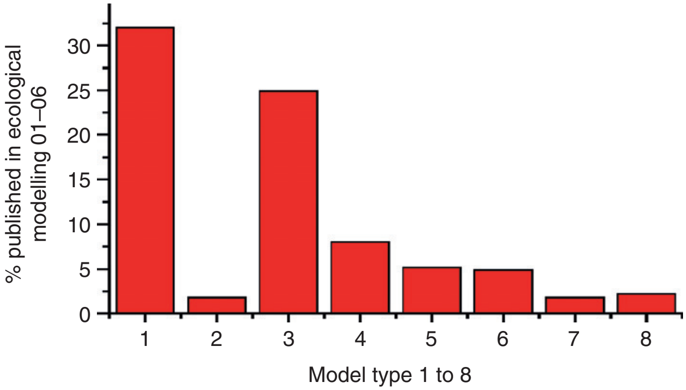

FIGURE 3.2 Percentage of papers published about the eight model types in *Ecological Modelling* from 2001 to 2006 previously listed and in Table 3.1.

With the present spectrum of model types, it is possible to address the major modelling problems from the 1970s. This development has increased the application of ecological models in general, particularly the use of the new model types. However, it is also clear that all the problems cannot be solved completely. We still have a number of problems that may not be possible to solve by use of a single model type. The very complicated problems require the use of hybrid models — a combination of the model types presented in this chapter.

New model types may be developed in the future to solve the complicated problems that today require the use of hybrid models. It is, however, agreed among ecological modellers that we currently have a sufficient toolbox of model types to address many ecological modelling problems we now face, although some modelling case studies are still need to guarantee their feasibility in real situations.

3.3. Conceptual Models

A conceptual model has a function of its own. If flows and storage are given by numbers, then the diagram gives an excellent survey of a steady-state situation. It can give a picture of the changes in flows and storages if one or more forcing functions are changed and another steady-state situation emerges. If first-order reactions are assumed, then it is even easy to compute other steady-state situations which might prevail under other combinations of forcing functions (see Chapter 6). Conceptualization is one of the early steps in the modelling procedure (see Chapter 2), but it can also have a function of its own, as will be illustrated in this section.

A *conceptual model* can be considered as a list of state variables and forcing functions of importance to the ecosystem and the problem in focus, but it also shows how these components are connected by processes. It is employed as a tool to create abstractions of reality in ecosystems and to delineate the level of organization that best meets the objectives of the model. A *wide spectrum* of conceptualization approaches is available and will be presented in this chapter. Some conceptual models give only the components and the connections; others imply the first steps toward a mathematical description.

It is almost impossible to model without a conceptual diagram to visualize the modeller's concepts and the system. The modeller usually plays with the idea of constructing various models of different complexity at this stage in the modelling procedure, making the first assumptions and selecting the complexity of the initial model or alternative models. It requires intuition to extract the applicable parts of the knowledge about the ecosystem and the problem involved. Models attempt to make a synthesis of what we know, and the conceptual diagram is the first step of this synthesis.

Construction of a conceptual diagram is system and developer dependent, but it is often better at this stage to use a slightly too complex model rather than an approach that is too simple. In the later stage of modelling, it is easy to exclude redundant components and processes. On the other hand, it makes the modelling too cumbersome if an overly complex model is used even at this initial stage. Generally, good knowledge about the system and the problem facilitates the conceptualization step and increases the chance to get closer to the right complexity for the initial model. The questions to be answered include: What components and processes of the real system are essential to the model and the problem? Why? How? In this process a suitable balance is sought between elegant simplicity and realistic detail.

Identification of the level of organization and selection of the needed complexity of the model are not trivial problems. Miller (1978) indicated 19 hierarchical levels in living systems. To include all of them in an ecological model is impossible, mainly due to lack of data and a general understanding of nature. Usually, it is not difficult to select the focal level — where the problem is or where the components of interest operate. The step below the focal level is often relevant for a good description of the processes; for instance, photosynthesis is determined by the processes occurring in the individual plants. One step higher than the focal level determines many of the constraints. These considerations are visualized in Figure 3.3.

In most cases it is not necessary to include more than a few or even only one hierarchical level to understand a particular behavior of an ecosystem at a particular level (see Patten, 1971, 1976; Wilson, 2000; Miller, 1978; Allen, 1976; Allen & Starr, 1982). Figure 3.4 illustrates a model with three hierarchical levels, which might be needed if a multi-goals model is constructed. The first level could be a hydrological model, the next level a eutrophication model, and the third level a model of phytoplankton growth considering the intracellular nutrients concentrations.

