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Tools for Water Management
One View of the Future

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Abstract: *Floods, droughts, water scarcity, and water contamination are some among many water problems that are present today and will be even more noticeable in the future. In the past, many different tools have been used for simulation and optimization of complex water resources systems in order to provide an improved basis for decision making. The continuing evolution of information technology (hardware and software) creates a good environment for the transition to new tools. Application of the systems approach to water resources planning, management, and operations has been established as one of the most important advances made in the field of water resources engineering. Based on the lessons learned, this contribution provides my personal view on the tools to be used in the future. Two paradigm shifts are discussed. The first one is focusing on the complexity of the water resources domain and the complexity of the modelling tools in an environment characterised by continuous rapid technological development. The second one deals with water-related data availability and natural variability of domain variables in time and space affecting the uncertainty of water resources decision making.*

Keywords*: Systems analysis, water resources, simulation, fuzzy sets, optimization, uncertainty, complexity.*

Introduction

The highest good is like that of water.
Tao te Ching, chapter VIII

The earliest agricultural settlements are identified as the start of a major human preoccupation with water issues like the protection of people against floods and insurance of an adequate and consistent supply of usable water. Quinn (1992, 1996) attributes to this event a division between two cultures, "takers" and "leavers," and the beginning of the destruction of human heritage. An opposing view expressed by Meadows et al. (1992) sees agricultural revolution as "a great step forward." Either view taken, water and its responsible management remains in the centre of attention. The UN estimates that in 1999 some 1.2 billion people in developing countries lack access to safe drinking water; another 2.9 billion lack adequate sanitation. Four million children die each year from water-related diseases, and women and children throughout the world spend billions of hours hauling water for domestic use. Solutions for assuring adequate water supply and protection from floods even at best can be regarded as only of transient value (Wallis, 1993). Water is an essential element embedded in the positive feedback loop describing the relationship between food availability and population growth as shown in Figure 1. Population and regulatory pressures, political and economic instabilities, and variation of climate can all contribute to further stressing of water resources as we proceed into the next millennium. In dealing with these pressures up to the present, water resources experts have been using different tools ranging from speculative, observation-based, experimental, to theoretical (Helweg, 1985). To offset these pressures in the future, we will have to rely more and more on sophisticated information management technology. Some current trends are indicating stronger future reliance on computer networking, easily accessible databases, decision support systems, object oriented programming, and system dynamics simulation.

The following section describes the two paradigms that form the basis for my vision of the future: the complexity paradigm and the uncertainty paradigm. The discussion will continue with the presentation of tools that may be used in the future for water resources management. The paper will close with the articulation of the vision for water management tools in the next decade.

Two Paradigms That Will Shape the Tools for Future Water Management

Professional experience acquired over 25 years taught me a number of lessons (Simonovic, 1999), organized below in two groups.

Domain specific lessons:

- Population increase creates serious water management problems.

- Agriculture, industry, domestic use, power generation, and navigation are the five socioeconomic sectors that depend directly on water.
- Demand for water is growing.
- Interdisciplinary studies are required in solving water resources management problems.
- The public must be involved in the management of water resources.
- Institutional change, education, training, and cooperation are necessary in order to address the water problems of the 21st century.

Technical lessons:
- Integrated planning and management based on the use of systems approach is one very efficient solution for complex water resources problems.
- Modelling tools have an application in water policy analysis.
- Decision support tools including optimization models are considered for operational application.
- Improved tools for planning and decision making are necessary together with a well co-ordinated database.
- Complex water decision-making processes require technical support.
- Training and institutional development play an important role in practical application of optimal management strategies.

Reflecting upon all personal experience, two paradigms are identified that will shape tools for future water management. The first one is focusing on the complexity of the water resources domain and the complexity of the modelling tools in an environment characterised by continuous, rapid technological development. The second one deals with water-related data availability and natural variability of domain variables in time and space affecting the uncertainty of water resources decision making.

Complexity Paradigm

The first component of the *complexity paradigm* is that water problems in the future are going to be more complex. Domain complexity is increasing (Figure 2). Further population growth, climate variability, and regulatory requirements are increasing the complexity of water resources problems. Water resources management schemes are planned over longer temporal scales in order to take into consideration the needs of future generations. Planning over longer time horizons extends the spatial scale. Matching increasing needs for water requires consideration of available water resources over the larger space. Meeting the water demands of people for life support, food production, and industrial development needs integrated management of surface and groundwater. If the balance cannot be made within the watershed boundaries, water transfer from neighbouring watersheds needs to be considered.

Extension of temporal and spatial scales leads to an increase in the complexity of the decision making process. Large-scale water problems affect numerous stakeholders. Environmental and social impacts of complex water management solutions must be given serious consideration. Equitable distribution of water and protection of water quality is regulated by a large number of agencies. Public interest is usually represented by non-governmental organisations (NGO).

The second component of the *complexity paradigm* is rapid increase in the processing power of computers (Figure 2). Since the 1950s, use of computers in water resources management has steadily grown. Computers have moved out of data processing into information and knowledge processing. Whether it takes the form of a laptop PC or a desktop multiprocessing workstation is not important anymore. It is important that the computer is a "silent partner" for more effective water resources decision-making (Simonovic, 1996, 1996a). The main factor responsible for involving computers in the decision-making process is the treatment of information as the sixth economic resource (besides people, machines, money, materials, and management).

