Modelling water resource systems: issues and experiences

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Since their first serious introduction in the early 1960s, systems analysis methods have held out a promise of providing information that can help improve decision making. This paper surveys a number of actual applications of optimization and simulation modelling that illustrate the variety of problems studied, the variety of approaches used to study them, and the variety of outcomes or results of such studies. Some studies have been very successful, some have not. Given the varying but generally beneficial results of such studies, it seems clear that research on, together with application of, systems analysis techniques to water resources and environmental problems should continue. The paper concludes with some suggestions for facilitating the development and effective application of this methodology.

Keywords: water resource systems, systems analysis decision making, mathematical modelling

Research in water resources and environmental policy modelling has involved professionals from many different disciplines in the engineering, social, and natural sciences. While the overall field of water resources and environmental systems modelling encompasses many different disciplines, those engaged in the development and application of models for assisting in the analysis of water resources and environmental management and policy issues have tended to become identified as water resources and environmental systems analysts. This, or any similar title, applies regardless of the professional background of the analyst, be it economics, engineering, geography or planning. This new 'discipline' now has its own professional journals, speciality conferences, awards, and textbooks. It is taught at most major universities.

The central objective of research in water resources and environmental management and policy modelling has been, and continues to be, focused on the development and application of mathematical models to assist decision makers. These models address questions pertaining to decision making: what, where, when, and how best to do (or not to do) something, and why.

Those in this discipline, as indeed in every discipline having an interest in influencing individuals responsible for management and policy, often tend to question their effectiveness. Are modellers very useful? Do they really help managers or policy makers? Is the role of modelling important and growing? Should modellers expect decision making organizations to seek the information modellers think they can offer on how better to use science, engineering, economics, law, and other disciplines for the benefit of us all? Have those involved in research in systems modelling and analysis achieved their goal of providing useable and useful tools and information for improved decision making? Are systems models increasing the efficiency and effectiveness of development programmes for water resources and environmental management? Have the models developed thus far been effectively adapted to the decision making process within various types of institutions, in both the developed and less developed regions of the world?

After some thirty years of experience in the application of systems analysis techniques to water and environmental problems, it seems reasonable to attempt to evaluate the results and, based on this evaluation, sketch some directions for future research. This paper begins with a brief review of some of the recent history of water resources and environmental systems modelling. This is followed by a summary and evaluation of a small but representative sample of some actual applications of policy and planning models throughout the world. This summary and evaluation is followed by a discussion of some current issues and concerns often voiced by managers and decision makers. These suggest some directions for future research activities in management and policy modelling.

A historical perspective

The Water Program at Harvard University was one of the first multidisciplinary teams to begin the development of some 'new techniques for relating economic objectives, engineering analysis, and government planning'[1]. Since then, an industry of water resource and environmental 'systems designers' has developed. The early research at Harvard and other universities and institutes in the US and Europe looked extremely promising. These results, coupled with an enthusiasm for the use of systems analysis in other areas of government, and an increasing concern for improved water resource management, resulted in substantial funding for research in the US for this new area. This led to the growth of water resources and environmental systems modelling groups within engineering, economic, and natural resource departments

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of many major universities and other research institutes in North America, Europe, Asia, Australia, and throughout much of the developed world. Thousands of journal articles, books, and technical reports have been published on this subject. The net result has been an increase in modelling capability as well as in the understanding of its potential, its benefits, and indeed, its limitations.

Critical to the successful application of mathematical models for management and policy planning is an institutional interest and commitment. In the two decades since Harvard's 'Design', there have been many applications of systems models to water resource planning, management, and policy studies. Many of these are relatively small applications, carried out by consulting engineers or planners, or by staff within agencies responsible for planning, managing, or advising higher level decision makers. These are rarely reported in the literature. Some of the larger, more comprehensive system modelling applications are reported. Many of these large applications have been funded by the UN Development Program and various international development banks. These international agencies often require the application of systems analysis methods for large scale regional water resource development and environmental management investment planning projects. Indeed, critical path methods are commonly used to help plan these planning projects themselves.