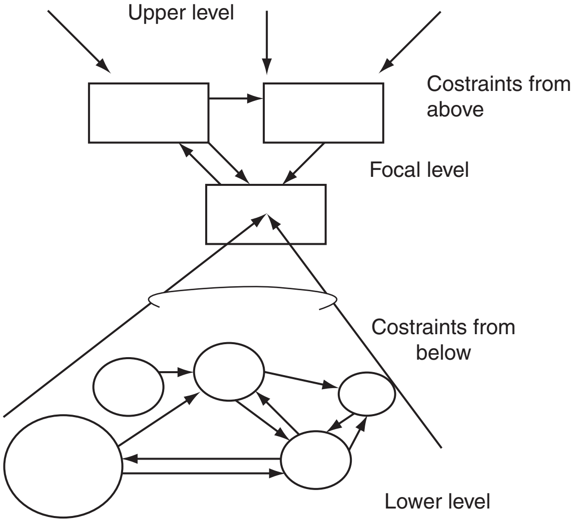

FIGURE 3.3 The focal level has constraints from both lower and upper levels. The lower level determines to a large extent the processes, and the upper level determines many of the constraints on the ecosystem.

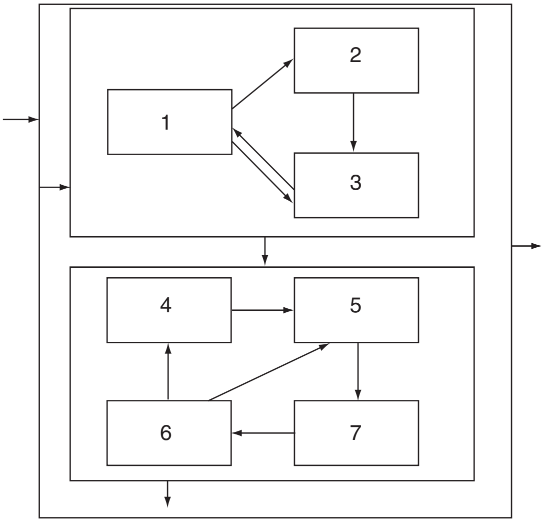

FIGURE 3.4 Conceptualization of a model with three levels of hierarchical organization.

Each submodel has its own conceptual diagram; for example, the conceptual diagram of the phosphorus flows in a eutrophication model (see Chapter 7). In the latter submodel there may be a sub-submodel considering the growth of phytoplankton by use of intracellular nutrients concentrations which is shown as a conceptual diagram in Figure 3.5. The nutrients are taken up by phytoplankton at a rate determined by the temperature and nutrient concentration in the cells and in the water. The closer the nutrient concentrations in the cells are to the minimum, the faster the uptake. The growth, on the other hand, is determined by solar radiation, temperature, and the concentration of nutrients in the cell. The closer the nutrient concentration is to the maximum concentration, the faster the growth. This description is according to phytoplankton physiology and will be presented in Chapter 7.

The modeller can choose among several conceptualization methods for the development of the conceptual diagram. Six of the most applied methods are presented next. Which one to choose depends on how much information the modeller wants to include in the conceptual diagram. The more information the modeller includes, the more informative the diagram is, but it becomes more difficult to interpret and manage.

Picture conceptual models use components seen in nature and place them within a framework of spatial relationships. Figure 3.6 is a simple example.

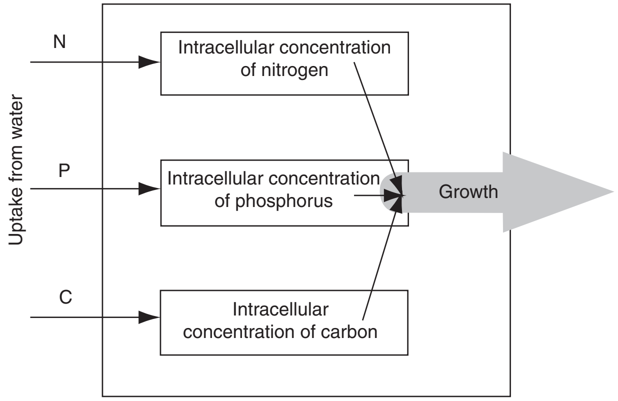

FIGURE 3.5 A phytoplankton growth model with two hierarchical levels: the cells that determine the uptake of nutrients and the phytoplankton population production (growth) determined by the intracellular nutrient concentrations. This model is applied in Chapter 7.

