REVIEWS OF GEOPHYSICS, VOL. 25, NO. 2, PAGES 107-112, MARCH 1987
U.S. NATIONAL REPORT TO INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS 1983-1986

Impact of Changing Computer Technology on Hydrologic and Water Resource Modeling

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The increasing availability of substantial computer power at relatively low costs and the increasing ease of using computer graphics, of communicating with other computers and data bases, and of programming using high-level problem-oriented computer languages, is providing new opportunities and challenges for those developing and using hydrologic and water resources models. This paper reviews some of the progress made towards the development and application of computer support systems designed to aid those involved in analyzing hydrologic data and in operating, managing, or planning water resource facilities. Such systems of hardware and software are being designed to allow direct and easy access to a broad and heterogeneous group of users. These systems often combine data-base management; simulation and optimization techniques; symbolic colored displays; heuristic, qualitative approaches; and possibly artificial intelligence methods in an interactive, user-controlled, easily accessible interface. Individuals involved in the use of such systems are not only those with technical training, but also those representing different interest groups and having non-technical backgrounds. The essential difference between what is happening now and the more traditional off-line, non-interactive approaches is that instead of generating solutions to specific problems, model developers are now beginning to deliver, in a much more useful and user-friendly form, computer-based turnkey systems for exploring, analyzing and synthesizing plans or policies. Such tools permit the user to evaluate alternative solutions based on his or her own objectives and subjective judgments in an interactive learning and decision- making process.

INTRODUCTION

Mathematical models and computers are by now standard tools of most scientists, engineers, and planners engaged in hydrologic and water resources activities. The use of models and computers is certainly well known to anyone familiar with both the research and practice of hydrology and water resources planning and management. What is new, and what has changed over the past four to eight years, is the extent to which computer technology is becoming directly involved in the processes of model application and decision-making.

Computer technology incorporating various models of hydrologic processes or of water resource systems is being used increasingly in a more interactive context by both technical and non-technical groups involved in decision-making. This review will focus on the recent literature in hydrology and water resources pertaining to these changes in modeling and computer use, and on the reasons for this shift towards a more supportive role in decision-making.

Two significant factors have motivated the development of computer support systems for hydrologic analyses and for water resources planning, management, and conflict negotiation. One is the growing awareness of the limitations of many of the earlier non-interactive modeling approaches, especially those designed to aid decision-making. The other is the explosion in the growth of computer technology. Developments in both computer hardware and software have given professionals these past four to eight years increased access to considerable computer power and at much lower costs, to more usable and useful computer programs and programming tools, and to an improved computer-user interface.

Communication between the computer and its users now can include visual (colored pictures and graphs), audio (voice and music), as well as alphanumerical inputs and outputs. Even conversational dialogues are being explored with some success [*Bolt*, 1985]. These and other advances in interactive computer graphics, expert system shells, regional geographic information systems that may include data stored on optical or laser disks, and related technology will undoubtedly have major impacts on future research and practice in hydrologic and water resources modeling and decision support.

Perhaps if this review were being written 4 to 8 years ago, the emphasis would have continued to be on the software, i.e. the more traditional optimization and simulation models developed by ecologists, economists, engineers, hydrologists, and planners. Clearly such models have been and are being used, and beneficially so, to help

Paper number 7R0049.
8755-1209/87/007R-0049$15.00

solve numerous problems in many different locations [*Austin*, 1986; Office of Technology Assessment, 1982; *Johnson*, 1985; *Loucks, Stedinger and Shamir*, 1985]. They will remain an essential component of computer support systems until perhaps they are replaced by, or are incorporated within, microchips. This very idea has been suggested by *Bugliarello* [1985] who proposes they be named hydrochips.

Any review written now, in 1986, must also emphasize the hardware as well as the software. Hardware has traditionally been more expensive than software. That situation is now changing. While some models and associated software may now cost more than the hardware, it is the hardware that is driving the developments in new interactive software. Together they are changing the way many in the profession are thinking about their approach to computer modeling and the role of computer technology in hydrologic analyses and water resources planning and management.

The following sections will outline some of these recent technological advances and their impacts on the methodology of solving hydrologic and water resources problems. This review will focus on both the advantages (or potential advantages) as well as some of the current (or potential) problems requiring further research and development in the technology of computer-assisted hydrologic and water resources systems analysis, synthesis, and decision-making.

