# Decision Support Systems for Sustainable Management of Water Resources: 1. General Principles

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**ABSTRACT**

*The new ethic of sustainable development reinforces and extends the main principles of water resources management. Computer-based decision support systems are explored in order to identify their role in the implementation of these principles into water resource management practice. The presentation is divided in two parts. This article starts with the general definition of sustainable development. A set of principles is then identified, and a short discussion of three main subsystems (ecological, economic, and social) follows. The main discussion is devoted to decision support systems (DSS) and their role in sustainable development. Discussion of DSS characteristics, architecture, and main components is provided, with special emphasis on the modifications required to address the principles of sustainability. A second article in this issue presents four successful case studies of decision support systems for sustainable management of water resources.*

## INTRODUCTION

The past three decades have brought a remarkable transformation of attitude and action by the water resources engineering community toward environmental concerns. There are many examples of initiatives taken for environmental assessment and planning as well as the considerable investment in environmental technologies and new processes designed to recover or eliminate pollutants. In developing countries the emphasis is on the "elementary environmental care" mostly oriented to meeting basic water supply, housing, and waste disposal needs. These initiatives have influenced not only the main activities of water resources engineers but also new interdisciplinary linkages, mostly with the social and biological sciences. The environmental management aspects of water engineering continue to be of major significance to the profession.

What is sustainable development? How does this new subject differ from the current vision of environmental planning and management? Why should engineers be concerned about this new era? What are some specific ways in which sustainability will affect the activities of water engineers? These are some of the questions for discussion addressed in this article.

The new ethic of sustainable development reinforces and extends the main principles of water resources management. However, the main challenge remains to be how to put these principles into practice. Computer-based decision support systems are explored in order to identify their role in the implementation of these principles into water resource management practice.

## SUSTAINABLE DEVELOPMENT

There are many definitions of sustainable development. One of the strengths regarding sustainable development discussions is the diversity of views expressed. In different ways all the views are building on the Brundtland definition:

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs* [1].

It can be compared with the definition of between-generational equity or wise use of the resources by the present generation so that the quality and quantity of

**There are many definitions of sustainable development**

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these resources are minimally impaired, if at all, for use by the future generation.

The focus in many national guidelines for sustainability is to expand the scope of responsibility for engineers, including water resource engineers, to include:

- help for the very poor;
- self-reliant development within the constraints of natural resources;
- extended meaning of cost-effective development;
- health control;
- use of appropriate technologies;
- food self-reliance, clean water, and shelter for all; and
- the notion of human beings as the resources [2].

What is emerging, despite the growing differences, is a new commitment based on fundamental linkages between environmental protection and management, economic development, and the social well-being of people. This three-dimensional approach to sustainability places water resource engineering in a new perspective. Solutions are required that are not only good for the environment but also for poverty alleviation and for wealth creation. It is important to note that sustainable development is not about weakening environmental standards or about compromises between environment and economy. Instead, sustainable development calls for new and innovative approaches, and fundamental institutional changes that will enhance efficient and modern decision-making. Any water resources development has some adverse impacts at a certain point. Therefore, the new designs should be guided by maximum overall benefits with minimal irreversible damages.

The focus of sustainable development is on both between-generational and within-generational equity concerns. It is also important for individuals to take the ideas of sustainability into their everyday practice. Some of the themes for sustainable development include: (a) capacity building (experimentation, transfer of experience, institutional change); (b) development of information systems (the sharing of information, increased interdisciplinary cooperation); and (c) technology sharing.

## PRINCIPLES OF SUSTAINABLE WATER RESOURCES MANAGEMENT

The new ethic of sustainable development not only reinforces but also extends the main principles of water resources management [3]. However, the main challenge remains to be how to put these principles into practice. Unfortunately, there are not too many countries that have a broadly-based consensus in practice about the principles that should guide water resources management. Lack of a consensus is judged to be the main reason in the past why different principles associated with water resources management have existed but not been put into practice. Sustainable development is providing a new context within which to consider the principles of water resources management as graphically illustrated in Fig. 1.

