Expert Systems for Environmental Screening

An Application in the Lower Mekong Basin

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Preface

This research report describes MEXSES, a rule-based expert system for environmental impact assessment at a screening level, implemented for the analysis of water resources development projects in the Lower Mekong Basin. The system was developed and implemented under contract to the Mekong Secretariat, Bangkok, Thailand.

The system provides an example of a qualitative and logic-based technique for the analysis of complex environmental assessment problems. Rather than attempting to predict, in any absolute sense, environmental impacts and to evaluate them, we have organized the available information in a consistent and plausible framework that links project characteristics and environmental features to expected impacts in a simple logical format of IF ... THEN rules. This assessment is based on mainly qualitative descriptions of the relevant variables and descriptors of development projects and the environment. It uses logic and rules derived from expert opinions, rather than algorithms and numerical models, to arrive at conclusions, and thereby an assessment of expected environmental impacts.

MEXSES represents an experimental approach to the analysis of complex systems. Recognizing that the uncertainties are tremendous, our main objective is to construct a plausible and consistent framework for thinking about the problem, a tool to organize and analyze the available information in a specific institutional and planning-oriented context.

Rather than numerical precision of questionable origin, we seek to identify basic patterns and trends and approximate classifications, and to challenge our own mental models (or any numerical ones for that matter), in a dialogue with the computer. The expert system is primarily an attempt to model our understanding, our perception of the problem, rather than "reality". It is also designed as a collection and repository of expertise and relevant information, compiled from more than one expert and numerous other sources of information, in a format that can directly, and in fact automatically, be brought to bear on the difficult task of environmental impact assessment.

So as to organize the relevant information, MEXSES provides specific checklists for development projects such as dams and reservoirs, hydropower and irrigation projects, or fisheries, aquaculture and navigation development. The checklists are based on the *Environmental Guidelines Series* of the Asian Development Bank.

The system uses hierarchical checklists, organized by problem classes, following the logic of project planning and implementation and a qualitative assessment procedure based on rules and descriptors, which allow the analyst to assess the individual subproblems identified in the checklists in terms of their expected environmental impacts. On the basis of this list of estimated impacts, a summary assessment of a given project can be performed in terms of a few aggregated criteria covering environmental as well as socio-economic aspects of river basin development.

The knowledge representation uses a simple syntax for rules and decision tables, that operate on descriptors of project features, environmental characteristics and impacts. The descriptor definitions are implemented in a frame-like, object-oriented language that includes the descriptor name, the list of symbols and associated numerical ranges for allowable descriptor values (most descriptors can have both numerical or symbolic values concurrently), references to rules that can be used to derive a descriptor value from other descriptors, instructions for an **ask** function to obtain the value from the user interactively, and the linkage to a hypertext system of *help* and *text explanation*, background information, definitions of concepts and a glossary of terms.

The inference engine uses look-ahead pre-processing for the dynamic pruning of the inference tree. It offers both forward and backward chaining functions for standard assessment and an alternative hypothesis testing feature, respectively. Different modes of interaction, all based on a fully menu-driven graphical user interface implemented in X Windows, offer alternative levels of verbosity with the optional display, and selection by the user, of rules, as well as an integrated hypertext system of *help* and *explanatory text* functions.

In addition to the expert system proper, the software system includes a project data base as well as an integrated geographical information system (GIS) for the management of spatial environmental data.

The report makes a brief review of environmental impact assessment methods and tools. It discusses expert systems technology, with emphasis on environmental applications. The Lower Mekong Basin and its specific environmental problems, as well as the Mekong Secretariat's environmental policy are examined. Subsequently, the software system is described from a user's perspective, followed by a detailed description of the methodology employed and its implementation. In the final chapter, a number of issues around the successful application of such a system are discussed, including a number of suggested improvements and extensions to the current operational prototype.

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Chapter 1

Environmental Impact Assessment: Background and State of the Art

Human activities, such as those that relate to large scale water resources development projects, construction, agriculture, energy, industry and development projects, considerably affect the natural environment. These effects or impacts occur during the construction phase, the operational life time of a project, and in many cases, as with waste disposal sites, may continue long after closure of a plant or site or the completion of a development activity. Consumption of natural resources, including space, water, air and biota, and the generation of wastes including the dissipation of energy and noise, usually lead to a degradation of the natural, and above all, the human environment.

Environmental considerations are becoming increasingly important components of planning. Many countries, pioneered by the 1969/70 *National Environmental Policy Act* (NEPA) of the United States, have introduced appropriate legislation calling for the explicit consideration of environmental impacts in the planning and decision making process for large projects. For an international comparison of Environmental Impact Assessment (EIA) procedures and examples from various countries, including developing countries, see e.g., Munn, 1979 for an international overview including the CMEA countries; Gresser, Fujikura and Morishima, 1981, for Japan; Clark, Gilad, Bisset *et al.*, 1984, for developing countries; or the Asian Development Bank (ADB, 1988) for selected member countries.

The landmark legislation of NEPA contains three major provisions (Liroff, 1976), by which it:

1. Established environmental quality as a leading national priority by stating a national policy for the environment;

2. Made environmental protection part of the mandate of all federal agencies, establishing procedures for the incorporation of environmental concerns into agency decision making. In particular, it requires federal agencies to prepare an environmental impact statement for major actions or projects that can affect the environment;

3. Established a Council on Environmental Quality in the Executive Office of the President to oversee and coordinate all federal environmental effort.

Environmental impact statements, as regulated by the Act, must contain:

- A description of the proposed action, its purpose, and a description of the environment affected;

- The relationship to land use plans, policies, and controls for the affected areas;

- The probable environmental impacts, positive and negative, direct and indirect, and possible international implications;

- A discussion of alternatives;

- The probable negative impacts that cannot be avoided or mitigated;

- The relationship between local and short-term use and long-term considerations;

- An irreversible commitments of resources;

- A description of federal actions to mitigate and offset adverse effects and

- Comments from reviewers.

Numerous regulations or guidelines for environmental impact statements follow this basic pattern, with some variations. One of the more recent is the Council Directive of the Commission of the European Community

(CEC, 1985). The Directive on the assessment of the effects of certain public and private projects on the environment (85/337/EEC, June 1985) requires comprehensive environmental assessments of projects and installations involving hazardous materials. These assessments are to include consideration of the production and storage of materials such as pesticides, pharmaceuticals, paints, etc. A broad analysis of the direct and indirect effects on people, environment, property and cultural heritage is also foreseen and the evaluation of alternatives is required.

EIA requires the qualitative and quantitative prediction and analysis of the impacts of human activities on the environment. Ideally, environmental considerations should be given equal weight as economic and technological considerations and be an integrated part of planning from the earliest stages. Further, the often long-term environmental, and thus social, costs should be included in a project's assessment and the minimization and mitigation of environmental costs should be a definitive part of the design.

For water resources projects in general, and river basin development projects in particular, impacts on the environment include:

- Land use and pollution during construction (of a dam/reservoir or irrigation project), including temporary, secondary problems caused by construction teams, transportation, equipment, etc.;

- Impacts on the environment during operation of the project due to alterations in the environment such as change of water flow and subsequent downstream effects, discharge of wastes into the atmosphere, water, and soil, possibly causing environmental and human health hazards, as well as those due to related or induced activities;

- Impacts on, or pollution of, the environment and acute hazards to man during abnormal operating conditions such as extreme floods or accidents such as dam breaks, or anaerobic water in reservoirs or hydrogen sulfide fish kills during and after reservoir filling;

- Environmental degradation due to the consumption or exploitation of renewable and non-renewable natural resources, in particular, land required for the project;

- Secondary environmental impacts due to changes in land use, population density, and the socio-economic structure around a new reservoir or development project.

Comprehensive impact assessment, however, should also look at the positive impacts, i.e., environmental improvements that are possible directly (e.g., material substitution or hydropower replacing fossil fuel) or indirectly (due to increased revenues) as a consequence of a new development project. Further, impact analysis should be a comparative, not an absolute assessment: the opportunity costs (in terms of the projects not chosen, including the alternative of no project at all, in favor of a given one) have to be considered.

Environmental impacts depend on two major factors:

- The choice and scale of the project and its technology, pollution control and mitigation measures, and the operating conditions (such as reservoir operating rules) and management of a project;
- The location of the activity, i.e., the specific environment that will be impinged upon and which may in turn affect the project.

While the technological aspects can be treated at a generic, site-independent level and thus with generic data that can be compiled *a priori*, the site-specific part requires a case-by-case study and local data collection effort as part of an environmental assessment.

Numerous sources of information on environmental impacts, pollutants, waste management, environmental standards and criteria, impact assessment methods and software tools exist in the scientific literature, the publications, manuals and guidelines of numerous institutions and government agencies, or in public and commercial data bases and information services. These sources of information provide necessary and critical inputs to the various impact assessment methods and therefore deserve special attention.

Methods for the assessment of environmental impacts range from simple checklists and qualitative impact matrices to much more complex computer-based approaches using, for example, simulation modeling and optimization, geographical information systems (GIS), or expert systems techniques. The methods of assessment also ought to include some of the more important aspects, such as legal, procedural and institutional components, that may differ widely from country to country and from project to project.

Methods that do have a track record of repeated use, and have been described in the respective literature, include, for example:

- Graphic overlay methods (McHarg, 1968; Dooley and Newkirk, 1976)
- USGS Matrix (Leopold, Clarke, Hanshaw *et al.*, 1971)

- Network Analysis (Sorensen, 1971; Sorensen, 1972)
- Cross-impact Simulation (Kane, 1972)
- EES: Environmental Evaluation System (Dee *et al.*, 1973)
- HEP: Habitat Evaluation Procedures (US Fish and Wildlife Service, 1976)
- Decision Analysis (Keeney and Raiffa, 1976)
- WRAM: Water Resources Assessment (Solomon, Colbert, Hansen *et al.*, 1977; Richardson, Hansen, Solomon *et al.*, 1978)
- EQA: Environmental Quality Assessment (Duke *et al.*, 1977)
- METLUND Landscape Planning Model (Fabos *et al.*, 1978)
- Goals Achievement Matrix (Hill, 1968)
- WES: Wetland Evaluation System (Galloway, 1978)
- AEAM: Adaptive Environmental Assessment (Holling, 1978)
- EQEP: Environmental Quality Evaluation Procedure (Duke, 1979)
- CBA: Cost–Benefit Analysis and related methods: numerous authors
- Interactive Systems Analysis and Decision Support (Fedra, Li, Wang *et al.*, 1987; Fedra, Karhu, Rys *et al.*, 1987; Fedra, 1988; Fedra, 1991).

In terms of causality considered, methods are based on checklists or questionnaires, cross-impact matrices, or complex network analysis involving second- and higher-order effects and feedback. In terms of formats, they range from narrative and qualitative descriptions to various attempts at quantification and formalization, from monetization to graphical methods. In terms of procedures, they may involve experts or expert teams and panels, workshops or public hearings, to court proceedings. In terms of tools, they may be based on guidelines and manuals or involve computer-based tools. Usually, any practical impact assessment involves a combination and mixture of several such components.

EIA procedures and approaches are often organized around checklists of data collection and analysis components (e.g., De Santo, 1978; Munn, 1979; Bisset, 1987; Biswas and Geping, 1987). Basic components of the assessment process are:

- A description of the current environment, which usually includes such elements as rare or endangered species, special scenic or cultural components;
- A description of the proposed project or activity, covering technological, socio-economic, and administrative and managerial aspects;
- A description of expected impacts, with emphasis on irreversible change and the consideration of mitigation strategies and project alternatives, including the alternative to not undertake the project;
- and, depending on the mandate given, a comparative evaluation of options.

Obviously, the prediction of impacts is the most difficult part. Approaches range from purely qualitative checklist-based matrix approaches (Leopold, Clarke, Hanshaw *et al.*, 1971), expert panels and workshop techniques (Holling, 1978), system diagrams and networks, to various computer-based modeling techniques (Kane, Vertinsky and Thompson, 1973; Thompson, Vertinsky and Kane, 1973; Gallopin, 1977; Patten, 1971; Walters, 1974; Bigelow, De Haven, Dzitzer *et al.*, 1977; Fedra, Paruccini and Otway, 1986), or any combination of these approaches. However, most of the accepted and routinely used tools of EIA are not based on the use of computers, but on more or less formalized qualitative assessment procedures. Also, most methods are somewhat general, and have been developed in a context other than the impact assessment of water resources projects. Few of the methods discussed below are associated with concrete tools: they are approaches rather than tools, and where tools have been developed, they have been adapted to very specific applications.

While a large number of impact assessment methods have been developed and more or less successfully applied worldwide, few, if any, are specifically geared toward water resources development projects with their specific hydrological dimensions. Most of the available techniques are ecological and resource oriented, designed to evaluate a given project or a set of alternatives. They are not, as a rule, designed to provide substantive input to the planning and design phase of a development project, which should be the ultimate goal of environmental impact assessment techniques.

Some of the most flexible and universal tools of impact assessment are certainly models and related information and decision support systems, implemented on computers.

The use of computers as a major tool for EIA is nowhere near as common as it could or should be. Problems, in developing countries in particular, range from the availability of the necessary computer hardware to the expertise in developing, maintaining, and using more or less complex software systems (e.g., Ahmad and Sammy, 1985). Further, lack of quantitative data is often cited as a reason for not using computers and simulation models.

However, the availability of increasingly powerful and affordable computers grows rapidly (Fedra and Loucks, 1985; Loucks and Fedra, 1987), and so does computer literacy among technical professionals. Even very powerful super-micro computers have become somewhat more affordable, and technical workstations are approaching the price class of personal computers. Many of the reasons cited for not using computers in environmental assessment are in fact problems that the computer can help overcome.

Chapter 2

Environmental Impact Assessment Methods

While most practical impact assessment studies use several methods or combinations of methods, a classification of methods and approaches will help in a summary presentation and discussion of the various techniques. The scientific literature on environmental impact assessment is very large and is growing rapidly. A more recent survey is compiled, in the form of a bibliography with abstracts, in Clark, Gilad, Bisset *et al.*, 1984. A classical overview of impact assessment is given in Munn, 1979, and a recent overview with special reference to developing countries can be found in Biswas and Geping, 1987. Greenberg *et al.* (1979) in their book on industrial environmental impact concentrate on industrial production and impacts in terms of noise, water and air pollution, and solid waste.

The following summary of methods is largely based on Biswas and Geping, 1987.

2.1 *Ad hoc* methods

Ad hoc methods provide little, if any, formal guidance for an impact assessment. While varying considerably with the team of experts, they usually identify a broad area of impact rather than define specific parameters which should be investigated or attempt a quantitative assessment. A major advantage, however, is in their ease of use and the possibility to tailor them to the specific circumstances of a given assessment problem without the constraints of a rigid formalism. As a consequence, however, they depend very much on the background, expertise and experience of the people undertaking them. While fast, and possible to conduct with minimal effort, they do not include any assurance of completeness or comprehensiveness; they may lack consistency in the analysis due to lack of guidance and a specific formalism; and they require the identification as well as the assembly of an appropriate group of experts for each new assessment.

2.2 Checklists and matrices

Checklists consist of a list of environmental parameters to be investigated for potential impacts. They therefore ensure complete coverage of environmental aspects to be investigated. Checklists may or may not include guidelines about how impact-relevant parameters are to be measured, interpreted, and compared. A typical checklist might contain entries such as:

1. Earth: mineral resources; construction material; soils; land form; force fields and background radiation; unique physical features;

2. Water: surface (rivers, lakes and reservoirs, estuaries); coastal seas and ocean, underground; quality; temperature; recharge; snow, ice, and permafrost;

3. Atmosphere: quality (gases, particles); climate (micro, macro); temperature;

4. Flora: trees; shrubs; grass; crops; microflora; aquatic plants; endangered species; barriers; corridors;

5. Fauna: birds; land animals including reptiles; fish and shellfish; benthic organisms; insects; microfauna; endangered species; barriers; corridors;

6. Land use: wilderness and open space; wetlands; forestry; grazing; agriculture; residential; commercial; industrial; mining and quarrying;

7. Recreation: hunting; fishing; boating; swimming; camping and hiking; picnicking; resorts.

Obviously, checklists do carry a geographical, as well as cultural, bias or, if universal in intent, carry a large number of mutually exclusive categories. They are usually also implicitly oriented towards certain categories of projects, related to the history of their development. Further, their elements may be interrelated (for example, the categories of water bodies and their relevant properties in the example above) such that the linear presentation in the listing has to be interpreted as a hierarchical or even multi-dimensional system in many cases.

Various sub-categories of approaches can be identified, based on checklists:

- Simple checklists, consisting of a simple list of environmental parameters.
- Descriptive checklists, including guidelines on the measurement of parameters (e.g., De Santo, 1978; Schaenman, 1976).
- Scaling checklists, including information basic to the (subjective) scaling of parameter values. Important concepts include the *threshold of concern*, the duration of an impact, and whether it is reversible or irreversible (e.g., Sassaman, 1981).
- Questionnaire checklists, containing a series of linked questions, which guide the user through the process. The possible answers are provided as multiple-choice, making the process easy to use even for less experienced persons.
- Environmental Evaluation System (EES): Checklist based, including scaling and weighting (Dee *et al.*, 1979; Lohani and Kan, 1982).
- Multi-attribute Utility Theory. Similar to the weighting method used in the EES procedure, developed by Batelle Columbus Laboratories in the USA, it is basically a decision support (weighting) method that can also be used in conjunction with other approaches to derive the impacts (Keeney and Raiffa, 1976; Keeney and Robilliard, 1977; Kirkwood, 1982; Collins and Glysson, 1980).

Impact matrices combine a checklist of environmental conditions likely to be affected with a list of project activities, the two lists arranged in the form of a matrix. The possible cause–effect relationships between activities and environmental features are then identified and evaluated cell by cell. Matrices can be very detailed and large, the classical Leopold matrix contains 100 by 88 cells, and is thus somewhat cumbersome to handle (Leopold, Clarke, Hanshaw *et al.*, 1971). As a consequence, numerous extensions and modifications have been developed for almost each practical application (e.g., Clark *et al.*, 1981; Lohani and Thanh, 1980; Welch and Lewis, 1976; Phillip and DeFillipi, 1976; Fischer and Davies, 1973). In a more strategic approach, project planning matrices are used to structure and guide the assessment procedures in the goal-oriented ZOPP (*Ziel-Orientierte Projekt Planung*) method (GTZ, 1987).

2.3 Overlays

Overlay methods use a set of physical or electronic maps, of environmental characteristics and possible project impact upon them, that are overlaid to produce a composite and spatial characterization of project consequences (McHarg, 1968; Dooley and Newkirk, 1976). Modern geographical information systems such as GRASS, developed for EIA by the US Army Corps of Engineers, use graphic workstations to implement overlay techniques using digital cartographic material and the more versatile logical interactions between spatial features.

2.4 Networks and diagrams

Networks are designed to explicitly consider higher order, i.e., secondary and even tertiary consequences in addition to the primary cause–effect relations addressed by the methods above. They consist of linked impacts including chained multiple effects and feedbacks (Sorensen, 1971; Sorensen, 1972; Gilliland and Risser, 1977; Lavine *et al.*, 1978). IMPACT is a computerized version of network techniques, developed by the US Forest Service (Thor *et al.*, 1978).

2.5 Cost–benefit analysis

Cost–benefit analysis (CBA), in a narrow sense, is an attempt to monetize all effects for direct comparison in monetary terms. While providing a clear answer and basis for the comparison of alternatives, the monetization of many environmental problems is sometimes extremely difficult and thus can affect the usefulness of the method considerably.

Numerous approaches to help monetize environmental criteria have been developed. Some of the more frequently used include the *cost of repair*, i.e., the estimated cost to restore an environmental system to its original state, or the *willingness to pay*, based on direct or indirect (e.g., travel cost) approaches to assess the value, for example, of park land or wilderness. Approaches and problems, as well as the underlying economic theories, are discussed (e.g., in Cottrell, 1978; Kapp, 1979; or Burrows, 1980). An excellent and critical treatment of cost–benefit analysis, and evaluation in environmental planning in general, can be found in McAllister, 1980. A discussion of the principles of environmental extensions to traditional cost–benefit analysis is given in Hufschmidt, James, Meister *et al.*, 1983.

Examples of cost–benefit approaches to environmental impact assessment include:

- the UNEP Test Model of extended cost–benefit analysis (Lohani and Halim, 1987), mainly oriented towards the natural resource base of a project. The basic format of the approach includes:
  - essential project description setting the physical and economic parameters for the analysis;
  - itemizing resources used in the project, those indirectly affected, and residues created;
  - resources exhausted, depleted, or that have deteriorated;
  - resources enhanced;
  - required additional project components;
  - formulation of the integrated cost–benefit presentation, summary and conclusions.
- the cost–benefit analysis of natural system assessment, developed by the East-West Centre in Hawaii (Hufschmidt and Carpenter, 1980).

Attempts to overcome some of the weaknesses of CBA have led to numerous extensions and modifications, such as the *Planning Balance Sheet* (PBS) or the *Goals Achievement Matrix* (GAM). The Planning Balance Sheet (Lichfield *et al.*, 1975) stresses the importance of recording all impacts, whether monetizable or not, and analyzing the distribution of impacts among different community groups. Thus it adds the analysis as to whom cost and benefits accrue to the basic concept of CBA. The Goals Achievement Matrix (Hill, 1968; Hill and Werczberger, 1978) defines and organizes impacts according to a set of explicit goals that the (public) action is attempting to meet and identifies consequences to different interest groups. It is also designed to accommodate non-monetizable impacts, and uses a set of non-monetary value weights for computing a summary evaluation; it is thus similar to CBA.

2.6 Modeling

Systems analysis and modeling are among the few techniques that allow consideration of multi-dimensional problems that involve multiple (and usually conflicting) objectives, multiple criteria, multiple purposes and users, as well as interest groups.

Basically, modeling attempts to replicate a real-world situation, so as to allow experimentation with the replica in order to gain insight into the expected behavior of the real system. Models, implemented on computers, are extremely powerful tools of analysis, though they are often demanding and complex.

Modeling has been used extensively in developed countries, but its use for impact assessment in developing countries has been rather limited because of constraints on resources, especially in expertise and data.

The two main problems, namely, lack of expertise and lack of data, are good reasons to look into the use of computers, in particular into new technologies such as expert systems, interactive modeling, and dynamic computer graphics. The basic idea behind an expert system is to incorporate expertise, i.e., data, knowledge and heuristics relevant to a given problem area into a software system.

Environmental impact assessment usually deals with rather complex problems that touch upon many disciplines, and rarely will an individual or a small group of individuals have all the necessary expertise at their disposal. The expert systems component of an EIA system can help to fill this gap and at the same time take over the role of a tutor. For recent surveys of the role and potential of expert systems technology in environmental planning and assessment, see Ortolano and Steineman, 1987; Hushon, 1987; Gray and Stokoe, 1988; Beck, 1990.

The same line of argument holds for the missing data. A forecast of likely consequences and impacts has to be based on some kind of model. Whether that is a mental model, a set of "rules of thumb" or heuristics an expert might use, or a formal mathematical model, the necessary information must be somehow inserted in the (mental or mathematical) procedure. If no specific data are available, one looks for similar problems for which information or experience exists and extrapolates and draws upon analogies. This role is usually filled by the expert's knowledge, or by handbooks and similar sources of information (Golden *et al.*, 1979; Canter and Hill, 1979). Such information, however, can also be incorporated in a model or its interface, or be made available through dedicated data bases connected to the models for the automatic downloading of parameters required. In a similar approach, basic parameters such as chemical properties relevant to environmental fate and transport calculations, for example, can be provided to the respective models through auxiliary models or estimation techniques (Lyman *et al.*, 1982; Lyman *et al.*, 1984).

Chapter 3

Expert Systems for Environmental Impact Assessment

Expert systems, an emerging technology in information processing and decision support, are becoming increasingly useful tools in numerous applications areas. Expert systems are man–machine systems that perform problem-solving tasks in a specific domain. They use rules, heuristics, and techniques such as first-order logic or semantic networks, to represent knowledge, together with inference mechanisms, in order to derive or deduce conclusions from stored and user-supplied information.

Application- and problem-oriented systems, rather than methodology-oriented ones, are more often than not *hybrid* or *embedded*, where elements of artificial intelligence (AI) technology, and expert systems technology in particular, are combined with the more classical techniques of information processing as well as the approaches used in operations research and systems analysis. Here, traditional numerical data processing is supplemented by symbolic elements, rules and heuristics, in the various forms of knowledge representation.

There are numerous applications where the addition of a quite small amount of "knowledge" in the above sense, for example, to an existing simulation model, may considerably extend its power and usefulness and at the same time make it much easier to use. Expert systems are not necessarily purely knowledge driven, relying on huge knowledge bases of thousands of rules. Applications containing only small knowledge bases, of at best a few dozen to a hundred rules, can dramatically extend the scope of standard computer applications in terms of application domains, as well as in terms of an extended non-technical user community.

Clearly, a model that "knows" about the limits of its applicability, what kind of input data it needs, how to estimate its parameters from easily available information, how to format its inputs, run it, and interpret its output will require not only less computer expertise from its user, it will also assist the user with domain expertise in the application area.

3.1 Artificial Intelligence and expert systems

In discussing a domain as loosely defined as expert systems, it may be useful to present a few definitions selected from the literature, to set the stage and introduce the jargon. Equally instructive are the essentially graphic definitions that are available (*Figures 3.1* and *3.2*).

Expert systems, or *Knowledge Based Systems*, are a loosely defined class of computer software within the more general area of AI, that go beyond the traditional procedural, algorithmic, numerical, and mathematical representations or models, in that they contain largely empirical *knowledge*, for example, in the form of rules or heuristics, and inference mechanisms for utilizing this form of information to derive results by logical operations. They are fashioned along the lines of how an expert would go about solving a problem, and are designed to provide expert advice. Like any other model, they are sometimes extreme simplifications and caricatures of the real thing, i.e., the human expert.

However, definitions or functional descriptions of expert systems and claims to the expert system category of software cover a broad spectrum, ranging from fairly modest to rather optimistic parallels to human, or even super-human, performance:

"Most existing expert systems work in analytic domains, where problem solving consists of identifying the correct solution from a pre-specified finite list of potential answers..." (Merry, 1985).

"Expert systems are computer programs that apply artificial intelligence to narrow and clearly defined problems. They are named for their essential characteristic: they provide advice in problem solving based on the knowledge of experts" (Ortolano and Perman, 1987).

"An expert system is a computer system that encapsulates specialist knowledge about a particular domain of expertise and is capable of making intelligent decisions within that domain" (Forsyth, 1984).

An expert system "handles real-world complex problems requiring an expert's interpretation [and] solves these problems using a computer model of expert human reasoning, reaching the same conclusions that the human expert would reach if faced with a comparable problem" (Weiss and Kulikowski, 1984).

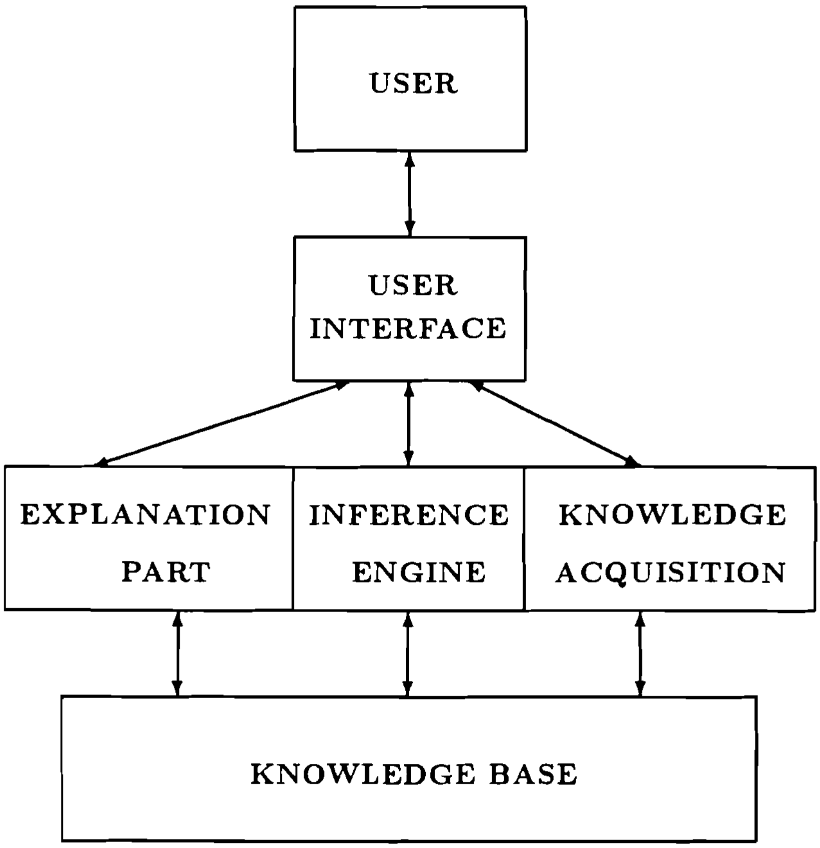

Figure 3.1. The five main components of an expert system. (Source: Trappl, 1985.)

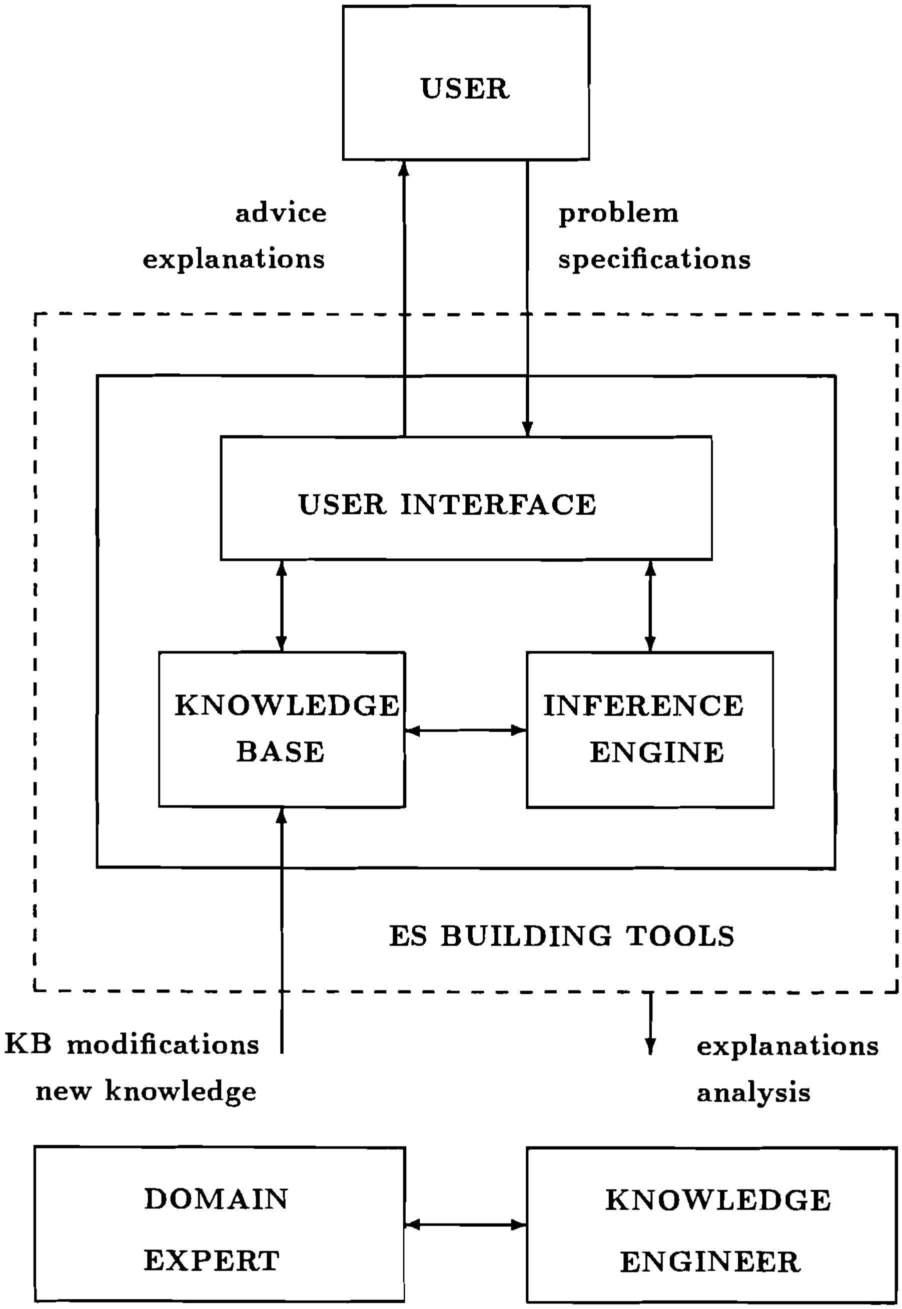

Figure 3.2. Interaction of knowledge engineer and domain expert with software tools that aid in building an expert system. (Source: Buchanan and Shortliffe, 1984.)