A second form of institutional commitment that has been critical to the successful application of models is the establishment and support of modelling centres. These centres develop, document, compare, and maintain models, and provide advice and instruction in their use. Three such centres in the US include the Hydrologic Engineering Center of the US Army Corps of Engineers at Davis, California; the Center for Water Quality Modeling of the US Environmental Protection Agency in Athens, Georgia; and the International Ground Water Modeling Center of the Holcomb Research Institute at Indianapolis, Indiana. Models maintained and made available by these and other centres have been applied throughout the world.

Models maintained by these modelling centres tend to be mathematical models describing the physical components of the water resources or environmental systems. Typically, such models are used to gain an understanding of the physical performance of these systems, and to simulate their physical response under various development and operation schemes. The models are not designed specifically for management or policy planning.

It is important to differentiate between mathematical models of physical systems and mathematical management or policy models. The latter must have within them an adequate representation of the physical system (eg as constraints in an optimization model), but their purpose is unique. Their objective is not to describe the behaviour of the physical system, nor to gain an understanding of this behaviour, but to aid in decision making. Therefore, the representation of the physical systems must be suitable for this purpose: adequate to capture the important features, yet efficient enough to allow solution of the management of policy model that includes many other aspects and considerations. The art of modelling the physical systems within management models is one of the most crucial and challenging aspects of any modelling effort.

Another factor that has influenced the successful development and application of management and policy models has been the spectacular growth in digital computer technology. When the Harvard Water Program began, IBM in the US was selling its top of the line 650 computer. By the time Harvard's 'design' book was published in 1962, the Harvard Water Group was solving its models using FORTRAN II on an IBM 704, having just over 32K 16-bit words of internal memory capacity. Today, this capacity can be contained in a single memory chip about the size of a pill enclosed in a computer the size of a pocket watch. In a few years, the memory capacity on such chips will be considerably greater[2,3].

Some modelling applications

There have been many applications of water resources and environmental management and policy modelling in the past two decades. To assess how effective past research in systems modelling has been, and to help identify current concerns and directions for future research, a sample of these applications has been reviewed. The conclusions drawn from this limited review are admittedly subjective, but seem representative of those that would result from a more thorough evaluation.

For this review, applications were chosen from throughout the world. Each is an actual application, not just an illustrative exercise. Each application involved a client, ie, a public (government) agency, who desired answers to a particular water resources or environmental management system planning, design, or operating problem. The selected applications, listed and summarized in the Appendix, range from some initiated and completed in the early 1960s to others that are very recent.

Problems addressed in applications include:

(a) conflict resolution involving water quantity and quality use and regulation
(b) multiple purpose regional or basin development and water management
(c) interbasin transfer of water supplies and wastewater effluents
(d) surface and groundwater quality protection and management
(e) design and operation of water distribution system
(f) wastewater collection, treatment, and disposal
(g) irrigation water supply design and operation
(h) hydropower development and operation
(i) flood control and flood plain development and regulation
(j) reservoir operation for multiple purposes
(k) environmental protection

The ultimate client has been one or more local, regional, or national government agencies. Collaborating agencies have included other government agencies, consulting firms, international organizations, research institutes, and universities. The modelling approaches most often used have been simulation, optimization (mostly linear and dynamic programming), decision analyses, and input-output analyses.

Table 1 presents a summary evaluation of these applications based on six different criteria. Clearly one

Table 1 Overall outcome of applications

Criterion	Relative frequency of occurrence
Model solution implementation	Very low
Model implementation and use by planners and policy makers	Low (policy studies); average (operation studies)
Model results entering into decision debate	High
Model results affecting institutional change	Very low
Training–technology transfer	High
Complete failure, no impact	*Low/medium*

would not expect complete success in meeting each of the six criteria, as indeed modelling efforts are rarely designed or expected to satisfy all of them. For example, most would agree that applications of modelling designed to help or aid decision makers should only rarely, if at all, be designed to provide actual decisions regarding often complex management or policy problems. Implementing a particular solution differs from implementing or using a particular model. In the latter case, the model output serves only to help focus the debate about what to do; it is not itself a substitute for the planning, managing, or policy making process.

These and other applications point to some major factors that influence the success or failure of modelling applications. These factors include:

(a) Institutional or political context within which the application is performed.
(b) Commitment to establish plans, procedures, and policies.
(c) Relationships between clients and analysts and the quality and frequency of communication between them.
(d) Extent of on-site training and model implementation by those within the institution desiring the study.
(e) Resistance to new approaches or technology.
(f) Availability of data and the appropriateness of the model given the data.
(g) Scope and complexity of the problems being addressed.
(h) Extent and duration of the study and whether or not there is any follow-up by those primarily responsible for model development and use, once modelling tools or model results are available.