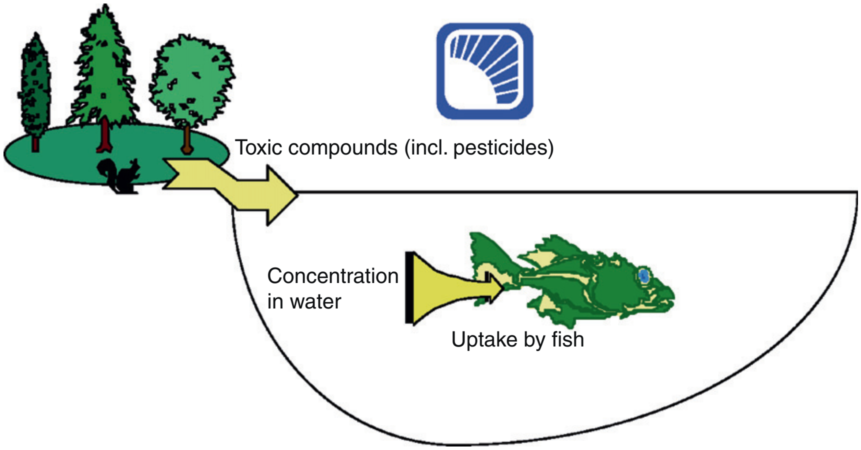

FIGURE 3.6 Example of a picture model: pesticides are coming from the littoral zone, resulting in a certain concentration in the water. Fish take up the toxic compounds directly from the water. The model attempts to answer the crucial question: What is the concentration of the toxic substance in the fish?

Box conceptual models are simple and commonly used conceptual designs for ecosystem models. Each box represents a component in the model and arrows between boxes indicate processes. Figures 2.1, 2.10, and 2.11 show examples of this model type. The conceptual diagrams show the nutrient flows (nitrogen and phosphorus) in a lake. The arrows indicate mass flows caused by processes. Some modellers prefer other geometric shapes, for example, Wheeler et al. (1978) preferred circles to boxes in their conceptualization of a lead model. This results in no principal difference in the construction and use of the diagram. A box model for predicting the carbon dioxide concentration in the atmosphere and the consequences for the climatic changes will be presented in Chapter 7, Section 7.7.

The term *black-box model* is used when the equations are set up based on an analysis of input and output relations, for example, by statistical methods. The modeller is not concerned with the causality of these relations, and such a model might be very useful provided the input and output data are of sufficient quality. Yet, the model can only be applied to the case study for which it has been developed. New case studies will require new data, a new analysis of the data, and, consequently, new relations. *White-box* models are constructed based on causality for all processes. This does not imply that these models can be applied to all similar case studies, because, as previously discussed, a model inevitably reflects ecosystem characteristics. In general, a white-box model will be applicable to other case studies with some minor or major modifications. In practice, *most models are gray*, as they contain some causalities but also often apply empirical expressions to account for some of the processes.

Input/output models differ only slightly from box models; they can be considered as box models with numerical indications of inputs and outputs. An example of this type of model is shown in Figure 3.7, which is an oyster community model developed by Dame and Patten (1981).

The *feedback dynamics diagrams* use a symbolic language introduced by Forrester (1961) (Figure 3.8). Rectangles represent state variables, parameters or constants are small circles, sinks and sources are cloud-like symbols, flows are arrows, and rate equations are the pyramids that connect state variables to the flows. Several modifications have been developed and they differ from the Forrester diagrams by giving more

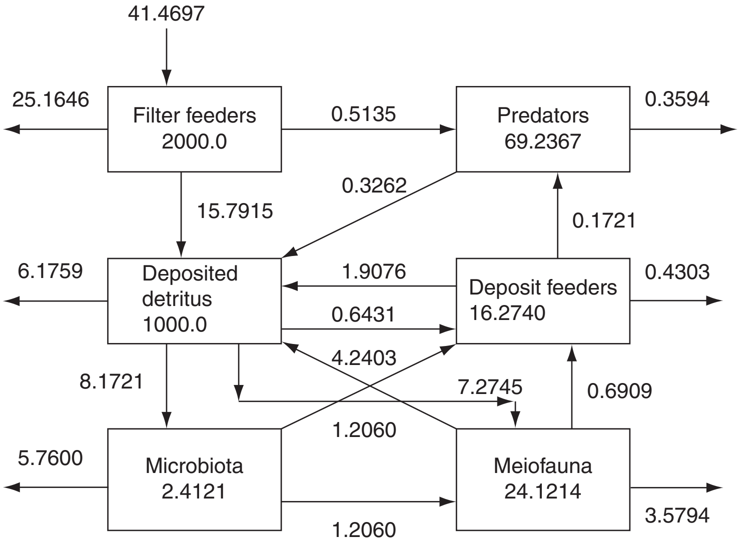

FIGURE 3.7 Input/output model for energy flow (cal m^{-2} d^{-1}) and storage (kcal m^{-2}) in an oyster reef community. Matrix representation: 1. filter feeders, 2. deposited detritus, 3. microbiota, 4. meiofauna, 5. deposit feeders, and 6. predators

