INTERACTIVE ENVIRONMENTAL SOFTWARE: INTEGRATION, SIMULATION AND VISUALIZATION

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INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
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Foreword

IIASA has a long tradition of environmental research, dating back to the very beginning of the Institute. Research on environmental problems, and the development of tools designed to better understand and solve environmental problems is a central component of IIASA's research agenda. This report describes software tools for environmental analysis, merging IIASA's expertise in environmental problems with methodological developments in advanced computer and software technology.

The research described here results from a series of research and development projects carried out by IIASA's *Advanced Computer Applications* group. The examples presented range from work done for the Commission of the European Communities' Joint Research Centre and the Dutch Ministry for Housing, Physical Planning and the Environment; the US Bureau of Reclamation and EPA; the State Science and Technology Commission of the People's Republic of China; the Mekong Secretariat in Thailand, to the City of Hanover in Germany.

Simulation models are integrated with various data bases and geographical information systems, as well as computer graphics for the visualization of information, problems and solutions, and provide the basis for easy-to-use interactive software tools. The research results presented demonstrate the role and potential of advanced software tools in environmental systems analysis and modeling – a key area of IIASA's applied research.

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Interactive Environmental Software: Integration, Simulation and Visualization

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Abstract

Environmental planning and management require comprehensive and interdisciplinary information as the scientific and technical information basis for what are, ultimately, political decisions. The volume and complexity of this information, uncertainty in the data and the understanding of processes, as well as the often very large number of alternatives to be considered require specific data processing tools.

Electronic data processing and in particular, the simulation and analysis of environmental problems and possible measures of environmental management require the development and implementation of the required data and numerical models, but also of appropriate user interfaces.

The user interface allows interactive control of the software, the graphical display and visualization of results, and the integration of models and data bases, multiple models, or expert systems components. It also facilitates customization of the system for specific institutional applications.

Important components are graphical and symbolic user interaction, the graphical display of results that are dynamic or spatially distributed, the integration of geographical information systems as a source of data, but also as a tool for further analysis, and the use of AI components that allow efficient systems behavior and easy, error-free use of the software.

The role of integrated systems is not only to model selected aspects of the environment, but to offer a broader view of the overall problems, and to provide tools and methods of analysis that distill the most critical features of decision-oriented information bases and explicit decision support.

Using a number of practical examples from application domains such as air quality, ground and surface water, hazardous chemicals, technological risk and environmental impact assessment, a number of interactive and integrated information and decision support systems, implemented in a number of countries for environmental planning and management, are described and discussed together with the architecture of their implementation and the basic approach.

1 Introduction

Human activities, and in particular large scale industrial, energy, construction, or agricultural projects adversely and considerably affect the natural environment. Consumption of natural resources, including space, water, air, and biota, and the generation of wastes, including the dissipation of energy, usually lead to a degradation of the natural environment. Environmental problems, including climatic change and ozone depletion, acid rain and forest die-off, marine pollution and eutrophication, groundwater contamination, or regional and local air pollution, are increasingly reaching alarming proportions.

Environmental considerations are, however, becoming important components of planning with many countries introducing legislation calling for the explicit consideration of environmental impacts in the planning and decision making process for large projects. More and more national and international legislation and agreements are designed to revert past and stop current environmental degradation.

The basic components of Environmental Impact Assessment (EIA) as the basis for the design and evaluation of any management or control options are a description of the current environment, of the proposed project or activity, and a description of the expected impacts. Obviously, the prediction of future impacts is the most difficult part. Approaches range from purely qualitative checklist-based matrix approaches (for a recent overview see Fedra, 1989a), and any combination of these approaches. However, most of the accepted and routinely used tools of EIA, and environmental planning and management in general, are not based on the use of computers, but on rather more-or-less formalized qualitative assessment procedures.

The availability of increasingly powerful and affordable computers is rapidly increasing (Fedra and Loucks, 1985; Loucks and Fedra, 1987), and so has computer literacy among technical professionals. New technologies such as expert systems, interactive modeling and dynamic computer graphics allow more powerful, more accessible and more directly useful environmental models to be built.

