ENVIRONMENTAL DECISION SUPPORT SYSTEMS

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Concluding one of his major studies on the planning of the River Nile, probably one of the largest environmental problems ever tackled in the world, H. Hurst acknowledged the fundamental work performed by 'computers' (Hurst 1952). At that time, in fact, the Egyptian Ministry of Irrigation, ruled by the British, had a 'computer room' crowded with a large number of clerks performing all the calculations needed to manage and to plan such a wide river basin.

A few years later, in 1958, an 'electronic computer' was used on the same problem in order to find the optimal allocation of water between Egypt and the Sudan in a study for the Sudanese Ministry of Irrigation and Hydroelectric Power (Morrice 1958). At that time, the water system contained five major dams, and several other barrages and control points. Many new structures had been proposed, of which the most important was the future Aswan High Dam. Monthly volumes of inflow in the period 1905–1942 were used as input data to a model describing the system in terms of mass balance equations at all the major junctions of the river and control equations at 16 control points. The system was developed on an IBM 650 which allowed the effect of 300 different project combinations to be tested, thus becoming probably the first real example of a computer-assisted environmental plan. The Nile became a showcase for the efficiency of using electronic computers in this kind of study. It was estimated that a 50-minute computer run could replace 1500 man-hours of traditional work!

Still in the sixties, in the first modern work on the managing and planning of water resources, which laid the basis for most environmental models in the following years, Maass et al. (1962) referred to the computer as an 'electronic computer' in order to distinguish it from accountants. However, the use of such devices was spreading rapidly and Chow (1964) was able to quote 51 papers reporting its application in the field of hydrology alone.

Today the meaning of the word 'computer' has been definitely established, in environmental as in other sciences, even if a lot of work has still to be done to permit the effective and generalized use of this tool.

If one goes back to the pioneering work on the applications of computers to environmental problems (see, for instance, Chow 1964), one realizes that their spread has been paralleled, if not induced, by the development of
mathematical formulations of environmental problems. During the sixties, in fact, the basic role of computers was in performing calculations, and as such they were used also in the environmental sector. Although the mathematical expression of many physical laws had been known for many years (sometimes for centuries), it was not until that time that the traditional notion of 'formula' was replaced by the more modern term 'mathematical model'. The latter is usually a collection of algebraic or differential equations which tries to represent not only a single phenomenon (for instance the diffusion of a pollutant in the atmosphere) but also the entire complexity of the causes and effects of that phenomenon (for example the economy of the processes generating the pollutant, its combustion and emission dynamics, and the damages caused by its diffusion).

While the first approach (physical formulas) was in various degrees amenable to an analytical study of some very simple conditions (diffusion among a homogeneous quiescent fluid), the mathematical models under development were too complex to be analysed by hand and were driven by a substantial amount of data concerning real conditions in order to allow the solution of practical problems. They necessitated an unprecedented amount of computing power, which could be found, even if at a relatively high cost, in the new computers with which several research centres and some environmental agencies were equipped (sometimes for the basic purpose of performing accounting).

The well-known trends in prices and performance of computer equipment have led to its diffusion to almost all human activities and thus also to environmental institutions. This penetration (and that of mathematical models) has not been even in all the different branches. As an example, several water resources studies were based on the use of computers long before the first attempts were made to solve an atmospheric pollution or population dynamics problem with such a device. This is certainly not due to intrinsic differences in the problems dealt with but probably to the different backgrounds of researchers involved in the studies. Water resources problems have usually been studied by people with an engineering background, who probably felt more comfortable with electronic machines and the formal and precise codes that were needed to operate them. Today these differences have become less perceptible although they still exist, as will become apparent to the reader in the following chapters of this book.

Technological changes in computer hardware and software and psychological changes in the users have induced, particularly in recent years, a major shift in the environmental applications of computers. The computer is now used not merely to perform calculations but also to collect, store and retrieve data, to present them in different ways, and to help people in understanding them. In other words, the computer is no longer an isolated and protected device in an inaccessible room, but has become a flexible, multi-purpose tool for supporting all activities of an environmental engineer: a complete 'information processor', part of a complex information system. This system normally contains, in addition to the computer(s) and the operator(s), a measuring and transmission network and an implement-
a series of real examples of environmental applications, which show the
different roles the computer can play.

2.1 DEVELOPING MODELS FOR ENVIRONMENTAL PROBLEMS

The modelbase plays an essential role in the architecture of any DSS. The
models it may contain are usually divided into descriptive and decision
(sometimes called normative) models.

The former simply portray the behaviour of a certain physical system as a
consequence of external inputs (also called forcing factors or driving forces).
All models used to simulate or to forecast the development of natural or
human-induced phenomena fall into this category.

Decision models are normally aimed at suggesting a decision on how to
act on a physical system in order to let it perform in a desired way. Planning
and management (or control) models are of this type; the main conceptual
difference between them is that, in the case of planning, the decision is taken
only once for a long period of time, while management implies repetitive
decisions which are close enough in time to influence each other. As pointed
out in section 1.4, this time range usually corresponds to the degree of
structure of the problem. Planning is much more likely to involve several
unclear elements, which are less relevant for short-term decisions.

The differences between these various types of models and the way they
may be coordinated into a modelbase will be discussed in Chapter 4. In the
current context, however, it should be stressed that, whatever mathematical
model one is trying to develop, in principle all the steps represented in Fig.
2.1 should be accomplished.