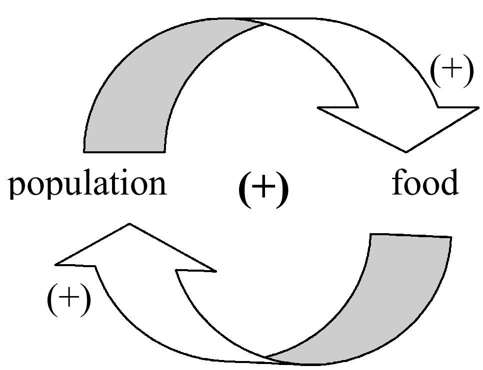

Figure 1. Life feedback loop.

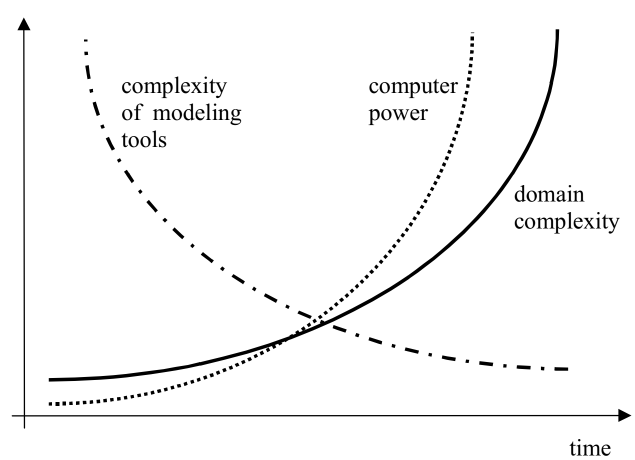

Figure 2. Schematic presentation of the complexity paradigm.

The computer is rightfully named "the machine that changed the world." First generation computers were normally based around wired circuits containing vacuum valves. One of the first computers, ENIAC, built in 1946, was typical of first generation computers; it weighed 30 tonnes, contained 18,000 electronic valves, and consumed around 25KW of electrical power. It was, however, capable of an amazing 100,000 calculations a second. The next major step was the invention of the transistor in 1947. Transistorised computers are normally referred to as "Second Generation," and they dominated the late 1950s and early 1960s. Despite using transistors and printed circuits, these computers were still bulky and strictly the domain of universities and governments. The explosion in the use of computers began with "Third Generation" computers. These relied on Jack St. Claire Kilby's invention – the integrated circuit, or microchip. It allowed the development of minicomputers. On November 15, 1971, Intel released the world's first microprocessor, the 4004 – a technology on which the "Fourth Generation" of computers are based. The microprocessor locates much of the computer's processing abilities on a single (small) chip. The microprocessor allowed the development of microcomputers or personal computers. Although processing power and storage capacities have increased beyond all recognition since 1972, the underlying technology of LSI (large scale integration) or VLSI (very large scale integration) microchips has remained basically the same, so it is widely regarded that most of today's computers still belong to the Fourth Generation.

The third component of the *complexity paradigm* is the reduction of complexity of tools used in water management (Figure 2). The most important advance made in the field of water management in the last century is the introduction of systems analysis (Friedman et al., 1984; Yeh, 1985; Rogers and Fiering, 1986; Wurbs, 1998). I define systems analysis as an approach for representing water-related problems using a set of mathematical planning and design techniques that are solved using a computer. In the context of this paper, systems analysis techniques, often called "operations research," "management science," and "cybernetics," include simulation and optimization techniques that are used to analyse quantity and quality aspects of watershed runoff and streamflow processes, reservoir system operations, groundwater development and protection, water distribution systems, water use, and various other hydrologic processes and management activities. Systems analysis is particularly promising when scarce resources must be used effectively. Resource allocation problems are very common in the field of water management and affect the developed and the developing countries that today face increasing pressure to make efficient use of their resources.

Simulation models play an important role in water resources assessment, development, and management. They are widely accepted within the water resources community and are usually designed to predict the response of a system under a particular set of conditions. Early simulation models were constructed by a relatively small number of highly trained individuals. Many generalised, well-known simulation models were developed primarily in the FORTRAN language. These models include, among many others, SSARR (streamflow synthesis and reservoir regulation – U.S. Army Corps of Engineers, North Pacific Division), RAS (river analysis system – Hydrologic Engineering Center), QUAL (stream water quality model – Environmental Protection Agency), HEC-5 (simulation of flood control and conservation systems – Hydrologic Engineering Center), SUTRA (saturated-unsaturated transport model – US Geological Survey), and KYPIPE (pipe network analysis – University of Kentucky). These models are quite complex, however, and their main characteristics are not readily understood by non-specialists. Also, they are inflexible and difficult to modify to accommodate site-specific conditions or planning objectives that were not included in the original model. The most restrictive factor in the use of simulation tools is that there is often a large number of feasible solutions to investigate. Even when combined with efficient techniques for selecting the values of each variable, quite substantial computational effort may lead to a solution that is still far from the best possible.

Advances made during the last decade in computer software provide considerable simplification in the development of simulation models (High Performance Systems, 1992; Lyneis et al., 1994; Ventana, 1996; Powersim Corp., 1996). Simulation models can be easily and quickly developed using these software tools, models that are easy to modify, easy to understand, and that present results clearly to a wide audience of users. They are able to address water management problems with highly non-linear relationships and constraints.