MICROCOMPUTER SUPPORT SYSTEMS IN RESEARCH AND PRACTICE

Over the past several decades professionals have been developing computer programs for solving water resources problems. These programs have been influential in bringing computers into practice. Recent advances in especially microcomputer technology have significantly changed the economics and logistics of computer use, and are changing the way many researchers and practitioners are using computers [e.g., *Wulliman and Muller*, 1985].

Not only have microcomputers given more individuals more convenient access to cheaper computing power, but also more useful software, software that is often interactive and that includes graphics for facilitating data input, editing, and display. Such software, written for microcomputers, is just beginning to be available on larger mainframes with specialized workstations.

With inexpensive personal microcomputers and "user-friendly" software available where professionals work, and often where they live as well, the potential for this technology to play a significant role in assisting water and environmental resource planners, managers, and policy-makers becomes much more likely. This opportunity has motivated a shift over the past 4 to 8 years from a non-timesharing, non-interactive batch solution approach by specially trained modelers or programmers (analysts) to a more responsive, flexible, friendly, interactive approach that can be mastered by many non-specialists as well as specialists involved in water resources decision-making. Terms such as Decision Support Systems and their relatives called Expert Support Systems and Decision Insight Systems represent a philosophy of man-model-machine interaction that is particularly appropriate for the microcomputer environment. These new terms are just some examples of the jargon being introduced into the discipline of hydrologic and water resources modeling.

The extent of this shift towards a more personalized computer-assisted interactive approach for analyzing and synthesizing system designs and operating or management alternatives and for gaining some understanding of the impacts of these alternatives is evidenced by the increasing number of publications and short courses offered in this area. Throughout North America, Europe, Japan, and Australia, and no doubt elsewhere, a growing number of continuing education workshops and courses are being offered to introduce this technology to everyone who wants to pay the tuition. The recent shift in emphasis at the U.S. Army Corps of Engineers Hydrologic Engineering Center from mainframe batch simulation to interactive menu-driven data base and model management on microcomputers is also evidence of this change and its impact [*Eichert, Davis and Barken*, 1986]. Another indication, even to the casual observer, is the proportion of space allocated to new computing technology on magazine racks in drug stores, supermarkets, and at gift and book stores at airports and elsewhere. Sometimes one will find more space devoted to computers than to sex. Microcomputers and their software certainly must be getting very user-friendly!

Underlying the concept of many computer support systems is the recognition that there exists a class of problems that are not well understood by all individuals involved in the search for solutions to these problems. One-shot, highly structured modeling attempts are not always appropriate, considering the uncertainty of the scientific aspects and the subjective and judgmental character of the socio-political aspects of these problems. Hence there may be no wholly objective way to find a best solution. In this often typical decision-making environment, computers can be used in a supportive role, helping to define the problem and the technical issues at conflict as well as, hopefully, helping to identify some possible alternative solutions.

There is no universally accepted definition of computer support systems. Almost any computer-based system involving data-base management or information systems, simulation models, and mathematical programming or optimization, could be used to support those involved in making decisions. The literature on information systems and decision support systems is substantial [e.g. *Bonczek et al.*, 1981; *Ginzberg et al.*, 1982; *Sol*, 1983; *Grauer and Kaden*, 1984; *Wierzbicki*, 1983; *Humphreys et al.*, 1983; *Phillips*, 1984; *Fedra*, 1983, 1984]. Approaches range from rigid mathematical treatment to applied computer sciences, management sciences, or psychology.

Most recent assessments of the field, and in particular those concentrating on more complex, ill-defined, policy-oriented and strategic problem areas, tend to agree on the importance of interactiveness and the direct involvement of the end users. Direct involvement of the users calls for interactive systems and effective user interfaces. The "decision support model" implies feedbacks from applications, e.g., communication, negotiation, and bargaining [*Steiner et al.*, 1985].

It is useful to consider what a decision-support system can do and what it cannot do. Its possible contribution depends very much on the level and scope of the decision problem. With more comprehensive strategic and policy-oriented problems, it would be naive to assume that any computer-based support system could come up with acceptable solutions ready to implement. Rather, one can expect the system to inform and educate its users, allowing them to build mental models on the basis of the system's models. These mental models will then serve as the basis for their decisions.

The number of considerations that enter any even moderately complex policy decision is very large in comparison to what a formal problem representation can include. Decision support here can only aim at structuring the problem and at providing auxiliary information. Rarely can it be expected to provide a complete representation of the problem. Consequently, providing background information about the problem area is becoming as important in such soft approaches to decision support as are attempts at multiple, parallel problem representation, e.g. by combining simulation and optimization techniques [e.g. *Kaden*, 1985; *Kaden*, 1986], by providing discrete optimization as a post-processor for simulation results [*Zhao et al.*, 1985], or by using several parallel, and possibly linked, simulation models with different emphasis and different degrees of resolution [*Fedra*, 1985, 1986].

