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MANAGING WATER RESOURCES: METHODS AND TOOLS FOR A SYSTEMS APPROACH

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SUMMARY

Water resources systems management practice around the world is challenged by serious problems. Climate change and land use change are increasingly recognized as having the major impact on hydrologic variables and therefore on management of water resources. Certainly, the profession has been slow to acknowledge these changes, and that fundamentally new approaches will be required to address them. There is a clear need to redefine the education and training of water resource engineers and increase their abilities to: (i) work in an interdisciplinary environment; (ii) develop a new framework for the design, planning and management of water infrastructure that will take into consideration current complex socio-economic conditions; and (iii) provide the context for water management in conditions of uncertainty. The main objectives of this review are to introduce the systems approach as the theoretical background for modern water resources management, and to focus on three main sets of tools: simulation, optimization and multi-objective analysis. Special attention is given to system dynamics simulation, evolutionary optimization and use of fuzzy sets to capture uncertainties in water resources management.

Keywords: Water resources management; systems approach; simulation; optimization; fuzzy sets

INTRODUCTION

Water resources systems management is an iterative process of integrated decision- making regarding the uses and modifications of waters and related lands within a geographic region (Simonovic, 2008). This process provides a chance for users to balance their diverse needs and uses of water as an environmental resource, and to consider how their cumulative actions may affect the long-term sustainability of water and related land resources. The guiding principles of the process are a systems view, partnerships, uncertainty, a geographic focus and a reliance on strong science and reliable data. This gives us a definition of water resources systems management which includes the traditional activities of water resources engineering: planning, design, maintenance and operation of the water-related infrastructure. It is more comprehensive, and integrates all these activities in an approach to support the decision-making process based on the engineering, natural, social and other sciences.

A systems view. We have inherited both natural water resources systems and many generations of human-made systems. Only recently have we come to understand the underlying structure and characteristics of natural and human-made systems in a scientific sense. The switch to thinking not in terms of single functions but in terms of 'systems' is still in progress. Nor are water resources systems isolated: they interrelate with human and physical systems, and this leads to innumerable financial, economic, social and political considerations.

Partnerships. Water resources systems management requires use of the engineering, social, natural, ecological and economic sciences. Common goals for water and land resources must be developed among people of diverse social backgrounds and values. An understanding of the structure and function – historical and current – of the water resources system is required, so that the various effects of alternative actions can be considered. The decision process must also consider the economic benefits and costs of alternative actions, and blend current economic conditions with considerations of the long-term sustainability of the ecosystem.

Uncertainty. Human modifications of waters and related lands directly alter the delivery of water, sediments and nutrients, and thus fundamentally alter aquatic systems. These alterations are made using imperfect information about many processes involved, and this brings multiple objective uncertainties into the decision-making process. People have varying goals and values related to uses of local water and related land resources. These form subjective uncertainties for inclusion in the decision-making process.

Space. As a form of ecosystem management, water resources systems management encompasses the entire watershed system, from uplands and headwaters to floodplain wetlands and river channels. It focuses on the processing of energy and materials (water, sediments, nutrients and toxins) downstream through this system. Of principal concern is the management of the basin's water budget: that is, the transformation of precipitation through the processes of evaporation, infiltration and overland flow. This transformation of groundwater and overland flow defines the delivery patterns to particular streams, lakes and wetlands, and to a great extent shapes the nature of these aquatic systems.

Science and data. Like water itself, the science of water resources systems management flows in all directions: to hydrology, hydraulics, geology, meteorology, oceanography, environmental science, engineering, law, economics and so on. Water resources management decision-making requires information on both specific locations and general principles. To provide appropriate water resources management decisions requires an integrated approach and reliable data (Flugel, 2007).

Economic efficiency With growing water scarcity and increasing competition across water-using sectors, the need for water savings and more efficient water use has increased in importance in water resources management. An improvement in the physical efficiency of water use is related to water conservation, through increasing the fraction of water beneficially used over water applied. Enhancing economic efficiency is a related but broader concept, which involves seeking the highest economic value of water use through both physical and management measures.