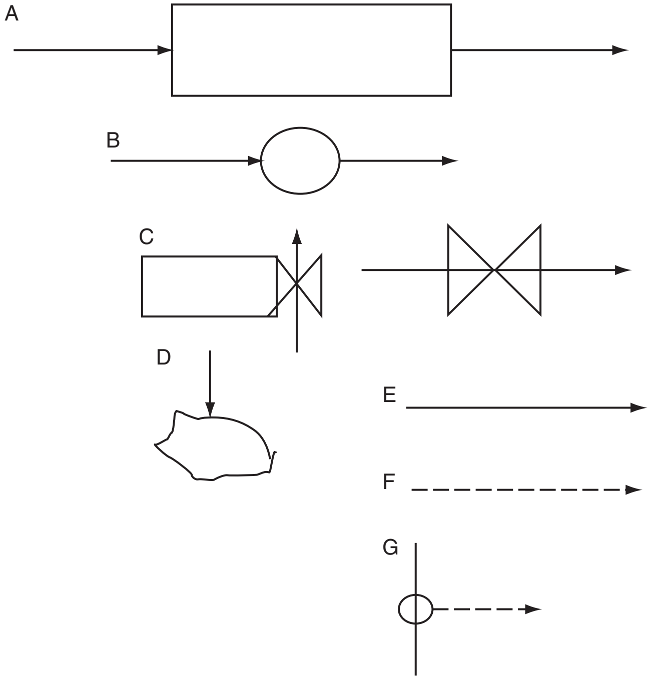

FIGURE 3.8 Symbolic language introduced by Forrester (Jeffers, 1978). (A) state variable, (B) auxiliary variable, (C) rate equations, (D) mass flow, (E) information, (F) parameter, and (G) sink.

information about the processes. The conceptualization used in the model development software STELLA (see Figure 2.3) uses symbols similar to the Forrester diagram (compare Figures 2.3 and 3.8).

Energy circuit diagrams, developed by H. T. Odum (1983), are designed to give information on thermodynamic constraints, feedback mechanisms, and energy flows. The most commonly used symbols in this language are shown Figure 3.9. As the symbols have an implicit mathematical meaning, it gives an abundance of information about the mathematics of the model. Furthermore, it is rich in conceptual information and hierarchical levels can easily be displayed. Numerous other examples can be found in the literature (Odum, 1983; Odum & Odum, 2000). A review of these examples reveals that energy circuit diagrams are very informative, but they are difficult to read and survey when the models become a little more complicated. On the other hand, it is easy to set up energy models from energy circuit diagrams. Sometimes it is even sufficient to use the energy circuit diagrams

