WATER RESOURCE SYSTEMS MODELING: ITS ROLE IN PLANNING

Daniel P. Loucks
School of Civil and Environmental Engineering, Cornell University, Ithaca, New York, USA

Keywords : water resource systems, modeling, planners, managers

Contents

1. Introduction
2. Challenges of Planners and Managers
3. Challenges of Modeling
4. Characteristics of Problems to be Modeled
4.1 A Modeling Exercise
5. Challenges of Applying Models in Practice
6. Evaluating Success
7. Modeling Technology in Transition
8. Shared Vision Modeling
9. Some Concluding Thoughts
Glossary
Bibliography
Biographical Sketch

Summary

Modeling is one way that planners, engineers, and economists, among others, attempt to predict the impacts of possible design, management and operation decisions or policies. Models are also ways of estimating just how important various uncertain assumptions and data are to the desired outcome or impact. Models are tools, not substitutes for human decision-making. They are intended to aid those who must recommend or make decisions, not replace them. Mistakenly, some reject modeling when they believe their data are not sufficient or accurate enough, or when they are uncertain with respect to events affecting their system that they cannot control. The alternative of course is judgment without any benefit of analyses—analyses that force some rigor on just what performance criteria are being used to judge system performance, and just what assumptions are being made with respect to exogenous inputs and the processes that take place in the system.

Modeling is a fundamental component in the current practice of water resource systems planning and management. Computer simulation as well as optimization methods are being used, in practice, to estimate and identify the "What if?" questions, and the tradeoffs among different and often conflicting system performance criteria. Modeling cannot identify the best assumptions, or the best scenarios of future events about which we can only guess. Modeling cannot forecast surprises, events no one has even thought of that often change the way we think and behave. But modeling, especially in today's interactive graphics and internet based computational environment, can help all

stakeholders obtain a better understanding of how their systems work or function, and just what issues are important to consider and study in more depth, all in order to manage their resource in a more adaptive, effective, and sustainable manner.

1. Introduction

Modeling provides a way, perhaps the principal way, of predicting future behavior, at least in a statistical sense, of existing or proposed water resource systems. The past 30 years have witnessed major advances in our abilities to model the engineering, economic, ecologic, hydrologic, and sometimes even the institutional or political aspects of large complex multipurpose water resource systems. Applications of models to real systems have improved our understanding of such systems, and hence have often contributed to improved system design, management, and operation. Evaluating the applications of numerous types of models has also taught us how limited our modeling skills remain.

Water resource systems planning, management, and operation is far more complex than what analysts have been, or perhaps even will be, able to model and solve. The reason is not simply any computational limitations on the number of model variables, constraints, subroutines, or executable statements in those subroutines. Rather it is because we do not understand sufficiently well the multiple interdependent physical, biochemical, ecological, social, legal and political (human) processes governing the behavior of such water resource systems. These processes are affected by uncertainties in what we manage, e.g., water quantities and qualities and water demands, as well as in the models we use to describe them. Uncertainties also result from the unpredictable actions of multiple individuals and institutions who are impacted by what they get or do not get from the management and operation of such systems, as well as by other events having nothing to do with water.

The development and application of models, or the practice of modeling, should be preceded by the recognition of what can and cannot be achieved from the use of such models. Models of real-world systems are always going to be simplified representations of those systems. What features of the actual system are incorporated into a model, and what features are not, depends in part on what the modeler thinks is important with respect to the issues being discussed or the questions being asked. How well this is done depends on the skill of the modeler, the time and money available, and, perhaps most importantly, the modeler’s understanding of the real system and decision-making processes. Developing models is an art, requiring a knowledge of the system being modeled, the client’s objectives, goals and information needs, and some analytical and programming skills. Models are always based on numerous assumptions, and some of these may be at issue. Applying these approximations of reality in a way that contributes to everyone’s improved understanding and eventually to a good decision clearly requires considerable modeling and communication skills as well as a little bit of experience.