Some of the factors influencing the success or failure of a particular application can only be assessed by those involved in the planning and implementation of such applications. Other factors can be given more attention by those involved in model research and development[4].

Current issues

Current status, concerns, and opinions regarding policy modelling can be obtained from reading or listening to what is written or spoken by those actually involved in water resources and environmental management planning. Some of those concerns are discussed next.

Model appropriateness, complexity and validity

Clearly there is no single best model for a given class of water resources problems. However, are the models now available sufficient for analysing present and future problems, given various levels of budget, time, personnel, and quantity and quality of data? Can existing models provide credible information, and are there ways of testing or evaluating model credibility? These issues need more attention from those developing planning, management, and policy models.

It seems certain that modelling for planning, management, and policy making will continue to be controversial. Politically, data and models are like guidelines and standards: they help shape the results, who wins and who loses. It is the handling of goals and values, ie, tradeoffs, that usually confounds its application the most. Decision makers want an indication of who cares and how much, as well as information on the physical and economic impacts of any proposed solution.

A wide gap exists between models developed for guiding decisions and the actual decision making process at various levels within an organization. Models are often conceptually inappropriate, or require data and parameter estimates which do not exist or in which one can have little confidence. Modelling should be technically sound, predict cause and effect, but should be done within the political and institutional frameworks in which problems are addressed and decisions made.

To most policy analysts, what is appealing is the detail. To most policy makers, simplicity and generality are appealing. How detailed should a model be to learn what one needs to know? How does one know what he needs to know before he knows it? This has been called the 'dilemma of rigour or relevance'[5]. It seems that model developers should seek simplicity, but distrust it.

A near cost-effective or economically efficient solution may be preferred to the most cost-effective or efficient solution. How does one develop models to identify more robust or flexible solutions that are economically acceptable, and also more adaptive to unforeseen events that could affect future system design, operation, performance, and cost? Also, how does one know when a good enough model or solution has been found? Are there standards of performance that can be identified that could apply to the art of policy model development and use, as there are for the art of structural design and construction?

Model validity is a common, widespread concern, and worthy of substantial additional study. Actual model validation can be done only by applying the model. This of course requires the acceptance of the model before its application. Similarly, there is a problem in comparing the performance of two models, because both models cannot be used simultaneously. Model appropriateness is difficult to judge because the decision maker's action has an effect on the system.

The problems and issues identified by the above concerns regarding model appropriateness, complexity, and validity are not simple ones. It seems evident that a spectrum of modelling approaches is needed. This spectrum includes models that are comprehensible and credible to the model users, ie, managers, planners, and policy makers or their staffs. Decision-making problems are often analysed by resorting to complex, comprehensive, and potentially less comprehensible models. Such models are inevitably difficult to verify. A better approach may be to combine a sequence, or hierarchy, of comprehensible models, when appropriate, to analyse features of more complex problems. Regardless of model complexity, verification or validation is essential, though difficult, especially for those portions of models that include assumptions concerning future costs, benefits, technology, and the like.

Information needs and communication

Do existing policy models provide information that policy makers need or consider useful? Can analysts communicate that information in a more meaningful and effective manner? How can analysts better assist decision makers and their staffs whose objectives and political considerations are, in large measure, unknown or unarticulated to analysts during the decision making process? Sometimes, even if the problem or system is the same in the minds of both analyst and decision maker, the questions asked are different. Analysts who ask 'What do we know or what can we learn?' may be of little value to a decision maker who wants to know 'What do we do and who will care?'

Most existing modelling approaches stress the economic, environmental, and hydrologic-engineering aspects of problems that are relatively easy to quantify and model. These physical/economic aspects must be coupled to more of the social and political aspects of planning, management, and policy problems if the information to be derived from modelling is to be more useful to decision makers. There is also concern about how both optimization and simulation models, and other types of analysis procedures, can be used in an exploratory context or environment where planning, management or policy objectives are not clearly specified. Finally, it is essential to learn more about how to identify what information is most useful for various levels of decision making, extract this information from all the data generated by systems models, and communicate it in a more effective manner[6].