Problem perception

The importance of this first step was dealt with in the previous chapter. It
must be recalled that problem perception is largely subjective, and thus two
people confronted with the same situation may conceive of two quite
different formal ways to deal with it. This step, while being part of model
development, should be directly performed by the decision maker, i.e. by
the person or institution responsible for taking the final decision on imple-
menting the solution of the problem. Too often in the past, the analyst has
taken the responsibility for defining the problem, and sometimes he or she
was biased by the availability of solution methods more than by the core of
the problem itself. This is probably one of the causes of the weak practical
impact that environmental modelling has had in comparison with the
massive research effort in the area. Strict cooperation is needed between the
decision maker and the analyst to produce an effective and viable problem
identification.

Conceptualization

This stage represents the formulation of the problem in analytical terms. It
should be noted that 'analytical' in this context does not mean a procedural
formulation, i.e. a set of mathematical tools which allow the problem to be
solved; rather, it may well be constituted by a set of 'rules' that express in
descriptive terms what is known about the problem. In most cases, however,
the output of conceptualization is a set of equations which should capture
the mechanism of reality. This output is not at all unique, and the same
problem can often be formalized in several different ways. Again, the choice
between different models is largely subjective and is the reason why, for
building a practical instrument to support decisions, a whole range of models
should be made available. This justifies once more the choice of including a
modelbase in the architecture outlined in the previous chapter.

A last, but important, point about conceptualization is the lack of
definite methods to perform it. The ability to formulate the problem in a
correct way usually derives from the experience of the analyst, which also
means from a critical appraisal of what has already been developed in the
field.

Data collection

The formulation of the model should in principle follow a certain analysis of
the data and influence the subsequent more accurate data collection. The
first analysis is in many cases redundant since the basic mechanisms of a
number of environmental phenomena are known, but it may be essential
when formulating a model for an entirely new problem. Usually, the first
analysis consists of statistical tests (several software packages are available
for any type of computer), particularly tests which may highlight the causal
link between some variables (see, for instance, Finzi et al. 1988).
The fact that further data collection must depend upon the model has often been disregarded in the past. It has been very common in environmental agencies to start collecting data (particularly after cheap computer mass storage became available) in the hope of creating a 'universal' data bank — an archive capable of containing any information needed to answer any question. However, one often realizes that the data necessary to implement a given model are missing, since model input and output data must be available in a precise sequence to be of some use, and they are almost always collected independently.

Parameter estimation
This is normally a very technical step in which the model that has been formalized is fitted to the particular situation under study. This means that the parameters of the equations (or of the rules) are estimated in order to represent as close as possible the data available on the case at hand. The parameters are normally estimated (the terms 'calibrated' or 'tuned' are used by some authors) in two different ways, depending upon what they represent. If they correspond to some rate or relation which can be measured on the real system, they are just the results of those measurements or are computed through some experiments. In many cases, however, it is too expensive or risky or time consuming to measure the relevant values on the real system; or the parameters represent a relation which has simply been hypothesized or the aggregation of several effects. These parameters are thus estimated by solving a mathematical programming problem that minimizes a measure of the differences between real data and those obtained from the model. As an example, consider the fate of toxic substances dispersed into the environment and passing from one organism to another until they end up in harmful concentrations at the top end of the food chain. It is impossible to follow their accumulation within a living species, since the only feasible experiment is to measure their concentration in a dead organism. Furthermore, the precise mechanisms of concentration and release of these substances from organisms are largely unknown. One possibility is to use a simple bioconcentration model, with only two compartments: the environment and the organism. Starting with data on the substance concentration in the organism and in the environment at different times, it is possible to estimate the uptake and release parameters (which determine the exchange of substance between the two compartments) using a method that minimizes the simulation error. It is even more important, in cases like this, to compute the variances of estimated parameters; this allows to assess the statistical significance of the estimates obtained from the available data (see Galassi et al. 1988 for details).

It is interesting to note that in almost all cases the model error is measured by the well-known sum of the squares of the differences between model results and real data, which has come to be known as 'least squares' parameter estimation. However, a careful analysis of the problem to be solved may sometimes suggest other criteria for tuning the parameters. Since a model always constitutes an approximation to reality, it would be wise to try to get better performances (i.e. be closer to actual data) in those particular circumstances which appear to be most influential in solving the problem. One may consider, for instance, estimating parameters just by looking at extreme episodes or at some other particular condition.

Validation
Before using the model to take real decisions, it is important to check whether it is robust enough, i.e. whether its capability of mimicking the real system is not confined to the set of data which has been used to formalize and to calibrate it. If the model can be proved to perform satisfactorily with different sets of data, it has a better chance of having captured the important mechanism of the real system. It is thus necessary to have additional data and let the model work with them. Again, what 'satisfactory' means is a matter of debate: by definition, each researcher on environmental modelling means the performance of 'his' or 'her' model, whatever statistical results it has. Also, there is no specific method to carry out validation, but again one should be guided by the type of problem which must be solved. In many environmental problems, for instance, the performance of a system under critical conditions is of more concern than its behaviour under normal circumstances; thus, the set of data used for validation must contain significant episodes of this type. A model which can always guarantee a maximum deviation from reality is often more acceptable than a model which is almost always quite precise but which may deviate in critical cases in an unbounded way. This is due to the natural risk aversion of all decision makers, who prefer to be guaranteed against very critical situations in exactly the same way as anyone who pays a small insurance premium every year (maybe for an entire lifetime) to protect himself or herself against some improbable, but potentially catastrophic, accident.