The following section provides a discussion of water resources systems management tools. The changing characteristics of water management practice are presented with two new paradigms that will shape future tools for water resources systems management. Section three presents the basic characteristics of simulation, optimization and multi-objective analysis tools. In the last section, the discussion of uncertainty in water resources systems management is provided and case is made for the introduction of the fuzzy sets. Paper ends with conclusions.

CHANGING WATER RESOURCES MANAGEMENT PRACTICE

In order to set the stage for our discussion of contemporary water resources systems management, only the period since the Second World War will be considered from this point on. The role of water engineers has expanded beyond the traditional concept of design and synthesis, to a larger multidisciplinary function serving a broad social environment. A key concept in the vision of the profession is the twofold role of professional engineers: first, a technical expert role, and second, the role of generalist. Engineers need to be skilled in managing technology within a social, cultural, political, environmental and economic context (Simonovic, 1992).

For a historical overview of water management practice since the Second World War, I shall divide the developments into three chronological phases (see Figure 1): (1) rapid development, with an emphasis on design and construction; (2) slower development: the consideration of more complex projects, with an emphasis on optimal planning and design; and (3) the utilization of existing projects, with an emphasis on operation, preventive maintenance and rehabilitation. In a broad sense, these three phases apply to any development conditions. Some developed countries are already in phase three, while some developing countries are in phase one.

The chronological order of these phases obviously follows the requirements of a social development process. Each phase is characterized by a certain level of technological knowledge. Analytical tools and numerical procedures are logical choices for the first phase. Systems analysis techniques, optimization and simulation are powerful tools to support the planning phase. For the further development phase, expert systems, neural networks, evolutionary programming and other emerging technologies seem to be the right technological choice. The water resources management profession is involved in seeking solutions to problems which have a complex impact on society. The range of solutions must be determined and evaluated in terms of life improvements, resource commitments, public health

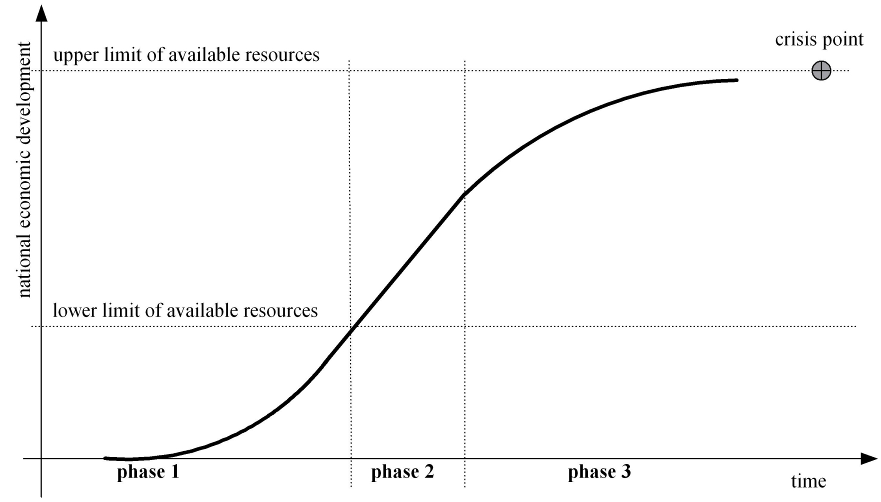

Figure 1. Schematic presentation of the development process

and safety. The solutions to such problems require the application of scientific principles and an understanding of the social, political and economic conditions in which these problems exist.

Tools for water resources systems management – two new paradigms

In the context of this article any empirical, analytical or numeric procedure used for water resources planning, operations and management is referred to as a 'tool'. The application of various tools for water resources management over the last 50 years shows a pattern of change. Some of the lessons summarized by Simonovic (2000) are noted below.