Water resource planners and managers must accept the fact that decisions may not be influenced by their planning and management model results. To know, for example, that cloud seeding may, on average, reduce the strength of hurricanes over a large region does not mean that such cloud-seeding activities will or should be undertaken. Managers or operators may know that not everyone may benefit, and those who may lose will likely scream louder than those who may gain. Hence, decision-makers may feel safer in inaction than action (Shapiro, 1990; Simon, 1988). There is a strong feeling in many cultures and legal systems that failure to act (nonfeasance) is considered more acceptable than acts that fail (misfeasance or malfeasance). We all feel greater responsibility for what we do than for what we do not do. Yet our aversion to risk should not deter us from addressing such sensitive issues in our models. After all, our modeling efforts should be driven by the need for information and improved understanding. It is an improved understanding (not improved models per se) that may eventually lead to improved system design, management, and/or operation. Models used to aid water resource planners and managers are not intended to be, and rarely are (if ever), adequate to replace their judgment. This we have learned, if nothing else, in our over 30 years of modeling experience.

This brief paper is to serve as an overview of modeling and its applications. The emphasis is on application. This discussion is about modeling in practice more than in theory. It is based on the considerable experience and literature pertaining to how well, or how poorly, professional practitioners and researchers have done over the past three decades or more in applying various modeling approaches or tools to real problems with real clients (see also, for example, Austin (1986), Gass (1990), Kindler (1987) and (1988); Loucks et al. (1985), Reynolds (1987), Rogers and Fiering (1986)). The focus in this article is the context within which the practice of modeling takes place.

Here, the terms *analysts* or *modelers*, *planners*, and *managers* can be the same person or group of individuals. These terms are used to distinguish the activities of individuals in the planning and management process, not necessarily the individuals themselves.

In attempting to understand how modelers can better support planners and managers, it may be useful to examine just what a planner and manager of any complex water resource system has to do. What planners or managers do governs to some extent what they need to know. And what they need to know governs to a large extent what modelers or analysts should be trying to provide.

First, I offer some general thoughts on the major challenges facing water resource systems planners and managers, the information they need to meet these challenges, and the role analysts have in helping to provide this information. Next, I will review some criteria for evaluating the success of any modeling activity designed to help planners or managers solve real problems. Finally, I will argue why I think the practice of modeling is in a state of transition, and how current research and development in modeling and computing technology are affecting that transition. New computer technology has already had a significant impact in the development and use of models for water resources planning and management.

2. Challenges of Planners and Managers

Planners and managers of water resource systems are those who are responsible for solving our particular water-related problems or meeting our special water resource needs. When they fail, the public lets them know. What makes their life particularly challenging is that the public has different needs and expectations. Furthermore, water resource institutions in which planners and managers work (or hire consultants to work for them) are like most institutions these days. They must do what they can with limited financial and human resources. Their clients are all of us who use water, or at least all of us who are impacted by the decisions they must make. The overall objective of these institutions is to provide a service, whether it is water supply, water quality, hydropower, flood control and protection, navigation, recreation, wildlife preservation, or some combination of these or other purposes. Furthermore they are expected to do this at a price people are willing to pay. Meeting these goals is not always easy, or even possible.

There are rarely simple technical measures or procedures available to ensure that a solution to any particular set of water resource management problems can be achieved. Furthermore, everyone who has had any introduction to water resources planning and management knows one cannot design or operate a water resource system without making compromises. These compromises are over competing purposes (such as hydropower and flood control) or competing objectives (such as who benefits and who pays, and how much and where and when). After analysts identify possible ways of achieving various goals and objectives and some of their economical, environmental, ecological and social impacts, it is the planners and managers who have the more difficult job. They must work with and influence everyone who will have a role or stake in deciding what to do and/or in implementing the decision.

Planning and managing involves not only decision-making, but also developing among all interested and influential individuals an understanding and consensus that legitimizes the decisions and enhances their successful implementation. Planning and managing are processes that take place in a social environment. These processes involve leadership and communication among people and institutions. Leadership and communication skills are learned from experience, not from computers or models.