2 Integration, Interaction and Visualization

The new approach to modeling environmental impacts, made possible by these advances in computer technology, is based on the concepts of integration, interaction, and visualization (Figure 1). To make complex simulation models and tools of analysis more accessible and easy to use, models can be integrated with data and knowledge bases that provide input data, parameters, but also domain-specific knowledge, by integrating expert systems technology in simulation models.

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, how to run it, and how to interpret its output will require not only less computer expertise from its user, it will also make less demands on his domain expertise. Environmental impact assessment usually deals with rather complex problems that touch upon many disciplines, and rarely will an individual have all the necessary expertise at his 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; Gray and Stokoe, 1988; Beck, 1990; Fedra 1989b.

The same line of argument holds for data base integration. 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 informa-

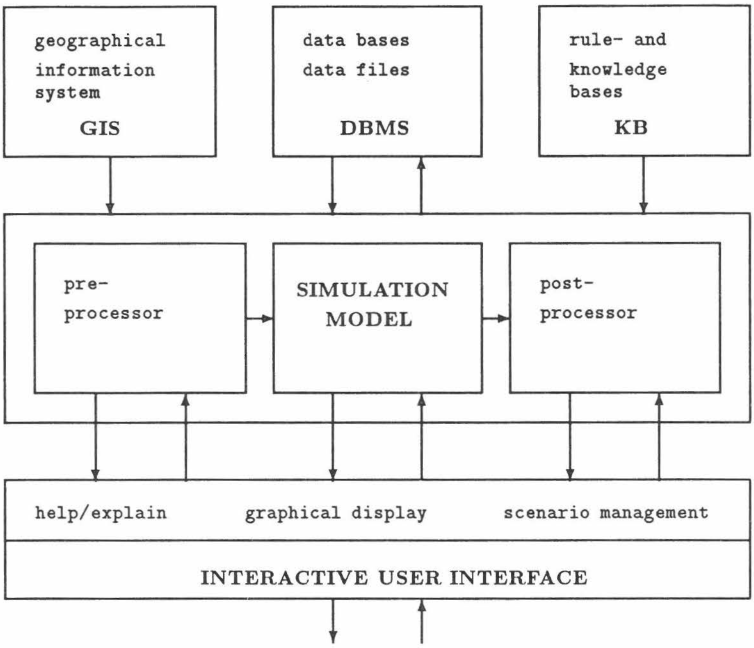


Figure 1: *Interactive simulation modeling in an integrated framework*

tion must be inserted in the (mental or mathematical) procedure somehow. 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. 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.

The analysis of environmental impacts is by definition a complex procedure that draws on numerous disciplines. This interdisciplinary nature also calls for an array of related tools, simulation models, information systems, and decision support components. At the same time, the subjective and discretionary human element must also be given due weight, in particular, where aesthetic or cultural values are concerned that are difficult or impossible to express in monetary terms or measure reliably on any cardinal scale. This necessary subjective element calls for the direct and interactive involvement of users, allowing them to exert discretion and judgement wherever formal methods are insufficient.

At the core of this interactive approach, developed by the ACA group at IIASA, is an integrated set of modular software tools, building on existing models and computer-assisted procedures. It is intended for a broad class of users and provides them with easy access to methods of analysis and information management which previously had been restricted to a small group of experts.

By providing a coherent user interface, the interactions between different models, their data bases and auxiliary software become more transparent to the user. Extensive use of symbolic representation with high-resolution color graphics and menu-driven operations aids this transparency and makes the systems user friendly. Visualization by displaying dynamic and often spatially distributed modeling results in a graphical and symbolic form, as animated graphics, topical maps, or graphs and diagrams, supports direct understanding of large amounts of information without complicated and time-consuming post-processing and interpretation.

Customizing the information and decision support systems for only a small set of specific applications, and then building the necessary background, context and expertise into this special-purpose system means trading off flexibility and generality for efficiency. However, as a consequence, a very efficient and largely error-free use of complex computer systems becomes possible even for users that have no expertise in the use of computers.

3 Application Examples

The R & D carried out by IIASA's ACA group (Fedra, 1985a, 1986a,b; 1989a; Fedra and Diersch, 1989; Fedra and Otway, 1986; Fedra et al., 1987; Weigkricht and Winkelbauer, 1987; Reitsma, 1990) concentrates on integrated systems of software tools to make the scientific basis for planning and management directly available to planners, policy and decision makers.