There are, however, even more demanding definitions. In their description of MYCIN, one of the classic expert systems, Buchanan and Shortliffe argue that an expert system "...is an AI program designed (a) to provide expert-level solutions to complex problems, (b) to be understandable, and (c) to be flexible enough to accommodate new knowledge easily." (Buchanan and Shortliffe, 1984). One of the more extensive definitions and more optimistic descriptions comes from Hayes-Roth: "An expert system is a knowledge-intensive program that solves problems that normally require human expertise. It performs many secondary functions as an expert does, such as asking relevant questions and explaining its reasoning. Some characteristics common to expert systems include the following:

- They can solve very difficult problems as well as or better than human experts;
- They reason heuristically, using what experts consider to be effective rules of thumb and they interact with humans in appropriate ways, including via natural language;
- They manipulate and reason about symbolic descriptions;
- They can function with data which contains errors, using uncertain judgemental rules;
- They can contemplate multiple, competing hypotheses simultaneously;
- They can explain why they are asking a question;
- They can justify their conclusions" (Hayes-Roth, 1984).

Obviously then, there seems to be no generally accepted definition of what exactly is an expert system. Descriptions and definition in the literature range from rather narrow automata selecting pre-defined answers to better-than-human reasoning performance in complex problem domains. There is, however, general agreement that an expert system has to combine:

- A knowledge base, that is a collection of domain-specific information;
- An inference machine, which implements strategies to utilize the knowledge base and derive new conclusions from it (e.g., *modus ponens*, forward chaining, backward chaining);

- A knowledge acquisition mechanism that elicits information required not only from the user, but also from domain experts so as to initialize the knowledge base,
- An explanation component, that can, on request, explain the system's inference procedures,
- and a conversational user interface that controls and guides the man–machine dialogue.

Obviously, an expert system must perform at a level comparable to that of a human expert in a non-trivial problem domain.

In summary, a concise description of AI would be *the art or science of making computers smart* and expert systems could be described as *smart problem-solving software.*

3.2 Basic concepts behind expert systems

What makes expert systems different from ordinary models and computer programs? Rather than trying to define differences in any formal way, it may help to introduce and discuss some of the basic concepts and approaches used in expert systems.

Expert systems are alternatively referred to as *knowledge-based* systems. Knowledge representation, therefore, is one of the fundamental concepts and building blocks in expert systems.

Knowledge is represented in various forms and formats, following different paradigms. The more commonly used forms include rules, attribute–value lists, frames or schemata, and semantic networks. A brief but comprehensive introduction to knowledge representation is given in Chapter 3 of Barr and Feigenbaum (1981).

Formal logic and propositional calculus offer a basic form of knowledge representation. Well-defined syntax and semantics and expressive power make it an attractive option.

A *proposition*, a statement about an object, is either TRUE or FALSE. Connectives permit the combination of simple propositions. The most commonly used connectives are:

AND	$\wedge$	or	&
OR (inclusive)	$\vee$		
NOT	$\neg$	or	$\sim$
IMPLIES	$\rightarrow$	or	$\supset$
EQUIVALENT	$\equiv$		

Rules of inference, such as *modus ponens*, allow the derivation of new statements from given ones: if X and $X \rightarrow Y$ are TRUE, then Y is also TRUE:

$$(X \wedge (X \rightarrow Y)) \rightarrow Y.$$

The rules of propositional calculus, extended by predicates, allowing more complex statements with more than one argument, quantifiers such as *for all* ($\forall$) and *there exists* ($\exists$), and inference rules for quantifiers, result in *predicate calculus* (Barr and Feigenbaum, 1981). Adding the idea of operators or functions leads to first-order predicate logic, and this, restricted to so-called Horn clauses corresponds to the syntax of Prolog (Clocksin and Mellish, 1984; Bratko, 1986).

Probably the most widely used format, and also the most directly understandable form of knowledge representation are rules, also referred to as productions or production rules, or situation–action pairs. They are close to natural language in their structure, and they are familiar to programmers used to classical procedural languages such as FORTRAN or C: IF ... THEN ... ELSE is easy enough to understand. Examples of rules would be:

```
RULE 1010320 #encroachment corridor by forest type
IF     landuse                == forest
AND    forest_value           == high
AND    [ vegetation           == rain_forest
       OR vegetation          == dense_forest ]
AND    wildlife               == abundant
THEN   encroachment_corridor = very_large
ENDRULE

RULE 1010532 #USLE soil_erodibility
IF   [  soil_type ==  very_fine_sandy_loam
     OR soil_type == silt_loam ]
AND  soil_organic_content < high
THEN soil_erodibility = high
ENDRULE
```

Obviously, the terms used in rules can be more or less cryptic and require proper definition and interpretation in the system:

```
RULE 1010201 #degradation by watershed class
             #and land requirements
IF        project_country     == Thailand
AND       [ watershed_class   == WSC1
          OR watershed_class  == WSC2 ]
THEN      Impact  = major
ENDRULE
```

Structured objects are another popular means of representation of information knowledge. They are known as *Schemas* (Bartlett, 1932); *Frames* (Minsky, 1975); *Prototypes* or *Units* (Bobrow and Winograd, 1977); or *Objects* in many languages or language extensions, e.g., SMALLTALK (Kay and Goldberg, 1977); LOOPS (Bobrow and Stefik, 1983); or FLAVORS (Moon and Weinreb, 1980).

Frames allow combinations of generic and specific information, where the former can be inherited within a hierarchy of frames, consisting of classes, super- and sub-classes, and instances. As a data structure, frames for example can combine declarative and procedural components. Slots as units of descriptions can hold attribute–value pairs, but also function specifications and of course reference to other frames.

Another form of representation is by means of *semantic networks*, which consist of nodes representing objects, concepts, and events, and links or arcs between the nodes, representing their interrelationships (Quillian, 1968). A well-known example of an expert system using semantic networks is PROSPECTOR, dealing with mineral prospecting (Duda, Gashnig and Hart, 1979).

A specific and very important feature of expert systems is the inference engine, i.e., the part of the program that arrives at conclusions or new facts, given the primary knowledge base and information supplied by the user. The basic principle was already hinted at above in the introduction of predicate calculus.

There are two basic strategies, namely forward and backward chaining. Forward chaining implies reasoning from data to hypothesis, while backward chaining attempts to find the data to prove, or disprove, a hypothesis

(Forsyth, 1984). Since both strategies have advantages as well as disadvantages, many systems use a mixture of both, e.g., the Rule Value approach (Naylor, 1983).

For many practical purposes, developers use expert systems shells and special development environments rather than basic languages such as C, C++, LISP, PROLOG, or SMALLTALK. While shells may offer the advantage of easy use and ready-made structures and formats, they sometimes tend to restrict the user to specific forms of representations, and, for the more complex and comprehensive ones, are expensive. For a more recent survey and discussion of selected software for expert systems development see Ortolano and Perman (1987).

3.3 Expert systems in environmental modeling

There is a rather extensive and very rapidly growing literature on AI and expert systems, starting from the, by now almost classic, four-volume Handbook of Artificial Intelligence (Barr and Feigenbaum, 1981; Barr and Feigenbaum, 1982; Cohen and Feigenbaum, 1982; Barr and Feigenbaum, 1990). Recent review articles concentrating on environmental systems and engineering, and water resources in particular, are for example, Ortolano and Steineman (1987); Rossman and Siller (1987); Hushon (1987); Gray and Stokoe (1988); Beck (1990).

The number of expert systems being described in the literature are many. The number of operational systems, in everyday use for practical purposes, however, seems to be rather small, in particular when looking at an area such as environmental impact assessment.

Of the 29 systems compiled in *Table 3.1*, almost all are in the R&D stage; little or no information exists on successful practical applications on a routine basis. This, however, does not make expert systems different from the vast majority of simulation and optimization models developed in the field.

Another feature is that a large number of systems have been developed for operational applications rather than planning, in particular in the wastewater treatment area. Groundwater systems, especially those related to hazardous waste management problems, are another obvious focal point. Finally, there are several *Intelligent Front-End* systems, i.e., model selection or parameter estimation tools.

Table 3.1. Selected list of expert systems.

Application Domain	Contact or reference
Screening of environmental projects	ESSA Ltd., Vancouver
Initial screening and scoping of envl. impacts	US Army Electronic Proving Ground, Ft. Huatchuca, Arizona
Environmental resource evaluation	Portugese Ministry of Environment
Consultative system for environmental screening	ESSA Ltd., Vancouver
Wetland management	U.S. Fish and Wildlife Service, Ft. Collins, Colorado
Environmental technical info. system	University of Illinois
Environmental assessment system	Institute for Environmental Studies, Free University of Amsterdam
Multiple-use watershed management (MUMS)	Hushon, 1987
Groundwater flow analysis	Andrew Frank, Dept. of Civil Eng; Univ. of Maine
Groundwater contamination (DEMOTOX)	Ludvigsen, Sims and Grenney, 1986
Groundwater vulnerability (AQUISYS)	Hushon, 1987
Well data analysis (ELAS)	Weiss, 1982
Water resources laboratory aide	Bob Carlson, Dept. of Civil Eng; Univ. of Alaska
Oil spill simulation	Antunes, Seixas, Camara *et al.*, 1987
HSPF simulation advisor (HYDRO)	Gaschnig, Reboh and Reiter, 1981
Mixing zone analysis (CORMIX1)	Doneker and Jirka, 1988
Input parameter estimation for QUAL2E	Barnwell, Brown and Marek, 1986
Hydrologic model calibration	J.W. Delleur, School of Civil Eng; Purdue Univ.
Parameter estimation for runoff model (EXSRM)	Engman, Rango and Martinec, 1986
Advisor for flood estimation (FLOOD ADVISOR)	Fayegh and Russell, 1986
Model selection for surface water acidification	Lam, Fraser and Bobba, 1987
Trickling filter plants (sludge Cadet)	Catherine Perman, Dept. of Civil Eng; Stanford University.
Anaerobic digester	Michael Barnett, Dept. of Envir. Science and Eng; Rice Univ.
French water treatment plant	Pierre Lannuzel CERGRENE/ENPC
New York water treatment plant	Steve Nix, Dept. of Civil Eng; Syracuse University
Activated sludge plants	Deborah Helstrom Dept. of Civil and Environmental Engineering, Utah State University
Activated sludge diagnosis	Johnston, 1985
Water system loss	Steve Maloney, CERL
Sewer system design	Lindberg and Nielsen, 1986

Compiled from Ortolano and Steineman, 1987; Rossman and Siller, 1987; Hushon, 1987; Beck, 1990; Gray and Stokoe, 1988.

3.4 Types of applications

There are several types of expert systems applications in any particular domain: they range from purely knowledge-driven systems or ES proper, to ES components in an intelligent front-end, to fully embedded or hybrid systems. Each of these systems have their specific characteristics, use, and problems. As with any attempt at classification, real things do not neatly fit into square boxes, but it helps to structure the discussion and appears to satisfy a basic need of the scientific mind.

An **expert system proper** would be a purely rule-based system, relying on a sizable knowledge base. As such, it is based on a largely empirical "model" or a qualitative, causal understanding of how things work. In the world of water resources modeling, that would put it in a class with the universal soil loss equation rather than a finite element model based on an albeit simplified version of the Navier–Stokes equations. What it describes or models is not "the system", but an expert's understanding of the system, in particular, his problem-solving approach and strategies.

There are only a few purely knowledge based systems that do not contain a substantial conventional component. Some of the operation and control systems, in particular in the wastewater treatment area, seem to fit into this category. Further, a large number of systems are being developed for hazardous waste site assessment and related topics, such as permitting or waste site management, e.g., WA/WPM Generator (Paquette, Woodson and Bissex, 1986); RPI Site Assessment (Law, Zimmie and Chapman, 1986); GEOTOX (Mikroudis, Fang and Wilson, 1986; Wilson, Mikroudis and Fang, 1986); DEMOTOX (Ludvigsen, Sims and Grenney, 1986); or SEPIC (Hadden and Hadden, 1985). Reviews of these systems can be found in Ortolano and Steineman, 1987; Rossman and Siller, 1987; Hushon, 1987.

"An **intelligent front-end** is a user-friendly interface to a software package, which enables the user to interact with the computer using his or her own terminology rather than that demanded by the package" (Bundy, 1984). What they can do, among other things, is to avoid or minimize misuse of complex models by less experienced users.

The QUAL2E Advisor, FLOOD ADVISOR, HYDRO, CORMIX1, or EXSRM are all examples of this type of application. Systems of this nature help a user to select the appropriate model to be used, assist in specifying input parameter values, and provide interpretation of the model's output (Rossman and Siller, 1987).

The QUAL2E Advisor (Barnwell, Brown and Marek, 1986) is a rule-based system, built with a commercial expert system shell, M.1. The system suggests appropriate parameter or input values for coefficients used in modeling stream temperature, the type of hydraulic model used and its associated coefficients, and biological oxygen demand removal, sediment oxygen demand, and reaeration rate coefficients. Appropriate values are suggested in a question-and-answer session, where information about stream characteristics that can be easily obtained, e.g., by visual inspection, such as shape of channel cross-section, slope and depth, nature of stream bed, bank vegetation, are used to classify the river and estimate corresponding coefficients.

Hybrid systems, finally, represent an integration of classical algorithmic techniques with AI and expert systems methods. The basic idea of an expert system is to incorporate into a software system expertise, i.e., data, knowledge and heuristics, that are relevant to a given problem area. However, classical simulation models are a rather powerful class of "heuristics" (after all, most of them incorporate a considerable amount of expertise, and they are empirical to a more or less obvious degree, even if they claim to be "physically based"). Models could also be viewed as a special case of production rules. In any case, they are useful in many situations, and are even more useful if combined and extended with rule-based components that add a considerable amount of flexibility in problem representation as well as estimation and evaluation methods.

Much of the above also holds true for the intelligent front-end system, and any attempt at a clean-cut classification will be found wanting; hybrid systems with embedded AI components would simply have several, in fact many, "micro expert systems" integrated into the overall software package. They rely on a number of disjunctive and specialized knowledge bases in different representation formats, depending on the domain and its most natural form of representation.

Several examples of integrated hybrid systems that also contain water resources models are described e.g., in Fedra, Weigkricht and Winkelbauer (1987); Fedra, Li, Wang *et al.* (1987); Fedra (1986); Fedra (1988). The basic philosophy and early examples are described in Fedra and Loucks (1985); Loucks, Kindler and Fedra (1985); Loucks and Fedra (1987).

3.5 Benefits from expert systems

AI and expert systems technology are certainly an intriguing new development in computer science that hold great promise for better applications. However, like any other method, they do not offer universal solutions and need a thorough understanding of their requirements and limitations for proper use.

By and large, expert systems are *empirical* systems, based on a more or less explicit, and usually qualitative, understanding of how things work. A perfect example of an ideal application area is law, or in the context of water resources, water rights and allocation problems. In water resources modeling, however, there is a substantial amount of physically based modeling, where an understanding of how things work can be expressed quantitatively. Much of our quantitative "understanding" is still empirical and not based on laws of nature (Darcy's law is an empirical formulation but then, physicists would argue, so is Schrödinger's equation).

However, it is important to realize that expert systems are certainly no substitute for many time-tested methods and models, but should be seen as complementary techniques which can improve many of these models. Obvious applications related to numerical models are in data pre-processing, parameter estimation, the control of the user interface, and the interpretation of results. There are certainly enough arts and crafts components in numerical modeling that open attractive opportunities for AI techniques.

While there is certainly some application potential for a purely knowledge-driven system in classifications and diagnosis tasks, the most promising area of application is in coupled, embedded, or hybrid systems, such as intelligent front-ends, intelligent interfaces, and modeling support rather than new models themselves. When integrated with data base management and interactive color graphics, AI concepts can help to shape a new generation of powerful but truly user-friendly "smart" software that actually gets used in planning and management.

AI applications are no longer restricted to expensive special-purpose hardware, but are increasingly supported on standard workstations and powerful PCs. With this wide accessibility, and an increasing number of affordable software tools, we may well be at the beginning of an exciting era of new developments and applications.

Chapter 4

Environmental Problems of Water Resources Development in the Lower Mekong Basin[1]

4.1 The river and its basin

One of the great rivers of Asia, and ranking twelfth among the world's longest rivers, the Mekong has its source at an elevation of 5000 m close to the Dzanag La pass in the Tanghla Shan mountain ranges, on the northeastern rim of the great Tibetan plateau, in southwestern China. Along it course, the Mekong flows through or along the borders of six countries, China, Burma, Laos, Thailand, Kampuchea and Vietnam before joining the South China Sea southwest of Ho Chi Minh City. In volume of water discharged into the sea, the Mekong, with an annual average discharge of approximately 475×10^9 m^3, is the sixth largest river in the world.

Its total drainage basin, including some 160,000 km^2 in China, is about 783,000 km^2. The river enters its lower basin at the common Burma–Lao PDR–Thailand boundary point and the distance from there to the ocean is some 2,380 km. It is this stretch of the river that is the subject of the water

[1]Based on Mekong Secretariat, 1982; and Pantulu, 1986.

and related resources development program, sponsored by the United Nations, The Mekong Project. This chapter concentrates on the lower Mekong river and its basin (*Figure 4.1*).

The lower Mekong basin covers an area of some 611,000 km^2, or about 77 percent of the total area of the river basin. It includes nearly the whole of the Lao PDR (202,400 km^2), the northern tip and the northeast area of Thailand (180,240 km^2), nine-tenths of Kampuchea (154,000 km^2) and the western flank and southern tip of Vietnam (65,200 km^2).

4.2 Environmental determinants of development

The distinct environment, geology and climate in the basin together dictate resource patterns and potential for development. The complex geological history of the basin has provided five physiographic units: the Northern Highlands, the Annamite Chain, the Southern Uplands, the Korat Plateau and the Mekong Plain (Pantulu, 1986).

The Northern Highlands, covering northern Lao PDR with only the western rim in Thailand is a strongly folded mountainous area where the processes of erosion have carved a highly complex and dissected relief. There are a few relatively large upland plains, such as the Plain of Jars on the Xieng Khouang Plateau (Lao PDR). The river valleys in the Lao PDR usually have small quarternary alluvial terraces. However, Chieng Rai province of north Thailand has extensive plains, with 2200 km^2 of wet rice fields.

Rainfall is high: 1,200 to 2,000 mm per annum. The temperature is generally high, occasionally, however, cold air from Siberia and China penetrates, lowering air temperatures to near zero.

The human population is sparse, averaging 5–14 km^{-2} except on the valley floors, as in Chieng Rai (Thailand), where numbers average 57.9 km^{-2}; however, population density reportedly is increasing.

All the factors described above have a significant influence on resource use. Wet rice cultivation is possible only in the deltas of tributaries. In the uplands, slash and burn cultivation practiced by hill tribes has contributed to considerable loss of natural forest cover and to erosion, which has a significant negative influence on water resource development in the plains. The potential for hydroelectric power development is substantial.

The Annamite Chain, located mainly in the Lao PDR, is 800 km long and has a steep and mountainous terrain in the north and central parts, but forms dissected hills and rolling-to-hilly plateau in the south. The chain

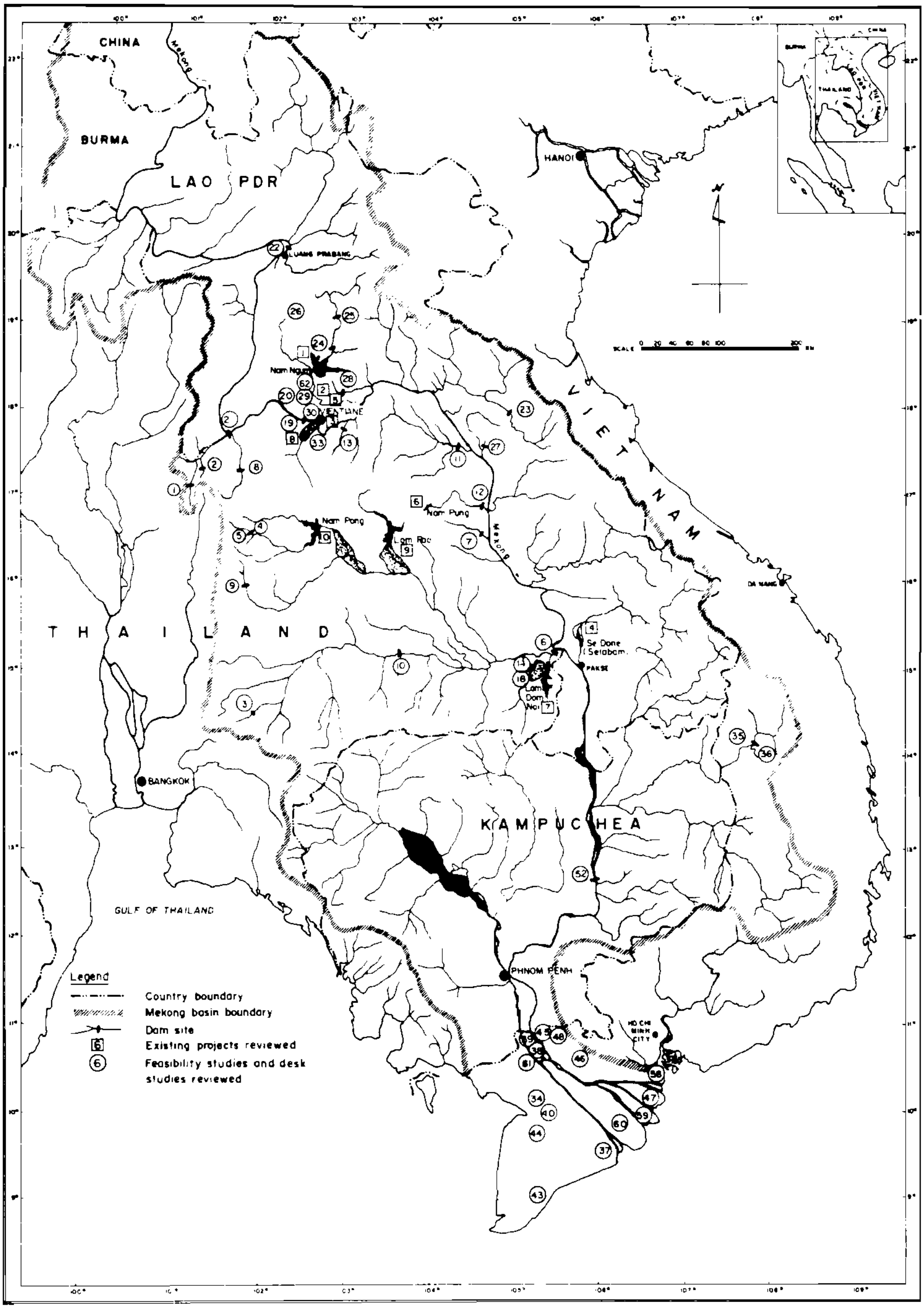

Figure 4.1. The Lower Mekong and its basin. (Source: Mekong Secretariat, 1987.)

extends into Vietnam and Kampuchea. Of interest is the hilly karstic limestone area—the Khammouane plateau, which is the single most extensive limestone deposit in the basin. This 50–300 km wide and 500–2,500 m high mountain chain divides the western Mekong drainage from eastern South China Sea drainage.

Rainfall is heavy on the south and west flanks which receive the brunt of the southwest monsoon; some inner valleys, however, are drier, with deciduous forests. Once areas which received more than 2,000 mm per annum were completely covered by dense rain forest but many of these have been cleared for swidden agriculture. Swidden agriculture still dominates, with less than one percent of the land under wet rice. The population is sparse (< 4 km^{-2}, N; 5–40 km^{-2}, S), but highly diverse hill tribes are to be found in the region.

The area's potential for agricultural development is limited. Although the tributaries of the Mekong have a more gentle profile than the streams draining into the South China Sea, they are broken by many falls and rapids in the northern sector and are suitable for the development of hydroelectric power. The less accentuated southern sector provides limited irrigation potential in tributary valleys. Vast areas of the chain which are now barren and covered only with grasses with a savannah type of character can be developed for live-stock grazing.

The Southern Uplands, consist of the Elephant and the Cardamomes mountains separating the Mekong Plain in Kampuchea from the Gulf of Thailand, and continuing into Thailand. To the east are continuous mountains, while the west comprises rolling, dissected plains, which yield orchard fruit and field crops. The Uplands are at an altitude of 500–1,700 m and except for some steep escarpments, slopes are moderate in the north and steep and eroded in the south.

Rainfall is very high—up to 5,000 mm per annum in places—with dense, tropical rainforest and very low human population densities (< 4 km^{-2}). Hill tribes are a negligible proportion of the population, and even swidden agriculture is very limited (though more common on the drier north side). There is little scope for agricultural development.

The Korat Plateau comprises northeast Thailand and adjacent parts of Lao PDR. It is a large (250,000 km^{-2}) saucer shaped inter-mountain basin tilted towards the southeast. The altitude of the floor is 100–200 m with the surrounding mountains reaching 1,400 m. The greater part of the plateau consists of relatively flat lands and is underlain by thick, cretaceous salt deposits. Due to the rain shadow effect of the surrounding mountains the area is dry.

Rainfall is erratic and fluctuates between 1,000–1,250 mm. Recurrent floods and droughts afflict the plateau, much of which is now covered with unproductive scrub or grassland vegetation, although it was originally forested. Extensive deforestation has contributed to erosional problems. Several major tributaries of the Mekong in the Lao PDR, the Nam Theun, Se Bag Fai, Se Bang Hieng and Se Done have alluvial valleys in the plateau. In northeast Thailand more than half the plateau is drained by the Mun and Chi rivers; this region experienced some of the earliest development of rice plantation in the basin and judging from archaelogical sites, supported fairly dense prehistoric and early historic human populations. Later populations were thinner, but recent agricultural advances have allowed the population to rise again and much of the plateau now supports between 80–150 people km^{-2}.

A number of reservoir sites have been developed mainly for hydroelectric generation and irrigated agriculture. Fisheries are an unforeseen ancillary benefit from the reservoirs. From a purely physiographic point of view the plateau would appear to offer substantial scope for further agricultural development by means of flood control, drainage and irrigation of the more productive soils.

The Mekong Plain is a vast low-lying area, a relatively small portion of which consists of fluviatile deposits of the young Mekong. It comprises most of lowland Kampuchea, the Mekong Delta of Vietnam and small sections of south Lao PDR and east Thailand. Most of it lies below 100 m, with a few higher outcrops scattered throughout the plain, while much of north Kampuchea comprises rolling and dissected plains between 100–200 m high. The Mekong Plain is the result of erosion and sedimentation; the sediments vary in depth, from at least 500 m near the mouth to only 30 m. At the "nine mouths" of the Bassac and Mekong, the combined action of river deposition and the sea has produced a coastal belt of slightly higher elevation. Deposition in the delta continues to extend the Ca Mau Peninsula to the south and west at a rate of 150 m per annum in some places.

The plain is the most densely populated part of the basin with more than 450 people km^{-2} in the rice growing regions of the delta (rice is grown on 50 percent of the land). The richest rice growing areas of Kampuchea are also densely populated, especially south of Tonle Sap and on the Battambang Plain. The north and east savannah, however, are very sparsely populated

(< 4 people km^{-2}). The lowlands, particularly the areas of Holocene alluvium, have historically been the most densely populated and productive agricultural parts of the Lower Mekong Basin, with apparent agricultural and water resource development potential.

4.3 Water resources

The Mekong discharges annually more than $475 \times 10^9 m^3$ of water into the South China Sea. The sources of this surface water are disparate. About 20 percent of the annual flow comes from the upper basin (i.e., above the Burma–Lao PDR–Thai boundary). Some 70 percent of the flow is contributed by the Thai–Lao PDR section. The remaining 10 percent comes from the Kampuchea–Vietnam sector, excluding the delta.

While snow melt produces a more or less uniform flow in the upper Mekong, the lower Mekong exhibits pronounced seasonal variations reflecting rainfall patterns. The river rises following the onset of the monsoon in May or June, and attains a maximum level in August or September in the upper section of the lower basin and in September and October in the lower section. It then falls off rapidly in December, slowly thereafter, to reach its lowest level in April. There are no mainstream storage structures and those on the tributaries do not have a significant effect on the mainstream flow. Only the Great Lake in Kampuchea significantly affects mainstream flow, largely in the delta.

There are distinct alternating dry and wet seasons in the basin area as a result of the monsoons. While there is a shortage of water during the dry season, large areas are flooded during the wet season. The flooding behavior of tributaries also varies from one part of the basin to another. Tributary basins in Thailand (e.g., Mun and Chi) have relatively small channels but have extensive flood plains up to 10 km wide. These basins, located as they are on the lee side of mountain ranges, receive low rainfall. They usually remain dry for several years, filling irregularly. Highest rainfalls occur along the windward slopes of Annamite mountains and in the Lao PDR and Kampuchea, thus floods of a different magnitude develop in these areas. Stream courses here are generally well defined and accommodate floods which are fairly uniform from year to year.

Resource development constraints: The main foci of water resource development in the Mekong basin are the production of the staple food, rice and fish (the principle source of protein), hydroelectric power for domestic, industrial and agricultural purposes and navigation of the river. Initial estimates place the theoretical potential of hydroelectric power resources of the lower Mekong basin at 58,000 MW installed capacity and 505,000 GWh for annual energy production. The estimated potential of the basin for year round irrigation with the help of storage and flood plain reservoirs is of the order of 6.4×10^6 ha. Development of the resources is sought to be achieved mainly through dam construction and enhanced irrigated agriculture. Due to physiographic limitations, rice cultivation in the basin is possible only in the delta, the Mekong plain, the Korat plateau, the tributary deltas in the Annamite Chain and valley floors in the northern Highlands.

In the natural state, development of rice cultivation is beset with problems of shortage of water in the dry season and flooding of vast areas in the wet season, particularly in the delta and the Korat plateau. Even in the wet season irregular rainfall which causes either dry spells or an over abundance of water, affects plant growth. Furthermore, in the delta inadequate flow in the Mekong for irrigation withdrawal during the low flow period and intrusion of salt water from the sea present additional constraints.

Dams and other water control and regulatory measures would appear, on the surface, to be the logical answer to help overcome the above constraints. However, soil conditions in the Korat plateau, and in the delta, present formidable problems in water management and irrigation development. About 1.8×10^6 ha in the delta are covered by acid sulfate soils and another 2 million hectares in the Korat plateau are influenced by underlying geologic salt deposits. Water control, drainage and irrigation acidify the potentially acidic soils and exacerbate the acid in developed acid sulfate soils. Irrigation of lands underlain with salt deposits results in salinization of top soils and render them unfit for cultivation. Furthermore, salinity control in the delta will affect the important fishery resources which depend on the salinity intrusion for breeding, nursery and forage in the delta wetlands. These problems are described in some detail in the following section.

4.4 Environmental problems

The environmental problems or issues that have direct relevance to water resources development in the basin are listed below:

- Watershed degradation, erosion and sedimentation;
- Acidification of soils in the delta;

Table 4.1. Changes in closed forest cover between 1970–1985 in the Lower Mekong Basin.