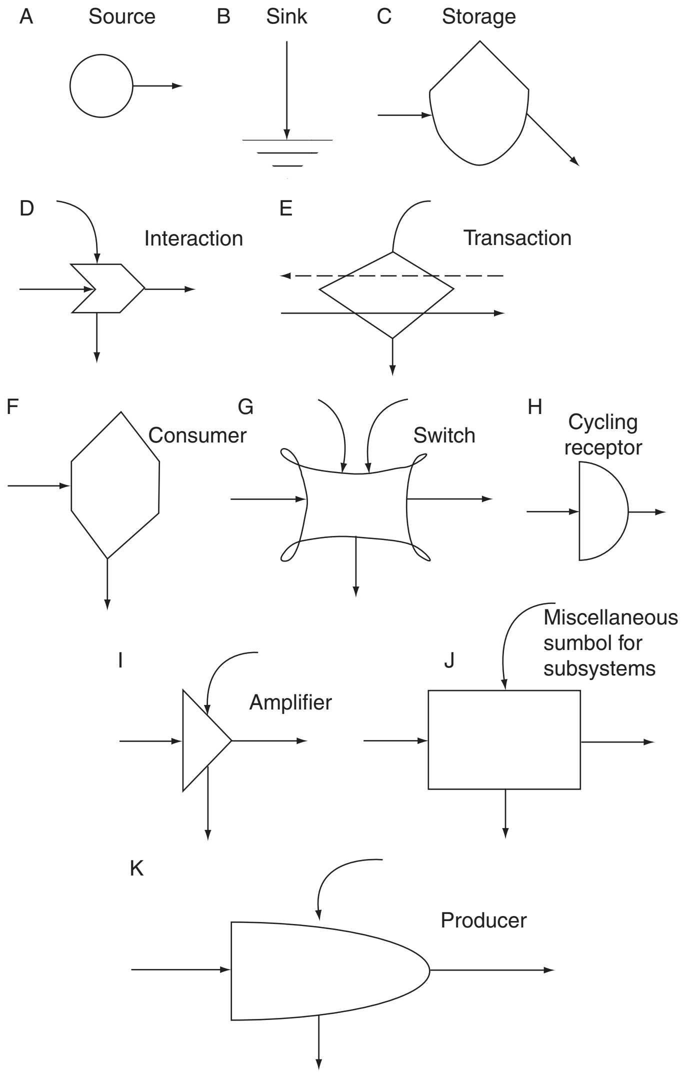

FIGURE 3.9 Diagrammatic energy circuit language of Odum (1983) developed for ecological conceptualization and simulation applications.

directly as energy models. These diagrams have found a wide application for development of ecological/economic models, where the energy is used as the translation from economy to ecology and vice versa. H.T. Odum has used the approach for developing models for entire countries.

3.4. Advantages and Disadvantages of the Most Applied Model Types

The characteristics, advantages, and disadvantages (mostly expressed as a limitation of the application) for all of the available main model types are given in this section. The applicability of the various model types is discussed in the next section. The application of catastrophe theory and chaos theory are not included in the overview, because they can be considered mathematical tools that, in principle, can be applied as mathematical tools in the development of several different model types. Furthermore, statistical models in this textbook are not considered as a particular model type, but as a tool that can be applied in ecological modelling to give a better process description. If a model is based entirely on application of statistics, then it is denoted as a black-box model, because it has no causality. Black-box models are not used to uncover new ecological knowledge where the focus is on causality. A short review of the most applied model types based on Jørgensen (2008b) is given in the following list.

1. Biogeochemical and bioenergetic dynamic models**.** This model type is widely used, as can be seen in Table 1.1. It applies differential equations to express the dynamics. Change in state variables are expressed as the results of the ingoing minus the outgoing processes and the model is therefore based on conservation principles. The process equations are usually based on causality. The model type has some clear advantages that make it attractive to use for the development of many models.
   Advantages:
   - Most often based on causality
   - Based on mass or energy conservation principles
   - Easy to understand, interpret, and develop
   - Software is available (e.g., STELLA)
   - Easy to use for predictions

   Disadvantages:
   - Not used for heterogeneous data
   - A relatively good database is required
   - Difficult to calibrate when they are complex and contain many parameters

- Do not account for adaptation and changes in species composition

The advantages and disadvantages define the area of application such as the description of the state of an ecosystem when a good data set is available. This model type has been extensively applied in environmental management as a powerful tool to understand the reactions of ecosystems to pollutants and to set up prognoses.

2. **Steady-state biogeochemical models.** Due to the limitations of this model type, it has not been used in more than 1.8% of the publications in *Ecological Modelling* from 2001 to 2006. This model type is a biogeochemical or bioenergetic dynamic model where the differential equations all are set to zero to obtain the values of the state variables corresponding to the static situation.

   Advantages:
   - Require generally smaller databases than most other types
   - Excellent for worst-case or average situations
   - Results are easily validated (and verified)

   Disadvantages:
   - Do not give any information about dynamics and changes over time
   - Prediction with time as independent variable is not possible
   - Only give average or worst-case situations

   This model type is often used when a static situation is sufficient to give a proper description of an ecological system or to make environmental management decisions.
3. **Population dynamic models**. This model type is rooted in the Lotka-Volterra model developed in the 1920s. Numerous papers have been published about the mathematics behind this model and a number of deviated models developed. The mathematics of these equation systems are not very interesting from an ecological modelling point of view, where the focus is a realistic description of ecological populations. Population dynamic models may include age structure, which in most cases is based on matrix calculations. The number of population dynamic papers is 5 times as much today as in the late 1970s, which illustrates that ecological modelling has developed significantly over the past 30 years. The

minor reduction in percentage is due to the application of a much wider spectrum of different model types.

Advantages:

- Able to follow the development of a population
- Age structure and impact factors can easily be considered
- Easy to understand, interpret, and develop
- Most often based on causality

Disadvantages:

- Conservation principles are sometimes not applied, although it is easy in most cases
- Application is limited to population dynamics
- Require a relatively good and homogenous database
- Difficult to calibrate in some situations

This model type is typically applied to keep track of the development of a population. The number of individuals is the most applied unit, but it can easily be translated into biomass or bioenergy. Effects of toxic substances on the development of populations can easily be covered by increasing the mortality and decreasing the growth corresponding to the effect of the toxic substance. This model type is extensively used in the management of fisheries and other natural resources and national parks.