Domain-specific lessons. 1 Population increase creates serious water management problems. 2 Agriculture (including fisheries), industry, domestic use, power generation, navigation and recreation are the six socio-economic sectors that depend directly on water. 3 Demand for water is growing. 4 The solution of water management problems must take into consideration the water needs of ecosystems. 5 An interdisciplinary approach is required for solving water resources management problems. 6 The public must be involved in the management of water resources. 7 Institutional change, education, training and cooperation are necessary in order to address the water problems of the future.

Technical lessons. 1 Integrated planning and management based on the use of systems analysis is a very efficient approach to finding solutions for complex water resources problems. 2 Mathematical modelling tools have an application in water policy analysis. 3 Decision support tools including optimization models can be considered for operational application. 4 Improved tools for planning and decision-making are necessary, together with well-coordinated databases. 5 Complex water decision-making processes require technical support. 6 Training and institutional development play an important role in the practical application of optimal management strategies.

Two paradigms were identified that will shape future tools for water resources systems management. The first focuses on the complexity of the water resources domain, and the complexity of the modelling tools, in an environment characterized by continuous, rapid technological development. The second deals with water-related data availability, and the natural variability of domain variables in time and space that affect the uncertainty of water resources decision making.

The complexity paradigm. The first component of the complexity paradigm (Figure 2a) is that water problems in the future will be more complex. Domain complexity is increasing. Further population growth, climate variability and regulatory requirements are factors that increase 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. The second component of the complexity paradigm is the rapid increase in the processing power of computers. Since the 1950s, the use of computers in water resources management has grown steadily. Computers have moved from data processing, through the user's office and into information and knowledge processing. 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). The third component of the complexity paradigm is the reduction in the complexity of tools used in water management. During the evolution of systems analysis in water management, it has become apparent that more complex analytical optimization algorithms are being replaced by simpler and more robust search tools. Advances in computer software have also led to considerable simplification in the development of simulation models.

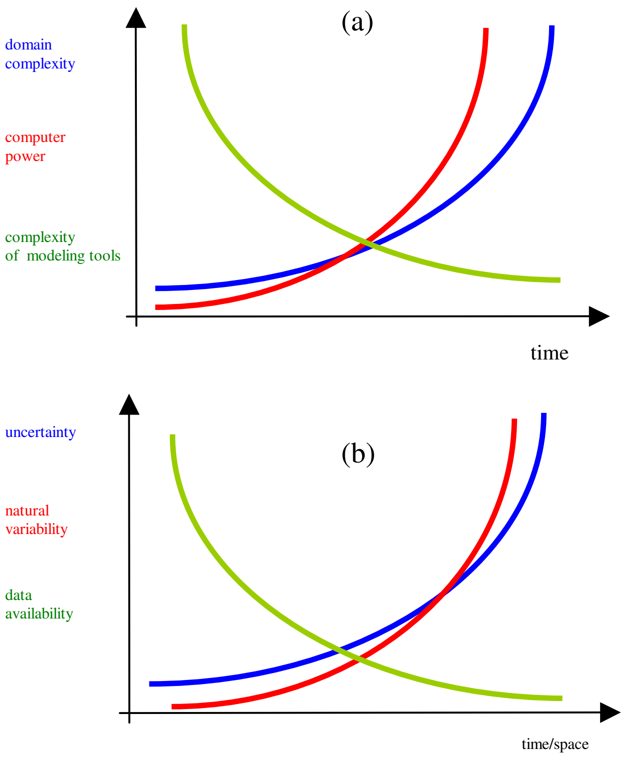

Figure 2. Two new paradigms (a) the complexity paradigm (b) the uncertainty paradigm

The uncertainty paradigm. The first component of the uncertainty paradigm (Figure 2b) is the increase in all elements of uncertainty in time and space. Uncertainty in water management can be divided into two basic forms: uncertainty caused by inherent hydrologic variability, and uncertainty caused by a fundamental lack of knowledge. The second component of the uncertainty paradigm is the decrease in water data availability. Hydrological information on water levels, discharge, sediment and water quality is necessary for water management. The financial constraints of government agencies that are responsible for the collection of hydrometric data have resulted in reductions in the data collection programme in many countries. The third component of the uncertainty paradigm is the increase in natural variability of water availability. Water flow exhibits both temporal (between years and seasons) and spatial variation. This variation, which can be crucial for water availability to domestic, agricultural or industrial use, is not detected if the selected timescale for water balance analyses is longer than the periods of such fluctuation.