The application examples from Europe, the United States, the People's Republic of China, India and Thailand discussed below cover air, surface and groundwater modeling, as well as general environmental impact assessment.

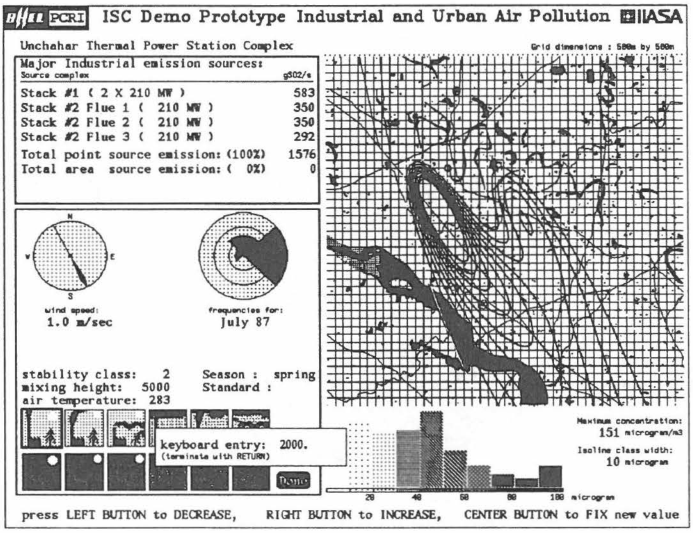
3.1 Air quality models:

A number of atmospheric simulation models, including several Gaussian models for buoyant or heavy gases and dust, local Lagrangian and box models, and diffusion models with dynamic and spatially distributed wind fields have been developed and implemented in several case studies.

As one example for the regional to local scale, and for continuous rather than accidental emissions, EPA's Industrial Source Complex (ISC) model, a Gaussian air quality model for multiple point and area sources, was adapted (Figure 2). Implementations have been designed for industrial centers in the People's Republic of China, a version including a deposition model for particulates, was implemented for the Pollution Control Research Institute (PCRI), Hardwar, India, and the model was also implemented in a version for the City of Vienna.

The model input defining a pollution scenario comes from three distinct sources:

- A site-specific library of data files, each characterizing for one location (industrial installation or zone, urban area) the location of the individual sources as well as the default values of emission characteristics, ie., an emission inventory for point and area sources. These include the yearly amount of fuel burned for each source, fuel characteristics, boiler and emission control parameters, stack height or height above ground for area sources, stack diameter, exit velocity, and exit temperature. Where available, a background map from an appropriate Geographical Information System (GIS) is used;
- Embedded in the code, the definition of a (generic) weather scenario (wind speed and direction, ambient air temperature, vertical mixing height, stability class); parameters such a mixing height can in turn be estimated from easily available data such as location and date, cloud cover, and wind speed;



ISC Demo Prototype Industrial and Urban Air Pollution

Unchahar Thermal Power Station Complex

Grid dimensions : 500m by 500m

Major Industrial emission sources:

Source complex	gSO2/s
Stack #1 (2 X 210 MW)	583
Stack #2 Flue 1 (210 MW)	350
Stack #2 Flue 2 (210 MW)	350
Stack #2 Flue 3 (210 MW)	292
Total point source emission: (100%)	1576
Total area source emission: (0%)	0

wind speed:
1.0 m/sec

frequencies for:
July 87

stability class: 2
mixing height: 5000
air temperature: 283
Season : spring
Standard :

keyboard entry: 2000.
(terminate with RETURN)

Maximum concentration:
151 microgram/m3
Isoline class width:
10 microgram

press LEFT BUTTON to DECREASE, RIGHT BUTTON to INCREASE, CENTER BUTTON to FIX new value