An unsatisfactory validation may be due to two main reasons. The formalization of the problem may have been poor, which means that the analyst has to change his or her mind and perhaps try to get more information from the decision maker in order to modify the description of the real system he or she has conceived. Alternatively, the parameters may not have been estimated with sufficient accuracy. This normally means that more data (or more accurate data) must be collected and the calibration has to be repeated. Sometimes the criterion for calibration may be changed to improve the performances that the validation has shown to be unacceptable.

Use
Only after a model has been validated can it be put to use. The usage of a model means, in the present case, to test on it the effects of one or more alternative situations, either to better understand the structure and the behaviour of the real system or to find how to act on this so that it behaves in a more acceptable way. It is essential to remember that the use must be consistent with all the previous steps, and thus a model should not be used to solve a problem for which it was not conceived. This is a common error made
by people who think, for instance, that a given model of air pollution may be used for both short- and long-term pollution forecasts, although the atmospheric components involved in the two cases are completely different.

Coding the model development procedure
Programming (or using some software package) is normally necessary in various steps of the procedure outlined above. First, the conceptualized model is usually translated into a computer program; then it may be run several times as a subroutine of some optimization procedure for estimating the parameters; and, finally, it may be rewritten in a different version for actual use. During the entire model development procedure, several approximations are introduced (see Fig. 2.2). Besides the approximations introduced in the conceptualization phase and those due to the finite length of the computer words, other errors are due to the methods used to translate the model into an executable program. For instance, a continuous variable must be sampled in a finite number of time intervals, and an improper sampling may cause divergence problems in the integration of differential equations. The same is true for all optimization methods, which often consider some very low but non-null values as zeros. These kinds of problems will not be discussed here; they are widely treated in the literature (the reader may refer to any textbook on numerical analysis) and their effects on the solution can usually be established fairly accurately.

![Diagram](Problem perception)

- Some external effects are disregarded
- Some internal structures are simplified

Conceptualized model

- Parameter values are approximated

Calibrated model

- Continuous phenomena are sampled
- All numerical values are truncated

Computer executable model

Fig. 2.2 — Errors in the model development procedure.

There is another implementation problem due to the use of computers. Since the estimation procedure may be very time consuming, it sometimes uses a simplified version of the final program and may require a larger computer and sometimes even a different computer language. This introduces an additional and often not quite predictable noise in the procedure outlined above, since the parameters may have slightly different values and the computer and the coding itself may cause differences in the way in which the various mathematical expressions are evaluated.

There is no guarantee that the computer code finally released for actual use may still be sufficiently precise to help in solving the original problem. It is thus important to perform the validation on the final version of the program on the target computer, since this is the only way to check whether the entire software/hardware system is robust enough to assist in making real decisions.

From this point on, the word ‘model’ will be used in referring to a validated set of mathematical expressions coded in any computer language.

2.2 CRITERIA FOR COMPUTER APPLICATIONS TO ENVIRONMENTAL PROBLEMS

Many recent environmental symposia and conferences have been held with the declared aim of filling the gap between computer experts and modellers, on one side, and practitioners on the other (see, for instance, Tavares and Da Silva 1986, Zannotte 1986, IAHS 1989). This is a clear symptom that there are still problems in the successful application of systems and computer science techniques to environmental planning and management. The large effort on the research side has not generated a comparable diffusion on the application side because certain criteria for applying computers in this area have not been completely satisfied.

Theoretical research has been going on to define abstract criteria for assessing the quality and the suitability of computer models. Ören (1984) quotes more than 80 papers on this topic. Henize (1984) and Meadows and Robinson (1985) have concentrated on quality criteria for models that are used to make social decisions, among which are environmental problems. Some basic requirements that should be fulfilled to make models easily accepted appear to be the following:

- accuracy,
- robustness,
- simplicity,
- transparency, and
- adequacy.

Accuracy
As already anticipated, accuracy is normally the major concern in model development. It means that the model represents reality in a fairly close way, and consequently decisions suggested by using the model can be implemented (almost) without any modification. A number of methods exist to check this characteristic of the model (Sargent 1984). Scientists seem to prefer 'objective' measures as statistical tests (even if the degree to which a
test can be considered as satisfied is still a subjective judgement), while people involved in practical decisions prefer a direct comparison of model output and real data, both in terms of numbers and graphically displayed on the computer screen. In certain particular cases, the perception of small deviations, which cannot appear in any statistical analysis, in the model results may be the most important element in judging the accuracy of the model in practice.

Robustness
Robustness is the capacity of the model to filter out noise due to factors which were disregarded in the model formulation phase. Any formulation, in fact, only partially translates the complexity of the original problem, and several aspects must be simplified or ignored. In the same way the values used for parameters in the model simply represent an estimate of the true parameter values. The difference is due to the limited amount of data on which calibration is performed and to the method used.

When data differ from those used for calibration (and thus parameters differ from their 'nominal' values) and some unforeseen inputs enter the system, the accuracy of the model should not decrease significantly.

Simplicity
The model must be 'simple'; that is, the number of variables and parameters must be limited and decision makers must be able to understand its behaviour easily. The number of parameters is limited not only by the speed of execution, but also, in several cases, by the availability of data, since at least few tens of data for each parameter are required to obtain a reliable estimate. Furthermore, parameter estimation methods may provide poor results when confronted with very complex models, and one often finds that an improvement in the complexity of a model does not generate a comparable improvement in results.

However, the simplicity of the model itself is important in allowing people who are not familiar with these techniques to understand what the model means and why it behaves in a certain way even if this may contradict intuition or past belief. The lack of this characteristic prevents practitioners from having confidence in the model and thus from implementing the suggested conclusions.

