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Models, GIS, and expert systems: integrated water resources models

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Abstract The use of computers for water resources planning and manage ment and the modelling and design of components of the hydrological cycle is a well developed field with a substantial tradition. Most hydrological and water resources problems do have an obvious spatial dimension. Within the domain of modelling this is increasingly being addressed by more complex spatially distributed models, in part made possible by the rapid development of computer technology. Geographic information systems can be used as tools to capture, manipulate, process and display the spatial or geo-referenced data for and results from these distributed models. Consequently, the integration of these two fields of research, or sets of methods is an obvious and promising idea. More complex and integrated tools however, also require a better user interface to fully exploit their potential. Advanced information technology provides the tools to design and implement smart software where, in a broad sense, the emphasis is on this man-machine interface and a flexible problem representation. Symbolic and analog, graphical interaction, visual display and animation, integrated data sources and built-in domain knowledge can effectively support users of complex and complicated software systems. Integration, interaction, visualization, intelligence and customization are key concepts that are discussed in detail, using a number of operational water resources models as examples.

INTRODUCTION

Software and computer-based tools are designed to make things easier for the human user; and they should improve the efficiency and quality of information processing tasks. In practice, only very few programs do that. They make things possible that would not be possible without the computer, but they don't always make it easy on the user. Computer based tools, and models in particular, have to be seen as an integrated part in a much more complex information processing and, eventually, decision-making procedure. This involves not only just running the model, but certainly preparing its input, interpreting and communicating its results, and making them fit the framework of the existing institutional procedures or personal workstyles.

Basic concepts of easy-to-use models and information systems include integration, interaction, intelligence, visualization, and customization. They are necessary, but certainly not sufficient conditions for useful software systems.

Integration implies that in a software system for real-world applications, more than one problem representation, model, or tool is used conjunctively; that several sources of information or data bases, possibly distributed, are accessible; and finally, that a problem-oriented user interface combines these components in a common framework to provide a rich and useful information base.

Interaction is a central feature of any effective man-machine system: a real-time dialogue allows the user to define and explore a problem incrementally in response to immediate answers from the system; fast and powerful systems with modern processor technology can offer the possibility to simulate dynamic processes with animated output, and they can provide a high degree of responsiveness that is essential to maintain a successful dialogue and direct control over the software.

Visualization provides the band-width necessary to communicate and understand large amounts of highly structured information, and permits the development of an intuitive understanding of processes and interdependencies, of spatial and temporal patterns, and complex systems in general. Also, many of the problem components in a real-world planning or management situation, such as risk or reliability, are rather abstract: visual inspection of systems behavior and the effective presentation of information is supported by symbolic, graphical representation.

Intelligence requires software to be "knowledgeable" not only about its own possibilities and constraints, but also about the application domain and about the user, i.e., the context of its use. Defaults and predefined options in a menu system, sensitivity to context and history of use, built-in estimation methods, learning, or alternative ways of problem specification, can all be achieved by the integration of expert systems technology in the user interface and in the system itself.

Customization is based on the direct involvement of the end-user, and the consideration of institutional context and the specifics of the problem domain in systems design and development. It is the user's view of the problem and his experience in many aspects of the management and decision making process that the system is designed to support. This then must be central to a system's implementation to provide the basis for user acceptance and efficient use.

INTEGRATED MODEL AND INFORMATION SYSTEMS

Integrated information and decision support systems, built around one or more numerical simulation models or rule-driven inference models, and integrated with data bases and GIS, feature:

(a) 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; help and explain functions can be based on hypertext and possibly include multi-media methods to add video and audio technology to provide tutorial and background information;

(b) dynamic color graphics for the model output and a symbolic representation of major problem components, that allow easy and immediate understanding of basic patterns and relationships. In parallel to the numerical results, symbolic representations and the visualization of complex patterns support an intuitive understanding of complex systems behavior; the goal is to translate a model's state variables and outputs into the information requirements of the decision making process, turning data into insight;

(c) the coupling to one or several data bases, including geographic information systems, and distributed or remote sources of information in local or wide area networks, that provide necessary input information to the models and the user. 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;

(d) embedded AI components such as specific knowledge bases ensure user specifications in allowable ranges to be checked and constrained, and ensure the consistency of an interactively defined scenario;

(e) and they are, wherever feasible, built in direct collaboration with the users, who are, after all, experts in the problems areas these systems address.