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 resources systems management. Technology is already 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 will continue for providing public access to all water-related data at reasonable cost and in a user-friendly format, and this will play an important role in supporting tools for water decision-making.

INTRODUCTION TO METHODS OF WATER RESOURCES SYSTEMS MANAGEMENT

Water resources systems management, as defined in this article, is an iterative process of integrated decision-making regarding the uses and modifications of waters and related lands within a geographic region. It relies on the application of a systems approach to formulating water resources management problems, and the use of systems analysis in finding their solutions. To use a systems approach calls for a change in our basic categories of thought about the physical reality under consideration. In contemporary water resources management we are forced to deal with complexities:

with wholes or systems. This implies a basic reorientation in thinking. System analysis is the use of rigorous methods to help determine preferred plans, design and operations strategies for complex, often large-scale systems. Its methods depend on the use of the computer for practical application.

Simulation

Simulation models describe how a system operates, and are used to predict what changes will result from a specific course of action. Such models are sometimes referred to as cause-and-effect models. They describe the state of the system in response to various inputs, but give no direct measure of what decisions should be taken to improve the performance of the system. Therefore, simulation is a problem solving technique. It contains the following phases: (1) Development of a model of the system. (2) Operation of the model (i.e. generation of outputs resulting from the application of inputs). (3) Observation and interpretation of the resulting outputs. The essence of simulation is modelling and experimentation. Simulation does not directly produce the answer to a given problem. Simulation includes a wide variety of procedures.

Simulation models play an important role in water resources systems management (Simonovic, 2008 page 297-428). 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 generalized, well-known simulation models are in use (for example SSARR - streamflow synthesis and reservoir regulation, RAS - river analysis system, QUAL - stream water quality model, HEC-5 - simulation of flood control and conservation systems, SUTRA - saturated-unsaturated transport model, and KYPIPE - pipe network analysis). 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.

System dynamics simulation. System dynamics is an academic discipline introduced in the 1960s by researchers at the Massachusetts Institute of Technology. System dynamics was originally rooted in the management and engineering sciences but has gradually developed into a tool useful in the analysis of social, economic, physical, chemical, biological and ecological systems (Sterman, 2000). In the field of system dynamics, as in the context of this book, a system is defined as a collection of elements which continually interact over time to form a unified whole. The underlying pattern of interactions between the elements of a system is called the *structure* of the system. The term *dynamics* refers to change over time. If something is dynamic, it is constantly changing in response to the stimuli influencing it. A dynamic system is thus a system in which the variables interact to stimulate changes over time. System dynamics is a methodology used to understand how systems change over time. The way in which the elements or variables comprising a system vary over time is referred to as the *behaviour* of the system. One feature that is common to all systems is that a system's structure determines its behaviour. System dynamics links the behaviour of a system to its underlying structure. It can be used to analyse how the structure of a physical, biological or any other system can lead to the behaviour that the system exhibits. This is achieved by developing a model that can simulate and quantify the behaviour of the system. The simulation of the model over time is considered essential to understanding the dynamics of the system. Software tools like STELLA, DYNAMO, VENSIM and POWERSIM, use the principles of object-oriented programming for the development of system dynamics simulation programs. They provide a set of graphical objects with their mathematical functions for easy representation of the system structure and the development of computer code. Simulation models can be easily and quickly developed using these software tools. The resulting models are easy to modify, easy to understand, and present results clearly to a wide audience of users. They are able to address water management problems with highly non-linear relationships and constraints.

So what are the advantages of system dynamics simulation over the classical simulation discussed earlier?