Decision makers usually cannot state their objectives in clear quantitative terms. Models which depend on prespecified objectives depend on too much. One could argue that objectives and goals could be established in public discussions and models can play a part in and during these discussions. Public information programs are needed but should not be substituted for public participation in establishing criteria for decision making. Setting specific goals is a dynamic process, taking place continuously throughout the decision making process.

Political decisions tend to be incremental, permitting interactive learning from both positive and negative political feedbacks from a continuing sequence of adapting incremental decisions. To be most useful, model solutions must also be incremental. Individuals committed to a previous decision are not likely to want to hear that they have been wrong but may, however, be willing to learn how to improve upon what they are currently doing by making some small changes.

Systems analysts are constantly being reminded that, as a group, they do not communicate very well with decision makers. How to communicate technical, environmental, economic, and social information so that busy decision makers and the public are able to visualize its impact on their physical and political environment is one of the most critical research needs today. Problems in communicating the right kind of information, and in the right (most meaningful) manner, will be a challenge to analysts, psychologists, computer programmers, and writers (including this one, a reviewer has stated) for years to come.

Model implementation, interaction, and technology transfer

There is an important difference between developing models for planning, managing, and policy making, and designing and building a physical structure. Operators of a physical structure do not usually need to know much about what is in it or how it was constructed. If a model is to provide useful information to a planner, manager or policy maker, they (or more realistically the individuals who, they trust, will use the model) must know something about the model. They must be able to work with that model, modify it as needed, and be able to test and evaluate its assumptions and results. Model implementation, interaction, and technology transfer are related to all of the issues previously discussed.

The demand for systems analysis has typically come from middle management levels. Some at this level have claimed that their biggest problem involves trying to inform higher level decision makers. The turnover of these higher level decision makers is often relatively rapid, and when not changing jobs, these higher level individuals are constantly in meetings. Analysts are often not sufficiently sensitive to the need for interaction with higher level decision makers. Who trains or advises these decision makers? It has been suggested that individuals are needed to serve as brokers who can facilitate the interaction between those who model and analyse, and those who can use the information. Brokers, knowledgeable about what analysts do and sensitive to the needs of decision makers, can provide a valuable link between these two groups.

Too often, models are viewed as static when they should be viewed as part of a process. Communication, coordination, and representation are decision-making processes rarely found in models. Yet, any environmental or water resources system contains, in addition to structural or physical components, behaviour relationships among people and institutions. Interaction among various groups of individuals and agencies takes place to maintain relationships and to facilitate adjustments to change, cooperation, competition and conflict. Objectives, targets, beliefs and opinions evolve from and reinforce this interaction, and result in action programs that create new images, attitudes and institutional alliances within the system. Any model in the system should include, or at least be adapted to, this dynamic interactive environment.

There are special problems in transfering the technology of model development and use to developing countries. Lack of computer facilities is one factor, but often minor compared with those involving personnel in decision making organizations. Lack of individuals exposed to systems modelling approaches, lack of communication between analysts and such individuals, lack of training of local analysts, low reliability of data, and the tendency to use models developed elsewhere that are not always appropriate for local conditions, are among many problems confronting the effective use of systems modelling in developing countries[7].

It is obvious that models will never be able to satisfy every decision maker or address every problem. These concerns, however, suggest some opportunities, and indeed some needs, for future research.

Future research directions

Given the assessment of past applications and the range of concerns and issues just discussed, it seems clear that there are opportunities to improve both the predictive capabilities of models and approaches taken to management and policy modelling. Some new approaches to systems modelling will surely result from addressing these issues and concerns as well as from the rapid growth in information processing technology.

Interactive modelling for synthesis and analysis

Additional research is needed to enhance 'human-computer-model' interaction, information management, and communication. This will facilitate the exploration, analysis, and synthesis of improved management plans or policies. To permit interactive exploration and synthesis, large complex models that are often needed to predict impacts of various policies or decisions may have to be broken down into a hierarchical sequence of models designed to be more adaptive to the changing needs of decision makers and solved more quickly in a dynamic decision making environment. Research will be needed in order to learn how best to do this, and how to link together models and data bases. This is especially challenging when the temporal and/or spatial resolutions of these component models and data differ. Much of this research will require some knowledge of computer science.