Moving an organization or institution into action to achieve specific goals involves a number of activities, including goal-setting, debating, coordinating, motivating, deciding, implementing, and monitoring. Many of these must be done simultaneously and continuously, especially as conditions (goals, water supplies, water demands, finances) change over time. These activities create a number of challenges that are relevant to modelers or analysts. Some include how to:

1. identify creative alternatives for solving problems;
2. make decisions and implement them given differences in opinions, social values, and objectives;
3. find out what each interest group wants to know in order to reach an understanding of the issues and a consensus on what to do; and
4. develop and use models and present their results so that everyone is able to reach a common understanding and agreement that is consistent with their individual values.

In addressing these needs or challenges, planners and managers must consider the relevant

- legal rules and regulations;
- history of previous decisions;
- preferences of important actors and interest groups;
- probable reactions of those affected by any decision;
- relative importance of various issues being addressed; and
- applicable science, engineering, and economics—the technical aspects of their work.

I mention these technical aspects last not to suggest that they are the least important factor to be considered. I do this to emphasize that they are only one of many factors and, probably in the eyes of planners and managers, not the most decisive or influential (Ahearne, 1988; Carey, 1988; Pool, 1990; Walker, 1987).

So, does the scientific, technical, systematic approach to modeling for planning and management really matter? In our opinion, it can. But the message, I suggest, is that analysts need to work on the issues of concern to their clients, the planners, and managers. Analysts need to be prepared to interact with the political or social structure of the institutions they are attempting to assist, as well as with the public and the press. Analysts should also be prepared to have their work ignored. Even if the analysts are presenting "facts" based on the current state of the sciences, sometimes these sciences are not considered relevant. Happily for scientists and engineers, this is not always the case. The challenge of modelers or analysts interested in having an impact on the practice of water resource systems planning and management is to become a part of the largely political planning and management process and to contribute towards its improvement.

3. Challenges of Modeling

To engage in a successful water resource systems study, the modeler must possess not only the requisite mathematical and systems methodology skills, but also an understanding of the environmental engineering, economic, political, cultural, and social aspects of water resources planning problems. For example, to study the impact of a large land development plan, the analyst should be able to predict how the proposed plan would affect runoff and, in turn, the quantity and quality of surface waters and ground waters, and how the development would affect flood flows and conversely, how flood flows would affect the planned development. Add to this the prediction of the increasingly important ecological impacts resulting from the land uses and water quantity and quality regimes we create. To do this the analysts must have an understanding of the biological, chemical, and physical and even social processes that are involved in water resources management.

A reasonable knowledge of economic theory is just as important as an understanding of hydraulic, hydrologic, ecologic and environmental engineering disciplines. Economics has always had, and will continue to have, a significant role in the planning of water resources investments. It is obvious that the results of most water resources management decisions have a direct impact on people and their relationships. Hence inputs from those having a knowledge of law, regional planning, and political science are also needed during the comprehensive planning of water resource systems, especially during the development and evaluation of the results of various planning models.

Some of the early water resource systems studies were often undertaken with a naive view of the appropriate role and impact of models and modelers in the policymaking process. The policymaker could foresee the need to make a decision.

He or she would ask the systems group to study the problem. They would then model it, identifying feasible solutions and their consequences, and recommend one or at most a few solutions. The policymaker, after waiting patiently for these recommendations, would then make a yes or no decision. Experience to date suggests the following:

1. A final solution to a water resources planning problem rarely exists; plans and projects are dynamic and change and evolve over time as facilities are added and modified and the uses and demands placed on the facilities change.
2. For every major decision there are many minor decisions, made by different agencies or management organizations responsible for different aspects of a project; plans evolve.
3. The time normally available to study a water resources problem is shorter than the time necessary for an adequate state-of-the-art mathematical modeling study, or if there is sufficient time, the objectives of the original study will have significantly shifted by the time the study is completed.

This experience emphasizes not only some of the limitations and difficulties that any water resource systems study may encounter, but more important, it emphasizes the need for constant communication among the analysts, engineers responsible for the systems operations, and policymakers.