In summary, integrated information systems are designed for easy and efficient use, managing potentially very large amounts of data but also usable in data-poor situations, and cater to the user's degree of computer expertise. Most importantly, they have to address the users specific information needs explicitly to be directly understandable and useful.

APPLICATION EXAMPLES

To better illustrate all the above concepts and ideas, a few operational software examples are described below. They are all drawn from customized development projects of the Advanced Computer Applications (ACA) group at the International Institute for Applied Systems Analysis in Austria. More detailed descriptions are given in Fedra (1991a,b; 1992a,b).

River water quality

A straightforward example of a single dynamic analytical model of water quality is implemented as a component of a Dutch national environmental information system, primarily designed for technological risk management. The river model is a complementary tool to a complex risk analysis system for process plants and the transportation system that focuses on atmospheric releases, fire, and explosion. However, chemicals might also end up in the river, and the model is designed to simulate and evaluate such spill scenarios.

The model simulates the propagation of an accidental spill of a chemical, represented by its initial mass, time pattern of the spill, and a first-order decay rate of the chemical substance. The underlying numerical model was developed by Delft Hydraulics (Bockholts & Heidebrink, 1988). The model uses the output from a complex hydrodynamic model to interpolate spatially distributed and, for longer model runs, dynamic flow fields for the rather complex Rhine-Maas system, including the operation of sluices and locks. Several control options allow the interactive definition of a spill scenario, and a number of model control options provide a set of display and analysis styles. There are several ways in which this problem specification is assisted by the system: for example, to obtain the necessary decay rates for a substance, the user can call up the chemical substances data base and select a substance for simulation. The required parameter, a lumped first order decay rate, is then automatically loaded from the data base into the simulation model.

Alternatively, the user can invoke the hypertext function from the respective editors and obtain information on typical decay rates for selected substances and substance groups. Similar information is available to help estimate the amount of the spill from the nature of the accident, or to obtain water quality standards for the substance. The model itself is then run interactively, with dynamic animation of the spill's propagation. The model can be run continuously or step by step, and allows to interactively query the display to read back concentration values for arbitrary locations at any point in time. The user can also set observation points and plot the time history of the spill for selected locations along the river (Fig. 1). The display also indicates a reference concentration so that violations of this water quality standard can be directly read from the graph.

River basin management

A prototypical example of an integrated information system for river basin management is currently being developed at ACA within the framework of the EUREKA project. Bringing together data bases and geographic information systems, and simulation models and expert systems, environmental considerations in water resources management are the central theme. Water quality in rivers, reservoirs and groundwater, primarily related to their use as drinking water, and various sources of pollution such as urban runoff and treatment plants, agricultural land use and land application of manure or treatment sludge, and land disposal of wastes are addressed by the system. Environmental impact assessment of major projects such as new reservoirs, irrigation systems, or industrial and urban development, and the environmental evaluation of water resources management policies in general, are another major focus of the system.

Rather than building one monolithic software system, the approach adopted in this project is modular and tool-kit oriented. Several alternative models, for example TOMCAT from Thames Water and QUAL2 of the US EPA, both simulating surface water quality, are being integrated. Within a common framework for information management, communication and model