Often the problem holder is not specialized in all the multidisciplinary aspects of the problem (e.g. economics, hydrology, environmental sciences, toxicology, etc.). Expertise in the numerous domains touched upon by the problem situation is therefore as much a bottleneck as is the structure of the decision problem itself. Building human expertise and some degree of intelligent judgment into decision-supporting software is one of the major objectives of Artificial Intelligence (AI).

Relatively recently, the area of expert systems (ES) or knowledge engineering has emerged as a way to apply AI techniques (see for example, *Pearl et al.* [1982]; *Sage and White* [1984]; or *O'Brien* [1985] on expert systems for decision support) . An expert system is a computer program that is supposed to help solve complex, but very specific, real-world problems [e.g. *Barr and Feigenbaum*, 1982]. These systems use large bodies of "domain knowledge," i.e. facts, procedures, rules, and models that human experts have collected or developed and found useful in solving similar problems.

Some beginning applications of artificial intelligence in hydrology and water resources include those of *James and Dunn* [1985, 1986], *Engman, Rango and Martinec* [1986], *Kangari and Rouhani* [1986], *Palmer* [1985], *Reboh, Reiter and Gasching* [1982], *Cuena* [1983], *Johnston* [1985] and *Ludvigsen, Sims and Grenney* [1986]. *Racer and Gaffney* [1985] discuss the potential role of AI/ES in the forecasting and warning operations of the National Weather Service. *Sweetnam and Dombroski* [1985] provide an example of the use of expert systems for snowstorm prediction. *Spooner* [1985] reviews the increasing uses of ES in the U.S. Environmental Protection Agency.

The introduction of AI/ES applied to water modeling and analysis is obviously just beginning. There will need to be many more such applications before anyone will be able to estimate the extent of the impact that this technology will have on those in the water resources and hydrology professions.

Another basic development is the increasing use of interactive models and computer graphics. A number of papers describing and summarizing these developments in the water resources field are included in the February 1985 issue of *Water Resources Research* [*Loucks et al.*., 1985a; *Kuenreuther and Miller*, 1985; *Fedra and Loucks*, 1985; *Cosgriff et al.*, 1985; *Loucks et al.*, 1985b; *Fedra*, 1985] and in the July 1986 issue of the *Journal of Water Resources Planning and Management* [*Labadie and Sullivan*, 1986; *Johnson*, 1986a; *Cunningham and Amend*, 1986; *Brown and Skelton*, 1986].

Additional developments in interactive modeling, often through the use of computer graphics, are reported by *Bonner* [1986], *Bissell, Hartman and Halquist* [1986], *Fleming and Fattorelli* [1986], *Loucks* [1986], *Loucks, French and Taylor* [1986], *Cunningham and Amend* [1985], *Tanner* [1985, 1986], *Franklin* [1985], *Johnson* [1986a, 1986b], *Steenhuis, Pacenka and Porter* [1985], *Leader and Curtis* [1985], *Sarikelle, Mehrfar and Chuang* [1985], *Casola, Perala and Farrell* [1985a, 1985b], *Southerland and Spooner* [1985], *McMahon, Taylor and Darragh* [1985], *Bernhard* [1985], *Schilling* [1985], *Shamir* [1985], *Abraham* [1986], and *Kindler* [1986]. The current implementation of interactive modeling and graphics in the Corps of Engineers is reported by *McAnally, Adamec and Beck* [1985] and by *Eichert, Davis and Barkin* [1986]. Similar developments are underway in parts of the National Weather Service and the U.S. Geological Survey pertaining to hydrology and water resources.

Data-base management plays an important role in the development and use of any computer-support system. *Unal and James* [1986] discuss the development of an intelligent menu-driven, central data base system for use in local area networks where continuous hydrologic modeling is taking place. *Baxter-Potter, Gilliland and Peterson* [1986] discuss geographic information systems designed to assist in predicting non-point pollution potentials.