Transparency
However, simplicity itself is not sufficient if it is not translated into an adequate computer code. This should allow the decision maker to look at single parts, variables or parameters or relations in the model and to modify them. In this way the user may 'play' with the model as much as he or she likes and may explore all the aspects of its behaviour. The possibility of modification enables more extensive testing of the model by the user and allows him or her to take advantage of the experience gained during model use. Sometimes this feature can be partially embedded into the model code by using recursive algorithms for parameter estimation or by using some artificial intelligence technique to improve or enlarge the fact base from which conclusions are derived.

Finally, the possibility of modifying the model has a clear psychological motivation. Users must perceive that they themselves are making the decision and that their responsibility is not taken over by the machine. The fear that a computer may prove to be more effective has motivated many managers to disregard it as an aid in their more difficult tasks. Computers are thus often used as data repositories or local controllers, but are rarely involved in the main decisions of environmental agencies. It is important to let users perceive them as tools that are able to perform more sophisticated calculations than old slide rules, but nothing more. There is no competition between the human and the computerized decision; the latter is simply the result of hypothetical well-defined conditions, which always differ from real ones, and as such is only an additional piece of information on which the final human decision is based.

Transparency is sometimes considered the most important characteristic of computer models and their major advantage over 'mental' models, those that anyone can use to make decisions. Even if transparent computer models are wrong, at least one can rigorously follow the path which leads them to a particular conclusion. One may suggest that this is typical of any computer program, but it is well known that logical errors may be so well hidden in a program that only a specialist can track them down.

Adequacy
The preceding features cannot be perceived, and thus have almost no practical meaning, if they do not emerge from the code in a form which is meaningful to the user. The suitability of the interface thus becomes a condition sine qua non for the acceptability of any model. The code should be able to speak the same language as the user, and the man–machine dialogue must be based on information which is known and accepted by the user. Chapter 6 will deal in detail with some of the problems connected with this aspect; at this point, however, it should be stressed that there are several ways to accomplish this. One is to target the software to a precise category of users. This means that a precise 'model' of user is known to the software developer and the required type of dialogue is included in the software specifications. The second is to prepare an interface which can interact according to various degrees of expertise of the users. Obviously, this means an increase in the time and cost required to develop software but the result may serve several different users within an institution. The choice of the level of the dialogue may be made directly by the person who sits at the keyboard or it may be made by the software itself, using some artificial intelligence features to test user understanding (see Chapter 6, and also Ushold et al. 1984 and Bundy 1985).

All of the criteria outlined above can only be judged from a subjective point of view, and therefore it is of great importance that they are agreed upon between the software developer and the program user. Sargent (1984) ranks this recommendation first in a list of possible measures to improve
2.3 ENVIRONMENTAL DECISION SUPPORT SYSTEMS

The rest of this book is devoted to the analysis of the various facets of what will be called an environmental decision support system (EDSS), i.e. a computer system to help decision makers in environmental agencies and organizations. Thus a detailed analysis of all its major components will be carried out in the following chapters. It should be pointed out from the very beginning, however, that an EDSS also fits nicely into the general framework presented in Chapter 1, and thus it has no peculiar architectural features. However, the contents of its data, model and knowledge bases must reflect the features of this application domain.

Before turning to a detailed discussion of EDSS, it will be necessary to analyse the kind of problems which could be solved with its support and the human environment in which the authors believe the EDSS will operate. It is clear that the definition of EDSS that will finally emerge from this chapter and, probably, from the entire book is too vague to represent a paradigm to follow in the realization of new EDSS. Nonetheless, attention will be drawn both to some common problems and to some possible solutions useful in the realization of effective systems. Any further objective is outside the scope of this book, given the complexity and variety of environmental problems and the general debate still taking place on what a DSS should be (see, for instance, Keen 1987).

Some common features characterize environmental problems even if they are not unique to this area.

Dynamics

Environmental problems have a significant dynamic component, which means that the conditions of the real system, at the time the decision is made, are the results of all the past history of the system and influence its subsequent behaviour. This dynamic characteristic of the environment may be represented explicitly in the problem formulation or only implicitly by suitably formulating the problem constraints (see Chapter 4). Usually, however, this characteristic is translated into the model formulation by using a set of difference or differential (total or partial) equations.

This dynamic aspect is possibly the major feature of environmental problems and stresses the importance of having in the model base the possibility of accurately portraying it. In this connection, it is important to underline the role of simulation models, in which this characteristic can be more easily and intuitively represented.

Spatial coverage

Another essential aspect of environmental problems is their spatial dimension. While in many other application domains the problems under study are confined within very precise (and usually small) borders, for instance a plant, a reactor or a firm, environmental problems deal with spatially varying phenomena with no or very unclear borders. For example, circulation in the atmosphere is a typically unconfined three-dimensional problem, and the circulation of a pollutant in a reservoir takes place in three dimensions, even if the borders are more precise (it is still unclear how to determine exactly where the reservoir starts and the tributary river ends).

This feature requires in principle the use of partial differential equations to model both the time and the spatial dimensions, but, in addition to their numerical complexity, it is often difficult to set sound boundary conditions for them. This is why a number of methods have been developed to lump spatially varying values into one or few aggregate measures. Partial differential equations reduce in this way to total differential equations, a tool which is less difficult to handle from a numerical point of view. Furthermore, continuous variables are always sampled at finite time intervals, and thus difference equations represent quite a common formulation for many environmental problems. It should be pointed out that this series of approximations may not result in a reduction in the accuracy of the model with respect to more sophisticated ones. It is, in fact, useless to utilize accurate mathematical descriptions, like partial differential equations, if the uncertainty about other information, for instance boundary conditions, is very high. A more crude (and simple) technique may have less technical problems and thus lead to results with similar (if not higher) accuracy.