Country	Closed forest 10^6 ha 1970	Closed forest 10^6 ha 1985	Annual Deforestation 10^3 ha	Deforestation %
Kampuchea	11.00	7.42	239	32.5
Lao PDR	13.00	7.91	339	39.2
Northeast Thailand	5.31	2.33	199	56.1
Southern part of Vietnam	3.60	2.67	62	25.8
Total: Lower Mekong basin	32.91	20.33	839	38.2

- Soil salinization in the Korat plateau;
- Problem soils—danger of desertification as a result of improper exploitation;
- Inundation control effects on fisheries;
- Toxic biocidal levels in edible organisms;
- Waterborne diseases, and
- Potable rural water supply in problem (saline and acid) areas.

4.4.1 Watershed degradation

The degradation of the Mekong watershed has become one of the main concerns in recent years. Millions of hectares of valuable forests have been degraded to inferior scrub, grasslands or savannah, or have been encroached upon by subsistence agriculture. As a result, soil conditions have deteriorated, with increased water run off and erosion. It is estimated that between 1970 and 1985 alone some 13×10^6 ha of closed forest disappeared in the lower Mekong basin (*Table 4.1*) through forest encroachment (both legal and illegal), shifting cultivation and agricultural development projects.

A major problem is forest degradation by fire, often started intentionally for reclaiming forest land for shifting cultivation. Forest fires combined with short fallow periods in between lead to soil exhaustion. Grasses such as *Imperata cylindrica* and *Themeda triandra* then take over, changing the forest ecosystem from savannah woodland into unproductive grassland. Approximately 8.5×10^6 people are said to depend on shifting cultivation affecting an area of some 17.5×10^6 ha in the lower basin. While slash and burn cultivation, practiced in the traditional way with short cropping and long fallow periods in between may be a sound land use measure, with population increases and the current intensive use, severe soil depletion has resulted. Population increase in the basin and the consequent increase in demand for fuel wood or charcoal have further increased inroads into forests. Except perhaps in the Lao PDR and Kampuchea, there is an acute scarcity of fuel wood in the basin. It is expected that the pressures on remaining forest resources will be extremely high. However, most of the deforestation goes to illegal logging, and effective control to stem this destructive practice seems to be almost impossible for various reasons. The lack of adequately staffed and effective technical organizations, lack of coordination among various agencies, shortage of funds and, at places, unstable political conditions are important contributory factors.

4.4.2 Erosion

The main areas of concern in relation to erosion are the hilly areas mainly in the Lao PDR. By 1972, more than 10×10^6 ha of forest were reported to have been destroyed (Singh, 1972). The annual rate of deforestation for shifting cultivation and through forest fires in the Lao PDR alone is estimated to be 300,000 ha. Generally, in the basin, excessive deforestation is attributed to the enormous increase in population densities in the basin from 16.3 persons per km^2 some 70 years ago to 66 persons per km^2 in 1988. As a result, the people living on the plains have encroached on forested hill areas and are reclaiming them for agriculture at a steadily increasing rate. In fact the problem of erosion-induced sedimentation of dams is so serious that power production at two dams, Selabam and Nam Dong, has been adversely affected. It is also apprehended that the rate of sedimentation in the Nam Ngum reservoir has reached alarming proportions. Elsewhere in the basin however, despite the rather drastic changes in forest cover, their erosional effects are not manifest at least in the main Mekong. Sediment yields in the river and tributaries are rather low compared to other Asian rivers (Pantulu, 1986).

4.4.3 Acidification of soils in the delta

An estimated 1.8 million hectares (approximately 45 percent of the Mekong delta in Vietnam) is covered by acid sulphate soils and is not readily amenable to agricultural development. These soils are characterized by pyrite deposits at relatively shallow depth, which react to oxygen intrusion with pyrite oxidation and development of sulphuric acid. Soil pH in acid sulfate areas may drop to values below pH2 and, under these conditions, toxic polyvalent cations (metals) are dissolved from the soil minerals. Secondary reactions relate to immobilization of phosphate, inhibition of the nitrogen cycle and potassium deficiency due to leaching. Although farmers in the delta have developed, through trial and error, ingenious water and soil management strategies to overcome these constraints and obtain yields from such soils, large parts of the most severely affected areas lie fallow in spite of the obvious need to reclaim all available land to increase food production in the country. Reclamation of these areas is fraught with difficulties, as inappropriate strategies may lead to enhancement of acidification and even successful strategies may cause damage in other areas, if they result in production of acidic and toxic drainage waters. Such drainage waters and also flood waters which flow over acid sulfate soils are not only unsuitable for all water uses but also cause acidification of adjacent lands and surface water bodies, with often catastrophic effects on agricultural crops and fisheries.

In the earlier days, vast areas of acid soils were covered with Melaleuca forest. However, population pressures have led to reclamation of these lands for irrigated agriculture. Furthermore, defoliation of the Melaleuca forest during the recent war was followed by harvest of the wood and cultivation of the lands for paddy. Lands so converted could only be used for one or two seasons. Thereafter they had to be abandoned because of increased acidity. Even raised-bed cultivation, a method used successfully by farmers, has resulted in the acidification of surface waters, affecting crops and fish in the entire area.

4.4.4 Soil salinization in the Korat plateau

In the whole of northeastern Thailand and parts of the Vientiane plain in the Lao PDR, the recent alluvium is underlain by a typical formation, the Mahasarakam formation. Different strata of this formation are more or less salt-bearing with a lower "rock salt" structure, comprising several strata from "basal salt to upper salt inclusive", and an "upper clastic layer" (Pantulu, 1988). The occurrence of salt-affected soils in the plateau coincides with the area of the Mahasarakam formation and saline ground water. The Korat plateau, as in other parts of the basin, is interspersed with wetlands of various dimensions. In recent years, water resource development activities including dam construction and "flood plain development" for irrigated agriculture have resulted in the draining of wetlands and their conversion into irrigated agricultural lands.

Prior to the "development activities", agriculture was mostly rain-fed and seasonal, yielding modest returns of 1.5 tons ha^{-1} per annum of rice. At that time, periodic flooding of the fields by rivers washed out the surface salts, besides providing fish harvests of 10–25 kg ha^{-1} for the duration of the flood. Embankment, dam construction and drainage of wetlands and the subsequent development of irrigation in these areas resulted in the elevation of saline groundwater levels, either due to hydrostatic pressure, caused by water storage in the dams, or due to downward seepage from the irrigated fields. This, coupled with capillary rise, has resulted in salinization of surface soils in irrigated areas. This type of secondary salinization in irrigation areas has been reported from many areas. Examples are the Nong Wai irrigation project area in Khon Kaen, Kampuwapi south of Udorn, the Lam Pao irrigation scheme at Kalasin and Nam Oon irrigation area in Sakhon Nakhon (Arunin, 1984). The progress of surface soil salinization in the irrigated areas is estimated at 10 percent over a period of 10 years. The areas thus salinized have become unsuitable for any productive use.

4.4.5 Problem soils: danger of desertification as a result of improper exploitation

Problem soils are defined as those which present inherent constraints to productive utilization. Besides the acid and saline soils mentioned above, there are various other problem soils in the basin, such as shallow skeletal soils and sandy surface soils in Thailand and the Lao PDR, and peats and exhausted grey soil in Vietnam.

Skeletal soils in this context are defined as soils containing 35 percent lateritic concretions or gravel of more than 2 mm diameter in a given volume of soil. Physical constraints to plant growth are coarse texture and shallow depth, which restrict root growth. Further, the capacity of such soils to retain water and nutrients is generally low.

Peat soils contain at least 20–30 percent of organic matter in the upper 80 cm of the profile. The main growth-limiting factors are low bearing capacity, shrinkage, irreversible drying, deficiencies of micro and macro nutrients and fungal diseases associated with them. Only peat soils of less than 1 m depth can be brought under cultivation.

The grey soil of the basin remains to be classified and characterized in detail. Its main constraint seems to be low fertility because of nutrient deficiencies.

As in the case of acid and saline soils, ever increasing population pressure in the basin (with the exception of the Lao PDR) and the vast areas the problem soils cover have rendered their reclamation imperative. Therefore, water resource development activities in the basin have to reckon with the problem of utilizing productively the problem soil areas. Unplanned and inappropriate use of these lands has already rendered vast areas irreversibly unproductive. This explains the urgency of addressing this problem in the basin.

4.4.6 Inundation control and its effect on fisheries

Historically, the most productive of all Mekong basin fisheries are those dependent on seasonal flooding; but these fisheries are unusually vulnerable to proposed schemes for the elimination of floods. The floodwater fisheries of the basin hinge on seasonal rains caused by warm humid monsoons from the southwest, which usually begin in May and extend through September, depending on latitude. Along with, and following the monsoon rains, waters of the mainstream and tributaries begin to rise. The timing and effects of this rise differ by river sector but generally floodwaters may cover almost the entire low gradient drainage basin of the Mekong and its tributaries, all the way to the estuarine zone in Vietnam. The natural, long-time evolution of the reproductive cycle of most freshwater fish of the basin has synchronized maturation of the gonads with the onset of the rainy season and flooding, and has led to extensive migration of these fish into the zones of inundation. These zones not only afford a rich variety of spawning habitats, but also, while inundated, provide nutrient-rich nursery grounds. As the flood water begins to subside following the onset of the dry, cool, northeast monsoons (usually beginning in October), both fingerlings and adults return to the river and its tributaries, and provide rich fishery there: some of the young remain in the wetlands in the flood plains and contribute to year round fish harvests there.

The natural system of high productive potential combined with the opportunity for efficient harvest makes the Mekong floodwater fishery, like those of the other great river-flood inundation zones, one of high catch and value. The seasonal fallowing and drying that follows annual inundation is the key to nutrient release from inundated land for cycling into aquatic production. These events accelerate the breakdown of organic materials, such as plant remains, for rapid transfer via food chains into fish and other aquatic crops during the next flood.

The fisheries of the brackish waters in the Mekong estuary proper and in the adjacent waters of the South China Sea exceed in magnitude the fisheries of the freshwater zone. In these estuarine and coastal waters, shellfish are more prominent than in the inland parts of the basin. Marine organisms predominate, as there is a progressive downstream change from freshwater to marine habitat. Like all estuaries, that of the Mekong is potentially among the most efficient of all aquatic systems for the conversion of solar energy via the food chain into fishery production. This efficiency is reinforced by the shallowness of the waters and the relative nutrient richness of the ecosystem which receives the nutrient-rich silt washed down seasonally during floods, the estuary being situated at the downstream end of the vast drainage basin.

The Mekong inundation zone and estuarial ecosystems contain delicately tuned interactions between the physical environment and the biota. These interactions are highly vulnerable to the alterations in quantity and timing of annual inundation and mainstream discharge implicit in the installation of engineering works and operation of water management systems upstream and in poldering of flood plains. These alterations will impinge upon the life cycles, distribution and abundance of the freshwater zone, estuarine and coastal fishery organisms. Of particular concern may be dispersion of commercially exploitable concentrations of valuable fish, which occur seasonally in the river and off the river mouths.

The fishery yield and value from these ecosystems—the Mekong freshwater zone, estuary and waters of the South China sea under direct Mekong influence—have never been precisely quantified in spite of substantial size and immense economic and nutritional significance at the local level. Extrapolations of existing records and statements by experienced government officials indicate that the annual production of these waters from all types of fisheries (commercial, artisanal and subsistence fishing and from aquaculture) may approximate 500,000 metric tons, valued in 1988 at US$225 million.

4.4.7 Toxic biocidal levels in edible organisms

One of the objectives of water resources development in the basin is raising agricultural production from the present 12.7 million metric tons to 37 million metric tons per year. This has required, among other measures, the intensive use of pesticides and herbicides; all the more so because monoculture enhances vulnerability to attack from plant and animal pests. The intensive use of herbicides and pesticides, as is well known, can render the aquatic ecosystems unproductive and even harmful to human populations. In order to avoid these impacts, agricultural development should be made compatible with aquasystem development. The problem of toxic biocides at present is not widespread, though acute in certain locations, particularly in northeast Thailand.

4.4.8 Waterborne diseases

Experiences in different parts of the world have shown that water resource development projects such as those implemented or contemplated in the lower Mekong basin, may result in serious, adverse health consequences. Especially in tropical and subtropical areas, where water and vector borne diseases such as malaria, *schistosomiasis* (blood fluke disease) and *filariasis* affect the lives of millions of people, ecological changes induced by water resource projects may directly contribute to the spread, propagation or introduction of such diseases by creating favorable habitats for vectors and intermediate hosts. The incidence of *schistosomiasis*, for instance, rose dramatically in many arid and semi-arid countries in Africa and the Middle East, after man-made irrigation supported the propagation of snails, which are intermediate hosts. In a southern province of Egypt for example, the prevalence of *schistosomiasis* reportedly grew from 3 percent to 42 percent within 20 years.

Water resource development projects do not only affect habitats of vectors and intermediate hosts but also contribute to the spread and introduction of pathogenic agents by attracting people representing a variety of epidemiological factors; examples are migrant laborers during construction work and settlers after its completion.

Waterborne diseases in the lower Mekong basin could be classified into the following three types:

- Water borne diseases *sensu stricto* or water transmitted diseases. In this category man or animal is the source of infection and the main host. The agent is discharged into the water with human or animal faeces or urine. Water is a vehicle for infective agents: bacteria, viruses or parasites. Examples are a variety of diarrheal, enterotoxic diseases, *escherichia coli* infections, *shigellosis, salmonelloses*, cholera, virus infections, typhoid and paratyphoid, virus hepatitis A, amoebic dysentery, *giardiasis*, *leptospirosis*, etc.

- Water transmitted helminthic diseases with involvement of an intermediate host or hosts living in the water. Examples are *schistosomiasis, opisthorchiasis* and *paragonimiasis.* Snails are the first intermediate host for parasite development and fish, crabs and plants the second intermediate host for certain parasites. Humans get infected through direct water contact (*schistosomiasis*) or by consuming uncooked, intermediate hosts;

- Water constitutes the breeding place for the vectors. Examples are malaria, filariasis and Japanese B encephalitis.

Of the variety of diseases, *schistosomiasis* is the primary focus of the Mekong Committee. The first human case of *schistosomiasis* originating from the Mekong basin, reported in 1957, was a Laotian living in Paris. Intensive studies showed that *schistosomiasis* in this area is caused by a then unknown parasite now called *schistosoma mekongi.* This parasite closely resembles *schistosoma japonicum*, but its intermediate host is a planorbid freshwater snail, *tricula aperta*, living in certain parts of the Mekong river. The snail is also abundant in the Mun river, a tributary running through Ubol Province in Thailand, where a major project, the Pak Mun dam is planned. So far, two foci of human *schistosomiasis* are known in the lower Mekong basin, one at Khong Island in the southern tip of Laos, the second one at Kratie, Kampuchea. No proven case has ever been diagnosed in Thailand, with the exception of refugees from Laos and Kampuchea.

The liver fluke *opithorchis viverrini* is considered another important potential health problem because of its high prevalence in the population of the northeastern part of Thailand (34.6%) and Laos (46.5% in Vientiane and 39.7% in Khong island). Infection is acquired by the habit of eating raw cyprinoid fish that serve as the second intermediate host for the parasite. Other waterborne helminthic infections such as *paragonimiasis, angiostrongylosis* and *fasciolopsiasis* and intestinal flukes, of which detailed data are only available from Thailand, appear relatively less important.

Among vector borne disease, malaria clearly constitutes the most serious health problem in areas of the Mekong basin. Considering the enormous obstacle of drug resistant strains of *plasmodium falciparum* rapidly spreading over southeast Asia, it is of utmost importance to prevent the creation of new breeding habitats for the vectors. Quite a number of primary vectors are known in the Mekong basin which require different types of breeding sites for efficient propagation, such as slow running, vegetated streams (*an. minimus, an. maculatus*), paddy fields (*an. nivipes*), stagnant water in forests (*an. dirus*) and brackish water (*an. sundaicus*). Other vector borne diseases in the Mekong basin include dengue haemorrhagic fever transmitted by *aedes* mosquitoes and Japanese B encephalitis transmitted by *culex* mosquitoes. Unlike malaria, which is endemic in the area, these two diseases usually manifest themselves as epidemics. In the Mekong delta dengue haemorrhagic fever was one of the leading causes of morbidity during the years 1976–1983. Japanese B encephalitis is usually associated with pig breeding as these animals serve as hosts for the virus.

As mentioned above, diarrheal diseases are known worldwide and are among the biggest killers of children below five years of age. This group of diseases is very common in all three riparian countries and rank high in prevalence and incidence in all age groups, especially in the densely populated Mekong delta where the sanitary standards are low. In water, fecal micro-organism indicators reach medium to high levels in 100 percent of surface water of the Mekong river, as well as in its branches, canals and ponds. The surveys further showed that 98.5 percent of dug well water samples were contaminated.

4.4.9 Rural potable water supply in problem areas

In the lower Mekong basin, as in most developing regions of the world, domestic water supply from central water treatment plants is only available for cities and major settlements. Villages and individual households in rural areas are not connected to such facilities. This means that more than 80 percent of the population have no access to treated water but depend directly on surface water bodies for domestic supply, including drinking water and preparation of food. Thus, public health and hygiene depend to a large extent on the quality of these water bodies and their contamination with pathogenic organisms and chemicals. With increasing population densities and intensification of agricultural land use, increasing amounts of domestic wastewater and agricultural chemicals (fertilizers, pesticides) have reached the surface water bodies. At present, tributaries in northeastern Thailand show signs of eutrophication and in the Mekong delta—where population density is highest—even the main river distributaries show levels of bacterial contamination which render them unsuitable as sources of drinking water. Consequently, there is a high prevalence of diarrhoea type diseases and intestinal parasites in these densely populated parts of the basin.

In addition to these anthropogenic problems resulting from a short-circuit between waste disposal and domestic water supply, two natural problems, namely salt contamination and acid waters, impinge on the quality and potability of water. These problems not only affect surface waters but also the groundwater, which could otherwise be regarded as a comparatively safe alternate source to domestic water supply. Thus, in large areas of the basin, rain water is the only water source of adequate quality for domestic consumption, but rain water is available only during a part of the year, and safe storage facilities are required to keep a sufficient quantity for the dry season, without risking secondary contamination. Taking 20 litres per person/day as the absolute baseline for the demand of good quality water, a storage tank of about 20 m^3 would be required to last a family of 6 persons over the 5–6 months of the dry season. Most families in rural areas are too poor to purchase such a tank, and the smaller tanks which are in use are often open and exposed to secondary pollution. When stored drinking water has been consumed, either water has to be bought, and in some instances transported over several kilometers, or low quality water has to be used, which of course has impacts on public health. In many households of the delta simple filtering techniques are used to make surface water more suitable for domestic purposes. From the above it is obvious that the supply of potable water to rural households in problem areas is at present rather urgent.

4.5 Program of action to solve the problems

The underlying philosophy of the Mekong Committee's environmental program is to cement the environmental dimension into Mekong development projects with a view to ensuring that productivity of primary natural resources (terrestrial, aquatic and human) does not deteriorate as a result of development activities in the basin and that maximum socio-economic benefits can be attained. Therefore, a comprehensive environmental program pervades all the Committee's development activities and includes steps to anticipate, as far as possible, both the undesirable side effects and unaccounted benefits resulting from development activities, and to demonstrate measures to maximize benefits and alleviate the adverse effects through effective management. The most important elements of the program are summarized below:

1. **Studies** leading to environmental assessment, including identification of problems, and
2. **Pilot management, rehabilitation and amelioratory activities** to demonstrate measures to enhance benefits and to offset adverse effects of water resource development projects on the environment.

4.6 Conclusion

It is now universally acknowledged that investigations of ecological consequences and broadly defined environmental impacts should be central to the planning and design of development projects. Often, quite minor alterations in plans and additional costs in the construction phase can prevent major environmental, economic and social costs.

In international river basin planning, such as that of the Mekong in particular, environmental parameters assume especial importance, since off-site impacts of development actions in one riparian state could manifest themselves in another. For instance, injudicious watershed management in an upper riparian country could have undesirable effects on water use or the viable life of impoundments in a lower riparian state. Unregulated withdrawals of water in upper sections of rivers may adversely influence agriculture and fisheries downstream. Impoundments upstream could alter downstream ecology to such a degree as to seriously affect various facets of river productivity. The Mekong Committee, recognizing in particular the transnational nature of the impacts of river basin development, has given due attention to environmental parameters in development planning.

One of the approaches to incorporate environmental criteria into project planning and assessment at an early, screening-level stage, is the methodology of environmental impact analysis. To develop this methodology and make it available to the staff at the Mekong Secretariat, a study to develop and implement a prototype level expert system for environmental impact assessment (see color Plate 1) was commissioned. The expert systems approach was selected not only to build a tool that is easy to use by project officers with little or no computer experience, but also to provide a common framework and easily accessible repository of environmental knowledge at the Secretariat. The development of the knowledge base of the system requires knowledge contributed by individual experts. The system also provides a mechanism to discuss, review and formalize the environmental policy of the Secretariat.

Plate 1. MEXSES start-up screen and top-level icon menu along the bottom of the screen.

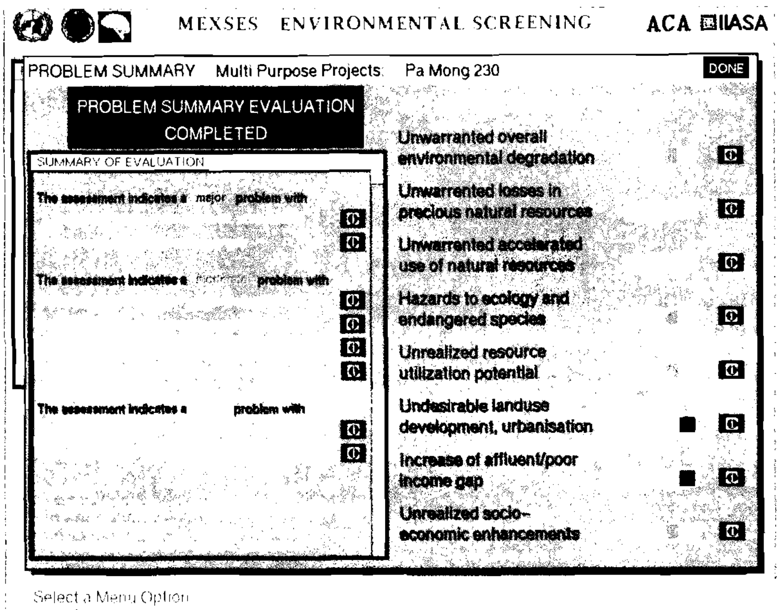

Plate 2. A completed problem summary evaluation.

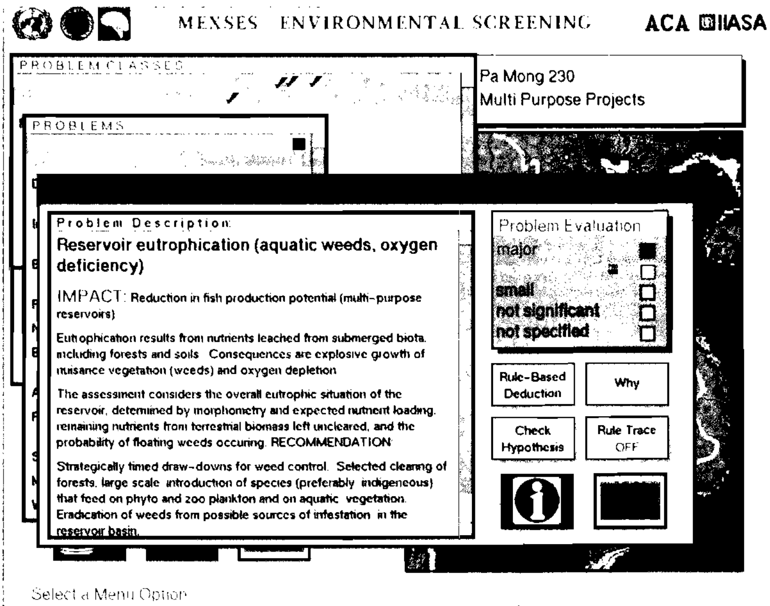

Plate 3. Hierarchical problem selection in the environmental impact checklists.

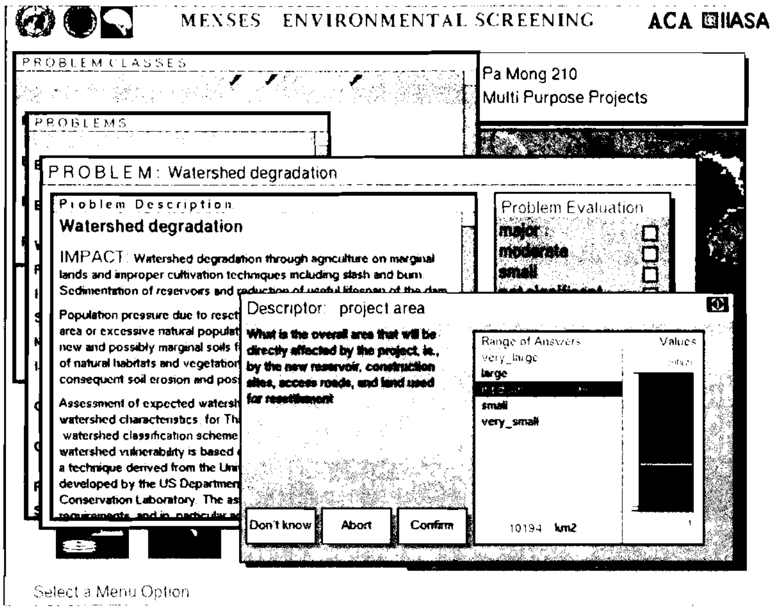

Plate 4. Setting a descriptor value at the problem assessment level.

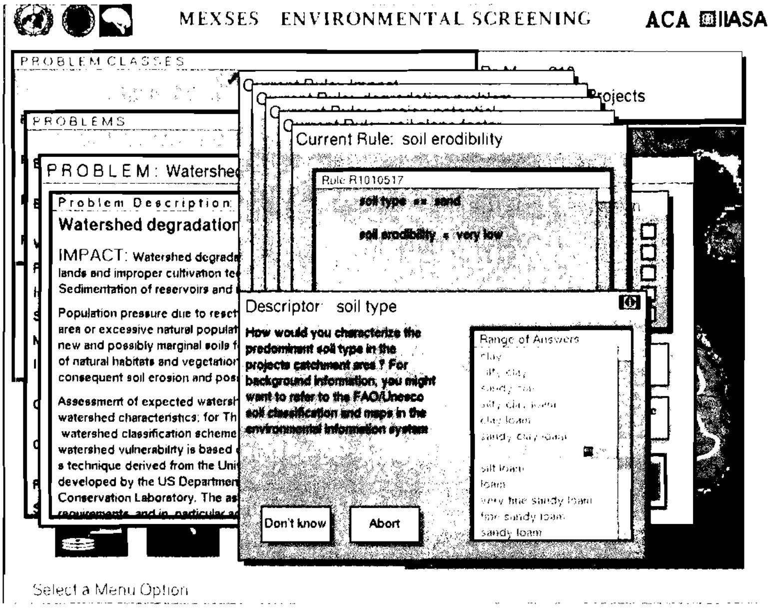

Plate 5. Setting a descriptor value with the rule display turned on.

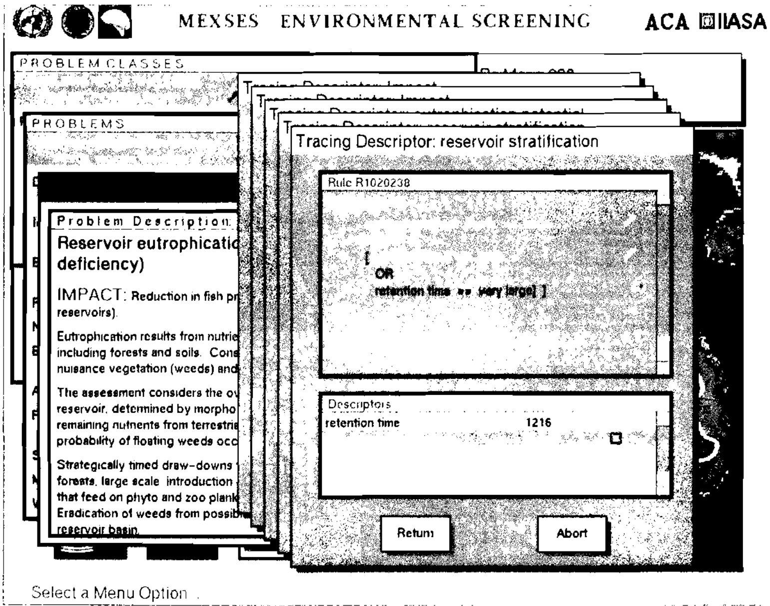

Plate 6. Explaining an assessment result by recursively tracing rules and descriptor values.

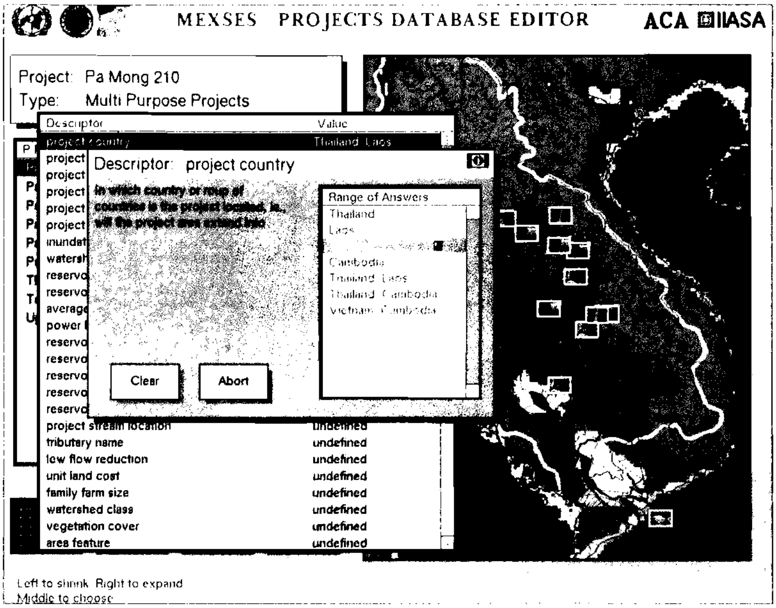

Plate 7. Projects data base editor.

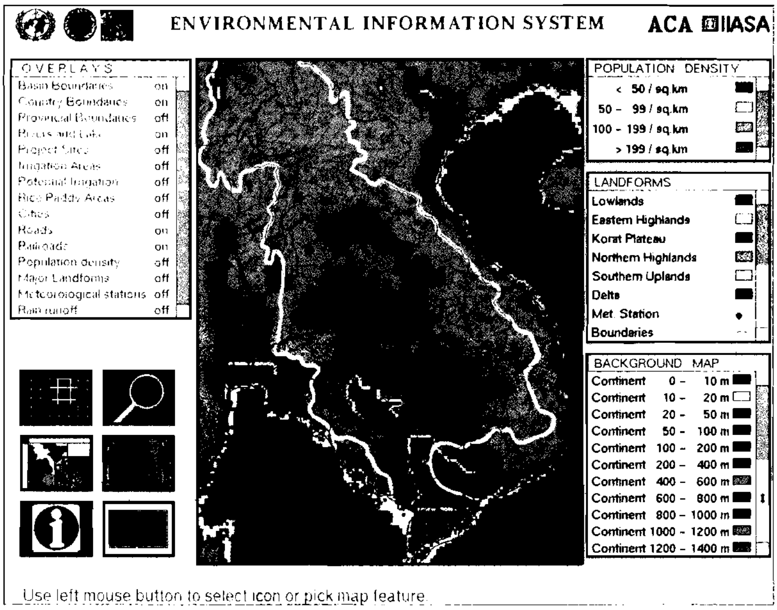

Plate 8. Highlighting a map feature in the environmental information system.