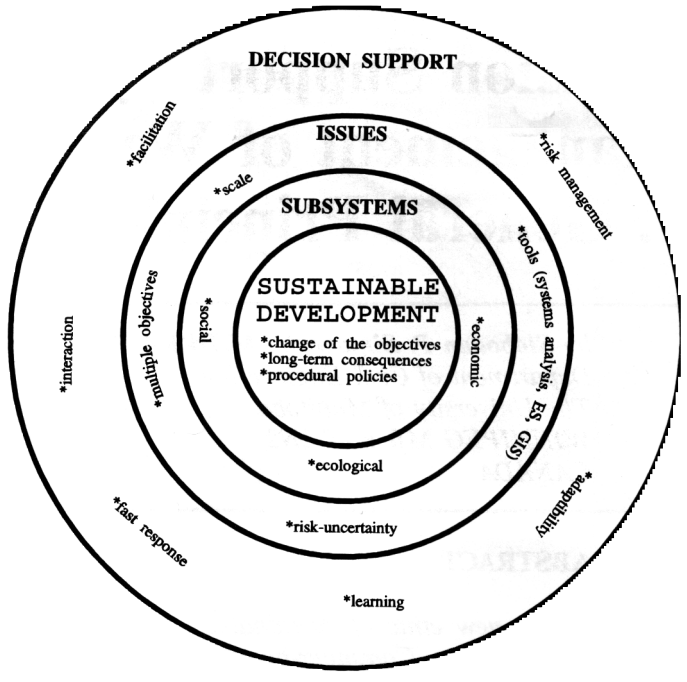


**Figure 1. Graphical presentation of the principles of sustainable water resource development.**

The following discussion will review first the context of sustainable development. Presentation of three subsystems linked by the principles of sustainable development follows. Several important issues used for water resources management are presented in the last section.

### *Context*

Sustainable development is providing a new context within which to consider the principles and practice of water resources management. Considering that sustainable development will build on the principle of comprehensive river basin development, it is essential to define what change will be introduced in future examinations. Pursuing sustainable development of water resources will require major *change in objectives.*

The "Principles and Standards for Planning Water and Related Land Resources" [4] in the U.S.A. identify only two national objectives: (1) to protect and enhance national economic development (NED); and, (2) to protect and enhance the quality of the environment (EQ). National objectives in developing countries are often more specific, including: (1) increase in food production; (2) encouragement of regional development; (3) provision of safe drinking water; and (4) better redistribution of national income.

Trying to manage water resources without understanding the complicated interrelationships between existing ecological, economic, and social factors is impossible. The broadest goals that should lead the sustainable development of water resources [5] are:

- environmental integrity;
- economic efficiency; and
- equity.

Water resources planning and management for maximum net economic benefits is not sufficient anymore. Introduction of the principles of sustainability is further expanding the range of issues that must be incorporated in the objectives of water resources planning. The main modifications are required to account for:

- noneconomic objectives (example no-net-loss of ecosystem productivity);
- needs of future generations;
- distribution of costs and benefits;
- balancing inequalities (within- and between-generational);
- increase in energy efficiency; and
- elimination of irreversible effects.

The second important aspect of the sustainable water resources planning and management context is *the challenge of time* (long-term consequences). Sustainable development requires forms of progress that meet the needs of the present without compromising the needs of future generations. We are failing in the first clause of the presented definition by not meeting the basic needs of more than one billion people [6]. We are not at the starting point in dealing with the second clause (the needs of future generations). One argument is that we have no responsibility for the future, since we cannot know the needs of future generations. This is partly true. However, it is reasonable to assume that future generations will need drinkable water, a predictable climate, energy, etc. For some developments, prediction of long-term consequences is not easy.

With all these difficulties, present sustainable water resources planning and management will need to include long-term consequences in the analysis. This implies examining not only the longer-term consequences of proposed developments but also the possibilities for reversing the consequences of past commitments. The process of change toward a sustainable form of water resources management will shape our lifestyles and the way we do business.

The third aspect of the sustainable context is *change in procedural (implementation) policies.* Pursuing sustainable development of water resources will require major changes in both substantive and procedural policies. The diverse policy questions raised include: How should the methods and processes of impact assessment and planning be used? What should be the reliance on the market as opposed to regulatory mechanisms? What should be the role of public and interest groups in the management of the resource? How much should be invested in managing the resource and how should this be financed?

Implementation of sustainable development principles requires new institutional arrangements, innovative approaches, and development of a new science. The main difference exists between the developed and developing world. Integrating the environment, the economy, and social well-being of people in the developed world is clearly a multiobjective problem. The main implementation problems are in allocating the appropriate preferences of decision-makers, and in the consideration of uncertainty. On the contrary, in the developing world, implementing principles of sustainability is a hierarchical process. To illustrate the statement, let me quote Mr. R. Leakey, Director of the Kenya Wildlife Service: "To care about the environment requires at least one square meal a day." Decomposition of the complete development process is a natural approach in implementing sustainability in developing countries. Economy, environment, and social issues will be dealt with at different levels. In such a way better comprehension of different problems will be possible and the transmission of pertinent information between different levels will be established.