The sectors of environmental science where spatial variability can be disregarded or where simplifying assumptions (such as spatial homogeneity) can be adequately made have benefited by the possibility of formulating problems in a more convenient way. Researchers in water resources, for instance, have developed a number of lumped models for superficial flows, while studies of atmospheric pollution have been based more on the use of two or three spatial dimensions.

The question on where to fix the model boundaries is also linked to the spatial characterization of environmental problems. Every model must in fact include a number of factors or a number of social entities or a certain area, but lump the effects of all the rest of the world into few input or parameter values. A careful decision on which part of reality can be formalized and which should be simplified is important in providing really useful suggestions to the decision maker. A support in this area may be, for instance, the possibility of running different models at a larger and at a smaller scale and then comparing their results. If they do not diverge too much, either may be used for further investigation. This again means that the modelbase must be rich in models with different coverage to allow these comparative evaluations.

Periodicity

Another important feature is periodicity. Although, in fact, long-term trends are sometimes important, even in environmental management and
planning, in the great majority of the problems there is a strong periodic component due to the annual cycle of nature.

In some problems, cycles with a longer period appear: for instance, hydrological variables seem to be influenced by sunspots (which have a period of about eleven years) or salmon come back to their birthplace to reproduce (and can thus be caught) three to five years after having left it to reach the ocean. In other situations, a shorter periodicity can be detected: the chlorophyll photosynthesis of vegetation typically has a daily cycle due to sunlight and, again, for solar radiation, the temperature of the air close to the ground oscillates in the same way.

Human activities also have the same kind of periodicities (daily and yearly cycles), but may also induce effects with a new and ‘synthetic’ time scale. The release of a reservoir to produce hydroelectric energy may show a weekly cycle due to the decrease of power demand during weekends. Thus, a river flow which receives water discharged from that reservoir may also oscillate with a weekly component in addition to the normal annual cycle.

Determining the appropriate time scale of the problem at hand is of major importance in formulating it in mathematical terms and deciding correctly upon it. The periodicity of the phenomenon is an important factor in determining the management or the planning horizon for which a decision must be made.

Randomness
A stochastic component is always superimposed on the cyclic one in environmental problems. There is no need to give examples of this aspect of behaviour of all natural and social systems. Strictly speaking, if one looks merely at microscopic phenomena (and avoiding any philosophical discussion on what ‘randomness’ really means), one can always find a cause for any particular natural event. However, since these causes are often outside the scope or the spatial or temporal resolution of the problem or if there is no precise data on them, it is often more simple to represent them as a stochastic noise or ‘disturbance’ of the natural periodicity. This conceptual simplicity corresponds, however, to an increase of the complexity of the mathematical formulation and raises some interesting questions about decision making in non-deterministic conditions, which will be briefly dealt with in Chapter 4.

Complexity
Another characteristic of environmental problems is their complexity in terms of the multiplicity of criteria or points of view under which they can be seen and of the involvement of different social groups. Several different technical means have been suggested to translate these complex facets into the problem formulation, but they have largely failed up to now to produce operative solutions that are acceptable to the decision makers. This is why a more recent and flexible approach (see again Chapter 4) has abandoned, at least in part, the idea of being able to translate an environmental problem into a mathematical optimization program, extending the use of simulation models which can easily answer ‘what if’ type of questions.

Simulation models are in fact easier to implement, may become very complex without being prohibitive for small computers and allow a direct involvement of the decision maker in the formulation of the hypothetical decisions to test.

Massive data requirement
The last characteristic to be emphasized here is the need for a great deal of data to properly model and verify an environmental problem. This is due to the complexity of the problems already mentioned and to the need for thoughtful experimentation before a model goes into actual use. Environmental decisions are in fact risky decisions, and one obviously wants to reduce the possibility of errors to a minimum.

Data used in these kinds of problems have, in general, a precise structure due to their time and geographical links (see Chapter 3). Time-varying data are usually connected into time-series and thus can be easily represented, for instance as arrays, in any programming language. Static data often describe the physical characteristics of the real system and are usually characterized by their position in space. A record structure, with three fields to describe the space coordinates and a fourth field for the specific value, is a possible data structure and is often used to represent these items. Obviously, there are many other less structured types of data, but they usually comprise only a very small percentage of the two quoted above. For instance, the computerized description of a certain area may be constituted by a regular grid of spatial positions, some time-series of environmental variables associated with specific measurement points, and a set of data representing the region border.

EDSS structure
In adapting the general DSS objectives stated in Chapter 1 to the case of environmental problems, an EDSS can be seen as a computer system that is able to handle models with the characteristics mentioned above; to connect them to create more complex model structures; to assist the user in developing new models following the procedure outlined in section 2.1; to manage the exchange of environmental data; and to include parameter estimation and optimization facilities. Its final aim should be to help the user in finding some structure in the problem to be solved by allowing him or her to screen different well-defined models (the only kind of models the computer can handle) to find those which appear close to the original system and to test on them the effects of some proposed actions. These actions, in turn, may be simply tried by the user or generated by the computer in order to satisfy some user-defined criteria.

To perform these tasks, the architecture proposed in Chapter 1 and presented again in Fig. 2.3 seems to be well suited.

The Database should be designed in order to perform in the best manner when dealing with spatial data and time-series; the Modelbase should
contain a large set of models of environmental systems; and the Knowledge base should provide all the necessary information for handling models and data, such as how to run each model, its data requirements, and in which cases it can be utilized. Finally, the System Manager should provide the necessary coordination between the various bases in order to create new models, or connect existing ones.