Chapter 5

MEXSES: An Expert System for Environmental Screening

5.1 Main systems components

MEXSES is designed for environmental impact analysis at a screening level, starting at an early stage of project planning and design. Environmental considerations should go hand in hand with the technical and economic feasibility and pre-feasibility studies. At these early stages of project development, the available information on the detailed project characteristics, but in particular on the project's environment, will usually be rather tentative, approximate, and sparse. Thus MEXSES must allow the analyst to utilize whatever information is at hand, and update this information adaptively as more detailed data become available during the project planning process. The system must also serve as a framework and tool for the compilation and organization of all environmentally relevant data. The assessment tool, a rule-based expert system, is integrated with a few basic building blocks that allow MEXSES to be used efficiently for this task.

The system is accessible from the top level and provides four major functional blocks or entry points: the *help* and *explanatory text* function, a geographical information system, the projects data base, and the expert system proper (*Figure 5.1*).

The *help* and *explanatory text* function is based on the concept of hypertext. It is accessible from every level of the system, and provides an

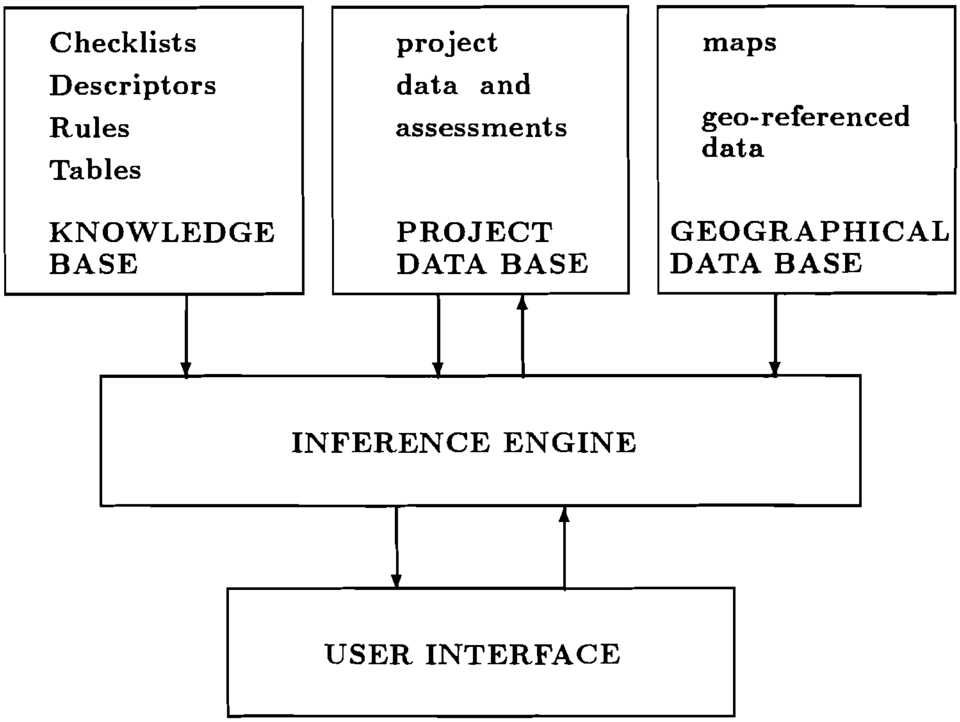

Figure 5.1. The basic structure and components of MEXSES.

on-line manual for the system's use. In particular, it is used to provide further information and explanation for the terms or descriptors used in the system's knowledge base. Objects displayed on any given screen, such as text strings, icons, or any graphical object, can be used as a keyword or entry point for the hypertext system: clicking on them with the mouse pointer will call up the corresponding hypertext *explanatory text* page, which in turn can contain numerous other keywords leading, recursively, to further related information.

The geographical information system handles a number of geo-referenced data sets and maps. They include a basic map of the lower Mekong basin, political boundaries, major landforms, and the river and its tributary system. Population data at the provincial level, elevation data, and a soil map derived from the FAO/Unesco global soil map. The GIS allows these data to be displayed, to generate arbitrary overlays of the various topics, zoom into the maps and to query them by identifying items displayed or data associated with a given item. An example would be to read back the name of a tributary by pointing to it, or displaying a population number from a province on the map.

Once a project area is defined, data associated with this area and stored in the GIS can be made available to the inference engine.

The projects data base compiles the complete set of primary descriptors used to characterize a given project and its environment. Primary descriptors are variables or parameters, that must be either supplied by the user or retrieved from the GIS; their value cannot be derived internally by the inference engine.

The data base allows this list of descriptors to be displayed and edited for each of the projects defined. It also allows modified data sets to be stored under different names, so that project alternatives can easily be generated.

The core of MEXSES is a rule-based assessment system, based on a classical checklist approach. It follows the basic sequential logic of project definition so that potential problem areas are grouped by project stages such as site selection, planning and design, construction, operation and finally, mitigation.

To make the checklists more flexible and easy to use, the checklists have been made project-specific. Only problems truly relevant to a given project type need to be addressed. The checklists help the analyst to address all the potential environmental problems a given development project might cause. The analyst has to assess each of the individual subproblems in order to complete a project assessment. Once all the subproblems have been addressed and classified in terms of

not significant — small — moderate — major,

the system can perform a summary evaluation, using a few top-level evaluation criteria.

Underlying the rule-based expert system is a knowledge base, which consists of the checklist files, descriptor definitions, the rules, and the hypertext files. The checklists provide the basic control structure for the assessment procedure. The descriptor definitions provide information on possible values and allowable ranges for these variables, and default values. They also provide the coupling between descriptors and rules. The rules link descriptors in IF .. THEN relationships, which allow values to be assigned to derived descriptors. Finally, the hypertext files provide basic problem definitions for the checklists and background information to place a given problem in a broader context. They provide definitions of concepts and terms, in particular, the descriptors used in the rules, and they reference sources of data or the background for rules and underlying assumptions.

5.2 Entering the assessment system

The **expert system** proper is entered via a project selector. Available projects, as well as an empty template **New Project** are offered. If an old, existing project description is loaded, all the associated data and the state of the evaluation that may already have been performed are loaded from the data base. The user can then continue and complete the evaluation procedure.

If the **New Project** is selected, the user first has to specify a project name, type and project location (*Figure 5.2*). Project types covered in the prototype are, e.g., reservoirs and dams, hydropower projects including transmission lines, irrigation projects, fisheries and aquaculture, and could also include infrastructure projects (roads and highways, sewerage, water supply, etc.), navigation, erosion control, etc.

The location of a project is defined by dragging a cross-hair cursor over the map displayed on the screen, and selecting the final position by pressing the left mouse button at the desired location.

The user can then save the project (possibly under a different name than that originally assigned when defining the project), and subsequently use the project editor on it, proceed with the analysis for the new project, load another existing project, or generate yet another new one.

The analysis can be started in two different ways: via the project summary evaluation option, or through the basic problem class oriented checklists. Either way can be chosen, and both approaches are fully interchangeable, using the same basic problems, although in different grouping and sequence, so that the analyst can switch from one mode to the other.

5.3 The project summary level

At the project summary level, for any specific project (one of a project type or class), the expert system uses a number of **overall environmental review criteria** that the system uses to summarize the assessment (in terms of the individual checklists of problems) for a given project (see color Plate 2). The summary evaluation criteria are:

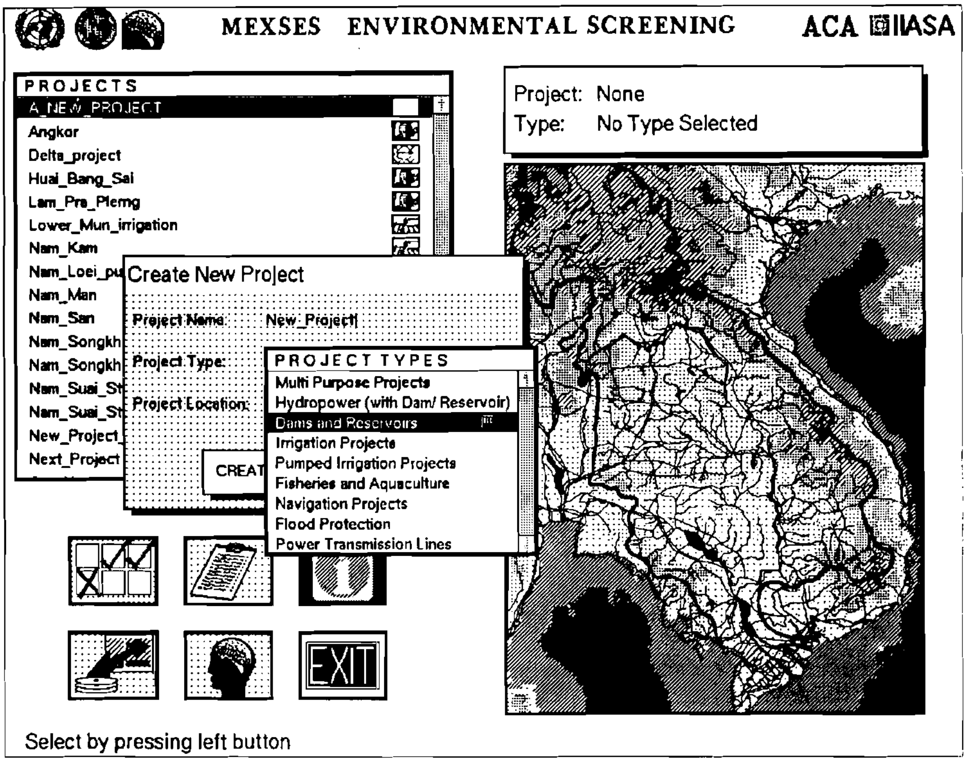

Figure 5.2. Defining a new project for assessment.

- Unwarranted overall environmental degradation;
- Unwarranted losses in precious natural resources;
- Unwarranted accelerated use of natural resources;
- Hazards to ecology and endangered species;
- Unrealized resource utilization potential;
- Undesirable land use development, urbanization;
- Increased disparity in affluent/poor income gap;
- Unrealized socio-economic enhancements.

The overall summary evaluation criteria thus cover physical and ecological as well as socio-economic aspects. Impact levels or severity for the overall review criteria are established from a weighted average of a set of lower-level problems from the checklists deemed of relevance in the context of the overall criteria. For example, **Overall Environmental Degradation** would include the results of the assessment for problems such as **watershed degradation**, **watershed erosion**, **mangrove destruction**, etc.

Each lower-level problem can contribute to more than one of the summary criteria, and it can contribute to each or any of them to a different degree. This degree is expressed as a simple weighting factor, that specifies the relative contribution a given assessment result for a specific problem will have on the overall review criteria. The method used here, meta-descriptors that summarize a list of individual problems, and again use rules to assign the final impact value, is described in more detail in the discussion of descriptor values and formats below.

These aggregation categories or environmental review summary criteria are evaluated, just like the individual problems of the checklists, in terms of impact levels, namely

not significant — small — moderate — major.

Depending on the result of the aggregation and top-level evaluation procedure (which is based on the completed analysis of the lower-level checklists and problems discussed below), various concluding recommendations are offered:

- If more than one of the eight top-level criteria are found to be a major problem, a complete and detailed environmental impact assessment with special emphasis on the criteria with the major impact assessment results will be required.

- No further display of the criteria with moderate or small impacts is provided at this level. The lower-level assessment results, however, can be viewed by calling up the respective subproblem listings for each of the top-level criteria.

- If only one of the top-level aggregated impacts is major, a complete and detailed assessment for this topic is recommended. This is combined with a recommendation for a more detailed assessment of all categories with a moderate impact level.

- For impacts that are evaluated as small, in combination with any of the above, a more detailed study of the respective topics may also be required.

- In the associated information box, a listing of all recommendations referring to the subproblems that contribute significantly to the respective top-level evaluation are displayed.

However, if the evaluation of these subproblems is not yet completed, the summary evaluation level can be used as an entry into the checklists (*Figure 5.3*). They will not, however, be organized by problem classes, i.e., in terms of location, planning and design, construction, and operation of a project, but by their contribution to the top-level review criteria (see Appendix 1). Selecting any of the incomplete topics for analysis of the lower-level problems will generate a listing of these subproblems, with an indication of their evaluation status. Any of them can then be selected for assessment. If a group is completed, the corresponding summary evaluation will be performed automatically upon leaving this group of problem evaluations and the corresponding summary display will be updated.

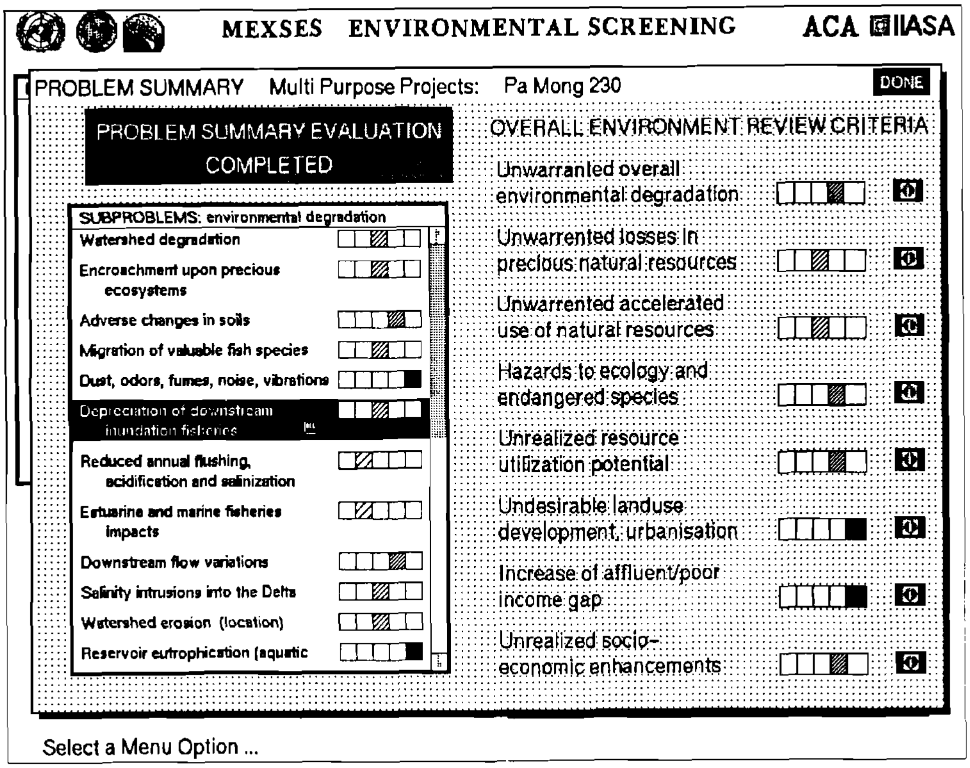

Figure 5.3. Entering the subproblem checklists from the summary level.

5.4 Environmental checklists

The same evaluation mechanism with its checklists can be entered via the **Environmental Checklists** option, this time organized by problem classes (see color Plate 3). The problem classes organize individual problems into categories such as **Problems due to Location**, **Planning and Design Problems**, **Problems during the Construction Phase**, **Problems during Project Operation**, and finally, **Environmental Enhancement Measures**, which looks at possible enhancement or mitigation strategies.

The checklists for each project type are designed to ensure reasonably complete coverage of all aspects of project-specific impact that can be expected; they could, in principle, be filled out directly. The most attractive feature of MEXSES, however, is in using the expert system to guide and assist the analyst in these assessments. The checklists are thus used as an entry to specific questionnaires to elicit more detailed information about the project and its expected environmental impacts. This information is used in an attempt to deduce answers, using the system's knowledge base and inference engine, which can ultimately be aggregated into the top-level questions and review criteria.

For each problem item on the checklists, the analyst can directly set an impact classification value i.e., choose one of the impact descriptors ranging from **not significant** to **major**, and then optionally ask the system to check the "hypothesis". This triggers a backward chaining inference system, that attempts to establish all the necessary preconditions to the specifications formulated by the analyst as the hypothesis. If the required "facts" cannot be confirmed, the inference procedure will invoke the interactive questionnaires and ask the user the necessary questions. As a final result, the user's assessment will either be confirmed or rejected (*Figure 5.4*).

Where the impact classification for a given problem on the checklist cannot be provided by the analyst with sufficient certainty, or his initial assessment is rejected by the system, the main assessment procedure can be used. This attempts to provide the analyst with a system-generated answer, deducing the impact assessment from project and environment characteristics, represented in the descriptors. The rules of the system's knowledge base are evaluated to arrive at the required problem classification.

Choosing the **Rule-based Deduction** option at the level of an individual problem, the analyst starts an inference procedure, where the system will reason from the available data to arrive at a classification of impacts for each problem. Again, using the interactive questionnaires, missing information

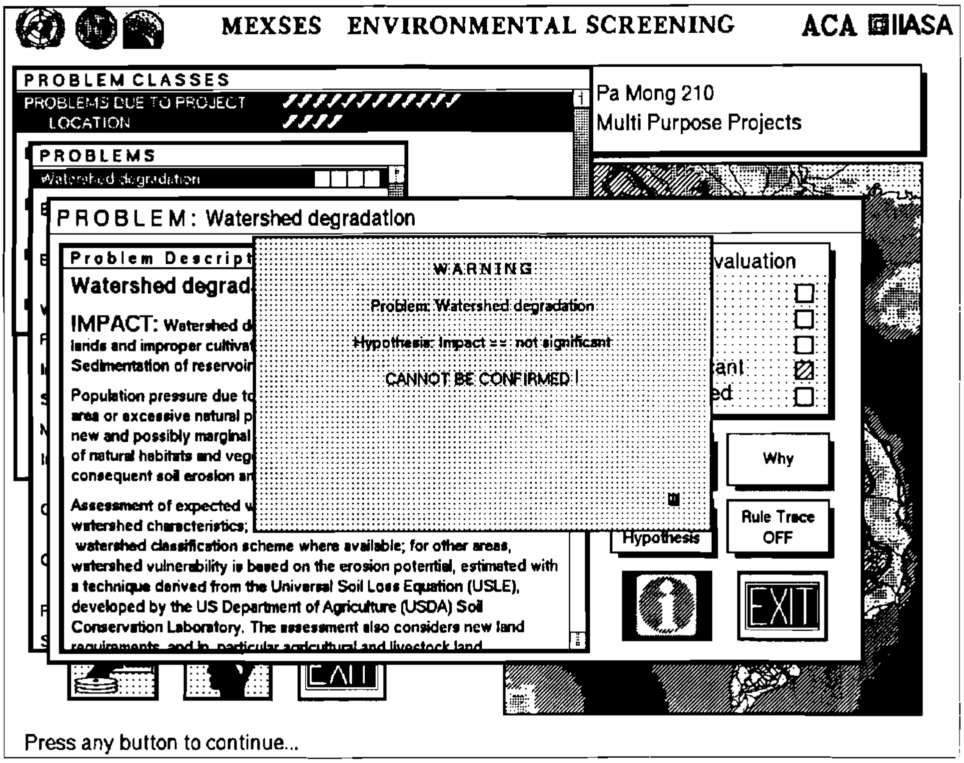

Figure 5.4. Check Hypothesis: hypothesis cannot be confirmed.

will have to be supplied by the analyst in a question–answer dialogue to provide intermediate descriptor values that are not yet defined in the project data base and cannot be derived from other rules, but are required to deduce an impact classification for the current problem (see color Plate 4).

Thus, unsatisfied goals at any level, starting from the overall problem assessment, are recursively decomposed into a set of subgoals at the next lower level, i.e., individual descriptors that are used to derive the final assessment, which are then analyzed in an attempt to satisfy the respective higher-level goal.

5.5 The projects data base

As an alternative or complementary approach to the interactive checklist questionnaires, a **project data base editor** allows the user to select one out of a set of available project description files, which have been saved from

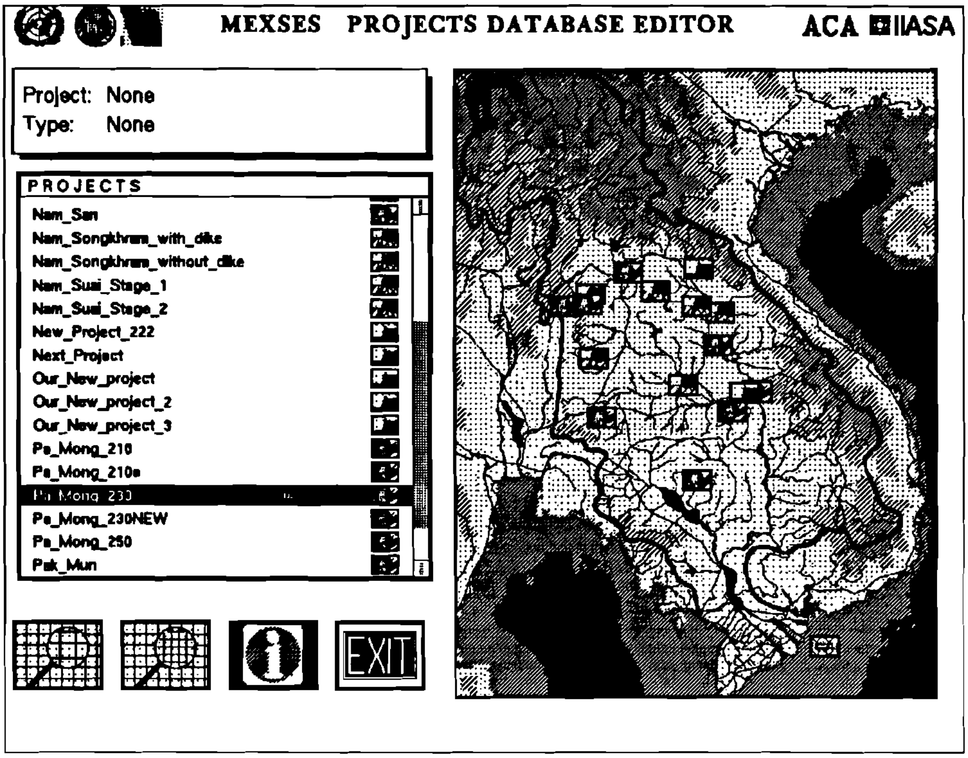

Figure 5.5. Selecting a project for the data base editor.

completed or partially completed runs of the expert system (see *Figure 5.5* and color Plate 7).

After selecting one of the projects from the list of available projects a listing of the project's primary descriptors is displayed with the values currently set, or labelled **undefined**, if no value has been set yet. Any of these descriptors can be selected and its value can either be cleared or "unset"; the user can also set a specific value, using the same menu-driven interface that indicates either the repertoire of possible values (in case of a symbolic descriptor), or the range of possible values in case of a numerical descriptor.

Obviously, modifying a descriptor value for a problem that has already been evaluated, i.e., where other descriptors have been derived by the rule-based inference mechanisms from user-defined values, at least in part (for at least one of the problem checklists) may require the rule-based evaluation procedure to be rerun. In the current prototype, consistency is enforced by simply setting **all** the derived descriptor values to **undefined**.

For a new project, the editor provides the possibility to set the descriptor values efficiently for the subsequent assessment, without having to go through the rule-driven sequence of questions.

The system offers to retrieve and modify previously stored project descriptions, including generic examples. A given example can be loaded, and then saved under a different name e.g., to provide a shortcut in generating a project variant. All values defined in the example loaded will thus be copied over into the new project. This feature is in particular relevant for the efficient definition of a number of basically similar project alternatives.

The project description language is geared toward the linkage to the expected environmental impact categories that are summarized in the checklists described below. In other words, the descriptors for a given project include all the variables used for the rule-based impact assessment. In addition, it is possible to use additional descriptors, relevant in a full description of a project, which are, however, not used in the rule-based assessment at this stage; they can be defined and added by updating the **Descriptors** file in the Knowledge Base directory.

At any stage, the system will attempt to satisfy the current strategic goal and questions at the level of entry chosen by the user, and indicate where information is still missing for a complete and satisfactory answer by requesting a definition of the missing descriptor value. It will also be able to explain how answers at the various levels were deduced, if they have not been entered directly by the analyst.

5.6 The geographical information system

Auxiliary software also includes basic data manipulation, analysis, and display facilities, including topical map drawing and processing for overlay analysis techniques, based on a DLG (USGS Digital Line Graph) derived data representation compatible with Arc/Info data formats.

The **Environmental Information System** option is entered from the top level of the system (see color Plate 8). It displays a map of the area, with an icon menu that allows selection of the listed features and display of the features selected. They include:

- Country boundaries;
- Major landform zones;
- Mainstream, tributaries, and tributary reaches;

- Major reservoirs;
- Population density by provinces;
- Runoff zones;
- Meteorological observation stations.

For the base map, the user can select an elevation map or a soil map. The map also allows arbitrary zooming for greater detail (*Figure 5.6*). In the current prototype, an interface is provided between this GIS functionality and the inference engine, that foresees using the GIS to provide some of the descriptor values required by the rules. It is, at this stage, not yet fully implemented, i.e., the GIS requests from the inference engine have been translated into a question to the user as an interim solution.

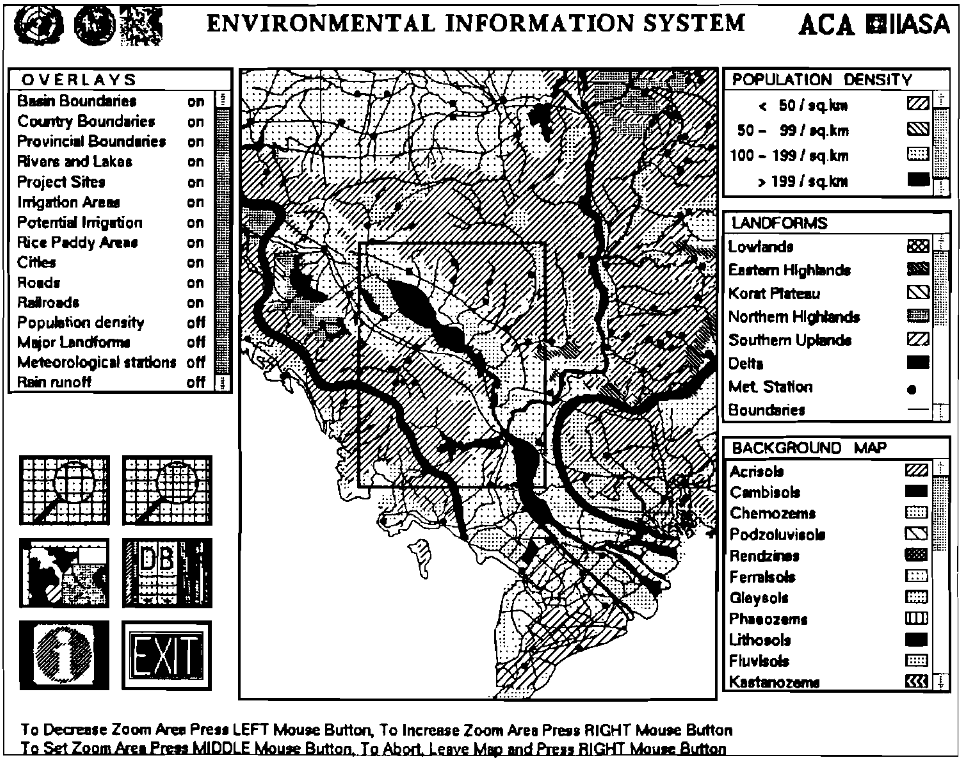

Figure 5.6. GIS country/provinces map; detail of the delta area.

5.7 Systems structure and function

MEXSES is a rule-based system. The core of the system is its knowledge base, which is contained in several files, namely:

1. The checklists
2. The descriptors
3. The rules
4. The decision tables
5. The overall review criteria
6. The project types
7. The hypertext files.

In addition, the system manages a data base of project assessments or descriptions, and a geographical data base of maps and geo-referenced data (see color Plate 8).

The checklists represent a hierarchical set of questionnaires, which help the analyst to assess a given project (*Figure 5.7*). The hierarchy considers the following three levels:

1. Project Type
2. Problem Class
3. Problem.

It is important to realize that while the principle of this three-level hierarchy (including aggregation of the Problems into a set of top-level problems collected in the first problem class, see below) is hard coded into the system, the contents or extent of each of the levels are fully determined by what the checklist files contain, i.e., is data-driven and can thus be adapted and extended very easily.

The checklists, including the overall criteria, are organized by project types. The prototype considers the following project types:

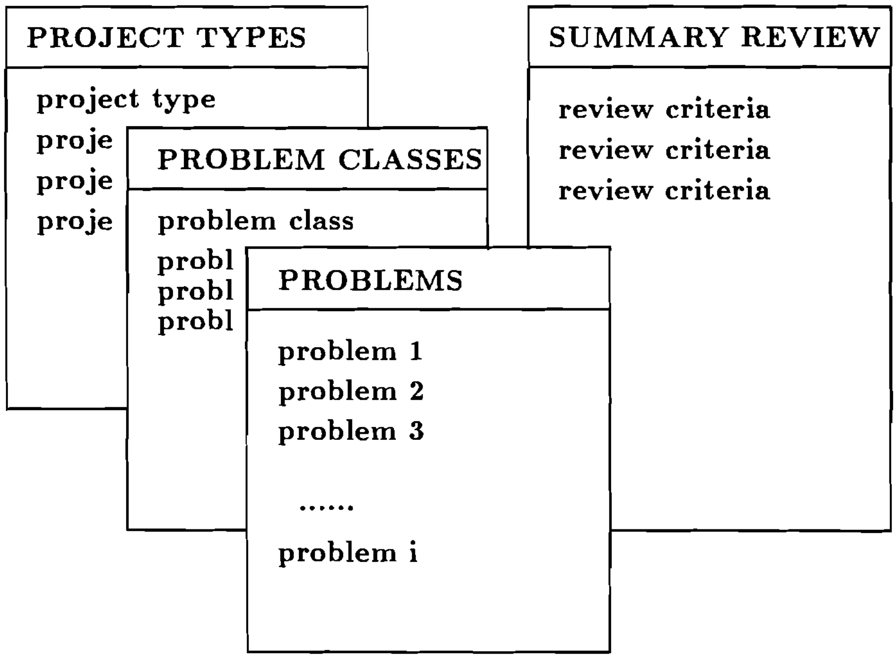

Figure 5.7. Hierarchical checklists and overall review criteria.

Project Types:

1. Multi-purpose Projects
2. Hydropower (with Dam/Reservoir)
3. Dams and Reservoirs
4. Irrigation Projects
5. Pump Irrigation Projects
6. Fisheries and Aquaculture
7. Navigation Projects
8. Flood Protection
9. Power Transmission Lines.

As stated above, this list can be extended or modified by simply changing the corresponding checklist files.

Within these Project Types, a set of five Problem Classes is defined. They include:

Problem Classes:

1. Environmental Problems due to Location
2. Environmental Problems due to Planning and Design
3. Environmental Problems associated with the Construction Stage
4. Environmental Problems resulting from Project Operations
5. Potential Environmental Enhancement Measures.

An example of the project type **Dams and Reservoir**, and the problem class **Problems due to Location** is given below:

1. Resettlement
2. Watershed degradation
3. Encroachment upon precious ecosystems
4. Encroachment on historical/cultural values
5. Watershed erosion
6. Reservoir siltation
7. Impairment of navigation
8. Changes in groundwater hydrology, waterlogging
9. Seepage and evaporation losses
10. Migration of valuable fish species
11. Inundation of mineral resources/forests
12. Other inundation losses and adverse effects

13. Earthquake hazards
14. Local climatic change.

Each of these individual problems is then evaluated, along the basic scale of **not significant – small – moderate – major**. This evaluation can be based on the analyst's assessment of the description of the problem, recommendations for mitigation, and guidelines for assessment, that are displayed by the system at this point.