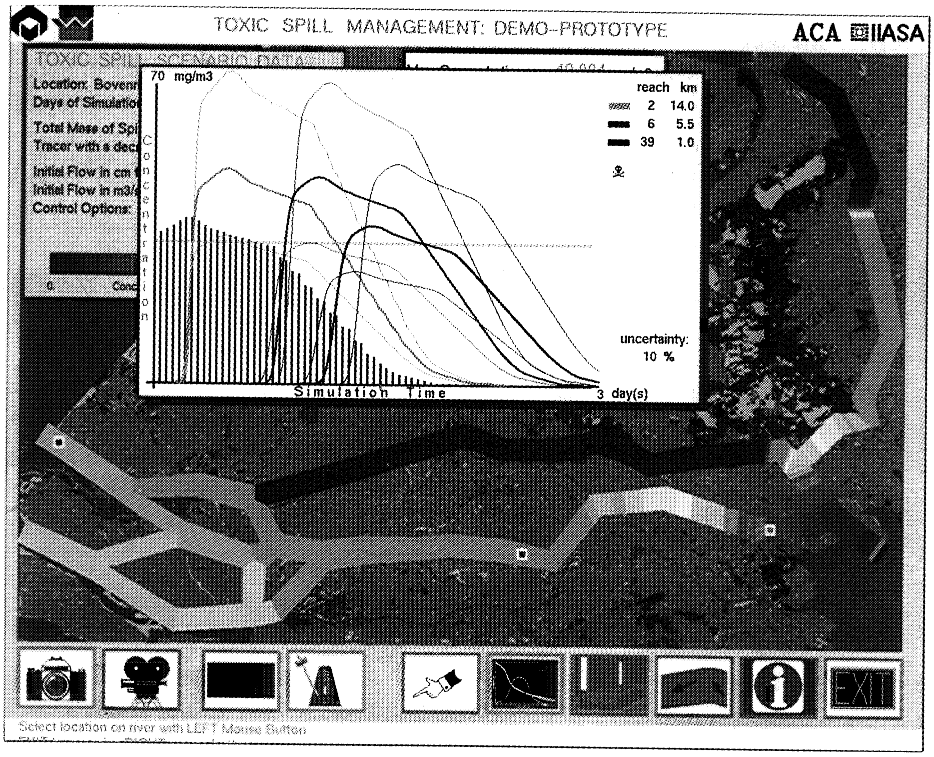

Fig. 1 Spatially distributed output from the spill model over the background map of The Netherlands. With the animation halted, diagrams for individual observation points can be drawn.

integration, different building blocks or "objects" can easily be assembled to work together. Exchange or addition of models or other building blocks should not require any major modifications in the overall system as long as the alternative or additional components comply with the generic interface definitions and are structurally equivalent.

The river basin is a natural and usually well defined unit. However, with users in the water industry or regulatory government agencies, administrative and political boundaries do not always coincide with the natural catchment borders. Embedded GIS technology provides the tools to manipulate and organize, analyze and display spatially referenced data with a flexible definition in a very efficient way.

A GIS is therefore in the core of the system, with the necessary linkages to the various data bases and models, and the multiple local study areas within one major river basin. And to obtain most recent and synoptic data with full coverage, satellite imagery such as Landsat TM or SPOT is used extensively (Fig. 2). Another important element are digital elevation models used for river basin definition. Together with the surface characteristics derived from the satellite imagery, soil maps, and hydro-meteorological station data, they provide the necessary information basis for surface runoff and routing models, and non-point source pollution or erosion modelling. The integration of necessary background data and the linking of tools to derive the necessary model input data makes sure that models are always ready to run, and that a set of default inputs is always available, that may only require small modifications to represent a new problem situation.

Within this framework of data bases and GIS, dynamic simulation models for scenario analysis are tightly coupled. Eventually, the system will comprise models describing rivers and reservoirs, the groundwater system, estuaries and the adjacent coastal marine areas. Water quantity, both for supply management and flood protection, and water quality must be considered, and different forms of water use, industrial, agricultural, and domestic as well as the regulatory framework of water use and environmental legislation provide the socio-political and economic context for a comprehensive approach to river basin management.

In the current prototype, the first model implemented is a groundwater model that simulates contamination problems due to landfills and possibly more wide spread sources of pollution such as agrochemicals and surface application of treatment sludges. The contamination of drinking water is the primary problem addressed. Alternative protection and clean-up strategies can be designed interactively and then simulated to evaluate their efficiency. Initial and boundary conditions for the 2D vertically integrated model are loaded from the GIS, where the respective data matrices are kept as topical maps or cell-grids (Fig. 3).

Groundwater management

For the management of hazardous waste, site selection and risk assessment of landfills, or the design and evaluation of groundwater remediation measures, a set of interactive groundwater models was developed at ACA (Fedra & Diersch, 1989; Fedra *et al.*, 1992). Using several basic 2D models, based on finite difference and finite element schemes respectively, these systems integrate a geographic information system for the manipulation of background maps such as geological, biotope, or land use maps, and input data sets for the model. The systems also incorporate a built-in expert system that assists in the definition of input parameters and decision variables such as source strength or pumping rates. One of these models is being integrated in the river basin management system described above.