### *Subsystems*

Sustainability definitions are emphasizing the integral treatment of three subsystems: economic, social, and ecological. The questions raised by the sustainable development perspective of river basin management reveal major gaps in knowledge about the behavior of diverse natural, economic, and human subsystems. In general, water resources management becomes progressively more complex with the growing recognition of the comprehensive linkages between natural (ecological), economic, and human (socio-political-institutional) subsystems to be considered. The more developed the basin and its associated subsystems, the greater the complexity to be dealt with.

The *ecological subsystem* is based on the theory that focuses on ecosystem functioning and the maintenance of environmental integrity. Ecology focuses on survival, with the emphasis on explanation of the functioning and how these processes can be understood. Water is a major part of the ecological subsystem. It is still considered by some countries to be boundless. Natural resources, including water, can be classified in a variety of ways and usually not in a very rigid sense. One way is to recognize that some resources are renewable. Others, because they are not renewable, can only be depleted. Most ecological principles [7] are presented as constraints that shape the feasible region.

The *economic subsystem* is concerned with those aspects of human behavior associated with the use of scarce resources for the production and distribution of goods and services. This subsystem is used to identify the most effective way to satisfy as many needs of individual people and the collective needs of society as possible. In some conditions within this subsystem, policies are developed to redistribute income and change social preferences. Usually, resource economics relies on a modeling approach, by which abstract mathematical models are used in an attempt to derive planning and management policies. The past, for most developing conditions, has been characterized by ignorance of linkages between the environment and economy.

The *social subsystem* is concerned with the problem of between-generational and within-generational equity. Eq-

uity is the fair distribution of resources, rights, and wealth among people over time. A consensus that seems to appear for between-generational equity is that the external costs of today's activities should not be passed to future generations. Each generation should have, at least, similar options to solve its own problems. This implies a need to maintain the value of conditionally-renewable resources and to avoid ecologically irreversible actions.

Within-generational equity means that: (a) all persons should have equal rights to basic liberty; and (b) social and economic inequalities are acceptable only when these inequalities are to the advantage of the worst-off members of society and all people have equal access to opportunities for advancement [7]. Such a situation is very different from the current distribution of the world's water resources. Practical implications are that programs and policies are required that will increase the welfare of the poorer members of society.

*Issues*

A number of important issues make water management in the sustainable development of river basins more challenging. Some issues that will be discussed in this article are: (a) scale; (b) multiobjective analysis; (c) risk and uncertainty; and (d) tools for the analyses.

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*Scale.* With the introduction of sustainable development principles comes the necessity to consider much wider spatial boundaries (spatial scale). Watersheds should be examined as subsystems of river basins and also subsystems of associated biophysical, socioeconomic, and political systems. Recognition of important interdependencies with other river basins at the international, national, and regional level has to be allowed for.

To provide the information base for between-generational equity analysis, much longer periods will need to be analyzed (time scale). Extension of the time scale implies examination of long-term consequences of proposed water developments and the possibilities for reversing the consequences of past development decisions.

*Multiobjective analysis.* Even though this concept is not new to water management, sustainability is placing much more weight on replacing single-objective optimization with multiobjective analysis. The importance of considering more then one objective at a time is emphasized by the existence of several conflicting and noncommensurable objectives in every step of the sustainable water management process. Multiobjective analysis considers change in objectives with time due to change in technology, weather, population, etc. The main concept of multiobjective analysis is the replacement of single optimal solution with a set of tradeoffs (nondominated, noninferior, compromise, Pareto optimal solutions). Selection of the *best compromise solution* is a political decision. Tradeoffs are an inherent part of the consensus-reaching process. Some specific aspects of sustainable water management are suggesting that the best compromise solution concept should be replaced with the concept of the *most robust solution* [8]. Sustainable water management is subject to two major sources of complexity regarding the application of multiobjective analysis: (a) quantification of different objectives; and (b) getting preferences from decision-makers regarding different objectives. Simonovic [8] has shown that the idea of combining the sensitivity analysis of the multiobjective solution to criteria values and preference structures and replacing the best compromise solution with the most robust solution is an appropriate idea to be used in the application of sustainability to multiobjective analysis of water resources.

*Risk and uncertainty.* Expanded spatial boundaries, lengthened time scale, comprehensive multiobjective analysis, and other issues related to sustainable water management are placing immense demands on science. A number of questions raised by the sustainable development perspective of water resources reveal major deficiencies in the knowledge of the behavior of a wide range of natural and human systems under consideration. Recognizing the fact that many of these deficiencies cannot be eliminated very fast makes it evident that risk and uncertainty are inherent concepts related to sustainable water management.