The example for the resettlement problem is given below:

Problem: RESETTLEMENT

- **Impact:** Serious social inequities, watershed degradation
- **Problem Description:** Resettlement of population from inundated area. This problem has often been serious because of failure to conduct proper studies on socio-cultural and economic aspects of population to be resettled, land suitability studies on areas earmarked for relocation, and failure to include sufficient funds in the project core budget to cover appropriate resettlement costs. Also, land available for resettlement is often of low quality, leading to encroachment of watershed areas, watershed degradation and erosion due to use of marginal lands.
- **Guidelines for Assessment:** Evaluation of the expected impact considers the number of people to be moved, the costs of relocation, depending on the location and size of the project, in relation to the available budget, the type of watershed and the land demand of the new settlement areas, and finally potential mitigation by watershed management, including activities such as zoning and land-use planning, erosion control, afforestation, etc.
- **Recommendations:** Carefully planned resettlement program including "hard" budgets. Provide family housing and socio-cultural amenities, plus developed land for the traditional land-use types rather than cash payments.

At this stage, the analyst can

1. Set the problem impact value directly, with the subsequent option of asking the system to CHECK the HYPOTHESIS;

2. Start the rule-based automatic deduction of the impact value with the subsequent option of asking WHY and have the deduction process explained step by step (see color Plate 6).

In the latter case, i.e., using the rule-based deduction mechanisms, there are two options, namely with and without RULE TRACING. If RULE TRACING is turned on, the system will display each rule and offer a choice of either applying it or skipping it (see color Plate 5). The display of rules allows the user to use any and all of the descriptors displayed as keywords for the hypertext system, providing further explanation of the concepts used in the rules. If the user wants to apply a given rule, it will either automatically lead to a conclusion if all its conditions are met, or ask for missing information. This process continues until an impact level has been deduced, or the analyst chooses to abort the rule tracing mechanism, or until the system runs out of applicable rules.

Once a final answer has been deduced by the system, with or without rule tracing, the analyst can invoke an explanatory text facility, asking WHY. Here the system will display the rule or rules that lead to the final conclusion, and the values of the various preconditions for applying the rule. The backward tracing of rules and preconditions can be continued by selecting any of the precondition's descriptor values for further explanation, which will again either be a rule that deduced the value, or the information that the user himself has supplied this value.

If the analyst sets the impact value directly, he can use the system to check his assessment, viewed as a hypothesis. This will again trigger the deduction process in an attempt to confirm the user's hypothesis. Here the deduction process, however, is more focused, as it only tries to confirm the hypothesis, and thus only examines rules that can lead to the conclusion specified by the user. Depending on the outcome of the hypothesis testing procedure, the user will be informed as to whether the system can confirm his assessment or not. As above, during the confirmation process, missing information required to apply some of the rules may be inquired of the user (see color Plate 4).

5.8 User interface

MEXSES is an interactive and completely menu-driven system. It is thus easy to use and guides the novice user with appropriate prompts and menu options.

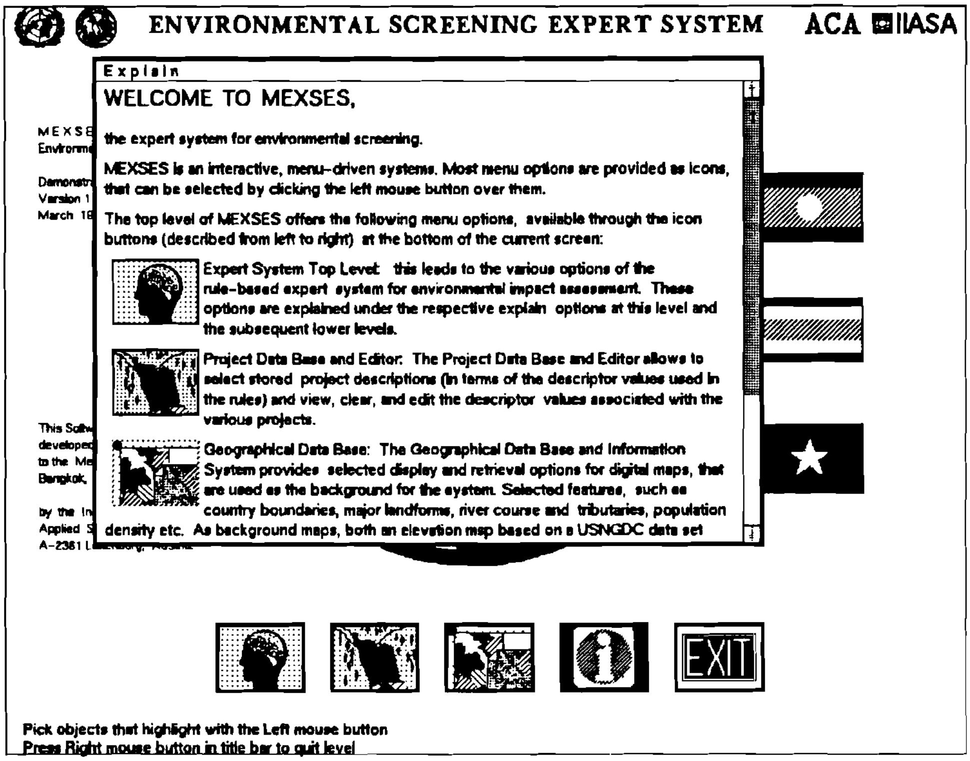

Figure 5.8. Explanatory function at the top level.

The user interface is graphical and window-oriented, and the interaction between user and system is largely by the manipulation or selection of symbols or text elements on the screen with a graphical input device, the mouse, in response to the system's textual or graphical displays and prompts. All required user input is pre-defined by the system as a set of options the user can choose from. No command language that needs to be learned is required, the system itself contains all the information necessary to use it effectively.

Icons and menu boxes, as well as a number of specific tools such as sliders or scrolling selector boxes allow the user to specify his input, usually under the guidance of the system's prompt messages in the status lines at the bottom of the screen. In addition, more extensive help in the form of explanation text screens are available in the on-line manual, again available through an icon button (*Figure 5.8*).

Menus are either icons, or selections of menu items in text boxes. They are selected or triggered by pointing at them with the mouse, and pressing the left mouse button. Items that can be selected, i.e., that are active, will provide an appropriate feedback to the user whenever the mouse pointer is moved over them: menu text boxes or lines in selector boxes will invert their colors, icons will change their boundary colors to indicate that they can be picked or selected.

In some cases, the same logical object can be selected in more than one way; for example, a specific project can be selected and loaded from a list of projects, but also, at the same time, from the map. Whenever either of the two representations of a project (its name in the selector box or its symbol on the map) highlights in response to the mouse pointer, the corresponding representation (map symbol or name, respectively), will also highlight to indicate the connection.

To select or set an impact value, the user has to pick the box adjacent to the verbal description of the impact level; the box will be filled with the corresponding colors (undefined: *white*; not significant: *green*; small: *yellow*; moderate: *orange*; major: *red*); the same color coding is also used at the level of the problem selection, and at the level of the problem class, where problems already assessed are indicated by a tick in the color corresponding to the impact level assigned.

To select a symbol, for example the value of a descriptor, a list of the possible answers is provided and the user can select the appropriate one. He can also, however, select a button to indicate that the value is unknown at this point.

To select or set a number, a similar tool is provided in the form of a vertical slider, that allows the user to move a bar in a colored field to the desired value; alternatively, numbers can also be entered directly through the keyboard or terminated by a carriage return. In the case of mixed descriptors (see above), the user can select the symbolic label (and the corresponding numerical value defaults to the mean value of the range associated with the symbol), or set the number explicitly, with the corresponding symbol selected automatically.

To define a text string, for example, to name a new project alternative for storage and later retrieval, the user enters the name on the keyboard, terminated by a carriage return or line feed key.

Outside MEXSES itself, the user can edit the basic input files (such as rules, descriptors, tables, project data, and explanatory texts) using any system's text editor. However, it is important to realize that in this case no control is exerted by the system, i.e., neither the syntax nor logic of the modifications are changed. Extreme caution, including making back-up copies of working files before attempting to modify them, is therefore strongly recommended.

The graphical user interface to MEXSES is based on the X Windows graphics system, explained in brief in the following section.

5.9 X-Windows

In March 1988, the Massachusetts Institute of Technology released Version 11 of the X Window System, referred to as X11.[1]

The X Window System is being adopted widely as a standard by nearly every workstation manufacturer and is expected in the long run to replace or be supported under proprietary windowing systems. Versions are also available for personal computers, e.g., under 386 UNIX on PCs.

For the first time a portable application of advanced raster functionality could be written for an entire class of machines rather than for a specific manufacturer's equipment. A program written in a single graphics language could thus be expected to work without significant modifications on dozens of different computers.

The X Window System is complex, but is based on a few premises and concepts that can be understood quickly. X is a windowing system for **bit-mapped** graphics displays. In bit-mapped graphics each dot on the screen (each pixel or picture element) corresponds to one or more bits in memory. Programs modify the display by simply writing into display memory which then immediately updates the screen display. Bit-mapped (or more generally, memory mapped) or raster graphics includes television-type scan technology, as well as dot-oriented displays, such as LCD screens.

The X Window system supports monochrome as well as color and grey scale displays. A display is defined as a workstation consisting of a keyboard, a pointing device such as a mouse, and one or more screens.

X is a network-oriented windowing system. An application can run on a computer other than the one physically supporting the display. Applications can of course also run locally on stand-alone machines, but in a network they can execute programs on different computers (hosts) in the network and display information and send keyboard and pointer events over the network. In its current release, X supports TCP/IP and DECnet networking systems.

[1]This section is based on Nye, 1988.

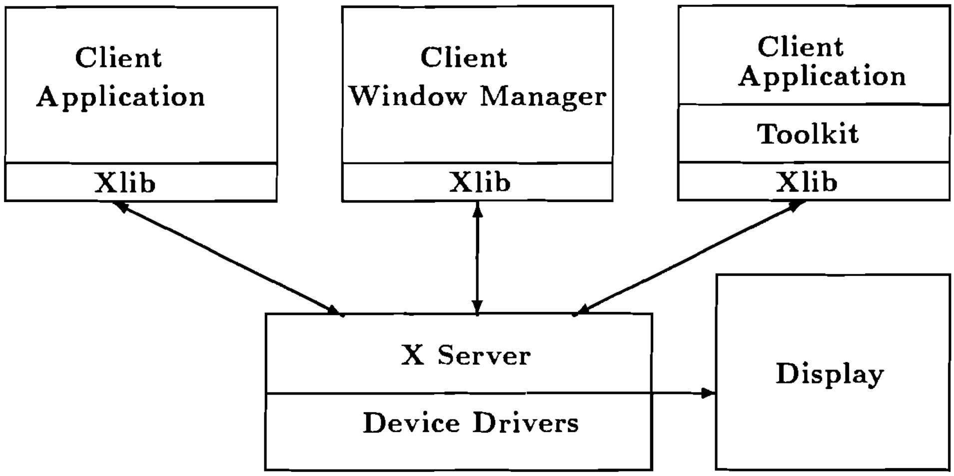

Figure 5.9. X architecture: client–server communication.

The program that actually controls a display is called a (display) *server*. The server acts as an intermediary between application programs (clients) running either locally or on any CPU in the network, and the resources and capabilities of the local system. The tasks of the server include:

- Allowing access to the display (screen, keyboard, and mouse) by multiple clients (application programs);
- Interpreting network messages from clients;
- Passing user input (from the display) to the clients through the network;
- Two-dimensional drawing; graphics are created by the display server rather than by the client, which only sends requests to the server;
- Maintaining complex data structures such as windows, cursors, fonts, and graphics contexts as resources that can be shared by several clients, referred to by resource IDs. The server maintains data as shared resources and thus considerably reduces the amount of information that has to be maintained by the client and passed between client and server over the network.

The graphics library developed at IIASA/ACA (*libaca.a*) is based on X11R4 with C-binding, i.e., it consists of C-functions which contain calls to the basic *Xlib* functions provided by X11R4. All the graphics in MEXSES use libaca functions (for complex graphics tasks) or (in the case of basic graphic operations) Xlib functions directly in the expert system's source code (*Figure 5.9*).

Chapter 6

Knowledge Representation and Inference Strategy

The knowledge representation in MEXSES uses a highly interlinked system of **Checklist questionnaire** files, **Rules** and **Decision tables**, and **Descriptors**.

The **Checklists questionnaire** files provide textual information about the individual problem and guidance for its assessment, and they control the set of rules to be used for each individual problem at the top level, i.e., directly affecting the impact value. These rules, in turn, use other descriptors to deduce the impacts, which in turn may refer to other rules that can deduce intermediate or auxiliary descriptor values. The descriptors provide the vocabulary of the assessment, and the cross-references to the rules and decision tables that are used to deduce descriptor values.

The descriptor definitions are implemented in a frame-like object-oriented language that includes the descriptor name, the list of symbols and associated numerical ranges for allowable descriptor values (most descriptors can have both numerical or symbolic values concurrently), references to rules that can be used to derive a descriptor value from other descriptors, instructions for an **ask** function to obtain the value from the user interactively, and the linkage to a hypertext system of *help* and *explanatory text*, background information, definitions of concepts and a glossary of terms.

Once a descriptor is needed (referred to in a rule) a descriptor is instantiated from its *generic descriptor definition*, i.e., "inheriting" its generic properties such as the list of possible values, the value ranges for numerical values, the default value, etc. The instantiated descriptors are organized in

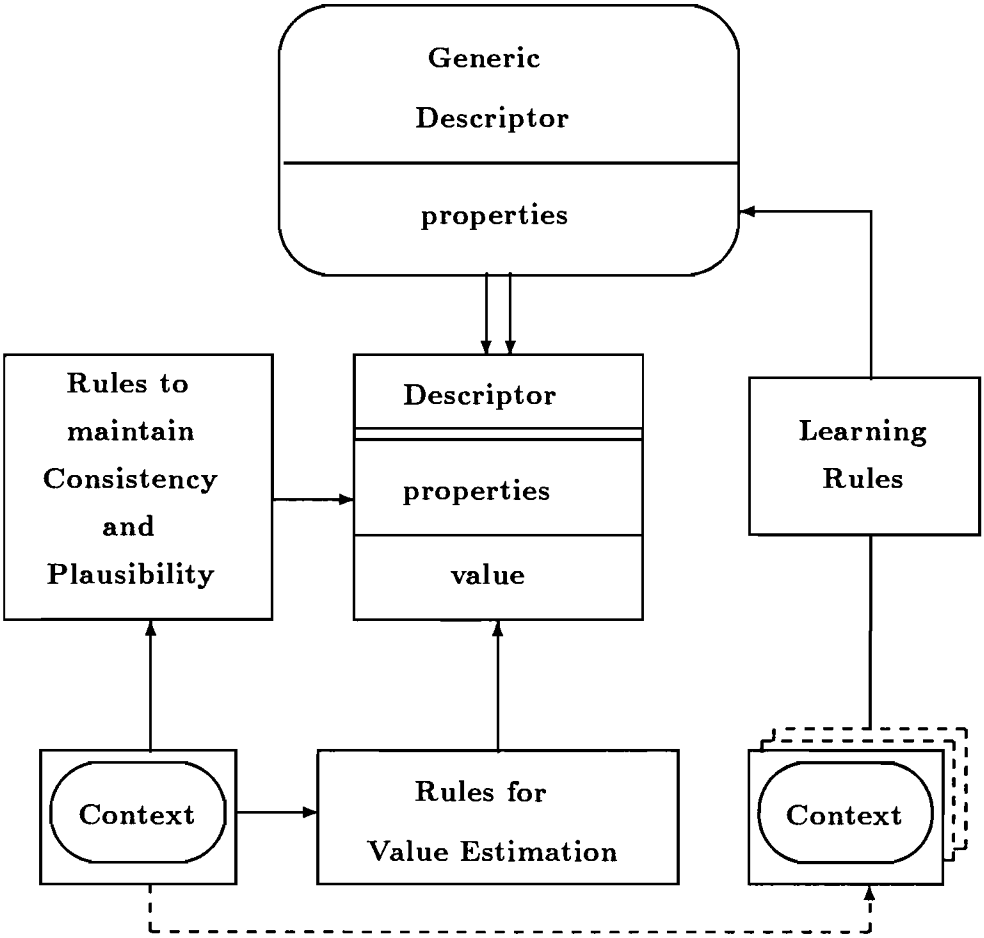

Figure 6.1. Inference strategy for one descriptor.

an object-oriented, heterarchical network which represents their interdependencies.

These interdependencies are represented by the *rules* associated with each descriptor which are the basis for the inference process (*Figure 6.1*). The rules are applied within the current *context*, which is defined by the values of the currently instantiated descriptors.

There are three different kinds of interdependencies which are represented by the following three different groups of rules:

- *Estimation Rules*, which deduce the value for a descriptor, either from other subproblems, which are represented as descriptors as well, or from facts entered by the analyst;
- *Consistency and Plausibility Rules*, which maintain the consistency and plausibility of the descriptor values by selectively restricting the list of possible values for descriptors to be instantiated, based on the current context;
- *Learning Rules*, which maintain the consistency of the value ranges of the generic descriptor definitions, based on a history of all contexts which have been generated in previous runs of the expert system.

These three groups of rules implement the inference strategy of the expert system which is guided by the checklists. Checklists can be interpreted as *entry level* descriptors. They contain the list of rules that directly apply to the impact level or severity of a given problem.

The inference process starts with the estimation rules in the checklist; if a descriptor in the condition part of the rule is unknown, the rules associated with the descriptor are triggered; if none of the rules can be used successfully, a question to determine the descriptor value directly from the analyst is asked; with the resulting value either a rule can now be applied, or another descriptor value has to be determined, until one of the top-level rules (directly setting the impact level of a problem) can be applied.

After all the rules which set descriptor values absolutely (for a given descriptor or the impact at the top level) have been tested and possibly applied, all the incrementing rules are evaluated. Incrementing rules, using the operators INCREASES and DECREASES, can modify descriptor values already set by another rule. The result of their evaluation is therefore a shift, up or down, in the final value of the given descriptor by one or more units. More than one incrementing rule can apply, and their individual modifying effects are accumulated. Corrected by this accumulated shift, the final value is then used at the next level of inference, or to set the impact level at the top level.

Once a value for a descriptor has been deduced the consistency and plausibility rules are activated; these check if the new descriptor value places any restrictions on the possible values of those descriptors which are not yet instantiated and mark those values which can be ruled out because of the new value instantiation as "not plausible". In the current implementation, this is restricted to setting descriptor values not required in the current inference chain to specific values automatically as a consequence of some user input. The more general case of excluding a certain range of possible values and thus restricting future input rather than anticipating it, is under development.

The checklists themselves are linked via rules which, together with a set of special descriptors, define how they are to be aggregated to the *overall environmental review criteria* which represent the highest (i.e., most general) level of impact assessment in the system.

In the following, a detailed description of the various types of descriptors and rules, as well as their interdependencies, is given.

6.1 Descriptors

Descriptors are the internal representation of the overall environmental review criteria, problem classes, problems (i.e., checklists), and subproblems in the system. They define the problem domain and the entities of the assessment process.

At the most aggregated level they appear as problem classes and overall environmental review criteria, on the intermediate level they represent the checklists (i.e., the problems to be assessed) and on the third level they define the subproblems used as the basis to deduce the higher-level problems.

For each descriptor there is a *generic descriptor definition* which defines its name, possible values, value ranges, etc. Whenever a descriptor is referred to in the inference process its generic definition is *instantiated* by assigning a value to it. The values for a descriptor in MEXSES can be either numerical, or symbolic, or both (*hybrid*). The three cases are given below as examples from the descriptor definition file.

All descriptors are defined between a pair of lines:

```
DESCRIPTOR
....
ENDDESCRIPTOR
```

```
DESCRIPTOR
total_precipitation
T N
U mm/year
# should be connected to the GIS to interpolate isohyetes
V 800 / 5000 /
Q what is the total annual precipitation  in the project area
ENDDESCRIPTOR

DESCRIPTOR
construction_risk
T S
V low / high /
R 9999033 / 9999034 / 9999035 / 9999036 / 9999037 /
Q how would you describe the risk for the labor force inherent
Q in the construction project, depending on its involving high
Q risk activities such as blasting and drilling in rock, use of
Q heavy earth moving machinery, high scaffolding and cranes,
Q extensive welding, high volume concrete pouring etc.
ENDDESCRIPTOR

DESCRIPTOR
average_reservoir_depth
T S
U m
V very_small[0,5] / small[5,10] / medium[10,30] /
  large[30,100]   / very_large[100,300] /
Q how would you classify the average depth of the reservoir
ENDDESCRIPTOR
```

The generic descriptor definition includes the name of the descriptor as it is used in the system's interface (underscores are filtered out for display; they are, however, required to simplify the file input procedures). The following records (lines) are all preceded by a one- or two-character symbol, namely:

- T: type of descriptor; either one of S (symbolic or hybrid), N (numeric), or M (descriptor for the assessment of the overall environmental review criteria);

- V: indicates the range or list of values the descriptor can take; this is either a range of numbers for a numerical descriptor, or a list of symbols for a symbolic descriptor; in hybrid cases, the symbol name is followed by two numbers indicating the numerical range associated with the symbol;
- U: the unit of measurement for the descriptor
- R: a list of rules that can be used to determine the value of this descriptor;
- TB: a list of decision tables used to derive a descriptor value;
- Q: the question to be asked if no rule can be used successfully to determine the descriptor value;
- P: to define the project type the following list of checklists is associated with (for aggregation of checklists to the overall environmental review criteria);
- L: the list of checklists and their associated weights for the aggregate evaluation of the overall environmental review criteria for the project type specified in the P line above.

In the case of a hybrid descriptor, the system uses either its numerical or symbolic value, depending on the context. The numerical ranges corresponding to a given symbolic value are defined in the generic descriptor definition (see above). If a symbol needs to be derived from a number, the corresponding interval/symbol pair is determined. If the number needs to be derived from the symbol, the mean value of the range corresponding to the symbol is used. Obviously, an extension to interval arithmetic or the use of fuzzy sets would improve the system at least in conceptual and theoretical terms.

For the assessment of the overall environmental review criteria the P and L records of the descriptor format are used. For each project type (P) they contain the list of checklists (L) (designated by their ID number) relevant to a top-level problem summary, together with the relative weight (a number between [1] and [100] assigned to each of the checklists in contributing to the overall assessment. An example of such a descriptor would be:

```
DESCRIPTOR
Resource_loss
T M
P Multi Purpose Projects
L 90109[100] / 90113[100] / 90408[100] / 90413[100] / 90412[100] /
  90103[ 80] / 90104[ 50] / 90305[ 50] / 90402[ 50] / 90105[ 40] /
  90114[ 40] / 90410[ 40] / 90106[ 40] / 90112[ 30] / 90108[ 30] /
  90301[ 30] / 90405[ 30] / 90406[ 20] / 90403[ 20] / 90409[ 20] /
P Dams and Reservoirs
L 10109[100] / 10113[100] / 10408[100] / 10413[100] / 10412[100] /
  10103[ 80] / 10104[ 50] / 10305[ 50] / 10402[ 50] / 10105[ 40] /
  10114[ 40] / 10410[ 40] / 10106[ 40] / 10112[ 30] / 10108[ 30] /
  10301[ 30] / 10405[ 30] / 10406[ 20] / 10403[ 20] / 10409[ 20] /
....
ENDDESCRIPTOR
```

6.2 Rules, formulae and decision tables

The interdependencies between the overall environmental review criteria, the problem classes, the checklists (problems), and the subproblems are internally represented as rules, formulae and decision tables. They form the basis of the system's inference mechanism (see *Figures 6.2* and *6.3*).

Rules consist of two basic parts:

Premise:	the list of conditions which are to be tested (which are connected by AND or OR)
Conclusion:	the actions to be performed, if all conditions of the premise have been fulfilled

Given below are examples of rules of various levels of complexity:

```
RULE 1010101 #country dependency of resettlement problem
IF        project_country == Thailand
AND       people_to_resettle >= 25000
THEN      E = major
ENDRULE

RULE 1010129 #people_to_resettle on project size
IF     project_area          == very_large
```

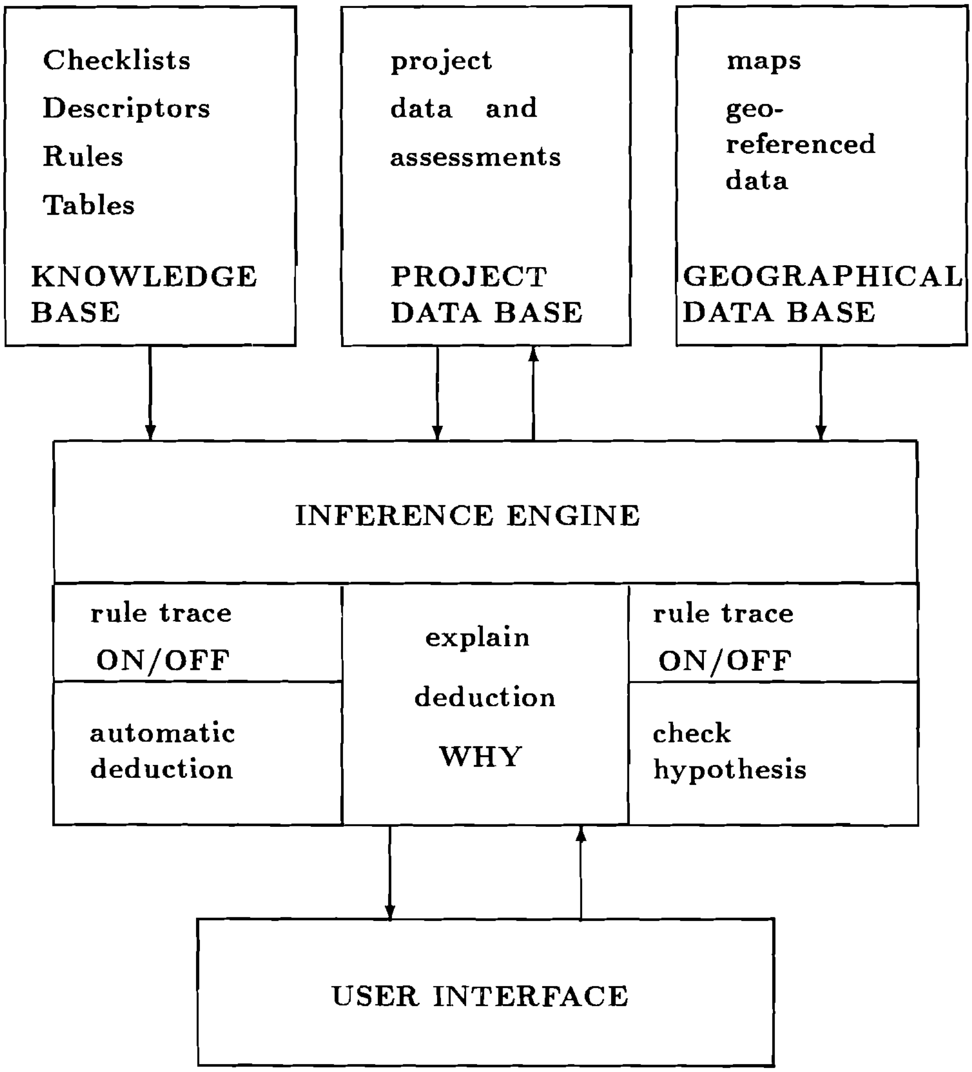

Figure 6.2. Options in the inference process.

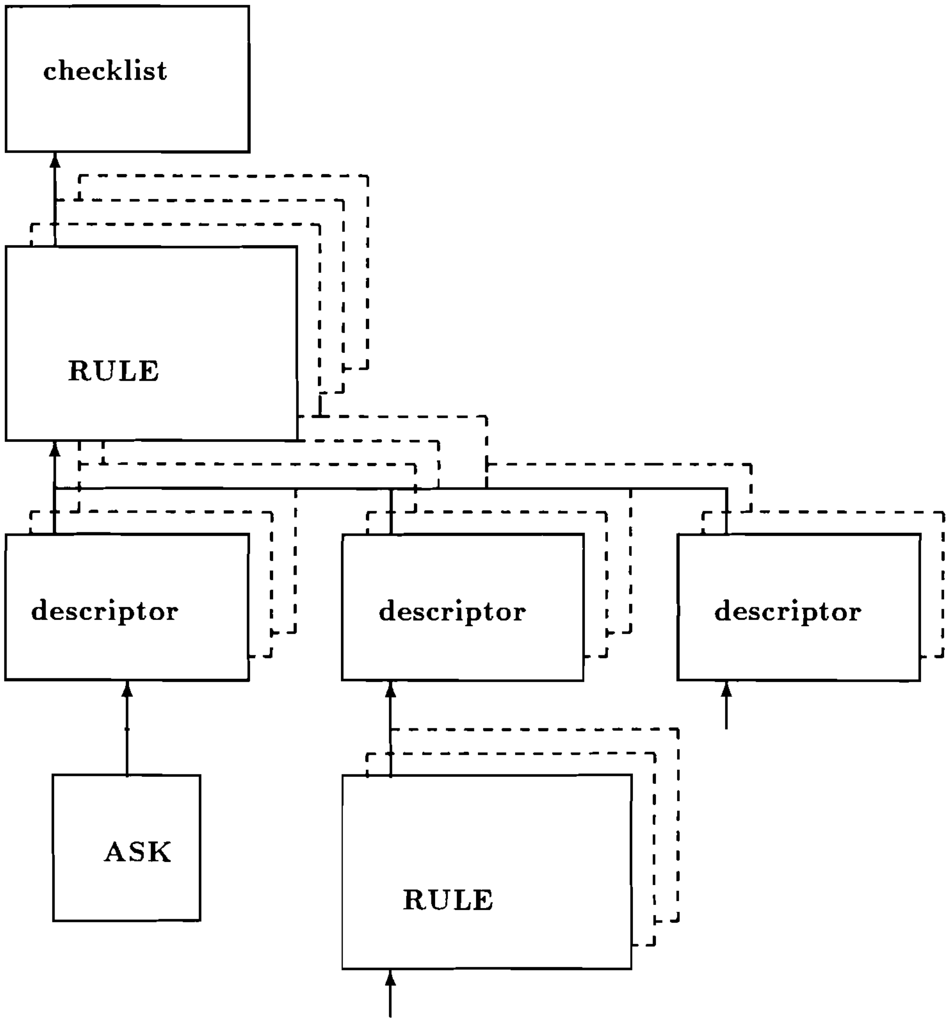

Figure 6.3. The structure of the inference mechanism.

```
AND     [  population_density == high
        OR population_density == medium ]
OR      project_area INCLUDES major_settlement
THEN    people_to_resettle = large_number

RULE 1010582 #USLE final round: erosion_potential
IF      [  rain_factor          == low
        OR rain_factor          == very_low ]
AND     [  soil_slope_factor    == high
        OR soil_slope_factor    == very_high ]
AND     [  vegetation_factor    == very_high
        OR vegetation_factor    == high ]
THEN    erosion_potential       =  medium
ENDRULE
```

Rules in MEXSES use a simple structure, based on the following operators or logical connectives:

```
IF, THEN

=  (assignment)
== (equality)
!= (inequality)

<<, <, <=, >, >=, >>

AND, OR

EXISTS, NOT_EXISTS

INCLUDES, NOT_INCLUDES

INCREASES, DECREASES
```

In the condition a descriptor value is compared against a fact (e.g., a number or a symbol) via one of the operators defined in the inference engine. The action represents the assignment of a value to another descriptor, i.e., the instantiation of a higher-level descriptor. The language which is used in the rules is defined by the descriptors (see above) and the list of possible operators.

A special case of rules are represented by so-called **formulae**, which may also include basic arithmetic operators such as

```
+ - * /
```

An example of a formula would be:

```
RULE 7777007
IF      TRUE
THEN    retention_time =
        365 * reservoir_storage_volume / mean_annual_inflow
ENDRULE
```

Another special case is decision tables. They represent a shorthand notation for a set of similar rules:

```
TABLE 1010502 #watershed erosion, USLE method
rainfall_intensity
total_precipitation
rain_factor
           | very_high |   high    | medium   |  low
-----------------------------------------------------------
very_high  | very_high | very_high | high     | medium
high       | very_high | high      | high     | medium
medium     | high      | high      | medium   | low
low        | high      | medium    | medium   | low
ENDTABLE
```

Tables are automatically translated into and processed as rules. For the above example, the translated rule version would look something like this:

```
IF     rainfall_intensity  == very_high
AND    total_precipitation == very_high
THEN   rain_factor = very_high
```

```
IF      rainfall_intensity  == very_high
AND     total_precipitation == high
THEN    rain_factor = very_high

IF      rainfall_intensity  == very_high
AND     total_precipitation == medium
THEN    rain_factor = high
```

and so on, with one rule for each cell of the table.