Figure 2: *Model output of the modified short-term ISC model*

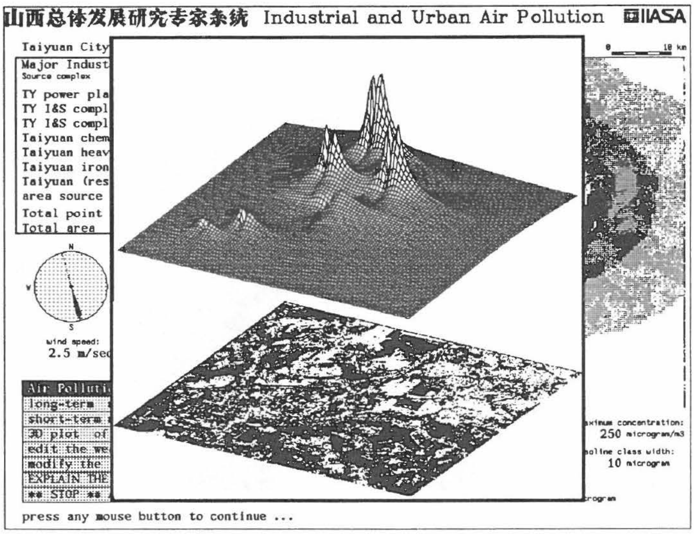
- The interactive user interface allows modification of several of the above default or input values, such as the amount of fuel burned for each source, source location (which can be interactively set on the map by dragging and positioning a source symbol), and technical characteristics such as fuel properties, stack data, potential pollution control equipment and its efficiency, etc., wind speed and direction, air temperature, or global weather characteristics, by selecting one of 12 distinct weather patterns that translate into different stability classes used by the model.

Model results are shown as a color-coded overlay on the background map, a histogram (using the same color code) of the frequency distribution of concentration values, and the maximum concentration value computed. The user can zoom into the map display for better local resolution, select an isoline display rather than the color-coded translucent overlay, redefine isoline boundaries or the color coding, and display the concentration field as a 3D display over the rotated and tilted map background (Figure 3).

3.2 Surface water quality models:

Several water quality models, for example EPA's SARAH (Ambrose and Vandergrift, 1986), a back-calculating toxic waste reduction model or a simple dynamic river water quality model for toxic substances, extracted from the generic screening level USEPA model system TOXSCREEN (Hetrick and McDowell-Boyer, 1984), were implemented in an interactive graphics framework.

The near-field surface water model SARAH calculates the maximum allowable hazardous waste effluent concentrations based on predicted exposure to humans or aquatic life from contaminated surface water. Acceptable leachate or industrial waste contaminant concentrations are computed by a back-calculation procedure from chemical safety criteria in surface water, drinking water, or fish. As an alternative to the back-calculating scheme of SARAH, the river model component of



press any mouse button to continue ...

Figure 3: *A 3D interpretation of a long-term yearly average concentration field*

TOXSCREEN, a system of dynamic simulation models, was adapted as part of an environmental risk assessment system (Fedra, 1985a).

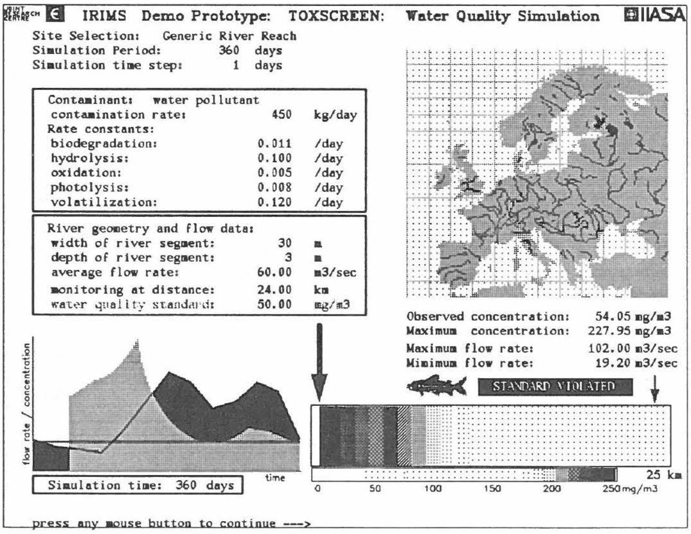
The river model component of TOXSCREEN simulates pollutant dispersion in an arbitrary river segment. The model implementation features a graphical user interface, extensive interactive input modification based on predefined default values as well as the animated graphical display of model results (Figure 4). The model is connected to a hazardous substances data base, so that the parameters for specific substances can be loaded from this data base after identifying a substance by one of the data base access mechanisms.