4. **Structurally Dynamic Models**. This model type can change the parameters, corresponding to the properties of the biological modelling components to account for adaptation and changes in species composition. It is possible either to use knowledge or artificial intelligence to describe the changes in the parameters. Most often a goal function is used to find the parameter changes. The thermodynamic variable, eco-exergy, is a commonly used goal functions in structurally dynamic models. Minor changes of the parameters may be due to adaptation to the changed conditions, but for major changes, it is most probably due to a change in the state variables — that is, a shift in the species composition — that causes the changed parameters. This approach can be used for a major change in the ecological network, although no reference to this application of the structurally dynamic modelling approach is yet available. SDMs are applied much more today than 25 to 30 years ago.

Advantages:

- Able to account for adaptation
- Able to account for shift in species composition
- Can be used to model biodiversity and ecological niches
- Parameters determined by the goal functions do not need to be calibrated
- Relatively easy to develop and interpret

Disadvantages:

- Selection of a goal function or use of artificial intelligence is needed
- Computer use is time-consuming
- Information about structural changes is needed for a proper calibration and validation
- No available software; programming needed (in most cases C++ has been used)

This model type should be applied whenever it is known that structural changes take place. It is also recommended for models that are used in environmental management to make prognoses resulting from major changes in the forcing functions (impacts).

5. **Fuzzy models.** This type of model may either be knowledge-based (the Mamdani type) or data-based (the Sugeno type). Mamdani-type models are based on a set of linguistic expert formulations, and they are applied when no data are available. The Sugeno-type model applies an optimization procedure and is applied when only uncertain data are available.

Advantages:

- Can be applied on a fuzzy data set
- Can be applied on semiquantitative (linguistic formulations) information
- Can be applied for development of models where a semiquantitative assessment is sufficient

Disadvantages:

- Not usable for more complex model formulations
- Cannot be used where numeric indications are needed
- No software available to run this type of model, although there are facilities in Matlab to run fuzzy models

This model type is applied when the data set is fuzzy or only semiquantitative expert knowledge is available, provided that the semiquantitative results are sufficient for the ecological description or the environmental management.

6. **Artificial Neural Networks.** This model type is able to show relationships between state variables and forcing functions based on a heterogeneous database. In principle, it is a black-box model and therefore not based on causality. It is very useful when applied for prognoses, provided that the model has been based on a sufficiently large database that allows the discovery of relationships and to test these discoveries on an independent data set. This model type was not applied in ecological modelling before 1982. It can be developed by using available software or Matlab.

Advantages:

- May be used where other methods fail
- Easy to apply
- Give a good indication of the certainty due to the application of a test set
- Can be used on a heterogeneous data set
- Give a close to optimum use of the data set

Disadvantages:

- No causality unless algorithms are introduced or a hybrid between ANN and another model type is applied
- Cannot replace biogeochemical models based on the conservation principles
- Accuracy of predictions is sometimes limited, although validation is almost always used.

The advantages and disadvantages of this model type indicate where it would be advantageous to apply ANN; namely where ecological descriptions and understandings are required on the basis of a heterogeneous database, such as data from several different ecosystems of the same type. It is also often applied beneficially when the database is more homogeneous; for instance, when the focus is on a specific ecosystem. The modeller should seriously consider using biogeochemical dynamic models due to their causality. ANN is, however, faster to use and the time-consuming calibration that is part of the biogeochemical models is not necessary.

7. **Spatial models.** Spatial differences of the forcing functions and the nonbiological and biological state variables may be decisive for model results, and are often required to obtain model results that reveal spatial differences. They are often urgently needed to understand the ecological reactions or to make a proper environmental management strategy. Models that produce spatial differences must also consider the spatial differences in the processes, forcing functions, and state variables. Due to the urgent need for a proper description of the spatial differences, it is not surprising that the journal *Ecological Modelling* has published almost 250 papers about spatial modelling from 2001 to 2006 and that the number of models that focus on spatial distribution is increasing rapidly. There are a number of ways to cover the spatial differences in the development of an ecological model. It is not possible to review them all here, but this important model type is presented in more detail in Chapter 11. For aquatic ecosystems, the ultimate spatial model is a 3D description of the processes, forcing functions, and state variables. When studying this ecosystem, there are often questions regarding a good description of hydrodynamics. There has been an increasing use of models that couple 3D hydrodynamic models and ecological models.
   Advantages:
   - Cover spatial distribution, which is often important in ecology
   - Results can be presented in many informative ways, for instance, GIS