The interactive model provides dynamic output, that can be viewed as a color coded overlay over various topical maps or a pseudo 3D display of concentration fields or groundwater head (Figs 4 and 5). The user can introduce new wells or contamination sources or modify existing ones, and then resume the simulation or "rewind" the model and start another run with the new scenario definition. To assist the specification of some of the input values

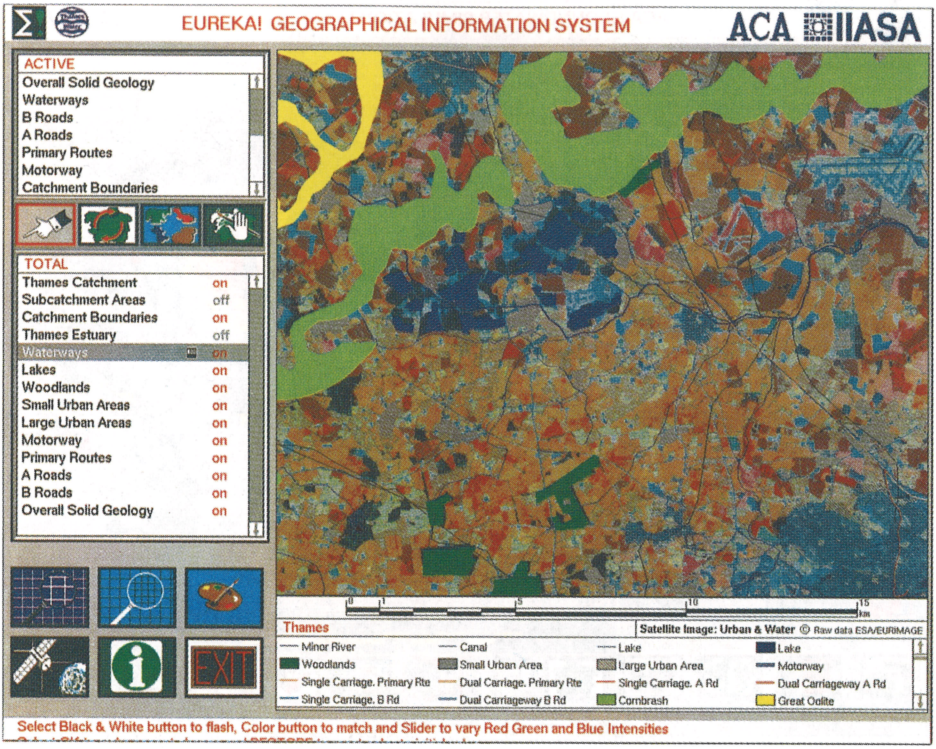

Fig. 2 The hybrid GIS of the River Basin Management System, combining polygon overlays from the land use and geology maps and line features over the basic Landsat TM scene.

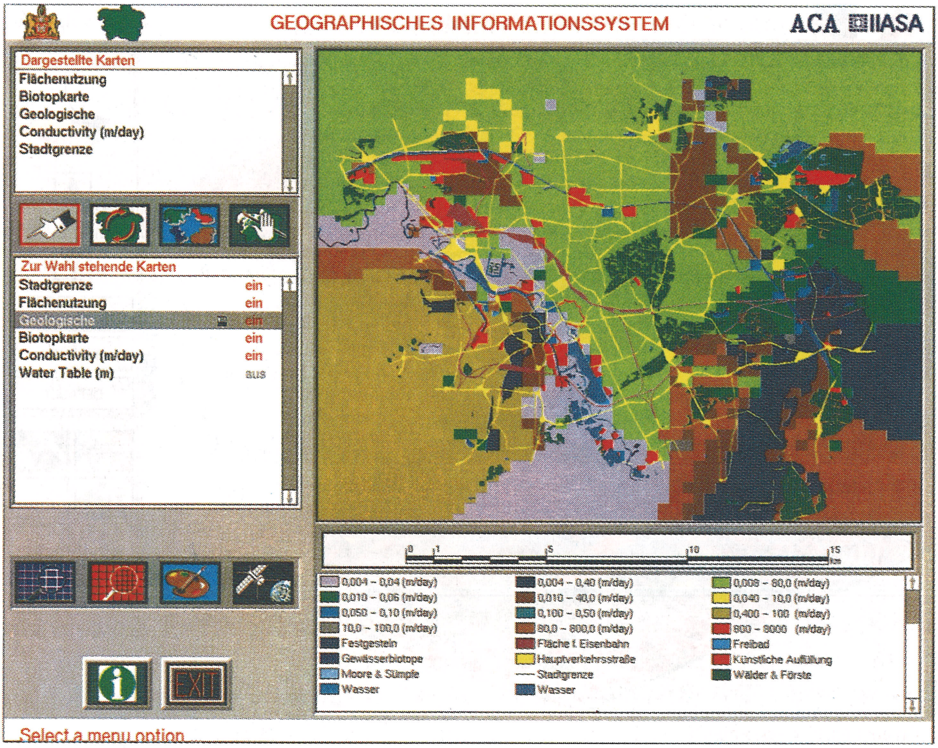

Fig. 3 Overlays of land use and geology over a cell grid file of conductivity. The conductivity map is directly used as an input data set for the 2D groundwater model.