The growth in the use of microcomputers and inexpensive minicomputers should help reduce the gap between model development and model use. There will be more development and transfer of tools rather than answers. Some of these tools will include the hardware as well as the software, as a turnkey package. More flexible, interactive computer languages can substantially reduce software development time and cost. Future research in computer software development and transferability is an absolute necessity if this increasing proportion of the total cost of model development and implementation is to be controlled.

Given the explosive growth in the capability and availability of interactive computer graphics, future research should also be directed towards learning more about how to use graphics more effectively for data and model management and communication. The advent of video disks or laser cards that can contain enormous data files, capable of being displayed in pictorial form when appropriate, and the ease at which digital data will be accessible to any potential user through computer networks, will make it all the more important that analysts of the future have available models that can take maximum advantage of this technology and information.

Models for improved impact prediction

A continual need will remain to improve existing models and develop new modelling approaches to more accurately predict the biological, chemical, and physical processes that occur within water resources and environmental systems. Improved methods of verifying these models are needed along with methods for reducing the number of parameters whose values need to be determined. Some of this improvement may come from a better understanding of natural phenomena, but, in addition, new mathematical methods may be needed to better identify parameter values as well as to validate model results. Also, better models are needed to explore the interfaces of larger physical and social systems involving air, land, and water and their use in both rural and urban environments. All this research may lead to increased model complexity that may be more appropriate for science than for planning or policy. Research will be needed on how to generalize the results of complex models, or how to simplify complex models and still maintain model credibility.

Risk and uncertainty and their perception

Improvements are needed in the prediction and assessment of risks and uncertainties. There is also a continuing need to improve how risk, and uncertainty are communicated to policy makers. Finally, more research is required to improve abilities to develop robust designs and policies that can adapt effectively to unexpected future events.

No matter how sophisticated the prediction, communication and compensation for future risks and uncertainties, estimates of the risks and uncertainties involved are inherently speculative. They are never definitive. Nor can such quantification shed light on the value-laden questions of whether the risks involved are socially or personally acceptable. Acceptability is, in part, dependent on the extent to which risk is involuntary or voluntary. Major discrepancies between technical evaluations of risk and uncertainty, and public perception of that risk and uncertainty, can often stalemate the decision making process concerning a project or policy. Hence, solutions to questions involving risk lie not only in research in the science of risk assessment, but in developing procedures that go beyond quantitative comparisons. These procedures must focus on the actual process of decision analysis and decision making in risky situations, and must also consider the cultural, social, economic, and institutional factors influencing decisions on issues involving risk and uncertainty.

Model validation and effectiveness

Because future events, objectives, and conditions are often significantly different than those envisaged during the planning and implementation of some past projects, and because of personal and institutional adversions to potential criticism, it is difficult to learn from past modelling applications how to improve the validity of modelling approaches. Research is clearly needed to learn how to do this, and to provide criteria and methods for evaluating the effectiveness of model use in a decision making process. Which modelling approaches are best for which institutional styles and settings? Can some modelling standards be identified, and should they be, at least for modelling practice if not for modelling research? Can a theoretical basis be developed for, say, comparing the effectiveness and efficiency of interactive procedures for data and model management, man–machine interaction, and graphical or pictorial displays of model results? These are questions that future research should address.

Modelling approaches and use

Continued research in management and policy modelling will, in all likelihood, lead to shifts in how models are developed and used in the future. These will be shifts in emphasis rather than shifts out of one approach and into another. Through an improved (friendlier and quicker) interface between any user and the models being used, there will be a greater potential for systems models to be used within dynamic policy making or planning process.

Information available from remote sensors and digital data banks, coupled with that derived from models, can be enormous. Research is needed on improved methods of linking models to such data bases, including digitized maps and other spatially and time varying data obtained from remote sensing or aerial photography. Further research is needed to determine how best to contrast and present this together with other information in the desired level of detail, and in a manner that will maximize the comprehension of that information by analysts, managers, planners, policy makers and the interested public. Research is also needed to improve the process of transferring modelling approaches and technology to the potential users for their continued modification and use.

Specific systems problems and broader policy issue analyses

This research on methodology is often best accomplished in the context of a particular and important problem or issue and institutional setting. The particular water resources and environmental management or policy problems considered important now and in the immediate future will vary from one geographical region to another.