(1) The power and simplicity of use of system dynamics simulation applications is not comparable with those developed in functional algorithmic languages. In a very short period of time, the users of the system dynamics

simulation models can experience the main advantages of this approach. The power of simulation lies in the ease of constructing what-if scenarios and tackling big, messy, real world problems. (2) The general principles upon which the system dynamics simulation tools are developed apply equally to social, natural and physical systems. Using these tools in water resources systems management allows for the enhancement of models by adding social, economic and ecological sectors to the model structure. (3) The structure–behaviour link of system dynamics models allows analysis of how structural changes in one part of a system might affect the behaviour of the system as a whole. Perturbing a system allows one to test how the system will respond under varying sets of conditions. The manipulation of graphical objects in the system dynamics model that describes the structure of a system is as easy as a click of the computer mouse button. (4) For well-defined systems with sufficient and good data, the system dynamics simulation offers predictive functionality, determining the behaviour of a system under particular input conditions. However, the ability to use system dynamics simulation models and extend water resources simulation models to include social, ecological, economic and other non-physical system components offers learning functionality – the discovery of unexpected system behaviour under particular input conditions. This is one of the main advantages of system dynamics over traditional simulation. (5) In addition to relating system structure to system behaviour and providing users with a tool for testing the sensitivity of a system to structural changes, system dynamics requires a person to take an active part in the rigorous process of modelling system structure. Since the use of system dynamics software is very simple, the modelling process can be done directly by most experienced stakeholders. Modelling a system structure forces a user to consider details typically glossed over within a mental model. System dynamics simulation can very easily become a group exercise, providing for the active involvement of all stakeholders and an interactive platform for the resolution of conflicts among them.

Optimization

The procedure of selecting the set of decision variables that maximizes/minimizes the objective function, subject to the systems constraints, is called the *optimization procedure*. Numerous optimization techniques are used in water resources systems management. Most water resources allocation problems are addressed using linear programming (LP) solvers. LP is applied to problems that are formulated in terms of separable objective functions and linear constraints. Nonlinear 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 nonlinear problem is a vector of decision variables that optimizes a nonlinear objective function subject to a set of nonlinear constraints. The main limitation in applying nonlinear programming to water management problems is in the fact that it is generally unable to distinguish between a local optimum and a global optimum (except by finding another better local optimum). 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 resources systems 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.

The complexity of real water resources management problems today exceeds the capacity of traditional optimization algorithms (Simonovic, 2000). Most water resources specialists have been looking for new approaches that combine efficiency and an ability to find the global optimum for complex water resources systems management problems. One group of techniques, known as evolutionary algorithms, seems to have a high potential since it holds a promise to achieve both these objectives (Simonovic, 2008 page 461-481). Evolutionary techniques are based on similarities with the 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 initialized 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 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.

Evolutionary algorithms are becoming more prominent in the water resources systems management field. Significant advantages of evolutionary algorithms include:

(1) no need for an initial solution;
(2) ease of application to non-linear problems and to complex systems;
(3) production of acceptable results over longer time horizons; and
(4) generation of several solutions that are very close to the optimum (and that give added flexibility to a water manager).

Multi-objective analysis

The management of complex water resources systems rarely involves a single objective. A multi-objective programming problem is characterized by a multi-dimensional vector of objective functions. The word 'optimization' has been purposefully kept out of the definition of a multiobjective programming problem since one cannot, in general, optimize a priori a vector of objective functions. The first step of the multi-objective problem consists of identifying the set of non-dominated solutions within the feasible region. So instead of seeking a single optimal solution, a set of non-dominated solutions is sought. The essential difficulty with multi-objective analysis is that the meaning of the optimum is not defined as long as we deal with multiple objectives that are truly different. To obtain a single global optimum over all objectives requires that we either establish or impose some means of specifying the value of each of the different objectives. If all objectives can be valued on a common basis, the optimization can be stated in terms of that single value. The multi-objective problem disappears and the optimization proceeds relatively smoothly in terms of a single objective.