It is important to realize that several different types of expertise must converge to implement such a system: computer experts for defining the bases’ structure and the system software; modellers to fit an accurate formulation of different problems in the modelbase; and environmental engineers to guarantee the coherence and the reality of the overall design and to fix a suitable level for the interface. These experts must work in strict cooperation, or the development of such a system will remain, as many others, a ‘paper project’.

2.4 USER AND SYSTEM ENVIRONMENTS

In order to discuss the EDSS structure in more detail, it is important to analyse who are the users of the system and its role in an environmental institution.

A computer system of the type proposed above may be the key instrument by which an environmental authority may test the effects of alternative decisions and perform a series of studies on the environmental problems in its area of interest.

The institution in which this system is to be implemented is supposed to bear full responsibility for a certain set of environmental decisions; it is in a higher position in the hierarchy than all the other parties involved in the real system. That is, there is a unique decision maker (the agency, even if decisions are taken by a group of people within it), and any other entity carrying out any activity in the system has to take the agency’s decision for granted. This means also that decisions taken by the agency enter into someone else’s problems as external inputs that cannot be modified.

This assumption, which is probably the most realistic one in environmental problems, means that all the multi-decision makers’ problems and techniques, for instance ‘game’ or ‘team’ theories, will not be dealt with by the proposed EDSS.

Since decisions usually become more complex and difficult in the medium to long range and different aspects of the solution have to be considered, the proposed EDSS is intended basically for planning purposes and not for routine control operations. It is not directly connected to a measurement network or to implementation devices. Occasionally, it may be connected to such existing networks to gather data and information necessary for a specific study, but it does not represent the normal database of the agency. A computer which (at least for software if not for hardware) works offline with respect to the routine activities of the agency can be used. The EDSS is thus a sort of laboratory to investigate environmental behaviour and the effects of man-made actions. In this connection, it may also be the prototyping environment in which other computer applications are tested.

If the problem at hand is a typical planning problem, such as locating a facility, investing in environmental protection actions, or formulating a rule regulating fishing or hunting, the EDSS should provide all the tools needed to devise and experiment with an acceptable solution which the agency can adopt.

In the case of more complex problems, the final decision may envisage the use of a computer for daily operations. For instance, in order to tackle the problem of reducing the short-distance fall of pollutants due to emissions from a power plant (see Chapter 4 for details on this problem), the computer is used to plan the type of meteorological variables to measure, the frequency of those measurements, the control policy to use (filter emissions, substitute fuel, etc.), and how to implement the policy. EDSS should help in deciding these points, but subsequently the control system must be implemented on a different computer, possibly in a different computer language, with different input-output facilities. The person in charge of the control of the plant will not in fact be the same person who made the decisions about the structure of the entire control system. This is, in a certain way, the approach followed by some recent simulation software packages (for example, Modeller 100, Xanalog, Genesis), which offer a wide variety of facilities to design a simulation or control program but then produce an executable version (in a different computer language) of the model which is much less flexible, even if computationally more efficient.

The user of an EDSS will most probably be an environmental engineer with some detailed knowledge about the problem he or she wants to solve and who must not be involved in software development or hardware problems. The user will be asked to suggest to some political authority or to
implement directly, if the social and economic involvement is below certain thresholds, technically sound decisions on a variety of problems in a time span which may vary from days to months. Thus, the user cannot undertake extensive research efforts or data collection campaigns. He or she will often have to operate with insufficient information and with poorly structured problems, owing to their complexity and multifaceted nature. The environmental engineer thus needs an instrument that allows him or her to model the problem and test alternative solutions in a relatively short time span, sometimes postponing the attainment of greater accuracy to subsequent, more detailed studies.

2.5 REMARKS ON HARDWARE AND SOFTWARE

The series of tasks outlined in the previous paragraphs call for some comments on the hardware and software necessary or useful to accomplish them. The computer may be of any type, although a personal workstation connected to the agency's local area network (LAN), as shown in Fig. 2.4, will probably be preferable. Mass storage for data should be largely available, but not comparable with the agency's main environmental data bank. The latter may be on some large device, which need not be extremely fast, since data retrieval (when data are available on a computer medium) is usually just a limited portion of the work needed to solve a problem. Environmental data are suitable for storage on a WORM device, a write-once/read-many times removable disk based on laser technology which may offer capacities of several hundred megabytes at a very attractive price. A characteristic of environmental data is that they are static in the sense that new data are always added to a time-series, but stored data are corrected only very rarely, for example when an error is discovered or when an unrecorded value can be replaced by a meaningful value.

A connection to the central data bank is obviously desirable, but this is automatically achieved with a connection to the agency's computer network. The computer will probably use a mouse as the standard input device, but a digitizer may be present to acquire geographical data directly as well as to digitize rapidly old data registered by instruments writing on paper strips.

A direct connection with the telemetering network should be available to test applications based on it, but it will be active only occasionally, since continuous data registration is not a task of the EDSS. It may not be necessary to plan such a connection, because it is quite probable that the telemetering system will also work, possibly through a concentrator, as a node of the overall computer network.

The major output device is represented by a high-resolution colour graphic monitor and by a printer–plotter for hard copies. The possibility of connecting the monitor to a videobeam is useful in order to use the machine as a device to generate and support an open-minded exchange of ideas during a meeting with people involved in the practical problem. A floppy disk system will also be required for the input of data from machines outside the network or for transferring the results of the prototyping phase to special-purpose computer systems.