A different type of rule is what has been termed **incrementing rules.** They only act on already instantiated descriptors, that is, the descriptors used in their action parts already have a value assigned. Hence they are the only rules which may be used to modify descriptor values instead of setting them absolutely. They represent a very convenient way of introducing exceptions and special conditions which otherwise would have to be expressed by the set of basic rules, thus making them significantly more complicated.

Examples of incrementing rules are given below:

```
RULE 1010213 #watershed degradation
IF      project_area INCLUDES rain_forest
THEN    Impact  INCREASES marginally
ENDRULE

RULE 1010233 #dependency on watershed management
IF        watershed_management  EXISTS
THEN      degradation_problem DECREASES considerably
ENDRULE
```

Only rules that can possibly succeed are tested. This pre-processing or screening of rules improves the performance, by pruning the inference tree and eliminating all rules for which the preconditions are already known to fail.

Similarly, in the backtracking case of the hypothesis confirmation, only rules that can lead to the required outcome are tested so as to speed up the system's performance.

In the current system, only rules which assign a value to a descriptor (i.e., instantiating a descriptor) or modifying an already instantiated descriptor are implemented.

The rules for consistency and plausibility maintenance, which restrict the list of currently possible values in a descriptor definition to make it consistent with the values already assigned to all instantiated descriptors, are currently under development.

Similarly, the *learning rules*, which modify the value ranges in the generic descriptor definitions according to instantiations which took place in all the previously performed expert system runs have not been introduced so far. They will, however, be based on the same syntax and semantics as the currently implemented rules, with the only difference being that they will act upon the list of possible values and generic descriptor definitions respectively.

Chapter 7

A Tutorial Example

To illustrate the way MEXSES assists in environmental impact assessment, a sample problem is described. It is taken from the checklists on **Environmental Problems due to Location**, namely **watershed degradation** and **reservoir eutrophication** from the **Problems Resulting from Project Operation**. An assessment is made, step by step, as if for a new project, using the corresponding screens for graphical illustration. For this exercise, a hypothetical, medium-sized to large reservoir is used, on a tributary such as the Mun-Chi river system in the Korat Plateau.

7.1 Watershed degradation

Upon selecting this problem from the listing of problems (*Figure 7.1*), the main assessment page is displayed (*Figure 7.2*).

The problem is described as follows:

> **Impact:**
> Watershed degradation through agriculture on marginal lands and improper cultivation techniques, including slash and burn. Sedimentation of reservoirs and reduction of useful life span of the dam.
>
> **Recommendation:**
> Carefully planned watershed management program including land use management and zoning, and reforestation where necessary.

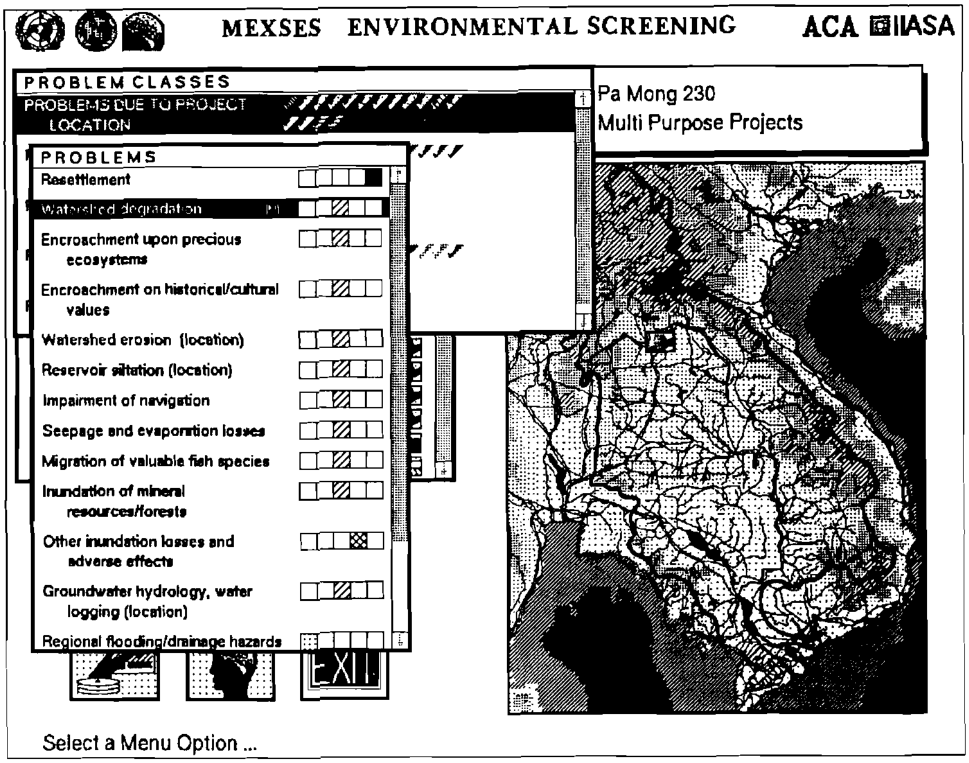

Figure 7.1. Impact checklists: the hierarchical problem selector.

Description:

Population pressure due to resettlement of population from inundated area or excessive natural population growth puts increasing demands on new and possibly marginal soils for agricultural use. This leads to a loss of natural habitats and vegetation cover, forests in particular, consequent soil erosion and possible desertification.

Assessment of expected watershed degradation is based on the watershed characteristics; for Thailand, this uses the official watershed classification scheme (see explanatory text option) where available; for other areas, watershed vulnerability is based on the erosion potential, estimated with a technique derived from the Universal Soil Loss Equation (USLE), developed by the US Department of Agriculture (USDA) Soil Conservation Laboratory.

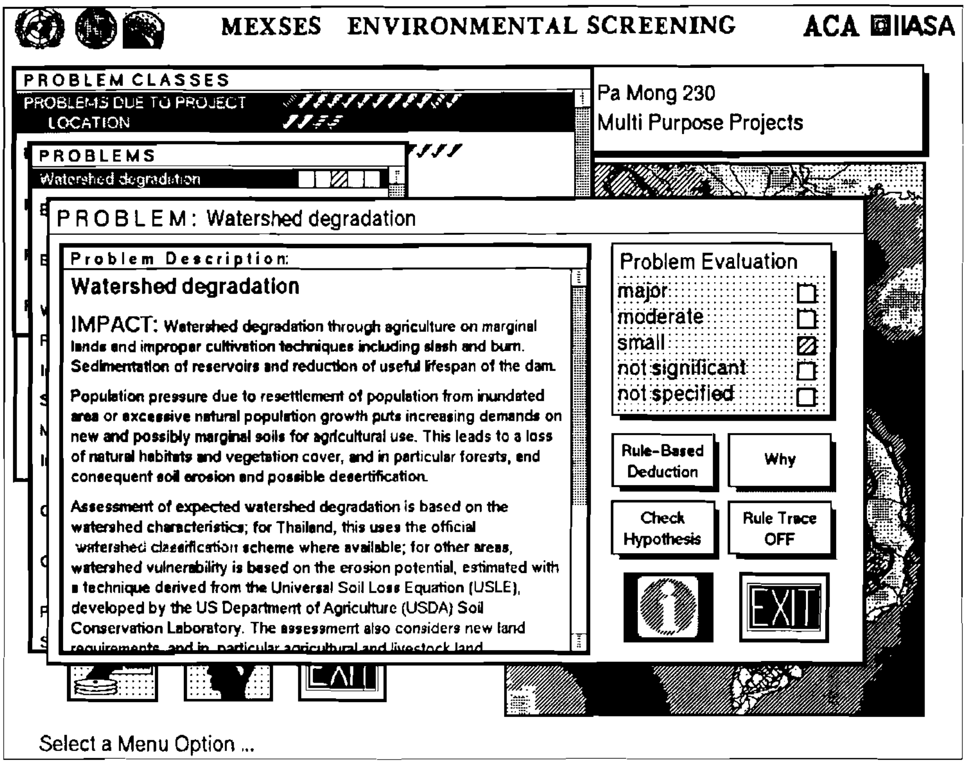

Figure 7.2. Assessment page for Watershed Degradation.

> The assessment also considers new land requirements, in particular agricultural and lifestock land requirements, caused either by forced resettlement or population increase that may be induced by the development project. An additional factor of watershed degradation can be forest fires, often used intentionally in slash-and-burn practices. In particular, short fallow periods lead to soil exhaustion.

If the description, in particular the part elaborating on the assessment is sufficient for the analyst, for example, if (s)he has access to studies on the topic, the appropriate Problem Evaluation box could be selected and (s)he can turn to the next problem. Alternatively, however, (s)he can trigger the Rule-Based Deduction, with or without the Rule Trace option.

The first rule presented (if the rule trace is on) is an example of a country-specific set of rules: it refers to the watershed classification used in Thailand,

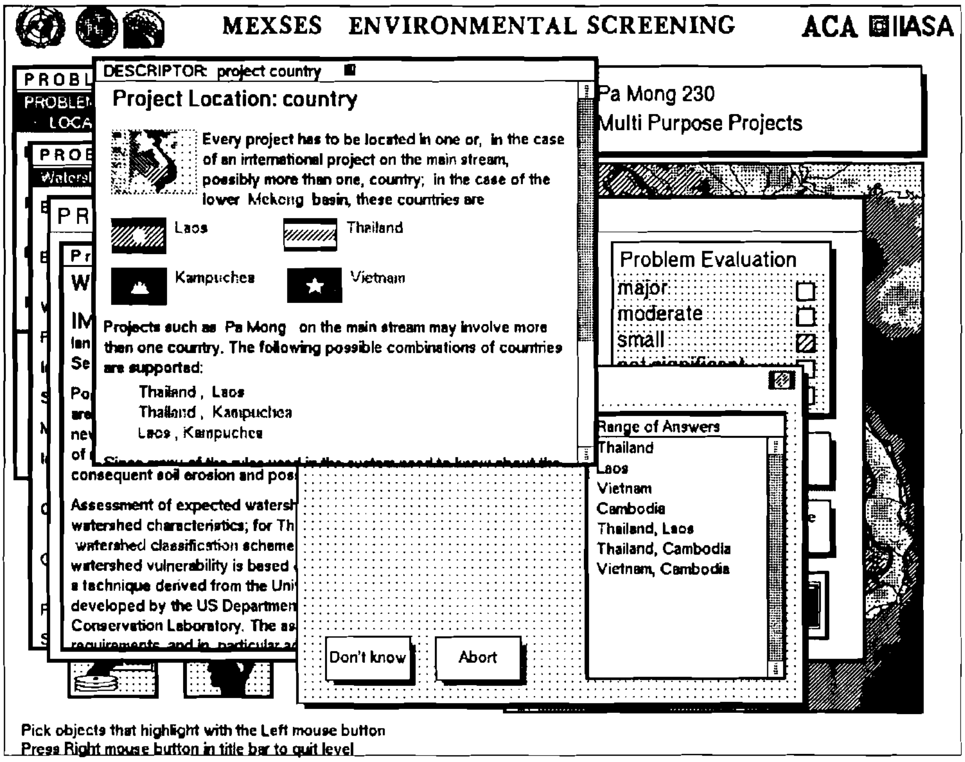

Figure 7.3. Additional explanation on an individual descriptor.

which offers a short cut for the assessment procedure. The first question asked, consequently, is the country in which the project is located. To support the answer, an information box can be displayed (*Figure 7.3*). Given the answer Thailand, the next question is about the classification of the watershed, where five classes are offered. With the appropriate GIS coupling, the watershed classification for the project area could be retrieved from the digital maps. If this fails, the user is queried. An information box can be displayed that will provide the necessary watershed definitions:

```
DESCRIPTOR:  watershed class

Thailand has a special watershed classification scheme;
these watershed classes are used to determine various
aspects of watershed degradation problems.
```

```
The definitions are given below:

WSC1,  Class 1A:
          Areas of protected forest and headwater source
          areas; usually at higher elevation with very
          steep slopes.
          Should remain in permanent forest cover.
WSC1,  CLASS 1B:
          Similar physical features and environment to 1A
          but portions have been cleared for agricultural
          use or villages. Require special soil
          conservation and protection; should be afforested
          or maintained in permanent agro-forestry.

WSC2:     Areas of protection and/or commercial forest,
          usually commercial forest; usually at higher
          elevation and steep to very steep slopes.
          Less erosive than WSC1, may be used for grazing
          or certain crops with soil conservation measures.

WSC3:     Uplands with steep slopes and less erosive landforms.
          May be used for commercial forests, grazing,
          fruit trees or certain crops with need for soil
          conservation measures.

WSC4:     Areas of gentle sloping, suitable for row crops,
          fruit trees and grazing with moderate need for
          soil conservation.

WSC5:     Gentle to flat areas, for paddy fields and
          agricultural use with few restrictions.

***************************************************************

file: ex.watershed_class
```

If WSC3 is selected (as a somewhat conservative or "pessimistic" answer), the next set of questions aims at estimating the **household land requirement** and **agricultural land requirement** in the project area. For resettlement, the

project proponent (in Thailand at least) plays an important role in determining land entitlements. Consequently, the next question asks for the project proponent. Answering **EGAT**, the Electric Power Generation Authority of Thailand, will set the land allowance used for further calculation to 20 rai.

In the next step, the number of **people to resettle** will be estimated. It is important to note, however, that the sequence of some of these questions also depends on the sequence of problems addressed: if the resettlement problem had already been covered, this information would already be available and the results of the assessment would pop up almost immediately after the first two questions.

People affected are estimated from the **area inundated** (*Figure 7.4*) and the current population living there (if this cannot be retrieved from the GIS, generic population densities and possible major settlements are considered), corrected by an estimate of population growth including in-migration depending on **project size** and **project type**.

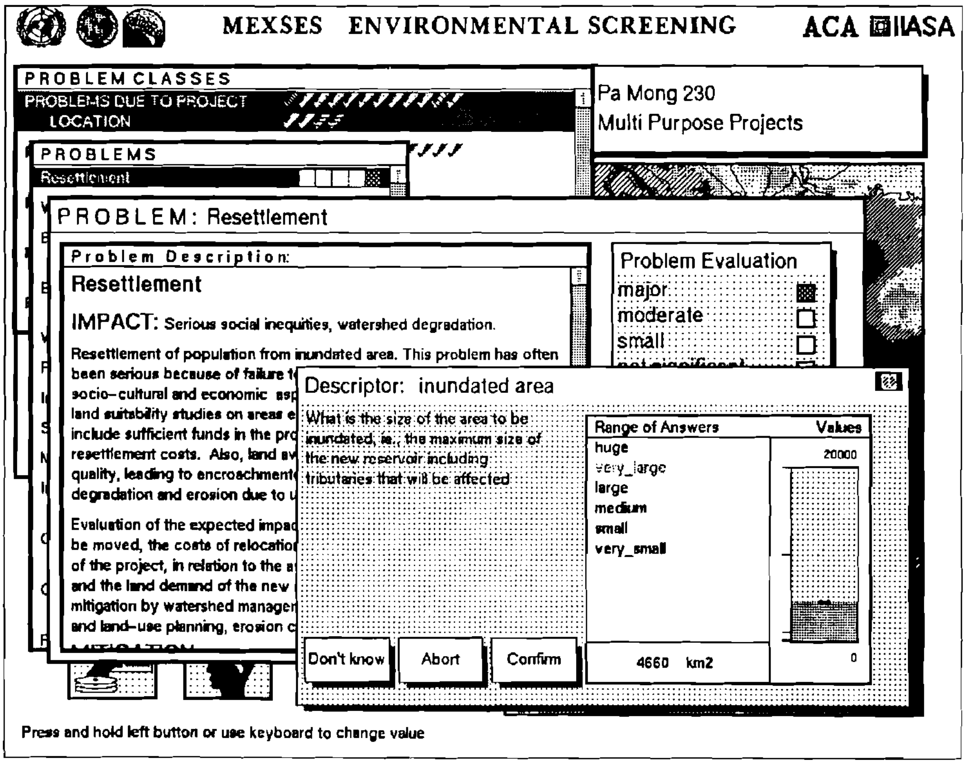

Figure 7.4. Asking the user for either a numerical or symbolic answer.

If, for instance, one or the other item required to estimate the size of the project area is not known, as for example the area directly affected by the project including the new reservoir, construction site, access roads, or land used for resettlement, the system would eventually have to ask the analyst directly for the project area.

After establishing the number of families affected (land entitlement is per family), the first assessment result becomes available: a **major** problem of watershed degradation is diagnosed.

However, following this there is a series of subsequent rules that can modify this assessment. In this particular case, one checks for rain forests as part of the vegetation cover of the basin; however, since one has already stated that the project is located in the Korat Plateau, the rule checking for rain forest being affected (which would aggravate the problem) is not applicable.

After the assessment was reached, the explain function **WHY** allows the different rules and descriptor values used to be traced: at the top level, being in Thailand in a watershed classified as WSC3, with large land requirements for resettlement, will result in a major problem (*Figure 7.5*).

The land requirement, in turn, was derived from the number of families estimated to be affected (about 460) and the individual household land requirement. This, in turn, can be traced back to the project proponent EGAT, and the project country, Thailand. Tracing the origin of these pieces of information, the system will display a message:

```
Descriptor value:  EGAT
for descriptor:    project_proponent
has been supplied by the user !
```

If the project were located in another country, the short cut based on the Thai watershed classification would of course not work. The system would then try to estimate watershed erosion from rainfall intensity and amount, relief, soil type and vegetation cover, land use, grazing lifestock, access roads and any possible watershed management or reforestation schemes. Erosion would be combined with land demand by resettlement and land use such as shifting agriculture in marginal lands and intensive grazing, to arrive at an overall estimate.

Possibly, if any of the descriptor values are found in error, or the analyst wishes to test the effect of changing any or all of them, he can then enter the project editor and directly set the descriptor to the desired value there.

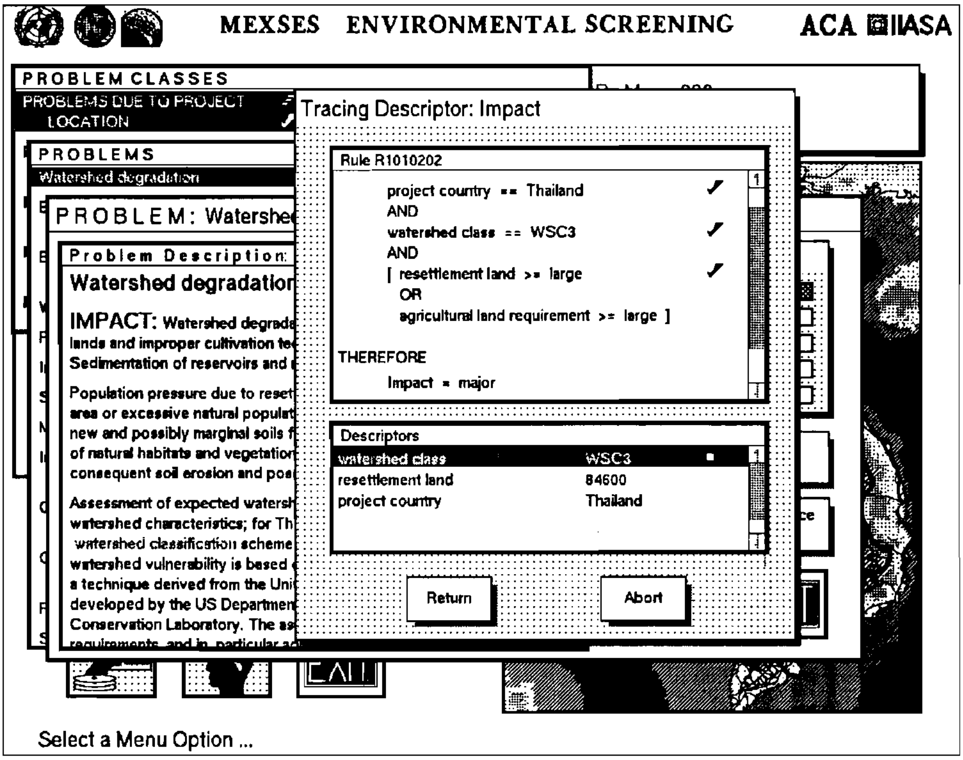

Figure 7.5. Tracing a result with the explanatory function WHY.

This will, of course, "purge" all the derived values that may depend on this descriptor, and thus at least part of the assessment procedure will have to be repeated to obtain a new problem evaluation.

7.2 Reservoir eutrophication

An alternative example, from the problem class **Problems resulting from project operation** is reservoir eutrophication, weeds and oxygen (deficiency).

In the problem assessment box it is defined as follows:

> **Impact:**
> Reduction in fish production potential.

Recommendation:
Strategically timed drawdowns for weed control. Selected clearing of forests, large scale introduction of species (preferably indigenous) that feed on phytoplankton and zooplankton and on aquatic vegetation. Eradication of weeds from possible sources of infestation in the reservoir basin.

Description: Eutrophication results from nutrients leached from submerged biota, including forests and soils. Consequences are explosive growth of nuisance vegetation (weeds) and oxygen depletion

The assessment considers the overall trophic situation of the reservoir, determined by morphometry and expected nutrient loading, remaining nutrients from terrestrial biomass left uncleared, and the probability of floating weeds occurring.

If the rule trace is turned on to follow the logic of the assessment better, the first rule displayed will introduce an auxiliary or intermediate concept, **eutrophication potential**, which together with **nutrient loading** is linked to the problem evaluation. This eutrophication potential, in turn, is deduced from reservoir morphometry and nutrients from the pre-impoundment land use. The concepts used are the likelihood of **reservoir stratification** which is used to summarize morphometric and hydrological characteristics, and the **remaining nutrients** in the reservoir at the time of filling.

The first of these concepts addressed is stratification. It is, primarily, linked to reservoir depth, usually increasing with it. The first question the analyst is asked therefore is about the **average reservoir depth**. The rule requesting this descriptor to be defined classifies reservoir stratification as unlikely if the reservoir depth is very small, i.e., the reservoir is shallow.

In the example run, a medium depth of 15 meters is specified. This will lead to another rule about reservoir stratification (the previous one requiring a very shallow reservoir obviously failed and thus was not applied), which states that if (even) the reservoir depth is medium and (but) the **retention time** is very small, reservoir stratification is (still) unlikely. Retention time is computed from the **storage volume** and the **mean annual inflow**, using a simple formula, again expressed as a rule (*Figure 7.6*). The next two questions to be answered are for reservoir storage capacity with 3000 M m^3, and for average annual inflow with 1,750 M m^3.

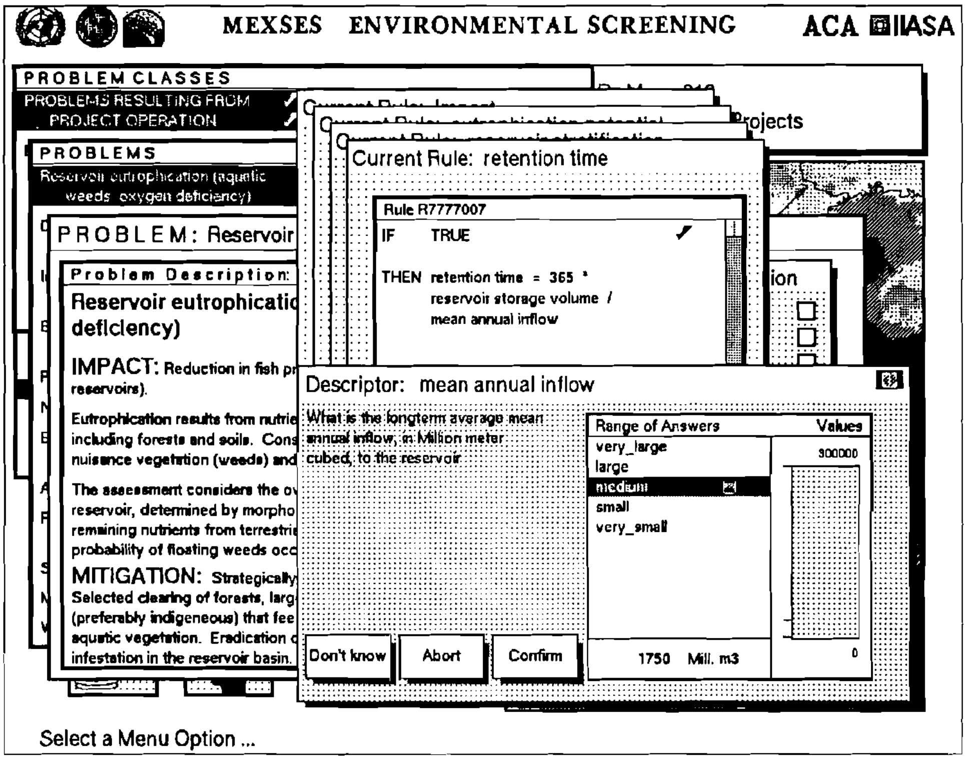

Figure 7.6. Rule display for a formula and ask function for one of the input variables.

The rule that will process this input now is that with a medium reservoir depth and a medium retention time, reservoir stratification is likely (*Figure 7.7*). The next rules are again modifiers to this intermediate result: they will use the reservoir position, sheltered or exposed to wind, to increase or decrease the probability of stratification. In the example the reservoir position is set to sheltered, which will make stratification even more likely. At this point, one is back at the level of eutrophication potential, with one of the two auxiliary concepts (reservoir stratifications) classified.

As a minor detour, the system will now look at modifiers. The sequence of questions and rules also depends, where there are no direct internal dependencies and references, on their sequence in the rule base, which can also be used to fine-tune the systems behavior by putting some of the shorter inference chains as well as the most likely ones to be pursued, on top. This

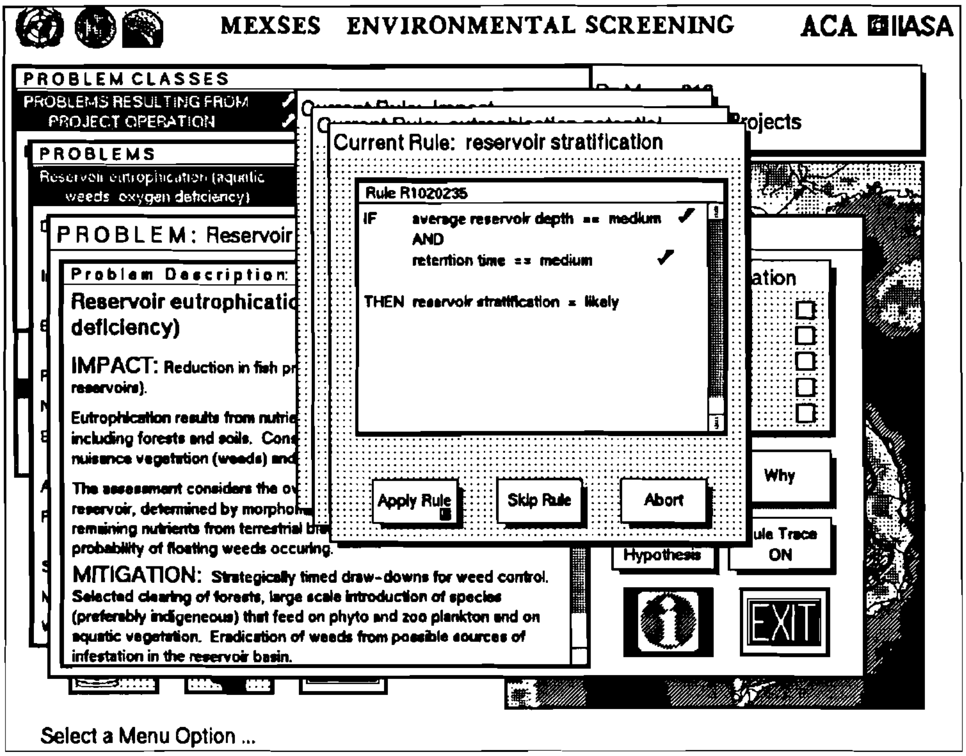

Figure 7.7. Rule Trace ON: displaying a rule before applying it.

will lead, at least possibly, to minimizing the number of avenues that need to be explored before a solution can be found.

Evaporation losses can aggravate the eutrophication problem. This relationship is direct as well as indirect, involving temperature, surface area and reservoir position. Specifying average **air temperature** as high and the **potential evaporation** as very high, the evaporation losses for the 200 km^2 reservoir are classified as very large.

Back to the upper level again, eutrophication potential is linked to reservoir stratification, just established as likely, and the amount of **remaining nutrients**. The path that tries to estimate the nutrient content of the reservoir is now pursued. **Remaining nutrients** are split into **mineral nutrients**, that are available immediately, and **remaining biomass** in the reservoir area, that may take a much longer time to mineralize and thus be available for algae production. The nutrients in the area depend on the original land cover or **land use**, which are specified as **shifting agriculture**, resulting in an estimate

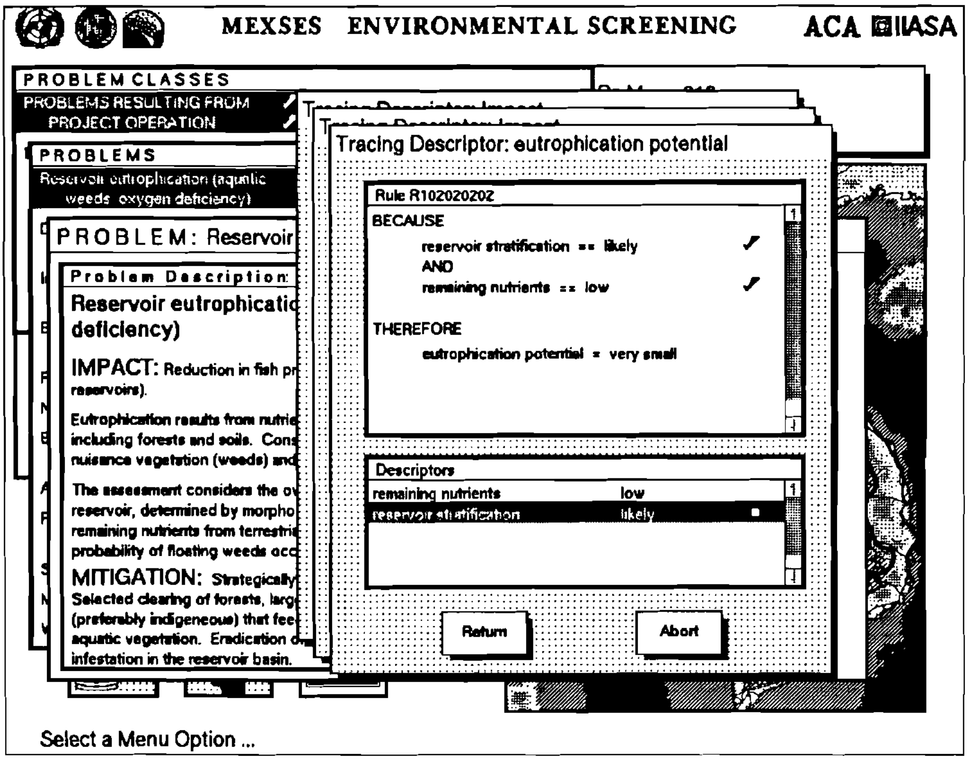

Figure 7.8. Explaining the reservoir eutrophication assessment.

of low biomass. Specifying forest would lead to another path that involves the preparation of the reservoir site, including cutting, removal and possible burning of forest biomass.

The low nutrient level resulting from the original agricultural land use of the reservoir site will lead to the assumption of a **very small** potential for eutrophication, even with a likely reservoir stratification (*Figure 7.8*).