Numerous optimization techniques are used in water management too. Most water resources allocation problems are addressed using linear programming (LP) solvers introduced in the 1950s (Dantzig, 1963). LP is applied to problems that are formulated in terms of separable objective functions and linear constraints. The objective is usually to find the best possible water allocation (for water supply, hydropower generation, irrigation, etc.) within a given time period in complex water systems. However, neither objective functions nor constraints are in a linear form in most practical water management applications. Many modifications have been used in real applications in order to convert non-linear problems for the use of linear programming solvers. Examples include different schemes for linearization of non-linear relationships and constraints, and use of successive approximations (Loucks et al., 1981).

Non-linear programming is an optimization approach used to solve problems when the objective function and the constraints are not all in the linear form. In general, the solution to a non-linear problem is a vector of decision variables that optimizes a non-linear objective function subject to a set of non-linear constraints. No algorithm exists that will solve every specific problem fitting the above description. However, substantial progress has been made for some important special cases of this problem by making various assumptions about these functions. Successful applications are available for special classes of non-linear programming problems such as unconstrained problems, linearly constrained problems, quadratic problems, convex problems, separable problems, non-convex problems, and geometric problems (Hillier and Lieberman, 1990). The main limitation in applying non-linear programming to water management problems is in the fact that non-linear programming algorithms generally are unable to distinguish between a local optimum and a global optimum (except by finding another better local optimum). In recent years there has been a strong emphasis on developing high-quality, reliable software tools for general use such as MINOS (Murtagh and Saunders, 1995) and GAMS (Brooke et al., 1996). These packages are widely used in the water resources field for solving complex problems, including hydropower generation problems and water network distribution problems. However, the main problem of global optimality remains an obstacle in practical application of non-linear programming.

Dynamic programming (DP) offers advantages over other optimization tools since the shape of the objective function and constraints do not affect it, and as such, it has been frequently used in water management. DP requires discretization of the problem into a finite set of stages. At every stage a number of possible conditions of the system (states) are identified, and an optimal solution is identified at each individual stage, given that the optimal solution for the next stage is available. An increase in the number of discretizations and/or state variables would increase the number of evaluations of the objective function and core memory requirement per stage. This problem of rapid growth of computer time and memory requirement associated with multiple state variable DP problems is known as the curse of dimensionality. Some modifications used in the field of water management in order to overcome previously stated limitations of DP include discrete differential DP (an iterative DP procedure) and differential DP (method for discrete-time optimal control problems).

In the very recent past, most researchers have been looking for new approaches that can combine efficiency and ability to find the global optimum. One group of techniques, known as evolutionary algorithms, seems to have a high potential since it holds a promise to achieve both. Evolutionary techniques are based on similarities with biological evolutionary process. In this concept, a population of individuals, each representing a search point in the space of feasible solutions, is exposed to a collective learning process, which proceeds from generation to generation. The population is arbitrarily initialised and subjected to the process of selection, recombination, and mutation through stages known as generations, such that newly created generations evolve towards more favourable regions of the search space. In short, the progress in the search is achieved by the evaluating the fitness of all individuals in the population, selecting the individuals with the highest fitness value, and combining them to create new individuals with increased likelihood of improved fitness. The entire process resembles the Darwinian rule known as "the survival of the fittest." This group of algorithms includes, among others, evolution strategy (Back et al., 1991), evolutionary programming (Fogel et al., 1966), genetic algorithms (Holland, 1975), simulated annealing (Kirkpatrick et al., 1983), and scatter search (Glover, 1999). Evolutionary algorithms are becoming more prominent in the water management field, see for example Goldberg and Kuo (1987); Wang (1991); Murphy et al. (1993); Simpson et al. (1994); McKinney and Lin (1994); Esat and Hall (1994); Fahmy et al. (1994); Davidson and Goulter (1995); Franchini (1996); Dandy et al. (1996); Oliviera and Loucks (1997); Savic and Walters (1997); Wang and Zheng (1998); Wardlaw and Sharif (1999); Ilich and Simonovic (1998, 2000). Significant advantages of evolutionary algorithms include: (a) no need for initial solution; (b) easy application to non-linear problems and to complex systems; (c) production of acceptable results over longer time horizons; and (d) generation of several solutions that are very close to the optimum (and that give added flexibility to a water manager).

Following the evolution of systems analysis in water management it becomes obvious that more complex analytical optimization algorithms are being replaced with simpler search tools. Also, advances in computer software provide considerable simplification in the development of simulation models.

Uncertainty Paradigm

The first component of the *uncertainty paradigm* is the increase in all elements of uncertainty in time and space (Figure 3). Uncertainty in water management can be divided into two basic forms: uncertainty caused by inherent hydrologic variability and uncertainty due to a fundamental lack of knowledge. Awareness of the distinction between these two forms is integral to understanding uncertainty. The first form is labelled as *variability* and the second one as *uncertainty* (Ling, 1993). Uncertainty caused by variability is a result of inherent fluctuations in the quantity of interest (hydrologic variables). The three major sources of variability are temporal, spatial, and individual heterogeneity. Temporal variability occurs when values fluctuate according to time. Values affected by spatial variability are dependent upon location of an area. The third category effectively covers all other sources of variability. In water resources management, variability is mainly associated with the spatial and temporal varia-

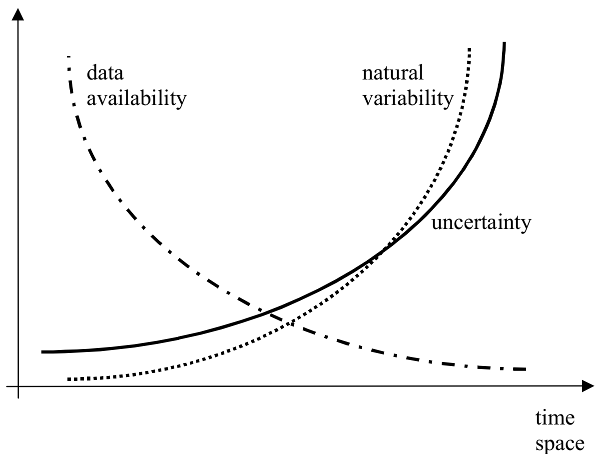

Figure 3. Schematic presentation of uncertainty paradigm.

tion of hydrological variables (precipitation, river flow, water quality, etc.).