The success or failure of many past water resource studies is in a large part attributable to the efforts expended or not expended in ensuring adequate and meaningful communication—communication among systems planners, professional engineers responsible for system operation and design, and public officials responsible for major decisions and setting general policies.

It is these engineers and public officials, after all, who need the information that can be derived from various models and analyses, and they must have it in a form useful and meaningful to them. At the beginning of any study, objectives are usually poorly defined. As more is learned about what can be achieved, people are better able to identify what they want to achieve.

Close communication among analysts, engineers, and public officials throughout the modeling process is essential if systems studies are to make their greatest contribution to the planning process.Furthermore, those who will use models, and present the information derived from models to those responsible for making decisions, must be intimately involved with model development, solution, and analysis. Only then can they appreciate the assumptions upon which any particular model is based, and hence adequately evaluate the reliability of the results.

Any water resource systems study that involves only outside consultants, and minimal communication between consultants and planners within a responsible management agency or involved stakeholders, is unlikely to succeed in having a significant impact on the planning process. Models that are useful are alive, constantly being modified and applied by those groups which are involved in plan preparation, evaluation, and implementation.

4. Characteristics of Problems to be Modeled

Problems motivating modeling and analyses exhibit a number of common characteristics. These are reviewed here because they provide insight into whether a modeling study of a particular problem may be worthwhile. If the planners' objectives are very unclear, few alternative courses of action exist, or there is little scientific understanding of the issues involved, then mathematical modeling and sophisticated methodologies are frequently of little use.

Successful applications of modeling are often characterized by:

1. A systems focus or orientation: Attention needs to be devoted to the interaction of elements within the system as a whole as well as to the elements themselves.
2. The use of interdisciplinary teams: In many complex and nontraditional problems it is not at all clear from the start what disciplinary viewpoints will turn out to be most appropriate or acceptable. It is essential that the participants in such work—coming from different established disciplines—become familiar with the techniques, vocabulary, and concepts of the other involved disciplines. It might be said that participation in interdisciplinary modeling requires a willingness to make mistakes at the fringes of one's technical competence.
3. The use of formal mathematics: Most analysts prefer to use mathematical models to assist in system description and identification and evaluation of efficient tradeoffs among conflicting objectives and to provide an unambiguous record of the assumptions and data used in the analysis.

Not all water resources planning and management problems are suitable candidates for study using modeling methods. Modeling is most appropriate when:

1. The planning and management objectives are reasonably well defined and organizations and individuals can be identified who have the necessary authority and power to implement possible decisions.
2. There are many alternative decisions that may satisfy the stated objectives and the best decision is not obvious.
3. The alternative solutions and the objectives of the system being analyzed are describable by a reasonably tractable mathematical representation.
4. The hydrological, economical, environmental and ecological impacts resulting from any decision are not obvious without modeling.
5. The parameters of the model are estimable from readily obtainable data.

-
-
-

Bibliography

Ahearne J, F. (1988). Addressing public concerns in science. *Physics Today*, 36–42.

Andreu J. J. et al. (1991). AQUATOOL: a computer assisted support system for water resources research management including conjunctive use. In Loucks and da Costa, eds. *Decision Support Systems*. Berlin: Springer-Verlag. [Discussion and description of model.]

Austin T. A. (1986). Utilization of models in water resources. *Water Resource Bulletin*, **22**(1), 49–56. [Review and evaluation of models used for water resources planning and management.]

Carey W. D. (1988). Scientists and sandboxes: regions of the mind. *American Scientist*, 76, 143–145.

Danish Hydraulic Institute (DHI) (1997). MIKE-BASIN: Operating manual and description. Hørsholm, Denmark. [Manual describing river hydraulic simulation model and its operation.]

Delft Hydraulics Laboratory (DHL) (1997), RIBASIM: River basin simulation program operating manual and description. Delft, The Netherlands. [Manual describing river hydrologic simulation model and its operation.]