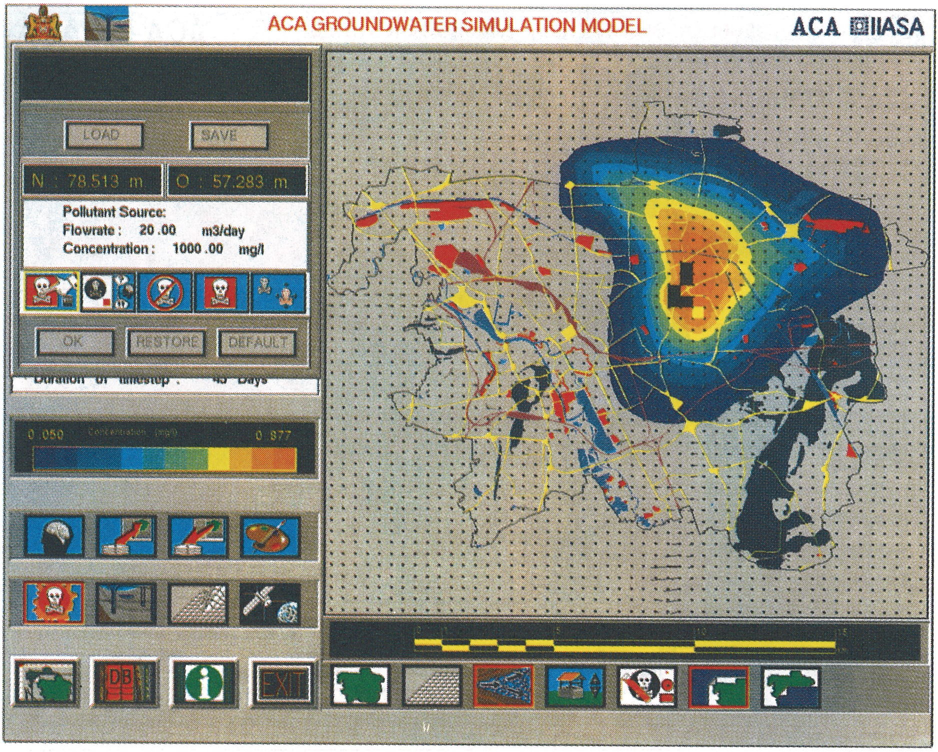

Fig. 4 Contaminant plume over a subset of map features. While the dynamic model is paused, wells or sources of contamination can be edited.