The more elusive type of uncertainty is due to a fundamental lack of knowledge. It occurs when the particular values that are of interest cannot be assessed with complete confidence because of a lack of understanding or limitation of knowledge. The main sources of uncertainty due to lack of knowledge are depicted in Figure 4.

Model and structural uncertainties refer to the knowledge of a process. Models are simplified representations of real world processes, and model uncertainties can arise from oversimplification or from the failure to capture important characteristics of the process under investigation. This type of uncertainty is best understood by studying its major sources. In sustainable water resources management, modelling includes surrogate variables (substitute variables for the quantities that are difficult to assess). They are an approximation of the real value. The second source of model uncertainty stems from excluded variables (variables deemed insignificant in a model). The removal of certain variables or factors introduces large uncertainties into the model structure and results. For example, many environmental risk assessment methods do not consider the propagating effects of hazardous chemicals through vegetation. Attempting to address excluded variables raises a paradox: we do not know when we have forgotten something until is too late. The impact of abnormal situations on models is the third source of uncertainty. The very nature of a water resource model requires model calibration and verification using a set of broad circumstances. The problem occurs when a model is used for some other situation outside the set of situations used in the calibration and verification process. Approximation uncertainty is the fourth source of model uncertainty. This source covers the remaining types of uncertainty due to model generalisations. Example of approximation uncertainty in hydrology can be found in the use of discrete probability distributions to represent a continuous process. The final type of model uncertainty, incorrect form (correctness of the model being used to represent the real world), is initially the most obvious. To properly address this source, we must remember that all results are directly dependent on the validity of the assumed model's representation of the true process.

The next general category of uncertainty is *parameter uncertainty*. This is the fine tuning of a model and cannot cause the large variations found in model uncertainty. The most common uncertainty in this category is caused by random error in direct measurements. It is also referred to as metric error, measurement error, random error, and statistical variation. This error occurs because no measurement in water resources can be exact. Imper-

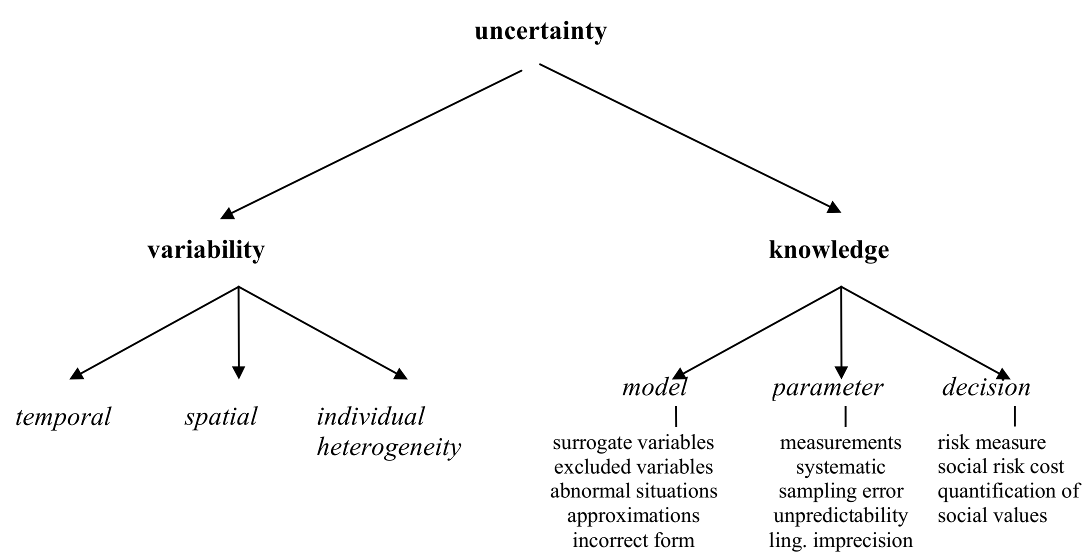

Figure 4. Sources of uncertainty (after Simonovic, 1997).

fections in the measuring instrument and observation techniques lead to imprecision and inaccuracies of measurements. The second, and largest, source of parameter uncertainty is systematic error (error due to subjective judgement). Measurements involve both random and systematic error. The latter is defined as the difference between the true value and the mean of the value to which the measurements converge. The third type of error is sampling error (error in drawing inferences from a limited number of observations). Sampling causes uncertainty in the degree to which the sample represents the whole. Well-developed statistical techniques such as confidence intervals, coefficient of variation, and sample size are used in water resources to quantify this type of uncertainty. The fourth type of parameter uncertainty is caused by unpredictability of an event. Limitations in knowledge and the presence of inherent unpredictability of the process make it almost impossible to predict, for example, the wind direction and velocity at a future date. The fifth source of uncertainty is caused by linguistic imprecision. Everyday language and communication is rather imprecise. It is possible to reduce linguistic uncertainty through clear specifications of events and values. The final source of uncertainty is derived from disagreement (conflicting expert opinion).