   Disadvantages:
   - Require a huge database
   - Calibration and validation are difficult and time-consuming
   - A very complex model is usually needed to properly describe the spatial patterns

   Spatial models are applied whenever it is required that the results include the spatial distribution, because it is decisive or the spatial distribution is crucial to the model results. Landscape models covering the exchange of matter among several different ecosystems in a landscape have been developed.
8. **Individual Based Models**. This model type was developed because all the biological components in ecosystems have different

properties, which is not considered in biogeochemical or population dynamic models. Within the same species the differences are minor and are therefore often neglected in biogeochemical models, but the differences among individuals of the same species may sometimes be important for ecological behavior. For instance, individuals may have different sizes, which gives a different combinations of properties from the allometric principles (see Chapter 2, Section 2.9). The right property may be decisive for growth and/or survival in certain situations. Consequently, a model that ignores the differences among individual species could produce a completely wrong result.
Advantages:

- Able to account for individuality
- Able to account for adaptation within the spectrum of properties
- Software is available; although the choice is more limited than software used by biogeochemical dynamic models
- Spatial distribution can be covered

Disadvantages:

- When a number of properties are considered, the models get very complex
- Cannot always cover mass and energy transfer based on the conservation principle
- Require a large amount of data to calibrate and validate the models

As mentioned earlier, we know that the individuals have different properties that may sometimes be crucial for model results. In such cases, IBMs are absolutely needed.

9. **Ecotoxicological models**. Ecotoxicological models, in principle, do not represent a separate model type. Biogeochemical models or population dynamic models are applied widely in ecotoxicology. It is, however, preferable to treat ecotoxicological models as a separate model type, because they are characterized by the following:
   - Our knowledge of the parameters is limited so estimation methods are needed to a much larger extent than for other model types. Fortunately, many estimation methods are available in ecotoxicology to estimate process rates.

- Due to the use of safety factors and the limited knowledge of the parameters, ecotoxicological models are often quite simple; particularly, the so-called fugacity models.
- They should often include an effect component.

Advantages:

- Tailored to ecotoxicological problems
- Usually simple to use
- Often includes an effect component or can easily be interpreted to quantify the effect

Disadvantages:

- The number of parameters needed to develop models for all toxic substances is very high and we know approximately 1% of these parameters
- It implies that we need estimation methods that inevitably have a high uncertainty; model results therefore have a high uncertainty
- Inclusion of an effect component requires knowledge of the effect, which is also limited

The area of application for this model is to solve ecotoxicological research and management problems and perform environmental risk assessment for the application of chemicals.

10. **Stochastic models**. This model type is characterized by an element of randomness. The randomness could be in the forcing functions, particularly the climatic forcing functions, or it could be in the model parameters. In both cases, it is caused by a limitation in our knowledge. For instance, we may not know the temperature on May 15 next year at a given location, but we know the normal distribution of the temperature over the last hundred years and can use it to represent the temperature on this date. Similarly, many of the parameters in our models are dependent on random forcing functions or on factors that we cannot include in our model without making it too complex. Using Monte Carlo simulations based on this knowledge, it is possible to consider the randomness. By running the model many times, it becomes possible to obtain the uncertainty of the model results. A stochastic model may be a biogeochemical/ bioenergetic model, a spatial model, a structural dynamic model,

an IBM, or a population dynamic model. In principle, a model can become a stochastic model regardless of its type.

Advantages:

- Able to consider the randomness of forcing functions or processes
- Uncertainty of the model results are easily obtained by running the model many times

Disadvantages:

- Must know the distribution of the random model elements
- High complexity and requires many hours of computer time

It is recommended to apply stochastic models whenever the randomness of forcing functions or processes are significant.

11. **Hybrid models**. In principle, hybrid models are any combination of two of the previously listed ten model types; but only few hybrid models have been developed. It is expected that many more will be developed in the future to combine some of the advantages and eliminate some of the disadvantages of the existing models. *Ecological Modelling* has published several hybrid models that combine a biogeochemical/bioenergetic dynamic model with other model types. The result of combining a biogeochemical dynamic model and an ANN is a hybrid model that may have causality and is able to squeeze as much information out of the database as an ANN.