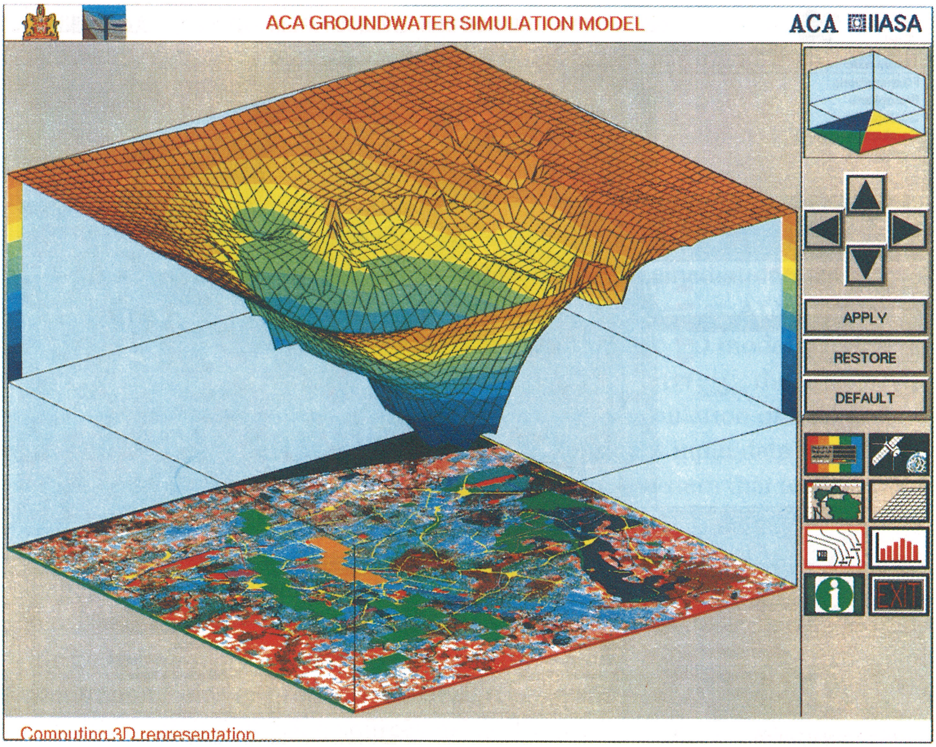

Fig. 5 A pseudo 3D view of the groundwater head over the background map. Different views can be generated by arbitrary rotation of the data set.

required, the system offers in addition to the basic editing function and hypertext support an embedded expert system. This will guide the user through a dialogue session, compiling information that will allow him to estimate the value in question. For example, when defining a pumping rate for a water supply well, the system will inquire about its purpose and then continue to compile information specific to this purpose. If, for example, an irrigation scheme is specified as the form of use, the system will inquire about the size of the irrigation area, irrigation technology and management, and crops irrigated. With reference to the GIS and its climate data base, crop water demand and irrigation water demand can be estimated by rules or simple models, and the estimated water requirement will be suggested to the user. The system will then check whether the expected drawdown from meeting these requirements is reasonable in relation to other, existing water uses in the area, and suggest a feasible pumping rate. During this dialogue, the user can display the rules used and, whenever the system reaches an intermediate or final conclusion, ask to have the underlying reasoning explained. The terms used in the rules are again linked to the hypertext system, so that further explanation can be provided for a better understanding.

The final value, or any intermediate one for that matter, can be modified by the user, overriding the expert systems suggestions. However, the system enforces some absolute bounds on the values a user can choose in order to ensure that the model is used within a reasonable range of parameters. The integration of expert systems functionality allows the user to draw on a larger information basis: often, exact parameter values or model inputs are not known, and have to be estimated. Many parameters are not directly measurable but require interpretation of usually scarce data, or, in the case of some of the control and decision variables, might have to be based on a lengthy engineering study. This requires considerable experience not only in the problem domain, but in many cases also in the use of a particular model. Both elements can be encoded in the knowledge base of the system, to provide an efficient but approximate answer for the experimental and explorative use of the software.

A common architecture

Other examples of integrated model and information systems include an expert system for environmental impact assessment of water resources development projects, Fedra *et al.* (1991), where data from the GIS are used both in the rule based deduction as well as in simulation models integrated into the inference trees; or models to simulate the effects of ocean outfalls on coastal water quality (Fedra, 1992c) (Fig. 6). They all share a common architecture designed to make them efficient to use and easy to understand: one or more simulation models are coupled with the necessary data bases, a GIS, and expert systems components, and integrated in an interactive, graphical user interface.

Linking the models to the GIS as a source of data describing initial and boundary conditions not only provides a convenient tool to download this