The third category of uncertainty is *decision uncertainty* that arises when there is controversy or ambiguity concerning how to compare and weigh social objectives. It influences decision making after parameter and model uncertainty have been considered. The first decision includes uncertainty in the selection of an index to measure risk. The measure must be as technically correct as possible while still being measurable and meaningful. The second source of decision uncertainty lies in deciding the social cost of risk (transforming risk measures into comparable quantities). The difficulties in this process are clearly illustrated in the concept of developing a monetary equivalent for the value of life in flood control analysis. The quantification of social values is the third source of uncertainty. Once a risk measure and the cost of risk are generated, controversy still remains over what level of risk is acceptable. This level is dependent upon society's risk attitude.

The second component of the *uncertainty paradigm* is the decrease in water data availability (Figure 3). Hydrological information on water levels, discharge, sediment and water quality is necessary for water management. Examples of water projects for which hydrological information is indispensable comprise water engineering infrastructure (dams, reservoirs, spillways, canals, diversions, hydropower, etc.) as well as projects in the area of water quality and protection from water (zoning, insurance, standards, legislation, etc.).

The numbers of hydrological stations in operation worldwide, as reported by WMO (1995), are very impressive. The INFOHYDRO Manual (WMO, 1995) estimates that there are nearly 200,000 precipitation gauges operating worldwide and over 12,000 evaporation stations. Over 64,000 stations monitored for discharge; nearly 38,000 monitored for water level; 18,500 monitored for sediment; over 100,000 monitored for water quality; and over 330,000 stations monitored for groundwater characteristics. Despite the apparently high global numbers, the situation is not uniform, being deficient over large areas.

Financial constraints of government agencies that are responsible for the collection of hydrometric data have resulted in reductions in the data collection program in many countries. In Canada, for example, budgetary cutbacks and shifts in government priorities have led to a dramatic reduction in the hydrometric network (Pilon et al., 1996; Burn, 1997). In many countries hydrological data collection activities are very fragmented. A similar fragmentation is observed at the international level. Of particular concern are the gaps in the existing data relative to the informational requirements. Many authors agree that current data collection networks are inadequate for providing the information required to understand and explain changes in natural systems. Given the reductions in the funding of data collection activities, it is clear that a change in the approach to data collection activities is essential. The Global Run-off Data Centre (GRDC) is working under the auspices of WMO with the mission to collect, store, and disseminate discharge data of the most relevant rivers of the world. GRDC will also lead the process of establishing regional and global databases, and a global network for discharge monitoring (GRDC, 1997).

The third component of the *uncertainty paradigm* is the increase in natural variability of water availability (Figure 3). Water flow exhibits considerable temporal (between years and seasons) and spatial variation. This variation, which can be crucial for water availability for domestic, agricultural, or industrial use, is not detected if the selected time scale for water balance analyses is longer than the time for such fluctuation. The water flow from the basin is the integrated result of all physical processes in the basin. Topography as well as the spatial distribution of geological phenomena and land use are the main source of spatial variability of flow.

Observed natural variability may be even further affected in the future by the potential climate change. One of the most important aspects of studying the hydrological consequences of potential global warming is estimating possible changes in the extreme characteristics of maximum and minimum river discharges (see Kundzewicz and Kaczmarek, this issue). Through analysis of empirical data and through modelling studies it can be shown, reasonably reliably, that potential global warming would lead to more changes in runoff extremes than in mean annual and seasonal flows, especially for small and medium size basins. On the one hand, increase in maximum floods can be expected and on the other, more frequent occurrence of severe droughts. Both could result in major economic and ecological consequences.

One Vision of the Future

My vision of the future for water management tools is based on the two paradigms introduced in the previous section and the current trends and experiences. There are four main elements of the vision: (a) object oriented simulation; (b) evolutionary optimization using powerful computers; (c) integration of fuzzy set analysis with simulation and optimization tools; and (d) integration of spatial analysis with simulation and optimization tools.

Object Oriented Simulation

Object oriented modeling, a new way of thinking about problems using models organized around real-world concepts (Rumbaugh et al., 1991), is being identified as a powerful approach for water management (Palmer et al., 1993; Simonovic and Bender, 1996; Simonovic et al., 1997; Simonovic and Fahmy, 1999). By separating policy questions from data, object oriented modeling makes the model results functionally transparent to all parties involved in the water management. The proposed approach is flexible, transparent, and allows for easy involvement of stakeholders in the process of water decision analysis.

There are numerous tools used for implementing the object oriented modeling approach. This vision focuses on the system dynamics simulation that has been used in water resources management in the past. Object oriented modeling is an appropriate approach for the implementation of systems thinking. Complex water resources planning problems heavily rely on systems thinking, which is defined as the ability to generate understanding through engaging in the mental model-based processes of construction, comparison, and resolution. Computer software tools like STELLA, DYNAMO, VENSIM, POWERSIM (High Performance Systems, 1992; Lyneis et al., 1994; Ventana, 1996; Powersim Corp., 1996) and others help the execution of these processes.