Among the problems that apear to be generally widespread and of immediate concern to policy makers are those involving the need for research on:

(a) Predicting water quality impacts from point and non-point waste sources, and establishing and achieving improved water quality standards.
(b) Surface-groundwater interactions, especially with respect to predicting and managing the transport and transformation of toxic contaminants.
(c) Estimating ecosystem responses to air, land and water use policies (including the acid precipitation issue) more accurately.
(d) Predicting demand, supply, and price relationships for municipal water supply systems.
(e) Identifying more rational pricing policies for water utilities (both municipal and agricultural).
(f) Designing and operating irrigation systems, re-use of saline water, and re-use of reclaimed sewage.
(g) The joint operation of multiple-purpose, multiple-reservoir systems, especially those that include hydropower production.
(h) Managing non-point wastewater sources and wastewater land disposal systems.
(i) Automated control and increased reliability of water supply, wastewater collection, and treatment systems, and determining appropriate tradeoffs between costs and expected information content.
(k) Synthesizing hydrologic records taking into account parameter uncertainty and 'non-hydrologic' evidence of hydrological events.
(l) Planning and financing of infrastructure expansion, replacement, and maintenance policies.
(m) Flood forecasting, flood management, and flood damage reduction.
(n) Identifying more flexible or robust alternatives for the capacity expansion of water-related systems.
(o) Water conservation, use and re-use policies.

Not only should systems analysis tools assist in providing quantitative 'answers' to these and other important problems at specific locations, but they should also assist in providing qualitative information on the more general or broader policy issues as well. A vigorous and explicit pursuit of such issue-clarifying analyses should shape an increasingly larger portion of future research.

Conclusions

It seems reasonable to conclude that in the two decades since Harvard's 'Design of water resource systems' model development and use has been increasingly influential. This is especially true for engineering design and operation studies, and perhaps less so for more strategic regional development and policy studies. The more political the problem (ie the greater its scope and the more conflicting economic, social as well as scientific evidence there is to support various political positions) the less dominance or influence one can expect from quantitative policy modelling efforts. This does not have to mean that, as the problem gets 'bigger', models will get relatively less useful. Rather, it suggests that, as the problem gets more complex, more attention should be given to successful model use within the political planning or policy making process.

The goal of modellers and analysts has been, and will continue to be, one of producing data, knowledge, and tools relevant to decision making. It will not be to determine the exact answer to a specific problem. Yet knowledge needed for understanding does not always correspond to knowledge needed for decisions. Model builders concerned with scholarship often have differing objectives from potential model users concerned with decisions and their political impacts. Research in the discipline of decision modelling and analysis should be tailored to the problems of action and issue clarification if it is to be relevant to decision makers. There is an important role for practitioners and 'brokers' to bridge the gap between those involved in model development research and those involved in model application and use.

An understanding of and a focus on decision makers' needs and decision making procedures is necessary in identifying the problems, questions, and issues that need study. To do this, one must have a knowledge of the particular decision making process. When such knowledge is employed, the information produced will more likely address the important policy questions, and hence play a more meaningful role in decision making. Proper decisions with respect to appropriate model complexity and suitability for the institution and the problem, model validation (if possible), model implementation (when appropriate) and sufficient attention to the communication of information derived from models and data are also critical factors for the success of any policy modelling effort. Model complexity can easily exceed what is justified given limited institutional sophistication and experiences, as well as limited quantity and quality of data. In such situations, excess model complexity often prevents effective model use for policy and planning. Sets of simpler models might be preferable, even for complex problems. In addition, any attempt to present too much information may be undesirable. It is necessary to identify and meaningfully communicate the right amount and kind of information at the right time.

While the above guidelines seem obvious, it is not at all clear how they can best be achieved. Research is needed on:

(a) Building models that permit planners, managers or policy makers, or their advisors, to explore and discover the likely impacts of their own ideas.
(b) Design of models that can easily be modified to examine situations unforeseen by the model builder.
(c) Building models that are credible and reliable, and compatable with available data.
(d) Improving the capability for single-objective or multiple-objective screening, especially in the presence of additional unknown objectives.
(e) Improving the means of synthesizing as well as analysing designs, plans or policies.
(f) Developing better tools for helping to improve the effectiveness (doing the right things, or asking the right questions) of the planning, managing or policy making process as well as for identifying efficient plans or policies.