*Tools for sustainable water management.* The specific character of sustainable water management calls for new tools. Occasionally they are only new in that they are actually being put into practice (optimization of the operation of water resource systems). In other cases they are new in that they implement techniques that are well established in the literature but yet have not been fully utilized (expert systems for monitoring, design, and operations of water resource systems). Often they are new in that they are modified to address new problems arising from the application of sustainability principles to water management (reallocation of reservoir storage and reassessment of reservoir operating strategies). In still other situations they are new in that they introduce new ideas and implement new technologies to solving water management problems.

Meeting the growing diversifying demands of sustainable water management requires use of very sophisticated and yet flexible-enough techniques; these must be capable of providing answers to many questions within the context identified earlier in this article. Four main categories of tools foreseen to be more actively used are: (a) information systems (spatial and temporal data processing including statistics, database management tools, and geographic

information systems); (b) systems analysis (simulation, optimization, and multiobjective analysis); (c) artificial intelligence (expert systems, neural nets, object oriented programming, fuzzy analysis, etc.); and (d) technological tools (computer graphics, sound, animation, etc.). All the tools to be used in sustainable water development will be incorporated into the decision support framework (Fig. 1), which is presented in one of the later sections.

## DECISION SUPPORT SYSTEMS FOR SUSTAINABLE WATER RESOURCES MANAGEMENT

Development of Decision Support Systems (DSS) is closely related to computers. The computer has moved out of data processing, through the user's office into knowledge processing. Whether it takes the form of a laptop PC or a desktop multiprocessing work station is not important. It is important that the computer is a "silent partner" for more effective decision-making in a decision support system environment. The main factor responsible for involving computers in decision-making is treatment of information as the sixth resource (besides people, machines, money, materials, and management). Even though a close link exists between data processing (DP), management information systems (MIS), and decision support systems (DSS) a widely accepted definition of DSS is not available. Some texts in the field of water resources provide a very general definition of DSS [9] as:

*computer-based tools having interactive, graphical, and modeling characteristics to address specific problems and assist individuals in their study and search for a solution to their management problems.*

Others are avoiding the definition of DSS, concentrating on the main purpose of such systems [10]:

*the support to decision-makers in solving problems that are poorly or insufficiently structured.*

The problem of defining DSS is continuing. On one side, all computer applications help in the decision-making process and therefore nearly all could be called DSS. On the other hand, there are a number of publications, providing a very detailed definition of DSS, trying to set the framework within which such systems will continue to be developed, used, and modified in the future [11,12]. The latter approach will be used in this contribution, trying to identify the role of DSS in sustainable management of water resources. Good additional reading on defining a DSS is provided by Parker and Al-Utabi [13], who reported a review of 350 papers related to the subject.

The word "system" is used in describing a large number of phenomena. Aggregating nine different definitions, Alexander [14] arrived at the following definition of a system:

*A system is a group of elements, either physical or nonphysical in nature, that exhibit a set of interrelationships among themselves and interact together toward one or more goals, objectives, or ends.*

Applying this broad definition to a computer-based information system, the primary group of elements is data, the set of relationships is the flow of data, and the goal is to have a well-informed user capable of making efficient decisions.

In recent years there has been increasing emphasis placed on helping decision-makers make decisions from good information. The need is much greater in fields where problems are poorly structured, as often happens in water resources. As a result, the decision support system has become an essential subsystem within the framework of broader management information systems. The difference between the two is that a management information system uses the computer for providing information to solve problems (usually recurring), and DSS positions the decision-maker in the center of the decision-making process providing help in solving both ad hoc problems as they arise and recurring problems. Within the framework of management information systems [11], the DSS has four primary characteristics:

it helps decision-makers at the upper levels;
it is flexible and responds quickly to questions;

**There has been increasing emphasis placed on helping decision-makers make decisions from good information**

it provides "what if" scenarios; and
it considers the specific requirements of the decision-makers.

Important characteristics of DSS for sustainable management of water resources include accessibility, flexibility, facilitation, learning, interaction, and ease of use. Since DSS have an added dimension not found in management information systems, the final *definition* will address each term in the expression "decision support system."

First, DSS is primarily concerned with supporting decision-making in terms of problem identification and problem solving at all decision-making levels. The most important issue of DSS is identifying the steps of the decision-making process or decisions that need to be made to help the decision-makers in fulfilling their organizational duties and responsibilities.

Second, a DSS provides support to the user and does not replace the individual. The emphasis is on the enhancement of a decision-making process by allowing use of quantitative models that are appropriate to the problem. In this way objective (quantitative) measurement introduced by models is combined with the subjective (qualitative) factors introduced by the user. The interaction of two is the most effective way in reaching a decision.