Systems thinking is a paradigm concerned with systems (defined as sets of interrelated objects) and interrelationships used to perform mental simulations. System dynamics simulation tools are well suited for representing mental models that have been developed using systems thinking paradigm. Practically, these tools are built around a progression of structures. Stocks and flows are the principal building blocks of structure (Figure 5). Stocks are the "things" in the language, and flows are the "actions." Stocks represent accumulations and serve as resources. They can also serve as constraints. Flows are inseparable from stocks; one does not exist without the other. If there is an accumulation of something (water in a reservoir), that accumulation had to result from some activity, a flow of something (reservoir inflow). Stocks and flows form the minimum set of structural elements needed to describe dynamics. The other two basic building blocks are converters and connectors (Figure 5). Converters convert inputs into outputs. They can represent information or material quantities. Connectors link stocks to converters, stocks to flow regulators, and converters to other converters. They do not take on numerical values; they are transmitting them. Basic building blocks are used to map a wide variety of dynamic processes. An example of a realistic system, the High Aswan Dam in Egypt, represented as a stock and flow object diagram is shown in Figure 6 (after Simonovic et al., 1997). Once a process is mapped, the next task is to model it. This is done in system dynamics by the specification of flows. Five available generic flow processes are: compounding, draining, production, co-flow, and stock-adjustment.

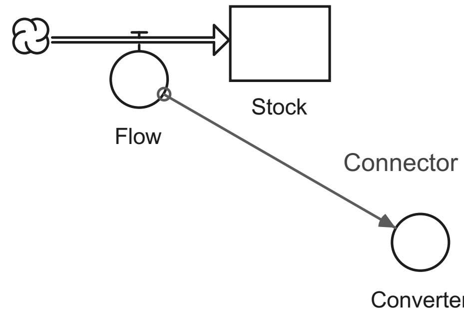

Figure 5. Basic building blocks of an object oriented simulation.

The power and simplicity of use of object oriented simulation applications is not comparable with those developed in functional algorithmic languages. In a very short period of time, the users of the water management tools developed by object oriented simulation can experience the main advantages of this approach. The power of object oriented simulation is the ease of constructing "what if" scenarios and tackling big, messy, real-world problems. In addition, general principles upon which the system dynamics simulation tools are developed apply equally to social, natural., and physical systems. Using these tools in water management allows enhancement of water models by adding social, economic, and ecological sectors into the model structure.

Evolutionary Optimization Using Powerful Computers

Use of the Darwinian "survival of the fittest" approach to solve difficult numerical optimization problems initially raised suspicion in much of the scientific community. Even conservative skeptics must accept the fact that research in the field commonly known as genetic algorithms, evolutionary strategies, evolutionary programming, or simulated annealing is here to stay and will shape the future of optimization.

The general characteristics of evolutionary optimization approach include: generation of a population of initial solutions, evaluating them, selecting a small fraction of the best solutions, and applying the recombination and mutation operators to generate solutions with better fitness values. The progress is achieved as long as the best