The second basic component of the potential eutrophication problem is external **nutrient loading**. This is broken down into loading from **point sources**, and **non-point source** loading, respectively. Using the shifting agriculture as the dominant land use in the immediate reservoir catchment, the system concludes a medium level of non-point loading. Since the land use is one of several possible agricultural land use forms, the next question refers to **fertilizer application rates**. Setting the application rate to very low will not affect, i.e., increase, the estimated non-point loading. The loading can, however, be modified by **grazing lifestock** in the area: a large grazing lifestock will lead to a marginal increase in the non-point source loading from small to large.

The next set of rules attempts to estimate soil loss in this catchment as yet another modifier in the non-point source equation. If, in the above example on watershed degradation, we had not selected the assessment path using the Thai watershed classification, this subproblem would already be solved, and its result would be available at this point, without any further questions asked of the user.

Expected soil loss is derived from the **watershed size** and its **erosion potential**. After deciding on a large watershed size, the system will establish the erosion potential.

This triggers a qualitative version of the Universal Soil Loss equation (USLE), involving a **rain factor** and a **soil slope factor**. The rain factor, related to rainfall intensity and frequency, is linked to the GIS and depends on the project's location. For a project situated in the relatively dry Korat Plateau, a small rain factor can be derived from the GIS information. The soil slope factor is now split into the **slope factor** and **soil erodibility**. The slope factor considers **slope gradient** and length. Again, the location information is used: for the Korat Plateau, a specification of a **hilly terrain type** will result in a medium slope gradient. This, together with a medium **average slope length** will lead to a medium slope factor.

The next concept to be addressed is soil erodibility, which leads to the dominant soil type. Selecting **silt loam** and a low **soil organic content** will result in high soil erodibility, which in turn leads to a high soil slope factor.

With a low rain factor but a high soil slope factor, we now need to estimate a vegetation factor to derive the final erosion potential: specifying **scrub** as the dominant **vegetation form** gives us a medium vegetation factor and an erosion potential classified as small. As a consequence, the overall estimated soil loss is also small. However, this conclusion will not cause a change in the previous tentative assessment of a large non-point source loading component.

This now returns us to the question of nutrient loading, combining non-point source and point source loading.

The point source component is related to the population size and possible industries in the immediate catchment of the reservoir, the degree of sewering, and levels and extent of waste water treatment, if any. No major settlements, no industries, partial sewering, and no wastewater treatment make the point source loading small.

The overall nutrient loading composed of a large non-point source loading and a small point source component, will be large. This large continuing nutrient loading, combined, however, with a very small initial eutrophication potential, will result in a tentative assessment of the eutrophication problem as **moderate**.

As a potential control strategy, the next question asked refers to the possibility to use multi-level outlets from the reservoir to control its nutrient and oxygen budget, and thus, eutrophication. The lack of multi-level outlets will leave the tentative assessment unchanged at **moderate**.

Another concern that can affect the assessment involves **macrophytes** and **floating weeds**. Their possibility depends on the extent of shallow areas in the reservoir. Setting these to large, the next question refers to the endemic occurrence of floating weeds in this section or tributary of the river. Assuming that such endemic weeds exist, confirmation is requested of the existence of any **weed control program** as a possible mitigation strategy. If there is none, floating weeds are possible, but not likely. The next factor possibly affecting weeds, is the extent of the **reservoir drawdown**. A medium drawdown will leave the possibility of floating weeds unaffected.

These possible macrophytes and floating weeds, in turn, will modify the eutrophication problem from moderate to major.

Chapter 8

Discussion

The current version of MEXSES, developed at IIASA and implemented at the Mekong Secretariat in Bangkok, is an operational prototype; several possible extensions and further developments, that could not be realized due to the time and resource constraints of the project, as well as some more general points on the use and usefulness of this expert system are discussed below.

8.1 Knowledge base

The knowledge base of the prototype at this stage mainly covers the first problem class, i.e., dams and reservoirs, and the dam and reservoir components of multi-purpose, hydropower and irrigation projects. The system currently comprises approximately one thousand rules, using a vocabulary of about 150 descriptors.

The basic format of the knowledge base is simple; the expert system is *data driven* to a very large degree. Extensions to the system, as long as they affect the knowledge base only and not the user interface or the data base and GIS connections, are therefore, in principle, straightforward, and can be implemented without any recoding. They do, however, require a thorough understanding of the inference engine and its assumptions, as well as a substantial background in the application domain.

Major extensions to the rule base are, of course, a rather complex task, and require careful analysis of the system's behavior with a changed rule base; since the number of possible permutations of answers to all the questions the system can pose is extremely large, testing the rule base is a difficult procedure, requiring a well thought out strategy and experience with the system.

As a concrete set of examples, projects for which some sort of environmental impact assessment or at least a detailed evaluation has already been performed, and for which sufficient background information is available, could be used to test the system and fine-tune the knowledge base.

Working through well-known case studies should not only give the analyst a better appreciation of the system's functions and inner workings, it would also allow testing of some of the rules in a known context.

8.2 Knowledge acquisition and inference engine

To ease the task of modifications to the knowledge base, several additional tools would be most useful. In particular, tools to interactively build rules, check their syntax, consistency and coverage, would be required. Building a knowledge acquisition and analysis tool would allow experts with little or no computer experience to update the knowledge base, following an interactive protocol that ensures the consistency of new rules, as well as the proper structure and complete coverage.

A simple example of consistency checking at the level of the inference engine is the following: suppose the analyst has already set the project country to Thailand; at a later stage, he may be asked in which of the major landform divisions the project is located. If he specifies the Delta (an obviously nonsensical choice), the system will proceed and probably not find an answer, but it will also not be able to diagnose the root of its problems. A more complex consistency check would be the following: suppose a reservoir was labeled shallow. For the subsequent definition of the available power head, this should obviously pose some constraints. At least the option **very high** should be disabled, and if the user sets the value to **high**, a warning message pointing out the potential inconsistency (after all, the reservoir could have a very unusual shape or a low lying power house could be connected by a tunnel or similar structure). Thus, the interdependency of descriptor values could be monitored.

The introduction of meta-rules that ensure the consistency of answers, for example by limiting the scope of possible answers dynamically depending on values already set, would constitute one such possible consistency-checking mechanism at the level of the inference process.

Another important extension could be the use of interval arithmetic or fuzzy set theory for the mixed numerical and/or symbolic treatment of descriptor values.

The issue of distributed data is related to the inference engine, but more importantly, to knowledge and problem representation. The current version of the system assumes a homogeneous project region, or a predominant feature (for example, in terms of land cover, soil type, etc.) that is characteristic of the entire area under assessment. For any larger area, this is a rather tenuous assumption. The possibility to define distributed parameters, say a list of soil or land use types with their relative frequencies or shares in the overall total, and then process them as weighted averages or sums, would greatly extend the descriptive power of the system.

Another useful feature would be the possibility of local or temporary descriptor modifications and sensitivity analysis: once the assessment is made, it would often be very interesting to modify one doubtful assumption and see what difference it makes, all other things being equal. This would mean following the same branch (possibly with alternative lower sub-branches) of the inference tree repeatedly, and being able to compare these alternative results.

8.3 Data base and GIS integration

Their integration with the expert system, allowing the automatic coupling of the inference engine with the various data bases would considerably improve the performance and usefulness of the system. In particular, coupling with a GIS to derive geo-referenced data for a given project location such as population density, land use, soil data, slopes, rainfall amount and intensity etc., would greatly simplify the analyst's task. At the same time, the expert system could provide an intelligent interface combined with display, and possibly an analysis program for the various data bases, as well as provide a framework for their integration.

8.4 Model integration

In addition to the data bases, there are several simulation models, in part also already available at the Secretariat, that could or should be integrated with the expert system. In many cases, they could be an integrated part of the inference engine, providing a complementary estimation procedure in extension of the heuristic rules. For example,

- water quality impacts
- watershed erosion and sediment transport
- effects on the groundwater, waterlogging and soil salinization
- flow modification and
- salinity intrusion

could all be estimated on the basis of numerical simulation models, thus greatly extending the power, and possibly, the accuracy of the expert system.

As with the case of the data bases, the expert system could not only use the models, it could in turn provide a framework for model integration, and provide an easy-to-use interactive interface and display system for the various simulation models.

Much of the environmental and project information available could be used in a similar framework for site selection: rather than estimating the impacts for a given, pre-defined site, the same logic can be used to find an appropriate "optimal" site with minimal environmental impacts and maximum socio-economic benefits for a given project.

Another extension to the expert system could be a discrete multi-criteria decision support module for the comparative analysis, ranking and evaluation of projects or project alternatives.

8.5 Uses and users

The MEXSES expert system for environmental screening has several possible functions and uses:

- It is primarily a tool for the project manager or analyst to assist in a well-structured, screening-level environmental impact assessment of water resources development projects;
- It is also a framework for the collection and integration, in a compatible format, of environmentally relevant data and expertise, a repository of experience, that can form a specific institutional memory;

- and it can be a tool for communication, not only between experts and project officers from different domains, but also between different groups, institutions, and riparian countries involved in the overall planning and development process, including the general public.

Although computers are becoming more easily available and easier to use, and one of the explicit design goals of MEXSES was an easy-to-use tutorial style interface, system's administration, and in particular knowledge acquisition, or the integration of further GIS data or models certainly require some computer expertise, and thus dedicated support staff. Further, development itself, not only of the knowledge base but of any functional extensions, requires the direct and close involvement of the end users: it is, after all, their tool, and should represent their view of the problem, using their language, style and symbols. This, however, requires an investment of effort and a considerable personal and institutional commitment on the part of the users.

Finally, it is important to understand what a system such as MEXSES really can do, and what it cannot do. It cannot solve problems. It cannot make environmental impact statements or make choices and it cannot define environmental policy. However, it can assist people to do all of the above. And it primarily does so by simply organizing the assessment procedure. It provides a framework and a language, and even if many of the components of the knowledge base are simplistic or incomplete, they can at least challenge the analyst to reflect on the problem with a new, different point of view. The system is, in some sense, a mirror that helps the analyst to check his own understanding, and eventually, to improve his understanding.

By organizing background information in a convenient format, and providing an interactive handbook and set of instructions and guidelines, the system can save data collection and manipulation effort. Of course these data and information have to be compiled first—but only once, and is then conveniently available for future applications. By making it easier to perform an individual assessment, the system offers the possibility to do that in a more experimental way, trying, exploring and comparing a larger number of alternatives.

The current prototype is only a first step in this direction. It will require considerable institutional commitment, and much further input, to eventually grow into a useful tool that can be integrated into the daily planning and decision making of the Mekong Secretariat.

Appendix 1:
A Sample Checklist

For each of its problem types, MEXSES uses a separate, type-specific checklist. Depending on project type definitions, these checklists may of course overlap. The checklist for Multi-purpose projects, which covers a superset of most project types, is given below.

```
PROJECT TYPE:  Multi Purpose Projects
PROBLEM CLASS: PROBLEMS DUE TO PROJECT LOCATION

90101  Resettlement
90102  Watershed degradation
90103  Encroachment upon precious ecosystems
90104  Encroachment on historical/cultural values
90105  Watershed erosion  (location)
90106  Reservoir siltation (location)
90107  Impairment of navigation
90118  Seepage and evaporation losses
90109  Migration of valuable fish species
90110  Inundation of mineral resources/forests
90111  Other inundation losses and adverse effects
90112  Groundwater hydrology, water logging (location)
90113  Regional flooding/drainage hazards
90114  Soil salinization and acidification hazards
90115  Earthquake hazards
90116  Local climatic change

PROJECT TYPE:  Multi Purpose Projects
PROBLEM CLASS: PLANNING AND DESIGN PROBLEMS
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90201 Watershed erosion (design)
90202 Road erosion (design)
90203 Reservoir site preparation
90204 Land use conflicts
90205 Water rights conflicts
90206 Inequities in water distribution
90207 Release of anoxic water downstream
90208 Fish kills, human health hazards due to H2S
90209 Downstream water quality problems
90210 Suitability of water quality for irrigation
90211 Overpumping of groundwater
90212 Adequacy of drainage planning
90213 Organization and maintenance problems
90214 Agricultural chemicals

PROJECT TYPE: Multi Purpose Projects
PROBLEM CLASS: PROBLEMS DURING CONSTRUCTION STAGE

90301 Soil erosion and silt runoff
90302 Safety of workers
90303 Sanitation at workers' camp
90304 Dust, odors, fumes, noise, vibrations
90305 Environmental aesthetics
90306 Construction monitoring

PROJECT TYPE: Multi Purpose Projects
PROBLEM CLASS: PROBLEMS RESULTING FROM PROJECT OPERATION

90401 Downstream flow variations
90402 Depreciation of downstream inundation fisheries
90403 Downstream erosion (operation)
90404 Lack of reservoir management
90405 Reservoir eutrophication (aquatic weeds, oxygen deficiency)
90406 Downstream water quality (operation)
90407 Insect/molluscan vector borne disease hazards
90408 Estuarine and marine fisheries impacts
90409 Reservoir bank stability (operation)
90410 Nutrient trapping in the reservoir

90411 Bogging, water logging, groundwater changes (operation)
90412 Adverse changes in soils
90413 Reduced annual flushing, acidification and salinization
90414 Salinity intrusions into the Delta
90415 Mangrove destruction
90416 Water-related disease hazards
90417 Toxic chemicals and fertilizers
90418 Aquaculture water supply
90419 Operations monitoring

PROJECT TYPE: Multi Purpose Projects
PROBLEM CLASS: POTENTIAL ENVIRONMENTAL ENHANCEMENT MEASURES

90501 Community water supply in service area
90502 Reservoir fisheries enhancements
90503 Drawdown agriculture
90504 Aquaculture in service area
90505 Forestry and wildlife reserves
90506 Recreation potential

Appendix 2: Summary Evaluation Level

For each of the eight summary evaluation criteria, a separate set of rules is used to aggregate an assessment value from a set of subproblem evaluations. The descriptions below provide examples of the corresponding checklist description files for the **Multi-purpose projects** category.

UNWARRANTED LOSSES IN PRECIOUS NATURAL RESOURCES

Dams and reservoirs could cause unwarranted losses in precious natural resources both directly and indirectly. Direct losses pertain to those that are submerged due to inundation consequent to reservoir filling. The permanent flooding of large areas of land inevitably results in loss of mineral deposits, forests, pastures and grazing land and prime agricultural tracts that may form the bed of the reservoir. Tropical forests such as those that are inundated are known for their high biological diversity and the component organisms could not only be of high scientific and ecological value in themselves but also in the contribution of their gene pools which when cross bred with domestic varieties could produce economically superior strains. Other direct losses include submerged archaeological sites, buildings of cultural or historical value or even as yet unexplored sites, some of which may be of great historical value. Indirect losses include decimation of populations of wildlife, since the reservoir constitutes an impediment to their migration. Large numbers of such animals congregate at the lakeside and fall easy prey to predators or hunters. Another indirect loss relates to important riverine aquatic species that cannot survive the changed lacustrine conditions.

This would include such important anadromous and catadromous species of fish for which access to sites above or below the dam respectively, is important for completion of their life cycles. Other indirect losses pertain to the destruction of wildlife and forests caused by resettlers from the reservoir basin. Losses of wetlands either caused by project structures by filling and of mangroves due to ecological changes should also considered.

The assessment summary considers the following subproblems:

- Inundation of mineral resources/forests;
- Other inundation losses and adverse effects;
- Estuarine and marine fisheries impacts;
- Flushing, acidification and salinization;
- Mangrove destruction;
- Watershed degradation;
- Bogging, water logging, groundwater changes;
- Encroachment on ecosystems;
- Encroachment on historical/cultural values;
- Environmental aesthetics;
- Downstream inundation fisheries;
- Watershed erosion;
- Reservoir siltation;
- Silt trapping in the reservoir;
- Impairment of navigation;
- Seepage and evaporation losses;
- Migration of valuable fish species;
- Soil erosion and silt runoff;
- Reservoir eutrophication;

- Downstream water quality;
- Downstream erosion;
- Reservoir bank stability.

UNWARRANTED HAZARDS TO ENDANGERED SPECIES

Unwarranted hazards to endangered species generally come as a result of impoundment and dam construction. Impoundment could submerge many endangered species of terrestrial plants and animals. The ecological and climatic changes resulting from the lake may not be suitable for propagation or even survival of some species that have escaped submergence. Further, the changed environmental conditions may render some endangered species more vulnerable to excessive hunting and eventual extinction. Some endangered species of aquatic animals may not survive the changes from a riverine to a lacustrine ecology. Further, migratory species of fish, for which access to sites above or below the dam is critical for spawning or feeding, could be adversely affected by the barrier created by the dam.

General assessment is based on the ecology of endangered species in the area *vis-à-vis* the predicted changes due to the dam and its construction.

The Assessment Summary is based on the following subproblems:

- Encroachment upon precious ecosystems;
- Inundation of mineral resources/forests;
- Other inundation losses and adverse effects;
- Migration of valuable fish species;
- Estuarine and marine fisheries impacts;
- Mangrove destruction (operation);
- Local climatic change;
- Downstream flow variations;
- Hydrological changes (operation);

- Reduced annual flushing, acidification, salinization;
- Reservoir bank stability (operation);
- Bogging, water logging, groundwater changes (operation);
- Depreciation of downstream inundation fisheries;
- Lack of reservoir management;
- Reservoir eutrophication, weeds, oxygen (operation);
- Downstream water quality (operation);
- Release of anoxic water downstream;
- Fish kills, human health hazards due to H_2S;
- Insect/molluscan vector borne disease hazards;
- Dust, odors, fumes, noise, vibrations;
- Environmental aesthetics.

UNWARRANTED ENVIRONMENTAL DEGRADATION

Population pressure due to resettlement from inundated area or excessive natural population growth puts increasing demands on new and possibly marginal soils for agricultural use. This leads to a loss of natural habitats and vegetation cover, and in particular forests, and consequent soil erosion and possible desertification. Erosion/silt runoff in the watershed induced by the project can lead to considerable loss of productive soils in the watershed. Hydrostatic pressure caused by the reservoir can cause downstream areas to become waterlogged; this could lead to soil salinization (e.g., in the Korat Plateau), and thus contribute to general environmental degradation. The access roads built for the project and the new lake will often serve to accelerate inroads into the watershed by farmers, hunters, timber exploiters, etc., thereby accelerating losses in forests and wildlife. Water flow regulation often changes salinity patterns in estuarine areas. This will have serious effects on mangrove forests.

The Assessment Summary considers the following subproblems:

- Watershed degradation;
- Encroachment upon precious ecosystems;
- Mangrove destruction (operation);
- Migration of valuable fish species;
- Dust, odors, fumes, noise, vibrations;
- Depreciation of downstream inundation fisheries;
- Reduced annual flushing, acidification, salinization;
- Estuarine and marine fisheries impacts;
- Downstream flow variations;
- Hydrological changes (operation);
- Watershed erosion (location);
- Reservoir eutrophication, weeds, oxygen (operation);
- Release of anoxic water downstream;
- Fish kills, human health hazards due to H_2S;
- Insect/molluscan vector borne disease hazards;
- Downstream water quality (operation);
- Road erosion (design);
- Soil erosion and silt runoff (construction);
- Downstream erosion (operation);
- Environmental aesthetics;
- Local climatic change;
- Earthquake hazards;
- Groundwater hydrology, water logging (location);
- Bogging, water logging, groundwater changes (operation);

UNREALIZED RESOURCE USE POTENTIAL

Unrealized resource use potential relates to the generally neglected areas of development related to dam construction, such as: (i) reservoir fishery development, (ii) aquaculture in irrigation service areas, and (iii) shoreline agriculture, horticulture or livestock raising. The above three opportunities are usually disregarded in the development planning due to ignorance of their potential. Tropical lakes are more productive than rivers submerged by newly created reservoirs. Due to the fertilizing action of submerged biota, plankton blooms develop. These blooms can support rich fishery if appropriate planktonophages occur in indigenous fauna or if proper species are introduced. This can lead to very high fish yields and consequently to economic growth for fishermen. Year round availability of water from irrigation canals can be taken advantage of to develop aquaculture downstream particularly in non-arable lands in irrigation service areas. Further, the reservoir can be used for floating-cage culture of fish. These types of fish culture can be very productive and economically beneficial. Reservoir shores are generally very productive due to mineralization of soils as a consequence of alternate inundation and dessication. These shore areas can be used profitably for agriculture, horticulture and livestock raising, with proper precautions to prevent shoreline erosion.

General assessment is based on water quality and ecological and morphoedaphic features for reservoir fishery development. For aquaculture the selection of species to be cultured will be the crucial one. Utilization of lake shores will depend on soil conditions and the nature of the terrain.

The Assessment Summary considers the following subproblems:

- Resettlement;
- Release of anoxic water downstream;
- Impairment of navigation;
- Reservoir fisheries enhancements;
- Watershed degradation;
- Inundation of mineral resources/forests;
- Safety of workers;

- Recreation;
- Encroachment upon precious ecosystems;
- Watershed erosion (location);
- Reservoir siltation (location);
- Seepage and evaporation losses;
- Migration of valuable fish species;
- Road erosion (design);
- Sanitation at workers' camp;
- Dust, odors, fumes, noise, vibrations;
- Environmental aesthetics;
- Downstream community water supply;
- Downstream aquaculture;
- Forestry and wildlife reserves;
- Soil erosion and silt runoff (construction).

UNDESIRABLE LAND USE DEVELOPMENT, URBANIZATION

Undesirable land use development could result from various factors: (i) improper resettlement and consequent encroachment on forests by resettlers, (ii) irrigation of marginal or problem soils, (iii) uncontrolled settlement of laborers and fishermen near reservoir shores particularly to exploit the initial boom of fish production. Improper resettlement could result in resettlers encroaching on watershed forests for agriculture, resulting in forest degradation and soil erosion problems. Irrigation of problem soils, such as potentially saline or acidic soils could lead to permanent soil degradation after a few years of cultivation. Uncontrolled settlements near the reservoir could lead to improper use of reservoir shores, over exploitation of fish populations and could cause sanitation and pollution problems in the lake periphery.

The general assessment is based on adequate resettlement requirements, such as on soil capabilities and quality for irrigation and on the fishing effort required for sustainable yields.

The Assessment Summary considers the following subproblems:

- Resettlement;
- Watershed degradation;
- Groundwater hydrology, water logging (location);
- Bogging, water logging, groundwater changes (operation);
- Forestry and wildlife reserves;
- Recreation;
- Drawdown agriculture;
- Depreciation of downstream inundation fisheries;
- Downstream aquaculture;
- Encroachment upon precious ecosystems;
- Encroachment on historical/cultural values;
- Watershed erosion (location);
- Road erosion (design);
- Soil erosion and silt runoff (construction);
- Construction monitoring.

INCREASE OF AFFLUENT/POOR INCOME GAP

Excessive irrigation projects may "dry up" established water uses downstream thus enriching irrigation farmers at the expense of downstream users. Further, inequities in water distribution throughout the service area might deprive lower water users of their rightful share in irrigation benefits. General assessment is based on water use requirements for various uses and users in the basin, both in the immediate irrigation area and downstream.

The assessment summary considers the following subproblems:

- Resettlement;
- Impairment of navigation;
- Reservoir fisheries enhancements;
- Depreciation of downstream inundation fisheries;
- Estuarine and marine fisheries impacts;
- Downstream aquaculture;
- Reduced annual flushing, acidification, salinization;
- Drawdown agriculture;
- Water rights conflicts;
- Reservoir site preparation;
- Lack of reservoir management;
- Watershed degradation;
- Groundwater hydrology, water logging (location);
- Bogging, water logging, groundwater changes (operation);
- Fish kills, human health hazards due to H_2S;
- Recreation;
- Inundation of mineral resources/forests;
- Other inundation losses and adverse effects.

UNREALIZED SOCIO-ECONOMIC BENEFITS

Unrealized resource use potential relates to the generally neglected areas of development related to dam construction, such as: (i) reservoir fishery development, (ii) aquaculture in irrigation service areas, and (iii) shoreline agriculture, horticulture or livestock raising. The above three opportunities are usually disregarded in the development planning due to ignorance of their potential. Tropical lakes are more productive than rivers and in newly created reservoirs, due to the fertilizing action of submerged biota, plankton blooms develop. These blooms can support rich fishery if appropriate planktonophages occur in indigenous fauna or if proper species are introduced. This can lead to very high fish yields and consequently to economic growth for fishermen. Year round availability of water from irrigation canals can be taken advantage of to develop aquaculture downstream particularly in non-arable lands in irrigation service areas. In addition, the reservoir can be used for floating-cage culture of fish. These types of fish culture can be very productive and economically beneficial. Reservoir shores are generally very productive, due to mineralization of soils as a consequence of alternate inundation and dessication. These shore areas can be used profitably for agriculture, horticulture and livestock raising, with proper precautions to prevent shoreline erosion.

The assessment summary considers the following subproblems:

- Resettlement;
- Release of anoxic water downstream;
- Impairment of navigation;
- Reservoir fisheries enhancements;
- Watershed degradation;
- Inundation of mineral resources/forests;
- Safety of workers;
- Recreation;
- Encroachment upon precious ecosystems;
- Watershed erosion (location);
- Reservoir siltation (location);
- Seepage and evaporation losses;
- Migration of valuable fish species;
- Road erosion (design);

- Sanitation at workers' camp;
- Dust, odors, fumes, noise, vibrations;
- Environmental aesthetics;
- Downstream community water supply;
- Downstream aquaculture;
- Forestry and wildlife reserves;
- Soil erosion and silt runoff (construction).

Appendix 3:
Sample Checklist Questionnaires

The current prototype version of MEXSES contains about 300 problem description and related questionnaires. Given below is a selection again largely taken from the **Multi-purpose** project type, listing the three text blocks displayed in the interactive assessment as background information for the analyst.

RESETTLEMENT

Impact: Serious social inequities, watershed degradation.

Description: Resettlement of population from inundated area. This problem has often been serious because of failure to conduct proper studies on socio-cultural and economic aspects of population to be resettled, land suitability studies on areas earmarked for relocation and failure to include adequate funds in the project core budget to cover appropriate resettlement costs. A further factor is that land available for resettlement is often of low quality, leading to encroachment on watershed areas, watershed degradation and erosion due to use of marginal lands.

Evaluation of the expected impact considers the number of people to be moved, the costs of relocation, depending on the location and size of the project, in relation to the available budget, the type of watershed and the land demand of the new settlement areas, and finally potential mitigation measures by watershed management, including activities such as zoning and land-use planning, erosion control, afforestation, etc.

Recommendations: Carefully planned resettlement program including a "hard" budget. The provision of family housing and socio-cultural amenities, plus developed land for the traditional land-use types rather than cash payments. The resettlement should be planned and carried out in accordance with the "Guidelines and Principles for Resettlement Projects in the Mekong Basin", developed by the Mekong Secretariat.

WATERSHED DEGRADATION

Impact: Watershed degradation through agriculture on marginal lands and improper cultivation techniques, including slash and burn. Sedimentation of reservoirs and reduction of useful lifespan of the dam.

Description: Population pressure due to resettlement of population from inundated area or excessive natural population growth puts increasing demands on new and possibly marginal soils for agricultural use. This leads to a loss of natural habitats and vegetation cover (forests in particular) and consequent soil erosion and possible desertification.

Assessment of expected watershed degradation is based on the watershed characteristics; for Thailand, this uses the official watershed classification scheme (see Explain Option) where available; for other areas, watershed vulnerability is based on the erosion potential, estimated with a technique derived from the Universal Soil Loss Equation (USLE), developed by the US Department of Agriculture (USDA) Soil Conservation Laboratory. The assessment also considers new land requirements, and in particular agricultural and livestock land requirements, caused either by forced resettlement or population increase that may be induced by the development project. An additional factor of watershed degradation can be forest fires, often used intentionally in slash-and-burn practices. In particular, short fallow periods lead to soil exhaustion.

Recommendations: Carefully planned watershed management program including land use management and zoning, and reforestation where necessary.

ENCROACHMENT UPON PRECIOUS ECOSYSTEMS

Impact: Loss of ecological values, wildlife, endangered animals and precious gene pools of animal and plant life, e.g., plants of medicinal value, wild varieties of plants and domesticated animals, useful but as yet unexploited life forms.

The access roads built for the project and the new lake will often serve to accelerate inroads into the watershed by farmers, hunters, timber exploiters, etc., thereby accelerating losses in forests and wildlife.

The assessment is based on the length of the access roads, the type of land use, in particular of forests (natural or managed forest, economic value of the predominant trees), which may provide targets for illegal logging, and the presence of wildlife, especially of endangered or rare species.

Recommendations: Careful planning plus use of measures for offsetting these effects: because of the adverse effects of the project in facilitating and accelerating encroachment into the upper watershed, it may be desirable to include, possibly as a project component, provision of forest/wildlife parks and conservation of gene pool resources in the upper watershed while this is still feasible

ENCROACHMENT ON HISTORICAL OR CULTURAL VALUES

Impact: Loss of cultural or historical values and national heritage.

Description: This must be carefully evaluated and, if precious items or sites of national importance are believed to be in the area to be inundated, a program for finding exploring/excavating and salvaging these should be undertaken prior to inundation.

Assessment is based on the existence of any sites of cultural value, historical monuments, religious shrines or temples, etc., and their location *vis-à-vis* the project itself, its access roads, and land requirements for possible resettlement, and the potential for further population increase in the project area possibly induced by the project.

Recommendations: Careful planning plus mitigation measures; survey of the land to be inundated and directly affected by the project is a basic requirement for the formulation of a preservation plan.

WATERSHED EROSION

Impact: Soil loss and watershed degradation.

Description: If the existing condition of erosion/silt runoff in the watershed is high enough to lead to considerable loss of productive soils in the watershed, consideration must be given to expanding the project to include a watershed afforestation and/or regreening program, to be included in the project's core budget.

Assessment is based on the erosion potential of the watershed, based in turn on precipitation patterns, slope and soil conditions and vegetation cover, as well as on land use and erosion control measures.

Recommendations: Watershed management program; zoning and land use regulations, reforestation programs and erosion control measures.

IMPAIRMENT OF NAVIGATION

Impact: Economic loss.

Description: The dam itself poses an obstacle to navigation, even if locks are provided; further, change in downstream flow may directly (flow reduction) and indirectly (bed sedimentation) impair river navigation, except where rapids or small waterfalls or other natural barriers to navigation exist, in which case the dam will help the navigator, either due to increase in volumes of flow or submergence of rapids and waterfalls.

Assessment is based on the project location (mainstream or tributary) and the natural navigability of the river reach affected. Original volume of traffic depending on the dam's location needs to be considered. Height of dam and availability and capacity of locks are additional considerations. Upstream improvements have to be weighed against possible downstream problems due to reduction of low flow.

Recommendations: Careful planning plus mitigation measures including dredging maintenance of reliable minimum low flow, adequate lock capacities, and auxiliary transportation systems

CHANGES IN GROUNDWATER HYDROLOGY, WATER LOGGING

Impact: Economic loss, soil salinization and drainage problems.

Description: Hydrostatic pressure caused by the reservoir can cause downstream areas to become waterlogged; this could lead to soil salinization (e.g., in the Korat Plateau).

The assessment is based on the reservoir size, in particular, head, the undisturbed groundwater head (the distance of the water table from the soil surface, and soil conditions). A special consideration is whether the project is located on the Korat Plateau with its abundant salt deposits and problem soils.

Recommendations: Careful planning plus mitigation (deep drainage) measures.

MIGRATION OF VALUABLE FISH SPECIES

Impact: Decrease in fish populations and catch.

Descriptions: The dam can pose a major obstacle to upstream migration, spawning and recruitment of valuable fish species and obstruction to the dispersal of young fish to downstream areas.

The assessment is primarily based on the location of the project, namely mainstream or tributary, and the location within the tributary (mouth, intermediate, upstream); it also considers the type of reservoir operation, i.e., pumped storage or run-of-the-river. The existence of anadromous or catadromous runs is also important.

Recommendations: Furnish fish passage facilities where they are likely to be effective and economically warranted; managing reservoir fisheries can mitigate losses by providing new and improved opportunities for fisheries in the reservoir.

INUNDATION OF MINERAL RESOURCES/FORESTS

Impact: Loss of mineral resources; impairment of human health.

Descriptions: The inundation area may include mineral resource deposits which would be lost for future exploitation.

The assessment is based on the existence and potential value of any mineral deposits in the planned inundation area. Water percolating through mineral deposits (e.g., fluorides) either in the reservoir or downstream could contaminate some traditional potable water sources and cause serious disease (e.g., skeletal fluorosis).

Recommendations: Proper scheduling of the project should allow for study and exploitation of any mineral resources in the inundation zone and downstream, prior to inundation.

SEEPAGE AND EVAPORATION LOSSES

Impact: Water loss, reduced storage, increased filling time, economic losses.

Description: Reservoirs with a large surface area and in particular shallow reservoirs with a low volume/surface ratio may be subject to considerable evaporation losses. In addition, seepage to the groundwater may cause losses from the reservoir. Evaporites in the reservoir bed will cause considerable seepage losses. Weed infestation causes excessive evapo-transpiration losses.

The assessment involves the reservoir's surface area, project location, and thus, climatic conditions, as well as vegetation in the shallow areas for the estimation of evapo-transpiration losses; hydrostatic pressure from the reservoir head, the permeability of the surrounding substrate and occurrence of evaporites are used to estimate possible losses due to seepage.

Recommendations: Where possible grouting with clay or other impervious material. Weed eradication.

RESERVOIR SILTATION

Impact: Loss of reservoir storage, shortened life time of the reservoir.

Description: If the existing condition of erosion/silt runoff in the watershed is high enough to jeopardize the life of the dam by excessive filling rate, consideration must be given to expanding the project to include a watershed afforestation and/or regreening program, to be included in the project's core budget.

The assessment considers the watershed erosion in the reservoir's catchment, the size and in particular volume of the reservoir, the expected variability of the reservoir level, land use of the drawdown zone, anticipated fetch and expected wave action which would influence bank erosion and contribute to the problem. Finally, siltation control techniques such as silt traps, dredging, or sediment flushing can mitigate the problem.

Recommendations: Watershed management program; erosion control and sediment removal measures.

RESERVOIR SITE PREPARATION

Impact: Affects reservoir water quality including nutrients for fisheries.

Description: Pre-inundation site preparation can affect water quality in the reservoir; excessive biomass may cause eutrophication and oxygen depletion problems. However, if the reservoir fishery is important, it is often preferable not to clear the reservoir site completely, except for valuable timber, in order to leave nutrients for the reservoir. Submerged tree trunks provide substrate for periphyton on which the fish feed and for the deposition of eggs by some fish.

The assessment is based on the remaining terrestrial biomass in the reservoir, the reservoir morphometry and retention time affecting water quality, and the importance of fisheries in the reservoir as well as downstream.

Recommendations: Prepare site according to planned reservoir usage. Strip clearing for navigation and gill net operation, and selective area clearing for shore-seine operation are recommended.

WATER RIGHTS CONFLICTS

Impact: Serious social conflicts, agricultural and flood damage.

Description: This involves balancing conflicting needs for use of the stored water for hydropower, irrigation, flood control, fisheries and other purposes, such as maintaining low flows or fluctuating reservoir levels to control disease vectors and maintaining the viability of valuable ecosystems downstream (e.g., wetlands, mangroves).

The assessment considers the mix of project objectives, relative economic benefits of various uses, and ecological value of non-project water requirements e.g., recharging wetlands

Recommendations: Careful management of water rights allocation.

RELEASE OF ANOXIC WATER DOWNSTREAM

Impact: Downstream water quality problems; fish kills.

Description: Due to chemical and thermal stratification of deep and less wind-exposed reservoirs, oxygen depletion in the hypolimnion may occur due to putrefaction of biomass or high BOD loading into the reservoir and/or upstream portions of the river. With reservoir release from the hypolimnion (lower layer) low oxygen water will be discharged to the downstream sections of the river. Also H_2S in the water can corrode turbines.

Assessment based on reservoir morphometry, particularly mean depth, and wind-action induced turbulence, which encourages mixing and breaks up stratification. The volume of submerged biota is also of importance. Impact magnitude depends on value of fishery, existence of fish spawning or feeding areas downstream and human uses of water in residual river.

Recommendations: Multi-level outlets to mix hypolimnic water with oxygenated surface water in the discharge, reduction of point and non point source loading of BOD into the reservoir. This would involve wastewater treatment and agricultural runoff management.

FISH KILLS AND HUMAN HEALTH HAZARDS DUE TO H_2S

Description: Due to chemical and thermal stratification of deep and less wind exposed reservoirs oxygen depletion and subsequent H_2S generation in the hypolimnion may occur due to putrefaction of biomass and high BOD loading into the reservoir, particularly within the first few months after filling, often resulting in fish kills in the reservoir itself. With reservoir release H_2S water will be discharged to the downstream sections of the river, leading to fish kills downstream. Further, H_2S leads to corrosion of turbines and other machinery.

The assessment considers the overall trophic situation of the reservoir, terrestrial biomass remaining in the reservoir basin, the use of river water as potable water, and possible mitigation measures.

Impact: Downstream water quality problems; fishery losses.

Recommendations: Multi-level outlets to mix hypolimnic water with oxygenated surface water in the discharge, reduction of point and non point source loading of BOD into the reservoir. This would involve wastewater treatment and agricultural runoff management.

SANITATION AT WORKERS' CAMP

Impact: Hazards to health of workers and nearby communities.

Description: Communicable disease hazards from poor sanitation and potential human disease reservoirs at workers' camps.

The assessment is based on the size of the workforce, the component of unskilled workers, health care at the construction site or in its immediate vicinity, sources of water supply and the nature of waste disposal, and project location in areas with disease vector populations.

Recommendations: Proper construction planning and monitoring, installation of appropriate sanitation, sewering, and waste management. Health care and medical services appropriate to the size of the construction project is required. Health screening of the work force for contagious diseases, health education and hygienic practices.

DOWNSTREAM FLOW VARIATIONS

Impact: Fishery losses, degradation of soils and destruction of valuable ecosystems.

Description: If natural flow variations are stopped, several ecological functions are disrupted. Changes in velocity of currents, and volumes of discharge remove environmental clues for fish migrations and fish congregations. Prevention of periodic inundation of flood plains eliminates breeding and nursery areas for fish and annual flushing of salts and acids from soils. Also eliminates recharge wetlands and groundwater, as well as other benefits. Threatens mangrove survival.

Assessment is based on natural variations in temperature and volumes of flow, existence of valuable fish runs, fish breeding and nursery grounds in the residual river, location of mangroves and wetlands, their ecological and socio-economic importance and dependence on river hydrology for recharging.

Recommendations: Release of water from the reservoir at appropriate times to allow fish migrations and flooding ecologically important flood plain areas and maintenance of sensitive and important ecosystems.

DEPRECIATION OF DOWNSTREAM INUNDATION FISHERIES

Impact: Socio-economic losses and reduction of fish supply.

Description: Considerable losses to downstream inundation fisheries occur as a result of regulation of flow. Reduction in wetted perimeter of downstream areas reduces productive surface area. Changes in current velocity and discharge patterns inhibit fish migrations. Drying up of flood lands eliminates fish spawning and nursery areas and thus affects recruitment to natural fish stocks and replenishment of wetland fish stocks.

Assessment is based on natural variations in temperature and volumes of flow, existence of valuable fish runs and fish breeding and nursery grounds in the residual river, the location of mangroves and wetlands, their ecological and socio-economic importance and dependence on river hydrology for recharging.

Recommendation: Reservoir water releases at appropriate times for fishery purposes. Aquaculture development in downstream areas to augment fishery losses. Improved management of riverine and estuarine capture fisheries.

LACK OF RESERVOIR MANAGEMENT

Impact: Non realization of full fishery potential, non utilization of production potential of shoreline soils. Conflicts among communities living around the reservoir. Economic deprivation of fishermen after trophic decline.

Description: Reservoirs have to be managed for maximizing fish production for organizing shoreline agriculture and for settlement of communities deriving livelihood from the reservoir, e.g., fishermen, boatmen, farmers around the reservoir. Regulation of fishing pressure, protection of spawning populations, introduction of new species to exploit unexploited trophic niches in order to ensure economically rewarding harvests even after the phase of trophic decline. Trophic decline leads to decline in fish populations and generally sets in 5–7 years after creation of the reservoir.

Assessment is based on the morpho-edaphic features of the shoreline as far as agriculture is concerned. For fisheries the nature and magnitude of indigenous river populations, their capacity to survive and multiply in the new lacustrine environment, the morpho-edaphic features of the lake, are all important in determining the nature of fishery development to be undertaken, especially regarding whether introduction of new species is warranted. Also to be considered in the assessment are water quality conditions including, in particular, TDS (total dissolved solids), pH, DO and other relevant parameters.

Recommendations: Institution of fishery development and management measures and effective management of communities and agricultural development.

RESERVOIR EUTROPHICATION

Impact: Reduction in fish production potential, restrictions to water use.

Description: Eutrophication results from nutrients leached from submerged biota, including forests and soils. Consequences are explosive growth of nuisance vegetation (weeds) and oxygen depletion.

The assessment considers the overall eutrophic situation of the reservoir and its catchment, determined by morphometry and expected nutrient loading, depending on wastewater treatment and the land use of the immediate shore zone and drawdown area, and remaining nutrients from terrestrial biomass left uncleared, depending on pre-impoundment site preparation, and the probability of floating weeds occurring.

Recommendations: Strategically timed draw-downs for weed control. Selected clearing of forests, large scale introduction of species (preferably indigenous) that feed on phytoplankton, zooplankton and on aquatic vegetation. Eradication of weeds from possible sources of infestation in the reservoir basin.

INSECT/MOLLUSCAN VECTOR BORNE DISEASES

Impact: Adverse effects on human health and productivity. Increase in mortality rates.

Description: Ecological changes contingent on project operations favor proliferation of disease vectors, e.g., particularly mosquitoes and snails, which are carriers of malaria, filariasis, bilharziasis and opistharchiasis.

Assessment is based on endemicity of vector borne diseases, occurrence of vectors and the ecological changes being favorable to their proliferation, as well as the presence of human disease reservoirs in the area.

Recommendations: Control of access to reservoirs of human disease carriers and mass medication of infected individuals. Control, where possible, of vectors. Provide health education to exposed populations in order to change hygienic practices that lead to the spread of diseases.

ESTUARINE AND MARINE FISHERIES

Impact: Reduction or failure of valuable fisheries. Elimination of sources of livelihood to human communities depending on wetlands and fisheries.

Description: Flow regulation changes ecology of estuaries and inshore areas. Trapping of nutrient rich sediments in upstream reservoirs along with flow regulation deprive these areas of natural replenishment of nutrients. Flow regulation also modifies environmental parameters, e.g., pH, salinity and DO in important estuarine fish breeding and nursery areas, thereby reducing fish stocks. Hydrological and water quality changes affect estuarine wetlands and mangroves.

Assessment is based on modification in the volume of flow and velocity of current as well as the nutrient content and volume of silt runoff. Seasonal occurrence and value of fish congregations in the inshore areas for feeding or breeding and of fish migrations attracted by flow conditions are also important in assessment. It is also based on natural variations in temperature and volumes of flow, existence of valuable fish runs and fish breeding and nursery grounds in the residual river. The location of wetlands, their ecological and socio-economic value and dependence on river hydrology for recharging are also of relevance.

Recommendations: Intense fishery development measures and provision of alternate livelihood in marine and estuarine areas.

NUTRIENT TRAPPING IN THE RESERVOIR

Impact: Downstream flood plains are deprived of nutrient rich silt as well as soil enrichment by deposition of fresh silt annually. This enhances the need for use of fertilizers, at huge expense, to replenish nutrient loss. Elimination of the fertilizing action of silt in estuarine and inshore areas prevents fish congregations, causing serious fishery losses. Elimination of periodic flushing might precipitate soil salinization and acidification in certain areas.

Description: Silt from upstream catchment is trapped behind the dam and clear water is passed downstream. This in turn, might lead to a reduction of nutrient transport downstream, in the river as well as onto the flood plains, and ultimately the river's delta. Positive effects may include an increase in riverine primary production due to an increase in light penetration.

Assessment is based on (i) nutrient content in the silt and (ii) the volume of silt carried by the river. This, in turn, would depend on watershed conditions and watershed management. Considerations include the balance of silt and nutrient level, estimates of nutrients lost as well as the cost of fertilizers to replace lost nutrients.

Recommendations: Properly managed agriculture with extraneous energy inputs, e.g., fertilizers. Management and development of estuarine fisheries to mitigate losses.

MANGROVE DESTRUCTION

Impact: Adverse socio-economic effects on communities depending on mangroves for their livelihood. Shore and bank erosion and reduction of fisheries due to ecological changes in fish breeding and nursery areas.

Description: Water flow regulation often changes salinity patterns in estuarine areas. This will have serious effects on mangrove forests.

Assessment is based on pre-impoundment mangrove ecology in the light of changes in volume of water flow and water quality characteristics, such as salinity, which are likely to to occur as a result of the development The importance of the ecological (hydrologic, water quality, life support) and socio-economic functions of the mangroves should also be taken into consideration.

Recommendations: Regulation of flow to prevent undue ecological changes. Mitigatory action to provide alternative livelihood for communities and development measures to improve fisheries.

ELIMINATION OF ANNUAL FLUSHING

Impact: Elimination of annual flushing increases soil salinization and acidification, eliminates fish breeding and nursery grounds, reduces fishery potential and fish catches, and also reduces the productivity of soils.

Description: Water control measures eliminate annual flushing which helps flushing salt and acid from surface soils. Annual flushing also helps recharging groundwater table and wetlands, provides environmental clues for fish spawning migrations, inundates flood plains which are natural fish breeding and rearing sites.

Assessment is based on volume of flow, areas flushed naturally, soil conditions, particularly permeability and the role of river hydrology in recharging wetlands. The geology of flood plains, particularly the presence of underground salt deposits and TDS in irrigation water should also be considerations. Occurrence of fish migration in the river and of breeding and nursery areas in flood plains have to be considered in the assessment.

Recommendations: Where possible, water releases from the dam to simulate annual floods.

SALINITY INTRUSION INTO THE DELTA

Impact: Loss of agricultural production, water supply problems.

Description: Hydrological changes have wide-ranging effects on fisheries, mangroves, soils, wetlands and various other uses and ecosystems. A very important aspect is the intrusion of saline water into the estuarine system of the Delta during the low flow period, January to May. The intrusion of saline water can affect the quality of the supply of water for irrigation, drinking water and industrial uses.

Assessment is based on the extent of the intrusion, which in turn depends on the relative and absolute volume of flow, and its distribution over time, including tidal conditions. Various zones inland from the coast have different agricultural potential with up to three harvests a year, and thus differing vulnerability to the saline water. Depending on the overall reduction of low flow and the change of the time distribution, different areas will be affected.

Recommendations: Low flow augmentation, combined with local salinity control measures such as dikes and sluices.

RESERVOIR FISHERIES ENHANCEMENTS

Impact: Positive impacts: increased revenue from fisheries provides livelihood for many farmers and fishermen; increased supply of protein. Enhancement of project benefits. Negative impacts: unless regulation of fishing pressure is imposed, the fishery bonanza can turn into a socio-economic disaster if too many fisherman are allowed to harvest the fish.

Description: New reservoirs offer an excellent opportunity to develop fisheries. Due to the fertilizing action of submerged vegetation and other biota, explosive growth of phytoplankton and zooplankton occurs. This can provide a good base for the production of planktophagous species of fish, mainly carp, and of predaceous fish which feed on the herbivores. To take advantage of this production potential, proper fishery management has to be instituted. Reservoirs can produce anywhere between 30–160 kilograms or more of fish per hectare, depending on edaphic and morphometric parameters and effectiveness of management

Assessment is based on the morpho-edaphic index of the reservoir, the indigenous fish populations and their ecology, in particular their ability to survive and develop in the changed lacustrine environment and thus the need to introduce exotic species. Other considerations are water quality parameters such as TDS (total dissolved solids), DO, pH, sources of pollution such as industries discharging effluents into the reservoir or agricultural practices, which result in the release of toxic chemicals and have to be carefully controlled to reduce pollution in the lakes. The number of fishermen have to be controlled and limited to economically viable fishing based on post-trophic depression levels of fish populations and not on the initial "boom phase". This will avoid unnecessary hardship to fishermen when the population declines.

Recommendations: Regulation of fishing pressure. Protection of fish spawning grounds, introduction of new species where necessary, and other effective management measures.

DRAWDOWN AGRICULTURE

Impact: Positive impact: increased revenues from agriculture. Enhancement of project benefits. Negative impact: agriculture may induce bank erosion, eutrophication and water quality deterioration due to fertilizers and pesticides leached from the cultivated area.

Description: Reservoir drawdown areas are generally fertile due to seasonal inundation and dessication. Reservoir management should therefore include opportunities for growing seasonal, lucrative crops, e.g., vegetables, pasture development and certain cereal crops.

Assessment is based on morphology and soil characteristics of the shoreline and careful evaluation of its suitability for agriculture, horticulture or livestock raising. Further, appropriate measures have to be implemented to eliminate or regulate agricultural return flows laden with toxic chemicals in the reservoir. Erosion control measures also have to be planned.

Recommendations: Proper agronomic practices and management.

DOWNSTREAM AQUACULTURE

Impact: Negative impacts: large-scale fish mortalities if aquaculture areas are not protected from agriculture return flows loaded with pesticides. Positive impacts: enhancement of fish supplies and increase in cost–benefit ratio for the dam project.

Description: Availability of adequate water supply year round in downstream areas particularly through irrigation canals provides an opportunity for the development of aquaculture either in non-arable lands, in irrigation service areas or in other suitable places where water is available. Development of aquaculture will serve to augment fishery losses downstream.

Assessment is based on location, soil conditions and available water quality and quantity. Annual closure of irrigation canals for maintenance and alternate water supply during that period should also be taken into consideration. The disposal of agricultural return flows laden with toxic chemicals has to be considered in the context of possible contamination of aquaculture water supply.

Recommendations: Proper management of water supply in quality and quantity.

Appendix 4:
Sample Rules for Reservoir Eutrophication

The current MEXSES prototype implementation includes approximately 1000 rules, covering, however, only a subset of all problem checklists. Given below is an example of a rule set, including decision tables for one specific subproblem, **reservoir eutrophication**.

It must be noted, however, that many of these rules are "shared" with other subproblems, for example, **Reservoir Site Preparation**, **Downstream Water Quality**, etc. In the example below, the entire set of rules referring to **soil loss**, used in the eutrophication example in the context of non-point source contributions to nutrient loading, is omitted. Soil loss is used in a number of different problems evaluations, and involves a large number of rules based on the Universal Soil Loss Equation; only the top level table providing the linkage is presented here.