Third, the term "system" includes both the user and the machine. The machine is a computer that, for now, operates in interactive mode through an input/output terminal. "System" also implies availability of quantitative models and some type of database. In the framework of this definition, these elements are more providing service to the decision-maker then directly delivering a decision.

Integrating all previous comments and characteristics, the decision support system can be defined:

*A Decision Support System allows decision-makers to combine personal judgment with computer output, in a user-machine interface, to produce meaningful information for support in a decision-making process. Such systems are capable of assisting in solution of all problems (structured, semistructured, and unstructured) using all information available on request. They use quantitative models and database elements for problem solving. They are an integral part of the decision-maker's approach to problem identification and solution (modified after Parker and Al-Utabi [13]; Thierauf [12]; and Simonovic and Savic [15]).*

This definition of DSS is based on the concept of management by perception. It relies on the decision-maker's insight and judgment at all stages of problem identification and/or problem solving. Thus, decision support systems add a new dimension to sustainable planning and management of water resources.

### *Characteristics of Decision Support Systems for Sustainable Water Resources Management*

Sustainable development principles, presented in the previous section, are imposing a new set of requirements on the tools to be used in sustainable management of water resources. The following discussion of DSS characteristics will address specific requirements of sustainable decision-making.

*Problem identification.* Sustainable water resource management contains a number of semistructured and nonstructured problems. The management problem that can be well formulated in an algorithmic way (a computer program), is called well-structured. Decisions in this case are straightforward because alternate solutions are known. If the management problem involves lack of data or knowledge, nonquantifiable variables, and a very complex description then it is called semi- or nonstructured. Structuring of the problem, in this case, must be done by the human in the man-machine system. One way of presenting the spectrum of decision-making is provided in Fig. 2. As the boundary moves to the right, more general man-machine solution procedures have to be used. They may include: analogy; problem redefinition; deduction; intuition; and approximation.

Because judgment and intuition are critical in examining and resolving many water resource problems, an effective DSS involves problem identification. This process includes searching the decision-making domain for future problems that need to be anticipated and solved. Future

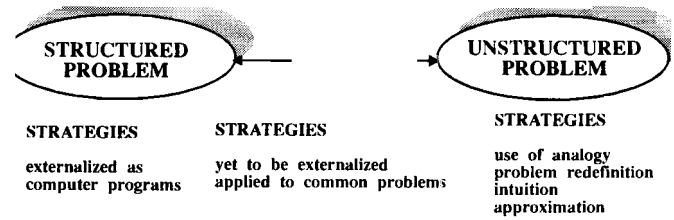


**Figure 2. The decision process structure.**

opportunities can be identified and implemented to address the long-term consequences of current decisions, defined as the second component of the sustainable water resources management context.

*Problem formulation (learning).* Before trying to implement principles of sustainable development, water resource DSS have been used in situations in which there is a clear problem definition. DSS serve to solve such problems. However, the concept of a "problem" as it relates to sustainable development may be expanded to include two perspectives [16]: (i) problem as objective reality; or (ii) problem as mental construct. In the first case, a problem is viewed as an unsatisfactory objective reality discovered by observations and facts. The decision-maker or expert has to define the problem. As a problem exists objectively, all participants in the decision-making process see it in the same way (even if there are different alternate solutions). Here, problem formulation is a preliminary step to DSS design. The second case presents an alternate view, considering a problem to be a subjective presentation conceived by a participant confronted with the reality perceived as unsatisfactory. Here, common threshold values have to be defined by the different participants in the decision-making process before another procedure can take place. This approach requires integration of the problem formulation process into the context of a DSS. The emphasis is shifted from the analysis phase. It is important to note that problem formulation in sustainable development is more a social process than a technical one.

*"What If" capability (adaptability).* The DSS environment allows a number of "what if" questions to be asked and answered. The main benefit of DSS is that a number of decisions can be tried without having to deal with the consequences. In this way DSS can guide decision-makers through most optimistic, most pessimistic, and in-between scenarios.

Many issues related to the implementation of sustainable principles to water resource management can be examined using the "what if" approach. A typical "what if" approach example is the question of between-generational and within-generational equity. In this example there is no need to rely on a water resource specialist. The ability to ask "what if" questions, to quantify uncertainties, and to recognize the sensitivity of results to varying assumptions stimulates the creative and analytical process of decision-making. The process provides a common ground for communication. Since the decision-

maker can use the tool directly, higher quality decisions can be made on a more timely basis.