4 Groundwater quality modeling:

The prototype groundwater contamination model system FEMCAD (Fedra and Diersch, 1989) consists of the following basic components:

- the user interface, based on interactive color graphics and a completely menu-driven dialog system with its component knowledge bases;
- the problem selection and data base management system;
- the interactive problem definition and editor module;
- and the 2D finite-element simulation model.

The user interface is always menu driven ie., the user is prompted to select options from menus of possible options the system offers. Wherever possible, the options are specified in a symbolic format, and can be edited by, for example, setting sliders.



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IRIMS  Demo Prototype:  TOXSCREEN:  Water Quality Simulation
Site Selection:   Generic River Reach
Simulation Period:        360  days
Simulation time step:       1  days

Contaminant:  water pollutant
 contamination rate:            450   kg/day
Rate constants:
 biodegradation:              0.011   /day
 hydrolysis:                  0.100   /day
 oxidation:                   0.005   /day
 photolysis:                  0.008   /day
 volatilization:              0.120   /day

River geometry and flow data:
 width of river segment:         30   m
 depth of river segment:          3   m
 average flow rate:           60.00   m3/sec
 monitoring at distance:      24.00   km
 water quality standard:      50.00   mg/m3

Observed concentration:    54.05 mg/m3
Maximum  concentration:   227.95 mg/m3
Maximum flow rate:        102.00 m3/sec
Mimimum flow rate:         19.20 m3/sec