Other developments are reported by *Chow, White and Rabalais* [1986], *Grayman* [1985], *Berich* [1985], *Riley and Bernard* [1985], *Showen* [1985], *Orr* [1985], *Greener, Lockhard and Epps* [1985], *Lee, M.T.* [1985], *Alexander and Rao* [1985], and *Ragan and White* [1986]. Real-time data collection using the microcomputer and other instruments is discussed by *Melroy and Huff* [1985], *Casola, Perala and Farrell* [1985a], *Robertson and Hardin* [1985], *Lee, H.C.* [1985], and *Startzman* [1985].

The increasing use of spreadsheet programs for data management and modeling is evident. Some examples of spreadsheets applied to water resources and hydrologic problems are found in *Horsey et al.* [1985], *Oulman* [1985], *Jewell* [1985], *Rossmiller* [1985], *Au-Yeung* [1985], *Brown* [1985], *Brown and Clyde* [1985], *Yu and Tisdale* [1986], and *Miles et al.* [1986]. *Wylie* [1985] reports on the use of equation solvers on microcomputers in civil engineering education.

SUPERCOMPUTERS IN RESEARCH AND PRACTICE

Not only are microcomputers becoming more available, so is access to supercomputers at many of the major university campuses and research institutions or laboratories. Supercomputers with parallel processors are especially well adapted, for example, to solving large dynamic programming problems of multiple reservoir systems, requiring the solution of numerous recursive equations, one for each of numerous states, at each stage or time period. Supercomputers are also well adapted to solving large finite difference or finite element representations of groundwater flow and contaminant transport equations. Large-scale economic models using input-output matrices that account for regional or global production, consumption and waste generation and transport have also been designed for solution by supercomputers. Any stochastic dynamic simulation for planning the future development of regional water resource systems requires numerous flow simulations at each time step [*Loucks*, 1986]. This coupled with the possible need to summarize and display the simulation results during the simulation can certainly place demands on any computer. Supercomputers coupled to graphics display devices can permit such simulation models to be made truly interactive by using parallel processing to reduce computation times. They also have the computing power to create images of dynamic processes, and to display these images dynamically in approximately real time [*Kuck et al.*, 1986].

PROBLEMS WITH COMPUTERS IN RESEARCH AND PRACTICE

There are still some barriers, or at least difficulties, in the development and application of computers to water and environmental management problems. One is standardization of software, or hardware, that permits what works on one machine to work on another. There are still problems, for example, in transferring a program written in FORTRAN 77 from a DEC to an IBM computer. Even adhering to a graphics standard does not make interactive graphics software machine-independent. But this situation is improving and is in a better state than, for example, magnetic storage media. Such media currently encompass at least four different sizes of floppy disks and an even larger number of uncompatible tape drives. The multiple possible formats on such media also make it difficult to be machine-independent.

Operating systems also present a problem in standardization. More than a half-dozen operating systems exist for microcomputers and almost none of these is compatible with operating systems for minicomputers and large mainframes. Each provides a different language for communication between users and computers.

The net result of these standardization problems is that a researcher or practitioner cannot expect to share very readily programs or data with other investigators or practitioners using other systems without obtaining specialized programs for transferring and editing such programs and data.

Problem solving software packages are becoming increasingly available in the fields of hydrology, water resources, and environmental management. In part because of this, researchers and practitioners are becoming increasingly dependent upon software support for statistical analyses, flood routing, groundwater simulation, linear or dynamic programming, hydraulic network design, water quality modeling, reservoir operation simulation, etc. This increasing dependency brings with it increasing problems in software quality control, and in discovering how to give the user the appropriate level of understanding about the theory behind the program so that he or she can recognize erroneous results when they appear.

CONCLUSION

A change is being observed in the manner in which models of hydrologic and water resource systems are being developed and used. This change is from what has been a relatively detached relationship between modelers or analysts and their clients or colleagues who are waiting for the results or solutions of such models, to a more interactive participatory role involving their clients. Instead of delivering the usual set of reports as the result of some assignment or study, the new product is now becoming an integrated tool kit. This change has proven to be demanding on developers and it requires considerable user involvement, but once developed it can allow the user to explore, analyze, synthesize, and evaluate his or her own solutions to his or her particular problems.

Precise objectives and requirements need not be defined a priori; the user can begin to develop clearer objectives and criteria and constraints during an interactive learning process involving models and computers. Methods of analyses can be made part of the decision-making process within the institutional framework in which analyses are performed, decisions are made, and conflicts are negotiated. This trend towards interactive modeling has clearly been facilitated by the growth in computer technology that has taken place during these past four to eight years.

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(Received September 2, 1986;
revised November 21, 1986;
accepted November 21, 1986.)