*Use of analytical models (facilitation).* The integration and administration of mathematical models within the general framework can be identified as the specific feature of the concept of DSS. Since sustainable development is principally concerned with the future and the implications of today's decisions, modeling capability is very important to grasp and manage water resource systems. For problem identification and problem solving, decision-makers deal with analysis. This fact underlines the need for DSS modeling capabilities for:

retrieval of data;
execution of ad hoc analysis;
evaluation of consequences of proposed actions; and
proposal of decisions.

Typical models that include database management system functions as data queries and data manipulation, range from simple arithmetic functions and statistical operations to the ability to call up optimization and simulation models. The scope of a DSS is in the integration of such different facilities. The idea of DSS integrates different fields of science, and puts weight on social circumstances that may decide or influence problem definitions and solution approaches.

*User-machine interface (interaction).* Whether the user is using a microcomputer or a powerful workstation is not the important issue anymore. What is important is an interactive processing mode incorporating a user-machine interface that provides answers to identified problems or "what if" questions. The user-machine interface provides answers that decision-makers can understand, when such information is needed, under their direct control. Therefore, DSS are intended to help decision-makers throughout the process of identifying and solving their problems. The merging of the computer output with the subjective judgment of the water resource decision-maker provides a better basis for making efficient decisions.

Computers are more than number crunchers or storage devices. With progress in the field of Artificial Intelligence (AI), computers are more capable of demonstrating their capacity to support humans in areas of creative and analytical thinking. It is important to note that DSS are not general problem solvers. They are a part of a complex user-machine system with the emphasis being placed on the "user" rather than on the "machine." Therefore, DSS are the possible tools to manage the complexity of water resource sustainable decision-making.

*Use of graphics (fast response).* Closely related to the previous two characteristics is the use of color graphics. In a DSS environment, graphic display of results allows users to quickly grasp the essence of large amounts of physical data and reduce considerably the printout into a few readily understandable graphs and charts. It is the way to select the important information in a user-machine interface such that the user retains control during the decision-making process.

### *Architecture of Decision Support Systems*

The architectural aspects of DSS are discussed to give a potential designer a conceptual tool for constructing a DSS, and to support a more practical and constructive definition of a DSS. Two main approaches representative of existing DSS are discussed with the proposed architecture to be used for the development of DSS for sustainable management of water resource systems.

*Functional approach.* The approach distinguishes three components, which differ according to their functions. They are: (a) the language system; (b) the problem processing system; and (c) the knowledge system. This approach does not explicitly represent modeling or data retrieval functions. The user states a problem using the language system, and the system responds by starting the problem processing system and looking up specific information in the knowledge system.

*Tool-based approach.* The main components of the tool-based approach are: (a) the database; (b) the model-base; and (c) the dialogue module. A tool-based approach is more general than a functional approach. Main components support the data retrieval, the modeling, and the model invocation functions. Tasks as problem processing or knowledge representation are not included in the model base or the dialogue module.

*Intelligent decision support approach.* This architecture is developed according to the objectives and properties of sustainable water resource decision-making. It takes advantage of combining two architectures described above. The approach originated in 1989 [15]. Appropriate modifications have been added through different applications of the approach [17-19].

The intelligent decision support concept, as shown in Fig. 3, links four basic elements of water resource decision-making: (a) engineering expertise; (b) a systems approach; (c) computer graphics; and (d) artificial intelligence (AI). As such, this concept becomes very similar to the integrated model-base decision support approach. The concept envisions technical specialists as the potential users of the software system and the decision- and policy-makers. In this environment, the computer is seen as a link between the field expert and the decision-maker, between science and policy. Therefore, the DSS is not only a tool for analysis, but an instrument for communication, training, forecasting, and experimentation. The major strength of this concept is that the products are application- and problem-oriented rather than methodology oriented. In this way, AI technology through expert systems, neural nets, fuzzy reasoning, and genetic programming is combined with more classical techniques of engineering analysis, data processing, and systems analysis.

### *Decision Support Systems Structure*

This section presents only those components of intelligent decision support systems that have been added to

the classical DSS structure, to better address requirements of sustainable water resource management. An intelligent decision support structure is adopted to address sustainable water resource management by the addition of an AI block (Fig. 3) and a major conceptual modification of the multiobjective approach, as one component of the systems analysis block.

*Use of artificial intelligence.* Progress in the field of artificial intelligence is significantly increasing the capacity of DSS to enhance human creative and analytical thinking. The power of AI products is still limited. However, expert systems, neural networks, fuzzy, and genetic programming are becoming keystones of the evolution toward greater complexity in today's society and in technological progress.