3.5. Applicability of the Different Model Types

Which model types are recommended to solve which problems? What are the data requirements of the different model types? These are questions answered in the first step of modelling development (see Figure 2.2). As mentioned in the introduction to this chapter, new model types were needed to solve specific problems that emerged during the late 1970s, when ecological modelling started to be applied more extensively as a tool in ecological research and environmental management. Biogeochemical/bioenergetic dynamic models and population dynamic models have shortcomings that ecological modellers have tried to solve for the last 30 years by developing new model types. Today, the shortcomings have at least been partially eliminated by the development of new model types, particularly spatial models, IBMs, and SDMs. It is possible with the available model types to make the best choice in a given model situation, which is defined by the available data and the combination of problem and system. It is possible to recommend a particular model type from the eleven model types presented in Section 3.4 based on (1) available data sets and the (2) combination of problem and system.

The core question, "Which model type should be applied in which context?", is answered in Tables 3.2 and 3.3, which cover, respectively, different data sets and different problem/system combinations.

Now we have a wide spectrum of model types available to solve a wide spectrum of relevant ecological problems, which include a description of shifts in species compositions, ecotoxicological effects and spatial distributions, and the use of heterogeneous data sets and uncertain data sets. This wide spectrum of models is richly represented in the ecological modelling literature (Table 3.4).

Table 3.2 Selection of Model Type Based on the Available Data Set

Data Set	Recommended Model Type
High quality, homogeneous	Biogeochemical dynamic models and population dynamic models
Medium-high quality, heterogeneous	ANN
Low quality, homogeneous	Steady-state model
Uncertain data	Fuzzy models
No data only rules	Fuzzy models

Table 3.3 Selection of Model Type Based on Problem/System

Problem/System	Recommended Model Type
Exchange of matter and/or energy	Biogeochemical dynamic model
Population dynamics	Population dynamic model
Toxic substances, distribution and effect	Ecotoxicological model
Individuality important for the results	IBM
Structural changes occur	SDM
Adaptation significant	SDM
Spatial differences	Spatial model
Stochasticity important for the results	Stochastic model

Table 3.4 Case Studies Illustrating the Application of the Various Model Types

Model Type	Description of Case Study
Dynamic biogeochemical models	Eutrophication of a lake; a relatively good database available
Steady-state biogeochemical models	Eutrophication of a lake; only three annual average values available
Population dynamic models	Management of deer in a national park; a relatively good database available
Spatial models	Distribution of nutrients in a landscape; a relatively good database available
Structurally dynamic models	Oxygen deficiency in a stream; significant changes of control functions are expected, and knowledge about shifts in species composition available
IBMs	Growth of trees in a forest; the trees have very different conditions (sun, exposure to wind, soil, etc.) and a good database with different growth pattern under different conditions available
ANN and use of artificial intelligence	The presence of different fish species in a wide spectrum of different streams; a huge but heterogeneous database available
Fuzzy models	Presence or absence of 5 species of songbirds in 20 different wetlands
Ecotoxicological models	The fate of an insecticide used in agriculture; an agricultural area, a wetland, and a stream are considered

Problems

1. Which type of model would you select for the following problems?
   - **a.** Protection of a lion population in a national park
   - **b.** Optimization of a fishery in a marine ecosystem like the North Sea
   - **c.** Construction of a wetland for removal of nitrate mainly by denitrification
   - **d.** Adaptation (change in the rate of evapotranspiration) of plants to a dry climate

  - **e.** Interpretation of a database with 12 stations in drainage areas, rivers, and many observations as function of time for the stations of (i) water quality, (ii) fish diversity, (iii) dominant fish species, and (iv) the use and composition of the land adjacent to the rivers

2. Consider a shallow lake with a surface of 100 ha and a depth of 2 m has an initial phosphorus concentration of 0.1 mg/L. The loading is 100 kg/year. The water retention time is 4 months. No input of phosphorus from the sediment is considered.

  - **a.** What would be the concentration of phosphorus in the lake by steady state if no settling of phytoplankton or suspended matter takes place?
  - **b.** What would be the concentration of phosphorus in the lake at steady state if it is considered that phosphorus is settled by a rate of 10 m/24h?
  - **c.** What would be the phytoplankton concentration in the two cases if phytoplankton contains 1% phosphorus?

The differential equation needed to answer question (a) and (b) should be indicated and the steady-state solution should be found.

3. Draw a Forrester and energy circuit diagram for Figure 2.9.

4. Develop a STELLA diagram of the picture model in Figure 3.6. Set up an adjacency matrix for the model.

5. Set up an adjacency matrix for the model in Figure 3.7.

6. Give an example of a case study that is best solved by use of the nine model types listed in Table 3.1. Describe the case study by the problem, the ecosystem, and the data needed. Present the answer by use of a table.