Choosing the kind of software necessary to accomplish this job is usually a twofold problem. On the one hand, one would like to give to the user the greatest possible power and freedom and thus will conclude that the user should simply be given a very powerful computer language with database access and advanced programming facilities (see Chapter 5) (a recent application of such languages for the development of environmental models can be found in Keffer 1988) or, at least, a general-purpose simulation language. On the other hand, one might think that the user should not be involved in programming and program testing but that some power and freedom may be sacrificed to allow him or her to state problems and models in the easiest possible way. In this case, the user will probably always operate within a very high-level software environment in which he or she may find a number of facilities useful in carrying out the job. The interaction will always be through reduced input facilities such as menus, and this will in some way limit the user's power to those functions which have already been prepared in the machine. Obviously, all menus could be modified and enriched, but this can be accomplished only through some programming and thus, in the present case, must be performed by someone other than the user, who has the necessary computer background. Such a software environment will probably also use an artificial intelligence technique to identify the user's needs and to allow a more natural interface. This confirms that any modifications of the software will normally be outside the user's reach.

A feature that would be advantageous in both cases is that of accessing from and embedding into the EDSS software all the models already
developed by the agency and available in a computer usable format. The optimum would be to reuse them without the need to recompile and relink them, but this implies a high level of compatibility between the EDSS and the operating systems of the agency’s other computers. One possibility (see, for instance, Taylor and Hurrien 1988) is to use the EDSS computer to drive another computer in which the required model is available through the network software and by exchanging messages and files between the two machines. This idea may be particularly attractive if the model the user wants to run is extremely large and thus requires a mainframe in order to get an answer in a reasonable time. However, these cases are normally limited, and the coordinated use of two machines on the network normally slows down the execution speed considerably.

2.6 LEARNING BY EXAMPLE

Given the problems outlined above, it appears impossible to devise a formal procedure for the synthesis of an EDSS. Thus, an alternative approach will be followed here, based on the analysis of several examples which reflect in various ways the general framework presented in this and the previous chapter.

The following four chapters will be devoted to the evaluation of single components of the EDSS database, modelbase, knowledge base, interface and will analyse in some detail existing systems in which that component has been particularly well developed. None of those systems fits exactly the definition of EDSS that has been given, and a fairly complete prototype will be illustrated in Chapter 7. However, each of the systems presented has been fully developed in order to fit some real decision context and thus reflects, at least partially, some of the needs of decision makers.

Before closing this chapter, a few examples of actual computer installations within environmental institutions will be given in order to show the range of possible applications and the kind of problems involved. They span the range of problems an EDSS may cover and are important either for historical reasons or because they are representative of new trends in the use of computers in environmental planning and management. Most of these examples are taken from the field of water resources management, since, as already pointed out, the application of computers in this area of environmental science started earlier and spread most rapidly (Rinaldi 1984).

NEDRES: A database of geophysical information

The US National Oceanic and Atmospheric Administration (NOAA) maintains a large database concerning all information on the natural environment, particularly oceanic and atmospheric measurements, in the United States (Barton 1987). The database, called NEDRES (National Environmental Data Referral Service), does not contain the data themselves but rather all the information necessary to check whether they are available and how to get them. The computer storing all this information is located at BRS Information Technologies, Latham, New York, and anyone who has been provided with the necessary NOAA password can access it through a standard telephone link.

The database constitutes a reference for any environmental research and considerably shortens the time which is normally spent searching for information as the preliminary step in any investigation. Furthermore, it combines information from many different sources and thus allows a multidisciplinary approach to any environmental problem.

NEDRES presently contains more than 16,000 data descriptions taken from data catalogues, publications, bibliographies, computer program manuals, users’ guides or related documentation. Each data description is quite large and contains a title, an abstract of about half a typewritten page, information about the data collection, the period of interest, the geographical location, a description of the measured quantities, the contact person, the availability and data-related publications. The overall description of a single entry of this type may thus last for several pages. A fairly similar data structure has also been used by Guariso and Werther (1988) to store information relative to environmental models.

The interesting aspect of NEDRES, from the computer science point of view, is that, being directed to a variety of people with extremely different degrees of computer experience, it has been organized for highly user-friendly interaction. The search for an item can be accomplished by asking for all records containing any English word or set of words. All words contained in an item are indexed (except conjunctions or prepositions such as ‘and’, ‘to’ or ‘not’). In this way, the text of each description can be in plain English and the retrieval does not need any particular query language. The disadvantage of this approach is obviously in the amount of mass storage needed for the index, which often exceeds the disk occupation of the data themselves. However, the availability of systems like CD-ROM (Compact Disk-Read Only Memory), read-only devices which use standard compact disks as a medium, may bring this kind of application into the range of personal computers.

Instead of publishing printed bulletins, a large environmental agency whose data are of interest to a sufficiently high number of users will probably issue in the future a quarterly or yearly CD-ROM with all environmental data and the required indexes in much the same way as has already been done for some publications of general interest (for instance, the American Encyclopedia).

The Cleveland solid waste collection system

At the beginning of the seventies, a severe budget reduction of the Waste Collection and Disposal Division in Cleveland, Ohio, called for a complete revision of the collection system and, in particular, for a change in the crew composition, in the type of trucks and in the general schedule of work (Clark 1973). At that time, the city had a population of over 700,000 and disposed of about 320,000 tons of solid wastes at a total cost of $14.3 million US dollars per year.
The first step towards the reduction of these costs was the establishment of a computerized information system containing all the information about the service from constant data, such as vehicle capacity, cost and expected life, to daily data such as precise time vehicles left and returned to the motor pool, mileage, weight of the collected wastes, etc.