*Expert systems.* Expert systems (ES) are defined as computer applications that assist in solving complicated water resource problems by incorporating experience, intuition, and engineering judgment in the solution process [20]. Expert systems simply extend the role of DSS, as a source of expert knowledge (problem-solving advice) and a storage of process knowledge (solution procedures). Expert systems provide an environment to help organize and structure these types of knowledge. On the other hand, ES are very useful in integrating different components of DSS for addressing problems in less-structured or ill-defined domains.

The goal of sustainable water resources management is to ensure water is available, in sufficient quality and quantity, at the right location and time, and to protect the population and their activities from harmful effects of water mismanagement, taking into consideration long-term consequences of current decisions. In hopes of achieving this goal, a combination of scientific principles and computational algorithms with heuristics is necessary. In theory, water resource engineering decisions are based on accepted underlying physical principles. However, this

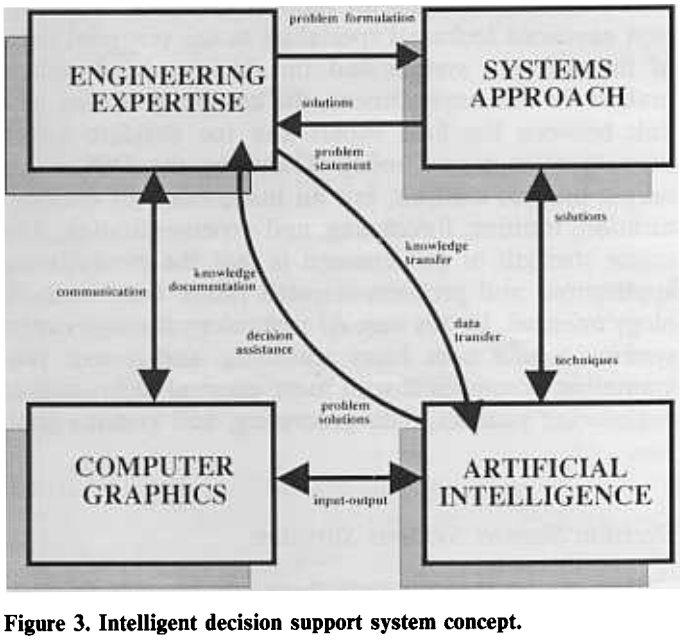


**Figure 3. Intelligent decision support system concept.**

trace-back to known facts is difficult to establish. In water resources, not only are fundamental principles scarce, but structured, procedural decision-making is almost impossible. It is under these circumstances that experience and judgment come into play.

The complexity of the water resource domain makes it necessary for engineers to specialize, making expertise in a particular area a scarce commodity. In addition, the main requirements of sustainable management and processes involved in water resources cannot be accurately or completely described using available techniques. Heuristics can compensate for a lack of complete theory and allow a decision-maker to make educated guesses. However, experience is needed to create heuristics.

*Neural networks.* Neural networks (NN) consist of many, simple processing units (neurons) that can be programmed for computation. We can program or train neural networks to store, recognize, and associatively retrieve patterns or database entries; to solve combinatorial optimization problems; to filter noise measurement data; to control ill-defined problems. In summary NN can estimate sampled functions when the form of the functions is not known.

A main characteristic of NNs is that they can learn new patterns and recall old patterns simultaneously. Since NNs do not use a mathematical model of how a system's output depends on its input, we can apply them to a variety of problems. Sustainable development is concerned with learning aspects due to the importance of having clear understanding of long-term consequences of present actions. This process is performed within the very complex ill-defined system that cannot be fully described by a mathematical model.

*Fuzzy programming.* Fuzzy programming (FP) allows DSS to be constructed using an approximate reasoning capability. FP provides a wide variety of concepts and techniques for representing and inferring from knowledge that is imprecise or uncertain. Now what is used in most practical applications is relatively restricted to the use of fuzzy if/then rules. On a more concrete level, the relation between water demand, water availability, and available capacity may be expressed as a collection of fuzzy if/then rules.

The importance of the calculus of fuzzy if/then rules come from the fact that much of our knowledge about complex water resource systems can be nicely represented in the form of a hierarchy of fuzzy rules. Furthermore, the reasoning mechanisms in the fuzzy environment are relatively simple and similar to human reasoning. The mechanisms of imprecise matching provide a basis for inter-and extrapolation making fuzzy systems simpler and more robust.

*Genetic algorithms.* Genetic algorithms (GA) are slowly demonstrating effectiveness at finding optimal solutions to a variety of problems. The technique fits well with complex "real-world" problems because it does not impose many limitations characteristic to more traditional techniques. The GA generates many possible solutions to

a given problem and then lets elements of each alternate solution compete to create increasingly better output. In this since, the GA evolves the problem toward the optimal solution rather than trying to solve it directly.