The current shifts in emphasis from design to management and operation, from large comprehensive regional or basin studies to more local and politically or institutionally viable project-oriented studies, and the current revolution in information processing and display technology, will affect future research in systems modelling. This will affect future types of models developed and applied to specific problems or issues being addressed. Data management will become an increasingly important aspect of decision analysis as modelling becomes more ambitious and more interactive. Improved human-computer-model interaction may tend to reduce the need for incorporating behavioural assumptions within models, and should provide an improved means of synthesis as well as analysis. In any event, decision making will continue to demand better modelling. Policy changes will continue to be incremental and, barring serious surprises, decisions will rarely be revolutionary. Hence, policy modellers and analysts should focus their problem and issue-oriented research on helping to guide these incremental changes. Environmental and water resource systems engineers and analysts can play a major role in helping to identify those incremental changes that will lead to more effective and efficient decisions regarding the planning, development, and management of natural resources.

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Appendix: A summary of some water resources and environmental modelling applications

Project	Location	Dates	Reference
Delaware river estuary	Eastern USA	Mid-1960s	8–10
High Aswan dam for hydropower and irrigation	Egypt	Mid-1960s	11
Waterlogging and salinity	Indus Plain, Pakistan	Mid-1960s	12–14
Water, irrigation and power resources development	West Pakistan	Late 1960s	15
Ganges–Brahmaputra basin	India and Pakistan	Late 1960s	16, 17
Texas water resources development	Texas	Late 1960s	18, 19
North Atlantic regional water study	Northeast USA	Late 1960s	20
National water management	Israel	Continuing, late 1960s	21, 22
Vistula river basin	Eastern Poland	Early 1970s	23, 24
Trent river system	England	Early 1970s	25
Tsengwen reservoir irrigation project	Southwestern Taiwan	1970	26
Upper Mures river basin	Central Romania	Early 1970s	Internal restricted FAO documents; some project reports written in Romanian
Saint John River	South eastern Canada and North USA	Early 1970s	27–29
Vardar/Axios river basin	Yugoslavia/Greece	Early 1970s	30, 31
Farm irrigation scheduling	Israel	Early 1970s	32–34, 84
Programming models of Mexican agriculture	Mexico	Early 1970s	35, 36
Land, water, and power studies	Bangladesh	Early 1970s	37–39
Mu river valley multipurpose scheme	Burma	Early 1970s	40
Rural water supply	North eastern Thailand	Early 1970s	41
Irrigation projects	North eastern Brazil	Early 1970s	42
Pricing irrigation water	Iran	Early 1970s	43
Optimal cropping pattern	Bari Doab tract Punjab, India	Mid-1970s	44
Estimating aquifer parameters	Tulum Valley and Mendoza Valley, Argentina	Mid-1970s	45
Water utilization and reallocation	Pirque Valley, Chile	Mid-1970s	46
Agricultural water conveyance system	Algeria	Mid-1970s	47
Flood control and protection	South western Holland	Mid-1970s	48
Elkhorn river basin	Eastern Nebraska	Mid-1970s	49, 50
Seversky Donnets river quality	Ukraine, USSR	Late 1970s	51
Rio Colorado river basin	Argentina	Late 1970s	52
Irrigation planning and development	Algeria	Late 1970s	53–56
Upper Paraguay river basin	Brazil, Bolivia and Paraguay	Late 1970s	57
National water management	The Netherlands	Late 1970s	58
Irrigation in the Chao Phraya river basin	Thailand	Late 1970s	59
Operation of High Aswan dam	Egypt	Late 1970s	60–62
Water resources and agricultural development planning	Qatar	1981	63–65
Reservoir yield and operation of proposed Sardar Sarovar dam	Narmada river, Gujarat, India	Early 1980s	66, 67
Regional wastewater management	Western Suffolk County, New York	Early 1980s	68
Washington metropolitan water supply	Eastern USA	Early 1980s	69–71
Eutrophication in Lake Balaton	Hungary	Early 1980s	72, 73
Water supply capacity expansion in southwestern Skane	Sweden	Early 1980s	74
Neusiedler See watershed development and quality management	Eastern Austria	Early 1980s	75, 76
Summary: reservoir operation	Numerous	1960s–1970s	77, 78
Other applications	Numerous	Late 1970s–early 1980s	27, 79–83