```
### L10405 RESERVOIR EUTROPHICATION

RULE 1040501
IF          eutrophication_potential == very_large
AND         [  nutrient_loading == very_large
            OR nutrient_loading == large
            OR nutrient_loading == medium ]
THEN        Impact  = major
ENDRULE
```

```
RULE 1040502
IF          eutrophication_potential == very_small
AND         [  nutrient_loading      == very_small
            OR nutrient_loading      == small
            OR nutrient_loading      == medium ]
THEN        Impact  = not_significant
ENDRULE

RULE 1040503
IF          eutrophication_potential == very_large
AND         nutrient_loading         == small
THEN        Impact  = moderate
ENDRULE

RULE 1040504
IF          eutrophication_potential == very_large
AND         nutrient_loading         == very_small
THEN        Impact  = moderate
ENDRULE

RULE 1040505
IF          eutrophication_potential == large
AND         [  nutrient_loading      == very_large
            OR nutrient_loading      == large ]
THEN        Impact  = major
ENDRULE

RULE 1040506
IF          eutrophication_potential == large
AND         nutrient_loading         == medium
THEN        Impact  = major
ENDRULE

RULE 1040507
IF          eutrophication_potential == large
AND         [  nutrient_loading      == small
            OR nutrient_loading      == very_small ]
THEN        Impact  = moderate
ENDRULE
```

```
RULE 1040508
IF          eutrophication_potential == medium
AND         nutrient_loading         == very_large
THEN        Impact  = major
ENDRULE

RULE 1040509
IF          eutrophication_potential == medium
AND         [  nutrient_loading      == large
            OR nutrient_loading      == medium ]
THEN        Impact  = moderate
ENDRULE

RULE 10405091
IF          eutrophication_potential == medium
AND         nutrient_loading         == small
THEN        Impact  = small
ENDRULE

RULE 10405092
IF          eutrophication_potential == medium
AND         nutrient_loading         == very_small
THEN        Impact  = small
ENDRULE

RULE 10405093
IF          eutrophication_potential == small
AND         nutrient_loading         == very_large
THEN        Impact  = major
ENDRULE

RULE 10405094
IF          eutrophication_potential == small
AND         [  nutrient_loading      == large
            OR nutrient_loading      == medium ]
THEN        Impact  = small
ENDRULE
```

```
RULE 10405095
IF          eutrophication_potential == small
AND         [ nutrient_loading      == small
            OR nutrient_loading     == very_small ]
THEN        Impact  = not_significant
ENDRULE

RULE 10405096
IF          eutrophication_potential == very_small
AND         nutrient_loading         == very_large
THEN        Impact  = moderate
ENDRULE

RULE 10405096
IF          eutrophication_potential == very_small
AND         nutrient_loading         == very_large
THEN        Impact  = moderate
ENDRULE

RULE 10405097
IF          eutrophication_potential == very_small
AND         nutrient_loading         == large
THEN        Impact  = small
ENDRULE

RULE 1040510
IF        multi_level_outlet EXISTS
THEN      Impact  DECREASES marginally
ENDRULE

RULE 10405101
IF        [  floating_weeds == very_likely
          OR floating_weeds == likely ]
THEN      Impact INCREASES considerably
ENDRULE

RULE 10405102
IF        floating_weeds == possible
```

```
THEN      Impact INCREASES marginally
ENDRULE

RULE 1040511
IF          reservoir_shallows == none
THEN        floating_weeds     = unlikely
ENDRULE

RULE 1040512
IF          retention_time == very_small
THEN        floating_weeds = unlikely
ENDRULE

RULE 1040513
IF          weed_control EXISTS
THEN        floating_weeds DECREASES marginally
ENDRULE

RULE 1040514
IF          endemic_weeds EXISTS
THEN        floating_weeds = possible
ENDRULE

RULE 1040515
IF          remaining_biomass  == high
AND         reservoir_shallows == large
AND         retention_time      > 90
THEN        floating_weeds     = very_likely
ENDRULE

RULE 1040516
IF          eutrophication_potential == very_large
AND         endemic_weeds EXISTS
AND         wastewater_treatment NOT_EXISTS
THEN        floating_weeds INCREASES marginally
ENDRULE

RULE 1040517
IF          drawdown == very_large
```

```
THEN        floating_weeds DECREASES marginally
ENDRULE

RULE 1040518
IF          drawdown == large
THEN        floating_weeds DECREASES marginally
ENDRULE

########################################################
# nutrient loading depending on:
# size of catchment
# landuse in catchment, including animal husbandry
# and population, sewering and waste water treatment

RULE 1040519
IF          wastewater_treatment == advanced
THEN        point_sources DECREASES considerably
ENDRULE

RULE 1040520
IF          wastewater_treatment == primary
THEN        point_sources DECREASES marginally
ENDRULE

RULE 1040521
IF          wastewater_treatment == none
THEN        point_sources INCREASES marginally
ENDRULE

RULE 1040522
IF          landuse == urban_settlement
AND         population_density == high
THEN        point_sources = very_large
ENDRULE

RULE 1040523
IF          landuse == urban_settlement
AND         population_density == medium
```

```
THEN          point_sources = large
ENDRULE

RULE 1040524
IF            landuse == urban_settlement
AND           population_density == low
THEN          point_sources = medium
ENDRULE

RULE 1040525
IF            landuse == rural_settlement
AND           population_density == high
THEN          point_sources = large
ENDRULE

RULE 1040526
IF            landuse == rural_settlement
AND           population_density == medium
THEN          point_sources = medium
ENDRULE

RULE 1040527
IF            landuse == rural_settlement
AND           population_density == low
THEN          point_sources = small
ENDRULE

RULE 1040528
IF            landuse != rural_settlement
AND           landuse != urban_settlement
THEN          point_sources = very_small
ENDRULE

RULE 1040529
IF            landuse           == rural_settlement
THEN          non_point_sources = small
ENDRULE
```

```
RULE 1040530
IF          landuse          == urban_settlement
THEN        non_point_sources = very_small
ENDRULE

RULE 1040531
IF          [  landuse         ==  natural_land
            OR landuse         ==  forest ]
THEN        non_point_sources = very_small
ENDRULE

RULE 1040532
IF          landuse         ==  range_land
THEN        non_point_sources =   small
ENDRULE

RULE 1040533
IF          [  landuse        == shifting_agriculture
            OR landuse        == rainfed_fields
            OR landuse        == rice_farming ]
THEN        non_point_sources =  medium
ENDRULE

RULE 1040534
IF          landuse          == irrigated_fields
THEN        non_point_sources = large
ENDRULE

RULE 1040535
IF          grazing_livestock == very_large
THEN        non_point_sources INCREASES considerably
ENDRULE

RULE 1040536
IF          grazing_livestock == large
THEN        non_point_sources INCREASES marginally
ENDRULE
```

```
RULE 1040537
IF          soil_loss == very_large
THEN        non_point_sources INCREASES considerably
ENDRULE

RULE 1040538
IF          soil_loss == large
THEN        non_point_sources INCREASES marginally
ENDRULE

RULE 1040539
IF          soil_loss == very_small
THEN        non_point_sources DECREASES marginally
ENDRULE

RULE 1020212
IF      landuse                    == forest
AND     pre_impoundment_measure    == none
THEN    remaining_biomass           = high
ENDRULE

RULE 1020213
IF      landuse                    == forest
AND     pre_impoundment_measure    == cutting
THEN    remaining_biomass           = high
ENDRULE

RULE 1020214
IF      landuse                    == forest
AND     pre_impoundment_measure    == cut&clear
THEN    remaining_biomass           = low
ENDRULE

RULE 1020215
IF      landuse                    == forest
AND     pre_impoundment_measure    == cut&burn
THEN    remaining_biomass           = low
ENDRULE
```

```
RULE 1020216
IF      landuse                        == forest
AND     pre_impoundment_measure        == partial_cutting
THEN    remaining_biomass               = high
ENDRULE

RULE 1020217
IF      landuse                        == forest
AND     pre_impoundment_measure        == partial_cut&clear
THEN    remaining_biomass               = medium
ENDRULE

RULE 1020218
IF      landuse                        == forest
AND     pre_impoundment_measure        == partial_cut&burn
THEN    remaining_biomass               = medium
ENDRULE

RULE 1020219
IF      [  landuse == urban_settlement
        OR landuse == rural_settlement ]
THEN    remaining_mineral_nutrients = low
ENDRULE

RULE 1020220
IF      [  landuse  == rice_farming
        OR landuse  == irrigated_fields ]
THEN    remaining_mineral_nutrients = high
ENDRULE

RULE 1020221
IF      landuse                        == forest
AND     pre_impoundment_measure        == none
THEN    remaining_mineral_nutrients  = medium
ENDRULE

RULE 1020222
IF      landuse                        == forest
AND     pre_impoundment_measure        == cutting
```

```
THEN    remaining_mineral_nutrients  = high
ENDRULE

RULE 1020223
IF      landuse                     == forest
AND     pre_impoundment_measure     == cut&clear
THEN    remaining_mineral_nutrients  = low
ENDRULE

RULE 1020224
IF      landuse                     == forest
AND     pre_impoundment_measure     == cut&burn
THEN    remaining_mineral_nutrients  = very_high
ENDRULE

RULE 1020225
IF      landuse                     == forest
AND     pre_impoundment_measure     == partial_cutting
THEN    remaining_mineral_nutrients  = high
ENDRULE

RULE 1020226
IF      landuse                     == forest
AND     pre_impoundment_measure     == partial_cut&clear
THEN    remaining_mineral_nutrients  = medium
ENDRULE

RULE 1020227
IF      landuse                     == forest
AND     pre_impoundment_measure     == partial_cut&burn
THEN    remaining_mineral_nutrients  = very_high
ENDRULE

RULE 1020211
IF      [  landuse   == urban_settlement
        OR landuse   == rural_settlement ]
THEN    remaining_biomass = low
ENDRULE
```

```
RULE 1020229
IF      average_reservoir_depth  == very_small
THEN    reservoir_stratification  = unlikely
ENDRULE

RULE 1020230
IF      average_reservoir_depth  == very_large
THEN    reservoir_stratification  = very_likely
ENDRULE

RULE 1020231
IF      average_reservoir_depth  == small
AND     retention_time            < 30
THEN    reservoir_stratification  = unlikely
ENDRULE

RULE 1020232
IF      average_reservoir_depth  == small
AND     retention_time           >= 30
THEN    reservoir_stratification  = possible
ENDRULE

RULE 1020233
IF      average_reservoir_depth  == medium
AND     retention_time           == very_small
THEN    reservoir_stratification  = unlikely
ENDRULE

RULE 1020234
IF      average_reservoir_depth  == medium
AND     retention_time           == small
THEN    reservoir_stratification  = possible
ENDRULE

RULE 1020235
IF      average_reservoir_depth  == medium
AND     retention_time           == medium
THEN    reservoir_stratification  = likely
ENDRULE
```

```
RULE 1020236
IF      average_reservoir_depth  == medium
AND     [ retention_time         == large
        OR retention_time        == very_large ]
THEN    reservoir_stratification  = very_likely
ENDRULE

RULE 1020237
IF      average_reservoir_depth  == large
AND     [ retention_time         == small
        OR retention_time        == medium ]
THEN    reservoir_stratification  = likely
ENDRULE

RULE 1020238
IF      average_reservoir_depth  == large
AND     [ retention_time         == large
        OR retention_time        == very_large]
THEN    reservoir_stratification  = very_likely
ENDRULE

RULE 1020239
IF      reservoir_position == sheltered
THEN    reservoir_stratification INCREASES marginally
ENDRULE

RULE 1020240
IF      reservoir_position == exposed
THEN    reservoir_stratification DECREASES marginally
ENDRULE

RULE 1020241
IF      drawdown == very_large
THEN    reservoir_stratification DECREASES marginally
ENDRULE

RULE 7777007
IF      TRUE
```

```
THEN    retention_time = 365 *
        reservoir_storage_volume / mean_annual_inflow
ENDRULE

TABLE 1020201  # remaining_nutrients
remaining_mineral_nutrients
remaining_biomass
remaining_nutrients
        | low        | medium     | high       | very_high
--------------------------------------------------------------
 low    | low        | medium     | high       | very_high
 medium | low        | high       | very_high  | very_high
 high   | medium     | very_high  | very_high  | very_high
ENDTABLE

TABLE 1020202  # eutrophication_potential
reservoir_stratification
remaining_nutrients
eutrophication_potential
          | unlikely   | possible   | likely     | very_likely
--------------------------------------------------------------
 low      | very_small | very_small | very_small | small
 medium   | very_small | very_small | small      | medium
 high     | small      | medium     | large      | very_large
very_high | small      | large      | very_large | very_large
ENDTABLE

TABLE 1040501  # nutrient_loading
non_point_sources
point_sources
nutrient_loading
          |very_small|small     |medium    |large     |very_large
-----------------------------------------------------------------
very_small|very_small|small     |medium    |medium    |very_large
small     |small     |medium    |large     |large     |very_large
medium    |medium    |large     |large     |very_large|very_large
large     |large     |very_large|very_large|very_large|very_large
very_large|very_large|very_large|very_large|very_large|very_large
ENDTABLE
```

```
TABLE 1010501 #watershed erosion
watershed_size
erosion_potential
soil_loss
           | very_large | large            | small
-----------------------------------------------------------
very_large | very_large | very_large       | large
large      | large      | large            | medium
small      | medium     | small            | very_small
very_small | small      | very_small       | very_small
ENDTABLE
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