Sustainable water resource management problems contain a large number of variables. Objective function surfaces in water resources are convoluted and gradient-based approaches usually become trapped in local optima. GAs are very well adapted for these situations, being neither as susceptible to traps nor as sensitive to initial variable values.

*Modified multiobjective approach.* Sustainable development and management of water resource systems are built on the assumption that an acceptable compromise must be achieved among the three main sets of objectives: ecological, economic, and social. Each of these three sets constitutes a larger subset of specific objectives. The quantification and evaluation of the objectives and their associated tradeoffs are the main tasks of multiobjective analysis [21]. It has been already presented, in very general terms, that sustainable development and management of natural resources are the epitome of multiobjective analysis [22]. Within the paradigm of sustainable development, the role of economics is viewed as one aspect of the problem. A multiobjective decision framework may discuss problems in terms of an economic model, substituting a welfare function for the summation of monetary benefits. The model is dependent on the definition of welfare, which requires relative valuation of social and ecological components.

Considerable uncertainty exists in evaluating future values and in choosing the best option at some point in the future, assuming we are aware of future consequences. Uncertainty breeds risk-averse decision-making, which implies a perceived cost of capital at a high rate.

One of the possible ways for dealing with intergenerational equity is a modified multiobjective framework. It requires definition of objectives of future generations. An arbitrary objective function can be expressed as the weighted combination of future values such that the sum of weights equals one. This is not a traditional form of showing a multiobjective model. The different objectives are related to time as opposed to physical objectives. Application of this formulation produces a set of nondominated solutions, as opposed to a single optimum followed by a subjective process to select one of the nondominated solutions, as a "best compromise" solution.

Uncertainty in selecting objectives for future generations, as well as selecting the combination of weights, may result in the selection of a "best compromise" solution that is not realistically sustainable. Some of these aspects of sustainable decision-making are calling for the replacement of the "best compromise" solution concept with the concept of the "most robust" solution. This idea has been introduced by Simonovic [8] and applied in a sustainable context by Bender et al. [23]. It has been demonstrated that the idea of combining the sensitivity analysis of the multiobjective solution to objective values and preference (weight) structures results in the replacement of a "best compromise" solution with the "most robust" solution. The "most robust" solution is defined as:

*a multiobjective alternate selection least sensitive to changes in the objectives and preference structure.*

If a number of alternatives is available in which the dynamic model is solved for a variety of circumstances, a multiobjective programming procedure can be used to test the relative quality of decisions under a number of weight combinations and objectives measures. It is important to note that this conceptual difference in applying the multiobjective analysis provides a direct way for incorporating intergenerational equity issues in sustainable water resource development and management.

### *Risk Management*

Principles of sustainable water resource management are based, by definition, on the operational principle of risk assessment and management. The main difference between sustainable and classical water resource management is in the evaluation of alternate solutions and associated tradeoffs in terms of all costs, benefits, and risks [22]. This change invites innovative ideas for derivation of appropriate risk measures. Use of the expected value of risk, and/or the conditional expected value is not sufficient anymore. Knowledge-based risk management is the idea that will be discussed here in more detail.

Knowledge-based risk management has been introduced in the area of construction management by Niwa [24]. In sustainable water resource management:

*risk is defined as the chance of certain occurrences adversely affecting project objectives. It is the degree of exposure to negative events, and their probable consequences. Therefore, the risk is characterized by the: (i) the risk event; (ii) the risk probability; and (iii) the risk severity.*

Following the specifics of the risk definition, a three-level structure of the knowledge-based risk management tool is suggested. The first level is constituted of forward reasoning, the second of backward reasoning, and the third of knowledge association. Techniques to be applied at the first and second level are considered to be classic in the field of ESs (available with almost all ES tools available on the market). The third level is a newly-proposed function derived from human experience. It is defined as the process whereby the availability of one piece of knowledge causes the recall of another piece of knowledge.

Development of an intelligent decision support system with an ES component based on the previously defined three-level structure allows risk management that will benefit from the available data, available risk modeling capability, and risk-related experience.

**Water resource practices must change to meet the challenge of the global environment**

## CONCLUSIONS

Is the current water resource management practice incompatible with environment? What is the meaning of sustainable management of water resources? The question is no longer whether water resource practices must change to meet the challenge of the global environment, or even when. The issue is *how.*

By developing some ideas and providing definitions, the author has tried to demonstrate the role of computer-base technologies and decision support systems, in particular, in the implementation of principles defining sustainable development.

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