The focus of multi-objective analysis in practice is to sort out the mass of clearly dominated solutions, rather than determine the single best design. The result is the identification of a small subset of feasible solutions that are worthy of further consideration. Formally, this result is known as the *set of non-dominated solutions*. Methods are developed for assessing trade-offs between alternatives based on using more than one objective. Contemporary research into multi-objective analysis has shifted away from continuous theoretical models, and explored issues in evaluating a discrete set of alternatives.

The shortcoming of most multi-objective methods is that they rely on an a priori articulation of preferences – an expression of the importance of each objective to a decision maker. In practice, the preferences of decision makers are not readily available. In some situations they are not able to articulate them easily; in others, they may not be willing to openly express their values. The difficulty for group decision-making is that conflicts arise, and complicate the evaluation process by tying decision-makers to their articulation of preference. Based on extensive use of various multi-objective methods in practice, I have developed a concept of *most robust solution* as a replacement for the *best solution* (Simonovic, 2008 page 527-615). The best solution is one closest to the ideal point for the fixed set of preferences. The most robust solution is one that occupies a high rank (not always the highest), the most often for various sets of preferences.

WATER RESOURCES SYSTEMS MANAGEMENT UNDER UNCERTAINTY – A FUZZY SET APPROACH

Uncertainty is in part about variability in relation to the physical characteristics of water resources systems. But uncertainty is also about ambiguity. Both variability and ambiguity are associated with a lack of clarity because of the behaviour of all system components, a lack of data, a lack of detail, a lack of structure to consider water resources management problems, working and framing assumptions being used to consider the problems, known and unknown sources of bias, and ignorance about how much effort it is worth expending to clarify the management situation. The scope for uncertainty in any water resources decision situation is considerable. We can see part of this scope by considering a generic water resources systems decision-making framework, defined as a sequence of stages, each of which involves associated sources of uncertainty, as shown in Table 1.

Experience, as well as this brief overview of sources of uncertainty in a water resources decision process structure, tells us that the scope for making poor-quality decisions is considerable. Difficulties arise at every stage. The uncertainties listed in Table 1 indicate the nature of what is involved. Have we correctly interpreted information about the system environment? Have we correctly identified problems in a timely manner? Have we adopted the most appropriate scope for our decision? Are we clear about the performance criteria and their relative importance to us? Have we undertaken a sufficiently thorough search for alternative solutions? Have we evaluated alternatives adequately in a way that recognizes all relevant sources of uncertainty? And so on.

Table 1. Sources of uncertainty in the water management process structure

Stage in the decision process	Uncertainty about
Assess the nature and status of water system	Completeness, reality and accuracy of information received, meaning of information, interpretation of implications.
Define short- and long-term goals for the system	Significance of issue, urgency, need for action, appropriate frame of reference, scope of relevant activities, who is involved, who should be involved, extent of separation from other decision issues.
Determine objectives (criteria) and actions to achieve goals	Relevant performance criteria, whose criteria, appropriate metrics, appropriate priorities and tradeoffs between different criteria. Nature of actions available (scope, timing and logistics involved), what is possible, level of detail required, time available to identify alternative actions.
Assess benefits and costs of each action	Consequences, nature of influencing factors, size of influencing factors, effects and interactions between influencing factors (variability and timing), nature and significance of assumptions made. How to weigh and compare predicted outcomes?
Implement desired actions	How will alternatives work in practice?
Evaluate the effects of actions	What to monitor, how often to monitor?
Re-evaluate goals and objectives	When to take further action, in what direction?

In order to manage all this uncertainty, water resources decision-makers seek to simplify the decision process by making assumptions about the level of uncertainty that exists, and by considering a model of the decision components. The value of this approach is a starting position for this article. A key aim of this section is to demonstrate that the quality of water resources systems management can be greatly improved by the use of formal decision support processes to manage associated uncertainty (Simonovic, 2008 page 120-229).

Implication of uncertainty is risk. It can be defined as a significant potential unwelcome effect of water resources system performance, or in a more pragmatic way as the probability of failure or the probability of load exceeding resistance. Three cautions surrounding risk must be taken into consideration: risk cannot be represented objectively by a single number alone, risks cannot be ranked on strictly objective grounds, and risk should not be labelled as *real*.