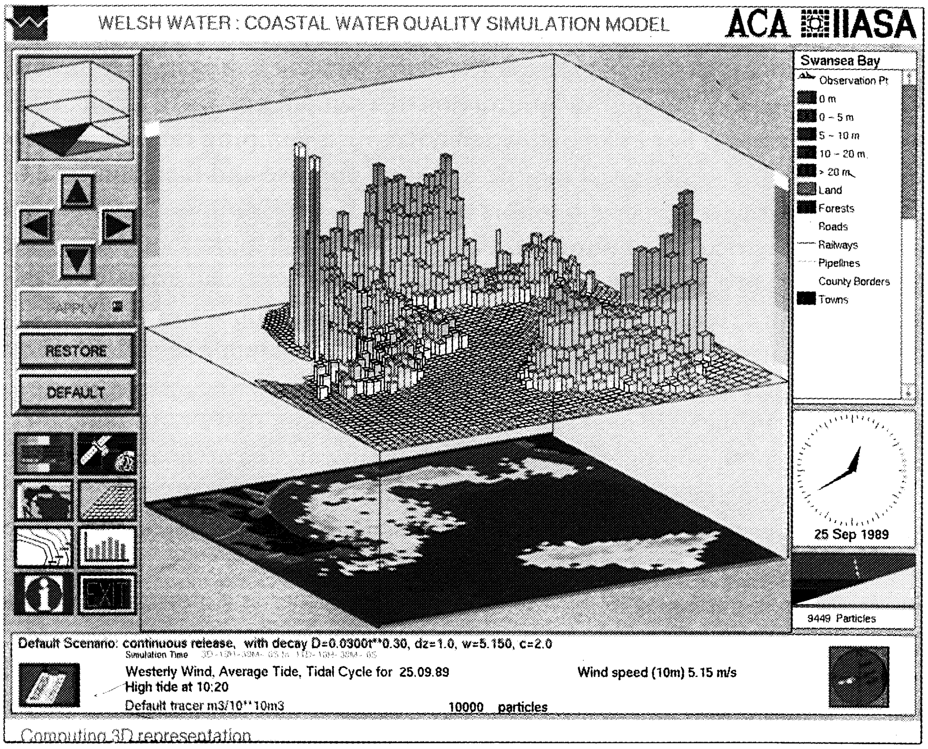

Fig. 6 Contaminant plumes from ocean outfalls in a combined 2D and pseudo 3D display. The concentration field and the models curvilinear grid are dynamic map overlays.

information. It is also a powerful tool to process some of the required information, for example, extracting catchment boundaries from a digital elevation model, or compiling transmissivity classes from geological maps (Fig. 3). However, most importantly the GIS provides the tools to efficiently display the data, also in combination with other related information for visual inspection. And if model output can be exported to the GIS, the same tools can be used to display and further analyze, e.g., by overlay analysis, model generated results as maps. If display functions and the dynamic models are tightly coupled, animated output can be generated (Figs 1, 4, 5 and 6)

Expert systems, in conjunction with simulation models, can serve two major roles: on the one hand, integrated with the user interface, they can assist in using a model or a data base by providing domain expertise and guidance. The estimation of model parameters, checking of completeness, consistency, and plausibility of scenario assumptions, the choice of appropriate tools, or paths through the information system, depending on context, are all possible examples (Fig. 6). The second major role is in modelling itself: expert systems components can be used as qualitative, logical models in combination with their algorithmic counterparts.

DISCUSSION

Integrated information and decision support systems bring together large volumes of background data, and interactively distill from it decision relevant information. Key technologies are workstations and networking, data bases and GIS, interactive graphics, modelling and optimization, and expert systems. The models, and their interfaces, are representations of the problems they address as much as of the planning and decision making processes they are designed to support. In the latter field, if not also in the former, their users are the real experts. Thus, their expertise and experience needs to be included in the systems. As a consequence, the user must be involved in the design and development, so that he can accept responsibility and ownership for the software system.

Institutional integration also must look at aspects such as user training, data entry, maintenance issues of keeping systems current and operational, providing adaptations and updates, etc. Any complex information system has more than one user at more than one level of technical competence and with different roles within an institution. Different users have different requirements that need to be supported: flexibility and adaptability are therefore important features. Systems must be able to grow with their users. Therefore, the institutional commitment and technical infrastructure to keep a system alive and evolving are as important as the scientific and technical quality of the original software system.

It is the easy-to-use "smart" interface, the fast and efficient operation, and the apparent intelligence of the programs that makes them attractive. For the specific model and GIS coupling, this means that their respective functions are fully and transparently integrated. The distinction between GIS and spatial model disappears. The system provides a coordinated set of functions or tools that cooperate in a common environment, within a single integrated system.

For the user, however, it is immaterial which method is used to generate the answer to his questions, to provide insights or arguments, help structure his thinking and communicate information within a group. And in fact, it will usually be the combination of several "methods" or tools that are required. This combination of methods of analysis, and the integration of data bases, geographical information systems, and hypertext, allows to efficiently exploit whatever information, data and expertise is available in a given problem situation. The integration of water resources management models and geographic information systems, expert systems, and interactive graphics, is an obvious, and a challenging and promising development in environmental research and applied informatics. The need for better tools to handle ever more critical environmental and resource management problems is obvious, and the rapidly developing field of information technology provides the necessary machinery.

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