Starting from these data, it was possible to formulate precisely a mathematical model of waste collection in order to reschedule it in a more cost-effective way. The model was coded in the programming language Fortran and used only by computer experts. Owing to limitations of the computer available at that time, the results were reported on paper to decision makers, who had to ask the computer people to check additional scenarios or produce more detailed outputs as required. The computerized planning of the service allowed a cost reduction of more than 6 million dollars per year (Clark 1974). This is often quoted as one of the first examples of the success of modelling and computer techniques in environmental problems (Beltrami 1977).

The River Dee Regulation Scheme
The River Dee has an 1800 square kilometre catchment area in North Wales; during the period 1966–1976, it served for a pioneer research programme on computer-assisted reservoir regulation sponsored by the UK Water Resources Board and by the Welsh Water Authority. It probably has one of the longest records of experience in applying computer and modelling techniques to environmental problems.

The first installation of a computer which connected some telemetering stations dates back to 1972 (Jamieson 1972, Wilkinson 1972, Jamieson and Wilkinson 1972). The purpose of the network was basically to improve knowledge of the current status of the river system in order to regulate the release from four upstream reservoirs (see the map in Fig. 2.5) with a total capacity of 147 million cubic metres. These reservoirs controlled about one-third of the total runoff of the area and were operated for several different purposes. Historically, the first purpose was to supplement the river's natural flow during the dry season in order to allow abstraction of about 10 m³/s and guarantee a minimum flow at Chester of about 4 m³/s. More recently, the system has also been used for flood control purposes in the downstream plain and in the town of Chester. Drinking water supply, hydropower production at the reservoir dams, recreation, safeguarding fisheries, and the control of the intrusion of salt water at Chester Weir during high tides are some of the other objectives of management.

The control system is based on a computer centre at Bala, near the major control point of the river. It receives information every half hour from the four reservoirs, 15 flow telemetering stations and five rain gauges connected through radio and telephone links. Forecasts of the situation for the next 48 hours (about the time it takes the water to travel from the most upstream reservoirs under low flow conditions) are computed on the basis of simple regressions and water balance models, and, if they are found unsatisfactory in some point of the basin, the calculation is repeated with different hypotheses on the releases from the reservoirs. In this way, the managers can test the effects of alternative solutions before taking their final decision.

The system is under continuous improvement (Lambert and Lowing 1980), and the managers are relying more and more on the information supplied by the computer: in 14 years of operation, the number of floods at Chester dropped from three per year to a single episode.

The Canal de Provence on-line control system
The Canal de Provence is a large artificial canal system in the south of France (see Fig. 2.6). It distributes an average flow of about 40 m³/s through a canal network of several hundred kilometres, mainly for hydroelectric and agricultural purposes.

The main feature of the system is that the agricultural irrigation network is under pressure and completely 'demand driven', which means that each individual user may freely operate the control structure for a direct supply of water. Thus, the purpose of management is to supply the required water, avoiding losses and minimizing cost, while always satisfying the hydraulic constraints of the system.

Starting in 1970, the system has been automated by mechanizing the main control structures, setting up a telemetering network which reports the situation at many control points to a main computer, and developing models to forecast users' demand. Since the travel time of water within the system is of the order of 6 hours, only variations of the demand within the same day are significant and a 12-hour forecast is sufficient to plan the discharge of upstream reservoirs and for setting the positions of all the control gates. In
In this case, the computer acts exactly as a standard process control system, almost without intervention of the operator. The agency responsible for water supply (Société du Canal de Provence) is quite satisfied with the performance of the forecasting and control system and quotes a maximum departure from the target flows of around 15% (Declaux 1985).

OASIS: An artificial intelligence tool to support water management in South Florida

This application relies heavily on artificial intelligence methods. The system has been designed to support the management of the South Florida Water Management District, which operates more than 200 water control structures along 3200 kilometres of primary canals in a region of about 46 000 square kilometres (see Fig. 2.7). The District operates its storage facilities and canal network in order to prevent flooding during the wet season (June–October) and to supply water mainly for agricultural purposes during the dry season. Other management objectives include environmental and water quality conservation, preventing salt water intrusion, protecting South Florida wetlands, and providing sufficient discharge to a national park. In order to monitor the behaviour of such a complex system, the District is equipped with a sophisticated microwave telemetering network, which processes up to 250,000 records per day from 650 gauges and field personnel observations. This information, together with meteorological forecasts, historical statistics, intuition and 'common sense', provides the basis for daily operation decisions of the District's managers.

In 1985, the District decided to automate part of the operation procedures, encoding the managers' experience into an expert system called OASIS (Operations Assistant and Simulated Intelligence System) (SFWMG 1987).

The system, which is presently under completion, utilizes special hardware (a Symbolics 3640 computer) and software (ART, Automated Reasoning Tool, an expert system shell from Inference Corp.). This shell translates a rule-oriented user language† into the programming language LISP and offers additional utilities to create a very friendly user interface. The rules used in the system are of the type 'IF a certain situation occurs THEN take a certain decision' and translate the experience acquired by the district managers over a period of 15 years. They represent the control and measurement actions which are undertaken by the agency in all possible situations. These rules are thus very complex and site-specific and submit to the operators a set of decisions for all storage, pumping and canal facilities based on the experience gained on past occasions.

The expert system has been integrated into a more complete information system that provides real-time data display and historical and current data plots, checks actual alarm conditions and forecasts future ones.

† Chapter 5 will discuss these software tools in some detail.
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