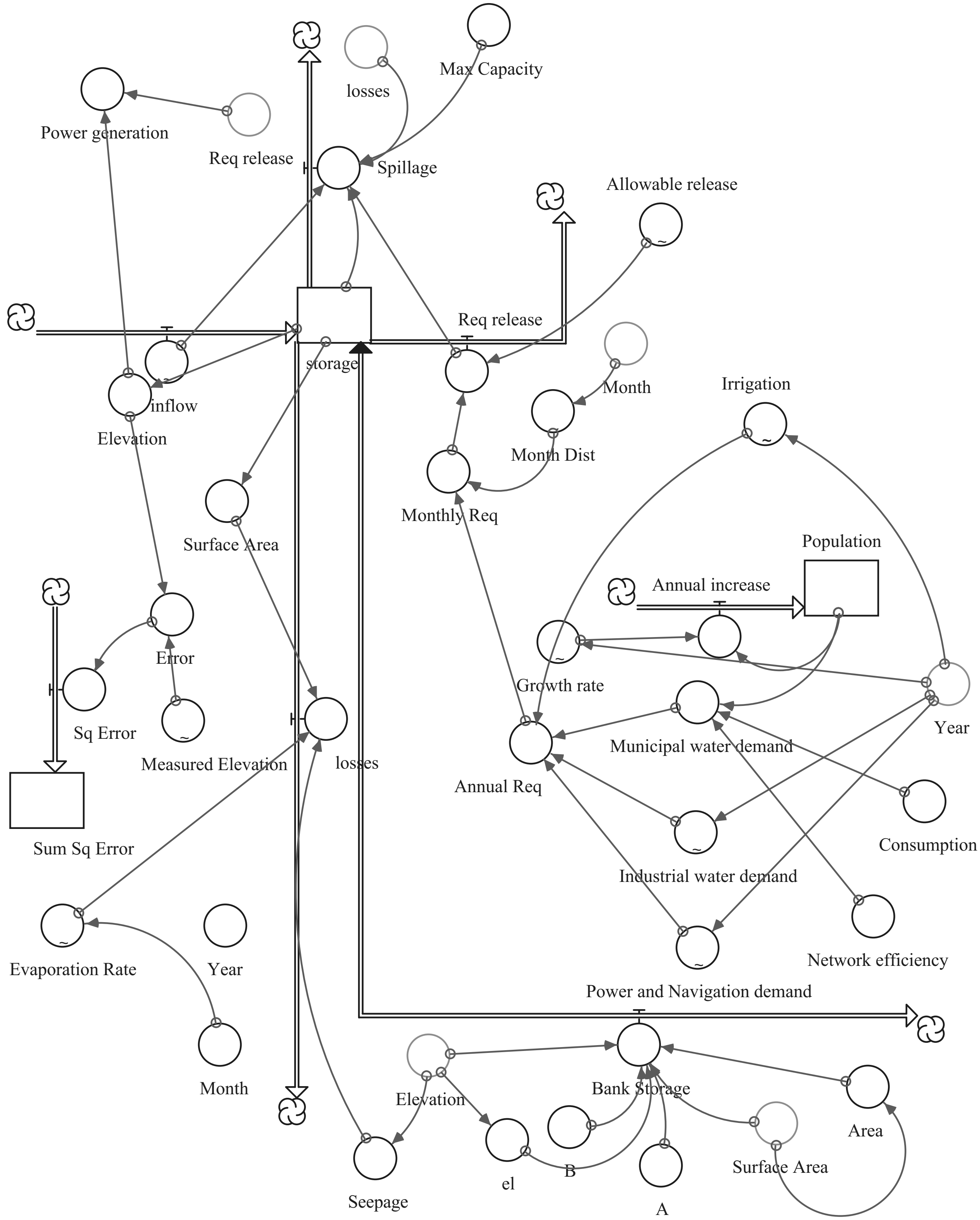

Figure 6. Object structure of the High Aswan Dam reservoir model (after Simonovic et al., 1997).

solutions that are selected as "parents" are capable of producing better "offspring." A terminating condition is met when there is no significant improvement in the objective function after a sufficient number of trials, or when a specified number of trials has been reached.

Most evolutionary algorithms converge to an optimal point both from inside and outside of the feasible region, which means that often times more than 90 percent of the search effort is wasted on generating solutions that are infeasible. Future improvements will identify a way to search only through the feasible region. Initial work is already in progress (Ilich and Simonovic, 2000). These algorithms do not take into account shape or gradient of the objective function, which gives them better chance to find a global optimum. Current algorithms are very efficient when the decision variable can take one of two possible states, such as deciding if a fixed head pump should be on or off. Their power and efficiency is reduced when they are applied to problems with a floating point decision variable (e.g., finding optimal head for a variable speed pump). In the near future, floating point algorithms will be operational. Again, the initial success has been demonstrated in the water management field (Ilich and Simonovic, 1998).

Integration of Fuzzy Analysis with Simulation and Optimization Tools

A standard definition of a set involves a universal set X and a property *p*. A set S may be defined as the set of all elements in X having the property *p*. If the property *p* is such that it clearly separates the elements of X into two classes (those that have *p* and those that do not have *p*), we say that *p* defines a *crisp* subset S of X. When there is no such clear separation, we say that the property *p* defines an *ill-defined* subset S of X.

For a proper mathematical definition of an ill-defined set, a *grade of membership* in S needs to be assigned to each element *x* in X. The grade of membership of *x* in S is a numerical value $\mu_S(x)$ in the interval [0,1], representing a measure of how strongly the element *x* shows the property *p*. Thus, an ill-defined set **S** is completely determined by the function $\mu_S : X \rightarrow [0,1]$. Once the function μ_S is defined, the ill-defined set S can be called a *fuzzy set*. A fuzzy set cannot be defined as a concrete set of elements of X. In order to define a fuzzy set S as a set of objects, consider the Cartesian product $\mathcal{X} = X \times [0,1]$ and let

$$\boldsymbol{S} = \{(x,\mu_S(x)) : x \in X\} \qquad (1)$$

The set ***S*** is a subset of the Cartesian product $\mathcal{X}$, which can be naturally identified with our notion of the ill-defined set S. Namely,

> *An element* $(x,\mu_S(x))$ *from* $\mathcal{X}$ *belongs to the set* ***S*** *if and only if x is an element of* X *whose grade of membership in* S *is equal to* $\mu_S(x)$.

The set ***S*** is a properly defined fuzzy set. Although the notion of an ill-defined set ***S*** is not clearly defined, we often think of the fuzzy set *S* in terms of S because of its more intuitive nature. The function μ_S is called the *membership function,* and it is an analogue of the characteristic function in the classical set theory.

For the various types of uncertainties encountered in water resources, Figure 4 presents a general taxonomy of the sources of uncertainty considering the use of modeling to quantify uncertainties through deterministic, probabilistic, and fuzzy set approach as appropriate to each specific source.

Two basic forms of uncertainties are: uncertainty caused by inherent hydrologic (stochastic) variability and uncertainty due to a fundamental lack of knowledge. Intuitively, the second form appears to be readily modeled by fuzzy sets. However, Simonovic (1997) points out that it is not the type of uncertainty that determines the appropriate way of modeling, but rather data sufficiency and availability. If sufficient data are available to fit a probability density distribution, then use of stochastic variables will be the best way to quantify the uncertain values. On the other hand, if the requirements of sustainability are to be addressed, such as needs of future generation: expanded spatial and temporal scales, and long-term consequences, then the information available is scarce. In this case, the fuzzy set approach can successfully utilize the information that is available.