STANDARD VIOLATED

Simulation time: 360 days

press any mouse button to continue --->
```

Figure 4: *TOXSCREEN river water quality simulation model*

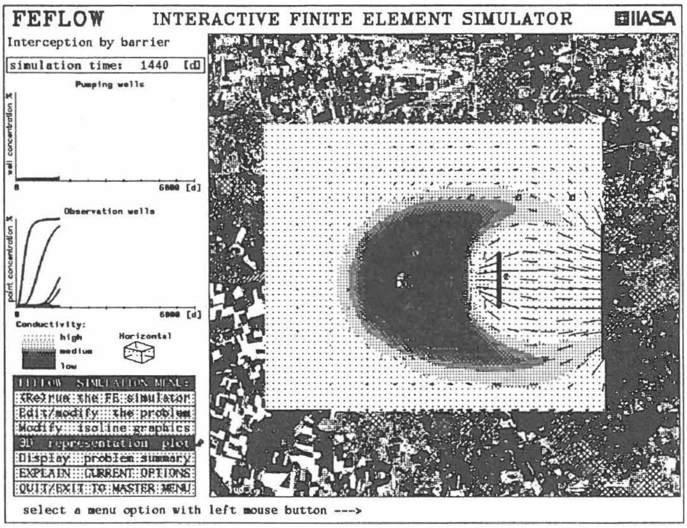
Changes are only allowed in a certain range fixed by the input data, and possibly modified by other changes specified by the user. In other words, the system maintains context-dependent bounds on input and control variables to guarantee consistent and feasible problem descriptions.

For site-specific problems, reference to a background map, either in the form of a raster map (LANDSAT or SPOT), or a vector-based map (in a binary version of the USGS DLG (digital line graph) format), is stored together with the problem description. This graphical background information may be loaded to provide a geographical reference for the problem in question.

The Problem Editor module allows the user to edit a problem description, or define a new problem from scratch, by sketching its geometry on the screen and editing initial and boundary conditions on this graphical problem representation. Model output is displayed dynamically as a color-coded concentration field over the background map; display parameters and styles can be chosen interactively (Figure 5).

To support the experimental features of the system, each of the control variables determining a problem situation can be modified independently. For example, once a certain problem is defined, the user can run it for several different amounts of substances, or different substances. Pumping rates may be changed, a hydraulic barrier may be introduced, or the dump site can be sealed off. The interactive problem editor with its graphical problem definition tools provides a convenient and efficient means of problem specification with immediate visual feedback.

Using the same interface style and philosophy, a finite-difference model developed at the University of Hannover (Meier and Mull, 1989) was implemented as part of an environmental information system for the City of Hannover (Figure 6).



Interception by barrier

simulation time: 1440 [d]

select a menu option with left mouse button --->

Figure 5: *Simulation of a hydraulic barrier to contain a contaminant plume from a land deposit*

4.1 Expert systems:

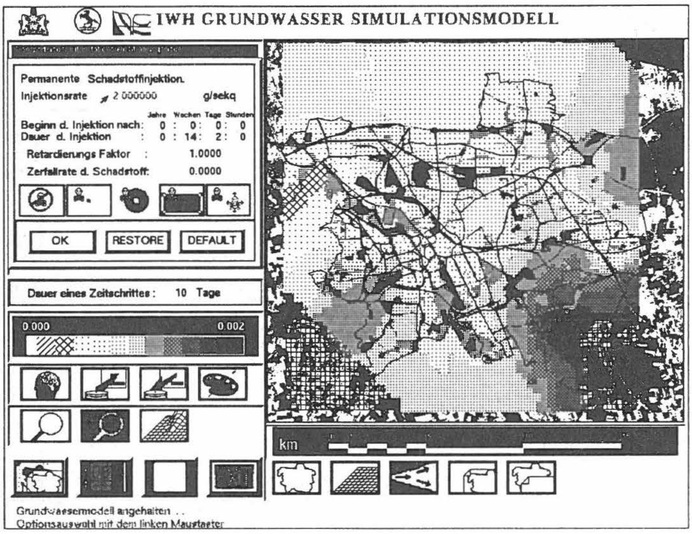
Expert systems, or *Knowledge Based Systems*, are a loosely defined class of computer software within the more general area of AI, that go beyond the traditional procedural, algorithmic, numerical, and mathematical representations or models, in that they contain largely empirical *knowledge* eg., in 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, ie., the human expert. In summary, a very short description of AI would be *the art or science of making computers smart*, and expert systems could be described as *smart problem-solving software.*

The expert system for environmental screening MEXSES was designed for the early assessment and screening of projects. It allows evaluation of a project in terms of its potential environmental impacts at an early stage of appraisal with a minimum of project-specific information. The system provides a model of environmental impacts of a given development project; however, this model is not based on mass and energy conservation, on transport and diffusion equations: it is based on expert knowledge, experience and heuristic rules, represented in production rules and decision tables, largely using qualitative, symbolic descriptors (Figure 7).

The system draws on extensive knowledge and data bases on project characteristics, based on generic project profiles and a hierarchical classification scheme. It also uses data and background information on the specific environmental conditions of the application area.

At the top level, the expert system establishes a number of strategic goals or questions for the overall environmental review that the analyst will need to answer for a specific project. Examples of such questions might be: *Will the project cause losses in irreplaceable natural resources? Will the project cause hazards to endangered species?*

The assessment is based on an adaptive checklist approach, ie., specific to the project type. Project



Permanente Schadstoffinjektion.

Injektionsrate 2.000000 g/sekq

	Jahre	Wochen	Tage	Stunden
Beginn d. Injektion nach:	0	0	0	0
Dauer d. Injektion:	0	14	2	0

Retardierungs Faktor : 1.0000

Zerfallrate d. Schadstoff: 0.0000

Dauer eines Zeitschrittes : 10 Tage

Grundwassermodell angehalten ..
Optionsauswahl mit dem linken Maustaster

Figure 6: *User interface to the finite difference groundwater model*