A major part of the water resources risk management confusion relates to an inadequate distinction between three fundamental types of risk: (i) *Objective risk* (real, physical), R_o, and objective probability, p_o, which is the property of real physical systems.; (ii) *Subjective risk*, R_s, and subjective probability, p_s. Probability is here defined as the degree of belief in a statement. R_s and p_s are not properties of the physical systems under consideration (but may be some function of R_o and p_o); and (iii) *Perceived risk*, R_p, which is related to an individual's feeling of fear in the face of an undesirable possible event, is not a property of the physical systems but is related to fear of unknown. It may be a function of R_o, p_o, R_s, and p_s. Because of the confusion between the concepts of objective and subjective risk, many characteristics of subjective risk are believed to be valid also for objective risk. Therefore, it is almost universally assumed that the imprecision of human judgment is equally prominent and destructive for all water resources risk evaluations and all risk assessments. *This is perhaps the most important misconception that blocks the way toward more effective water resources risk management***.** The ways society manages risks appear to be dominated by considerations of perceived and subjective risks, while it is objective risks that kill people, damage the environment and create property loss.

A need for change – from probability to fuzziness

Probability is a concept widely accepted and practiced in water resources systems management. One of the main goals of water resources management is to ensure that a system performs satisfactorily under a wide range of possible future conditions. This premise is particularly true of large and complex water resource systems. Water resource systems usually include conveyance facilities such as canals, pipes and pumps, treatment facilities such as sedimentation tanks, and filters, and storage facilities such as reservoirs and tanks. These elements are interconnected in complicated networks serving broad geographical regions. Each element is vulnerable to temporary disruption in service due to natural hazards or human error whether unintentional as in the case of operational errors and mistakes or due to intentional causes such as a terrorist act.

The sources of uncertainty in water resources are many and diverse and, as a result, impose a great challenge to water resource systems management. The goal to ensure failsafe system performance may be unattainable. Adopting high-safety factors is one way to avoid the uncertainty of potential failures. However, making safety the first priority may render the system solution infeasible. Therefore known uncertainty sources must be quantified. The problem of engineering system reliability has received considerable attention from statisticians and probability scientists. The probabilistic (stochastic) reliability analysis has been extensively used to deal with the problem of uncertainty in water resources systems management. Prior knowledge of the probability density functions of both resistance and load and/or their joint probability distribution function is a prerequisite to the probabilistic approach. In practice, data on previous failure experience is usually insufficient to provide such information. Even if data is available to estimate these distributions, approximations are almost always necessary to calculate system reliability.

Fuzzy set theory was intentionally developed to try to capture judgmental belief, or the uncertainty that is caused by the lack of knowledge. Relative to probability theory, it has some degree of freedom with respect to aggregation operators, types of fuzzy sets (membership functions) and so on, which enables it to be adapted to different contexts. During the last 40 years, fuzzy set theory and fuzzy logic have contributed successfully to technological development in different application areas such as mathematics, algorithms, standard models and real-world problems of different kinds (Zadeh, 1965; Zimmermann, 1996).

In essence, whenever there is an experiment for which we are not capable of 'computing' the outcome, a probabilistic approach may be used to estimate the likelihood of a possible outcome belonging to an event class. A fuzzy theory extends the traditional notion of a probability when there are outcomes that belong to several event classes at the same time, but to different degrees. Fuzziness and probability are orthogonal concepts which characterize different aspects of human experience. Hence, it is important to note that neither fuzziness nor probability governs physical processes in nature. These concepts were introduced by humans to compensate for our own limitations.

CONCLUSIONS

This paper describes the 'systems approach' and its application to contemporary water resources management, focusing on three main sets of tools: simulation, optimization and multi-objective analysis. This approach is presented in the context of sustainable planning and development under conditions of uncertainty. Some innovative points of this discussion include: its introduction of system dynamic simulation as a tool for integrated water resources modeling and its coverage of the use of fuzzy sets for incorporating objective and subjective uncertainties.

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