Quantification of complex qualitative criteria, a process often encountered within water resources management, is a typical example where fuzzy systems modeling is favorable. Water quality, flood control, recreation, and many other qualitative criteria are still far from precise analytical description. Intuitive linguistic formulations are worth considering since fuzzy set theory provides a successful way to operate them (linguistic calculus). The main problem here is in the word “intuitive.” Many qualitative criteria in water resources decision making are far too complex to be intuitively understood. This complexity is the natural characteristic of the system, in addition, it is also due the technical, environmental, societal, institutional, political, and economic aspects of the decision-making process in water resources (Rogers and Fiering, 1986). One way to deal with this complexity is to carefully derive the decomposition model for each complex criterion. The model would then provide an easy evaluation of criteria through the evaluation of components that are generally less complex. Furthermore, the decomposition models can be used repeatedly in various situations, once they are developed (Despic and Simonovic, 2000).

When fuzzy sets are employed to model less complex parameters, some of the methods for membership construction listed in Despic and Simonovic (2000) can be applied directly. Table 1 gives a list of some sources of uncertainties within water resources, along with the corresponding methods for membership evaluation whenever a fuzzy set approach appears to be appropriate way of modeling.

Integration of Spatial Analysis with Simulation and Optimization

Most of the simulation and optimization tools used in

Table 1. Interpretation of Fuzziness for Various Problems in Water Resources

Areas in Water Resources	*Interpretation of Uncertainty*	*Membership Evaluation Method*
Degree to which model truly represents the actual system Human subjectivity in system analysis	Likelihood view	Neural-fuzzy techniques Horizontal methods
Errors in parameter estimation Qualitative criteria in decision making	Random set view	Interval estimation Vertical methods
Weight estimation for criteria of unequal importance	Utility view	Pairwise comparison
Reliability and sensitivity levels of different operations	Measurement view	Clustering methods Pairwise Comparison Direct rating method

water management up to now do not consider spatial dynamics of water systems in an explicit manner. In most cases, the approach has been to summarize the spatially important features of the water system with one or two aggregate relationships. For example, in the case of a reservoir, the spatially important details are summarized by nonlinear functions linking surface area and elevation to the volume of water in the lake. Our understanding of some systems may be improved by introducing spatial dimensions in an explicit manner.

Spatial modeling can be implemented with any of the system dynamics simulation stock-and-flow software packages. The information in the dynamic model can be integrated with a geographic information system (GIS) to improve communication and interpretation. In this way, dynamic simulation models can deal with spatially explicit information while allowing fundamental laws to be expressed at one point in space (at the cellular level). The power of GIS is enhanced as well. When linked to a system dynamics simulation model, a GIS provides a dynamic perspective as well as a spatial perspective. Some early attempts in water management include modeling coastal landscape dynamics (Costanza et al., 1990; Ruth and Pieper, 1994) and watershed management (Jordao et al., 1997).

One common use of GIS is to find locations in a region where several criteria are met, such as flat land, proximity to a road, and areas with a catchment population greater than 70,000. A great deal of effort has been applied to generating spatial modeling software for solving this type of problem. Location-allocation models are embedded within the latest versions of many GIS packages (Birkin et al., 1996). The best known is the "p-median problem," which can be presented as:

$$\underset{\{S_j\}}{Minimize}\ Z = \sum_{j=1}^{p} \sum_{k=1}^{q} X_k h_{jk} c_{jk} \qquad (2)$$

subject to:

$$\sum_j h_{jk} = 1 \qquad (3)$$

$$h_{jk} = \begin{cases} 1 \\ 0 \end{cases} \qquad (4)$$

where: $S_j = (x_j, y_j)$ is a source location; X_k is the demand at k; and c_{jk} is the distance from j to k. The problem is to find the optimal locations for p sources (hence the name "p-median") relative to q demand points or demand zones. In this model "optimization" means transport-cost minimization, and the "allocation" element of the problem comes through the zero-one variables, h_{jk}, which allocate each demand point to the nearest source.

Analytical optimization tools still have a great advantage over standard GIS in solving optimization problems. Therefore, an alternative approach to embedded optimization programs in GIS is to embed spatial interaction models within a procedure that optimizes locations. In either case, in the not-so-distant future we will definitely see more and more powerful GIS packages capable of optimizing variety of water management problems with emphasis on spatial variability of decision variables, objectives and constraints.

Conclusions

In the past, stakeholders not actively involved in the development of a model tended to mistrust the results of the model. Computer power has increased and costs have fallen to the point that all stakeholders in the resource can play a very important role in water management. Technology is already today a facilitating force in political decision making, and will be more so in the future. Spatial decision support systems using object oriented programming algorithms are integrating transparent tools that will be easy to use and understand.

National and international databases, both static and dynamic, now provide much of the necessary information in digital form. The trend in providing public access to all water-related data at reasonable cost and in a user-friendly format will continue and will play an important role in supporting tools for water decision making.

The speed with which data and ideas can be communicated has historically been a control mechanism of scientific progress. The Internet began in 1968 by connecting four hosts. In 1997, over 15,000,000 hosts were connected to multiple computer networks (Kristula, 1997). Virtual libraries, virtual databases, virtual forums and bulletin boards, web-enabled software packages, and use of web that allow "writing once – running anywhere" languages (such as Java by Sun Microsystems) will create new opportunities for water managers.

The future of water resources management will be difficult for both the developing and developed world. My hope is that the tools discussed in this paper, supported by good data communicated through powerful networks, will empower the people to make wise decisions on how to make best use of limited water resources.

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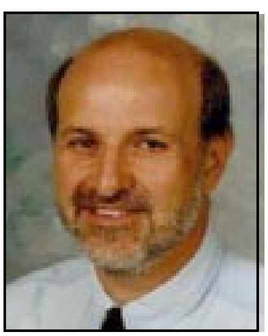

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