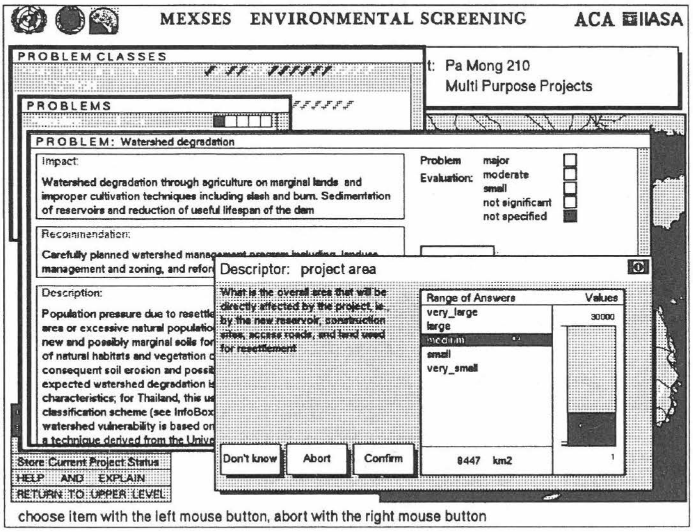
types covered in the prototype are, eg., reservoirs and dams, hydropower projects including transmission lines, irrigation projects, fisheries and aquaculture, and could also include infrastructure projects (roads and highways, sewerage, water supply, etc.), navigation, erosion control, etc. The checklists are designed to elicit more detailed information about the project and its expected environmental impacts, in an attempt to deduce answers which can ultimately be aggregated into the top-level questions. The analyst can start a forward-chaining inference procedure, where the system will reason from the available data to arrive at a classification of effects. Missing information, that cannot be deduced by the system, will have to be supplied by the analyst in a question–answer dialog. Alternatively, the analyst can choose/set an impact value and then ask the system to check his "hypothesis". This triggers a backward chaining inference system, that will attempt to establish all the necessary preconditions to the specifications formulated by the analyst as the hypothesis. Again, if the required "facts" can not be confirmed, the inference procedure will ask the user the necessary questions. As a final result, the user's assessment will either be confirmed or rejected.

At any stage, the system will attempt to satisfy the initial strategic goals and questions, and indicate where information is still missing for a complete and satisfactory answer. It is also able to explain how answers at the various levels were deduced, if they have not been entered directly by the analyst. Auxiliary software includes basic data manipulation, analysis, and display facilities, including topical map drawing and processing for overlay analysis techniques.

5 Discussion

Although they differ widely in their degree of sophistication, detail, and complexity, all of the above application examples have a common structure:

The systems are built around one or more coupled simulation models and feature:



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

Recommendation: Carefully planned watershed mana
management and zoning, and refor

Description:
Population pressure due to resettle
area or excessive natural populatio
new and possibly marginal soils for
of natural habitats and vegetation c
consequent soil erosion and possi
expected watershed degradation is
characteristics; for Thailand, this us
classification scheme (see InfoBox
watershed vulnerability is based on
a technique derived from the Univ

What is the overall area that will be directly affected by the project, ie., by the new reservoir, construction sites, access roads, and land used for resettlement

8447 km2

choose item with the left mouse button, abort with the right mouse button

Figure 7: *Setting a descriptor value in the expert system's user dialog*

- an interactive, menu-driven user interface, that guides the user with prompt and explain messages through the application. No command language or special format of interaction is necessary, the computer assists the user in its proper use;

- dynamic color graphics for the model output and a symbolic representation of major problem components, that allow for easy and immediate understanding of basic patterns and relationships. Rather than emphasizing the numerical results, symbolic representations and the visualization of complex patterns and time and space support an intuitive understanding of complex systems behavior;

- the coupling to one or several data bases that provide necessary input information to the models. The user's choice or definition of a specific scenario can be expressed in an aggregated and symbolic, problem-oriented manner without concern for the technical details of the computer implementation;

- embedded AI components such as specific knowledge bases allow user specifications in allowable ranges to be checked and constrained and ensure the consistency of an interactively defined scenario.

In summary, the models are designed for easy and efficient use, even in data-poor situations, and do not require specific technical expertise of their user. The "intelligent" interface and its pre- and post-processing functions free the user from the time-consuming and error-prone tasks of data file preparation, the mechanics of model runs, and finally the interpretation and translation of numerical results into meaningful and problem-adequate terms. This not only allows the user to employ the models more freely in a more experimental and interesting way, it also allows the analyst to concentrate on the more important tasks he can do best, ie., the recognition of emerging patterns, the comparative evaluation of complex alternatives, and the entire institutional aspects of any environmental impact assessment rather than its technicalities.