Fedra K. (1992). Advanced Computer Applications. *Options* (December). Laxenburg, Austria: IIASA. [Description of decision support systems being developed at IIASA.]

Gass S. I. (1990). Model world: have model, will travel. *Interfaces*, **20**(2), 67**–**71. [Essay on use of models for decision-making.]

Georgakakos A.P. and Martin Q. W., eds. (1996). An International Review of Decision Support Systems in River Basin Operation. Proceedings of the Fifth Water Resources Operations Management Workshop, ASCE, Arlington, VA., March [State-of-Art review of decision support systems in water resources.]

Goeller B. F. (1988). A framework for evaluating success in systems analysis. *Report P-7454***.** Santa Monica, CA: The Rand Corporation. [Criteria for judging modeling success.]

Hamlet A. et al. (1996a*). Simulating Basinwide Alternatives Using the ACT-ACF Shared Vision Models*. Mobil, AL: US Army Corps of Engineers, Mobil District, September. [Description of shared vision modeling in Southeastern US.]

Hamlet A. et al. (1996b). *A History of Shared Vision Modeling in the ACT-ACF Comprehensive Study*. Mobil, AL: US Army Corps of Engineers, Mobil District, September. [Experiences using shared vision modeling in Southeastern US.]

Hamlet A. et al. (1996c). *Basic STELLA II Users Manual for the ACT-ACF Shared Vision Models*. Mobil, AL: US Army Corps of Engineers, Mobil District, September. [Guide for shared vision model users in a river basin in Southeast US.]

Kindler J. (1987). Systems analysis approach to water resources management: state of the art. *Symposium On Recent Developments and Perspectives in Systems Analysis in Water Resource Management*. Perugia, Italy: WARREDOC. [Overview of water resources systems analysis.]

Kindler J. (1988). Systems analysis and water resources planning. *International Symposium on Systems Analysis Applied to Management of Water Resources*. Rabat, Morocco. [Overview of water resources systems analysis.]

Loucks D.P. (1995). Developing and implementing decision support systems: a critique and a challenge. *Water Resources Bulletin* (Journal of American Water Resources Association) **31**(4), August. [Overview of development and use of decision support systems.]

Loucks D. P., Stedinger J. R., and Shamir U. (1985). Modelling water resources systems: issues and experiences. *Civil Engineering Systems*, 2, 223–231. [Some applications of optimization and simulation models to water resources problems.]

Loucks D. P. and da Costa (eds.) (1991). *Decision Support Systems*. NATO Series G. Vol. 26. Berlin: Springer-Verlag. [Articles in the application of decision support systems.]

Majoni H. and Quade E. S. (1980). *Pitfalls of Analysis.* New York: John Wiley. [Common mistakes of systems analysts.]

Miser H. J. (1980). Operations research and systems analysis. *Science*, **209**, 174–182. [Some history and critique of systems analysis and its use.]

Palmer R.N., Keys A. M. and Fisher S. (1993). Empowering Stakeholders Through Simulation in Water Resources Planning. Proceedings of 20th Conference on Water Resources Planning and Management Division, ASCE, NY, NY. [Shared vision modeling experiences and approaches.]

Pool R. (1990). Struggling to do science for society. *Science*, **248**, 672–673. [Difficulties in applying science in policy-making.]

Reynolds P. J. (1987). Future research needs in systems analysis and to application to water resources management. *International Symposium on Recent Developments and Perspectives in Systems Analysis in Water Resource Management*. Perugia, Italy: WARREDOC. [Research needs.]

Rogers P. P. and Fiering M. B (1986). Use of systems analysis in water management. *Water Resources Research* **22**(9). [Critical review of applications using optimization and simulation models. Experiences using shared vision modeling in Southeastern US.]

Shapiro H. T. (1990). The willingness to risk failure. *Science*, **250**, 609. [Risk bias in systems and policy analysis.]

Simon I-I. A. (1988). Prediction and prescription in system modeling. *15th Anniversary of IIASA*. Laxenburg, Austria: Institute for Applied Systems Analysis. [Critique of systems modeling.]