6 References

Ambrose, R.B. and Vandergrift, S.B. (1986) SARAH, A Surface Water Assessment Model for Back Calculating Reductions in Abiotic Hazardous Wastes. EPA/600/3-86/058. Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency. Athens, GA 30613. 95p.

Beck, M.B. (1990) Expert Systems in Environmental Systems Analysis and Control. Dept. of Civil Engg., Imperial College, London. Draft Expert Tutorial submitted to WHO. Forthcoming.

Diersch, H.J. (1980) Finite-Element-Programmsystem FEFLOW. (Finite-Element Program Description FEFLOW). Institute for Mechanics. Academy of Sciences of the GDR. Berlin. In German.

Fedra, K. (1989a) Simulation Modeling in Environmental Impact Assessment. Presented at the International Conference on Environmental Impact Analysis for Developing Countries. November 28–December 2, 1988. New Delhi, India. Organized by Pollution Control Research Institute, Bharat Heavy Electricals Limited. Hardwar, India.

Fedra, K. (1989b) Expert Systems in Water Resources Simulation and Optimization. Presented at NATO Advanced Study Institute on Stochastic Hydrology in Water Resources Systems: Simulation and Optimization. Peniscola, Spain. September 18–29, 1989.

Fedra, K. and Diersch, H.J. (1989) Interactive Groundwater Modelling: Color Graphics, ICAD, and AI. In A. Sahuquillo, J. Andreu and T. O'Donnell [eds.] Groundwater Management: Quantity and Quality. International Association of Hydrological Sciences (IAHS) Publication No. 188. pp.305–320.

Fedra, K., Li, Z., Wang, Z. and Zhao, C. (1987) Expert Systems for Integrated Development: A Case Study of Shanxi Province, The People's Republic of China. SR-87-001. International Institute for Applied Systems Analysis. A-2361 Laxenburg, Austria. 76p.

Fedra, K. (1986a) Advanced Decision-oriented Software for the Management of Hazardous Substances. Part II: A Demonstration Prototype System. CP-86-10. International Institute for Applied Systems Analysis. A-2361 Laxenburg, Austria. 98p.

Fedra, K. (1986b) Decision Making in Water Resources Planning: Models and Computer Graphics. In Arne J. Carlsen [ed.] Proceedings of a UNESCO Symposium on Decision Making in Water Resources Planning Vol.2. Norwegian National Committee for Hydrology. Oslo, Norway. pp.451-468.

Fedra, K. (1985a) Advanced Decision-oriented Software for the Management of Hazardous Substances. Part I: Structure and Design. CP-85-18. International Institute for Applied Systems Analysis. A-2361 Laxenburg, Austria. 61p.

Fedra, K. and Otway, H. (1986) Advanced Decision-oriented Software for the Management of Hazardous Substances. Part III. Decision Support and Expert Systems: Uses and Users. CP-86-14. International Institute for Applied Systems Analysis. A-2361 Laxenburg, Austria. 44p.

Fedra, K. and Loucks, D.P. (1985) Interactive Computer Technology for Planning and Policy Modeling. Water Resources Research, 21/2, 114-122.

Gray, A. and Stokoe, P. (1988) Knowledge-based or Expert Systems and Decision Support Tools for Environmental Assessment and Management. Their Potential and Limitations. School for Resource and Environmental Studies. Dalhousie University. Nova Scotia.

Hetrick, D.M. and McDowell-Boyer, L.M. (1984) User's Manual for TOXSCREEN: A Multimedia Screening-level Program for Assessing the Potential Fate of Chemicals Released to the Environment. ORNL-6041. Oak Ridge National Laboratory and EPA-560/5-83-024. USEPA. Washington, D.C. 301p.

Loucks, D.P. and Fedra, K (1987) Impact of Changing Computer Technology on Hydrologic and Water Resource Modeling. In Review of Geophysics, 25:2, March.

Meier, W. and Mull, R. (1989) Nitrate in Groundwater. In A. Sahuquillo, J. Andreu, and T. O'Donnell [eds.] Groundwater Management: Quantity and Quality. Proceedings of the Benidorm Symposium, International Association of Hydrological Sciences (IAHS) Publication No. 188. pp.181–190.

Ortolano, L. and Steineman, A.C. (1987) New Expert Systems in Environmental Engineering. Proceedings of the American Society of Civil Engineers. Computing in Civil Engineering, 1(4), pp.298-302.

Reitsma, R.F. (1990) Functional Classification of Space. Aspects of Site Suitability Assessment in a Decision Support Environment. RR-90-2. International Institute for Applied Systems Analysis. A-2361 Laxenburg, Austria. 300p.

Weigkricht, E. and Winkelbauer, L. (1987) Knowledge-based Systems: Overview and Selected Examples. WP-87-101. International Institute for Applied Systems Analysis. A-2361 Laxenburg, Austria. 102p.