Simonovic S. P. et al., eds. (1990). Water resource systems application. Proceedings of International Symposium on Water Resource Systems Application, University of Manitoba. [Ariticles describing applications of systems analysis to water resources planning and management. Experiences using shared vision modeling in Southeastern US.]

Stokey E. and Zeckhauser R. (1977). *A Primer for Policy Analysis*. New York: W. W. Norton. [Elements of and applications in policy analysis and modeling. Experiences using shared vision modeling in Southeastern US.]

Tomlison R. (1980). Doing something about the future. *Journal of Operational Research Societies*, 31, 467–476. [Critique of limitations of policy and systems analysis. Experiences using shared vision modeling in Southeastern US.]

Walker W. E, (1987). Important hard problems in public policy analysis. *Report P-7282*. Santa Monica, CA: The Rand Corporation. [Characteristics and challenges of policy analysis. Experiences using shared vision modeling in Southeastern US.]

Werick W. J., Whipple, W. Jr., and Lund J. (1996). *ACT-ACF Basinwide Study*. Mobil, AL: US Army Corps of Engineers, Mobil District, August [Description of modeling exercise for a river basin in Southeast US.]

Biographical Sketch

Daniel P. Loucks obtained a BS from Pennsylvania State University in 1954, a MF from Yale University in 1955, and a Ph.D. from Cornell University in 1965. Since 1965 he has been on the faculty of the School of Civil and Environmental Engineering, Cornell University. In 1976 he was appointed Professor of the Department of Environmental Engineering in the School where he teaches and directs research in the application of economic theory and systems analysis methods to the solution of environmental and regional water resources problems. He has authored numerous articles and book chapters in these subject areas. He served as Chairman of the Department from 1974 to 1980, and as Associate Dean for Research and Graduate Studies in the College of Engineering from 1980 to 1981. During periods of leave from Cornell, Loucks was a Research Fellow at Harvard University (1968); an Economist at the Development Research Center of the World Bank (1972–73); a Research Scholar at the International Institute for Applied Systems Analysis (1981–1982); and a Visiting Professor at the Massachusetts Institute of Technology (1977–78), the University of Colorado in Boulder (1992), the University of Adelaide in South Australia (1992), the Aachen University of Technology in Germany (1993 and 1995), the Technical University of Delft in the Netherlands (1995), and the University of Texas in Austin (2000). Since 1969 he has served as a consultant to private and government agencies and various organizations of the United Nations, the World Bank, and NATO involved in regional water resources development planning in Africa, Asia, Australia, Eastern and Western Europe, Latin America, the Middle East, and the previous USSR. Since 1976 he has been a visiting professor in water resources-environmental systems engineering at the International Institute for Hydraulic and Environmental Engineering, Delft, The Netherlands.

Loucks has served on various committees of the National Research Council of the National Academy of Sciences, and from 1977 to 1990 was a U.S. member of an advisory committee for the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria. The Secretary of the Army appointed him to US Army Corps of Engineers Environmental Advisory Board in 1994. He served as Vice Chair of the EAB in 1995, as Chair from 1996 to 1998, and received the Commander’s Award for Public Service in 1998. Loucks was awarded the Huber Research Prize in 1970 and the Julian Hinds Award in 1986 by the American Society of Civil Engineers. He was elected to Fellow in the Society in 1983 and to Honorary member in 1998. In 1975 he received a Fulbright-Hayes Fellowship to lecture in Yugoslavia. He has served as chairman of various committees in professional societies in civil engineering, geophysical science, and operations research. He serves as an associate editor and as a member of editorial boards of several professional journals in the U.S. and in Europe. He was elected to the National Academy of Engineering in 1989. He received Distinguished Lecture Awards by the National Research Council of Taiwan in 1990 and 1999, an EDUCOM Award for software development in 1991, the Senior U.S. Scientist Research Award from the German Alexander von Humboldt Foundation in 1992, and the Warren A. Hall Medal from the Universities Council on Water Resources in 2000.