**State-of-the-Art Report on
Systems Analysis Methods for Resolution of Conflicts in
Water Resources Management**

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Acknowledgements

Summary

Water is an important factor in conflicts among stakeholders at the local, regional, and even international level. Water conflicts have taken many forms, but they almost always arise from the fact that the freshwater resources of the world are not partitioned to match the political borders, nor are they evenly distributed in space and time. Two or more countries share the watersheds of 261 major rivers and nearly half of the land area of the world is in international river basins. Water has been used as a military and political goal. Water has been a weapon of war. Water systems have been targets during the war. A role of systems approach has been investigated in this report as an approach for resolution of conflicts over water. A review of systems approach provides some basic knowledge of tools and techniques as they apply to water management and conflict resolution. Report provides a classification and description of water conflicts by addressing issues of scale, integrated water management and the role of stakeholders. Four large-scale examples are selected to illustrate the application of systems approach to water conflicts: (a) hydropower development in Canada; (b) multipurpose use of Danube river in Europe; (c) international water conflict between USA and Canada; and (d) Aral See in Asia. Water conflict resolution process involves various sources of uncertainty. One section of the report provides some examples of systems tools that can be used to address objective and subjective uncertainties with special emphasis on the utility of the fuzzy set theory. Systems analysis is known to be driven by the development of computer technology. Last section of the report provides one view of the future and systems tools that will be used for water resources management. Role of the virtual databases, computer and communication networks is investigated in the context of water conflicts and their resolution.

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1. Introduction

1.1 General

Water is very vital for the sustenance of life. Agriculture requires vast amounts of water. Many industries require substantial amounts of water as well. Besides these direct or consumptive demands, the indirect or non-consumptive uses of water are also important. For example, water is crucial for energy production whether it is hydro, nuclear or thermal. Water continues to be an important means of transportation. Water is used for recreation, for cleaning, for maintaining ecological habitats, and numerous other economic, environmental and social uses. There is no substitute for this essential resource. Without water, life on earth would not be possible.

Water is the most abundant substance on the Earth. Moreover, it is a renewable natural resource, cleansing and redistributing itself through natural cycles. However, its global quantity is finite. Only a fraction of this resource is freshwater. While water covers some 70% of the planet's surface, less than 3% of this consists of freshwater. Much of these world's freshwater resources are frozen in polar ice caps or deep underground and less than 0.3% of the global water resources consist of accessible freshwater.

When population densities were low, there was plenty of water for all. However, with the rapid population and economic growth experienced in the past two decades many regions of the world are facing serious water problems and related stress is likely to grow considerably in the foreseeable future.

Freshwater is a very unevenly distributed natural resource both temporally and spatially. Frequent and regular rainfall in some regions contrasts sharply with prolonged drought in others. Some regions are blessed with an abundance of freshwater while others face scarcity. Growing conflicts over increasingly scarce freshwater resources looms ahead.

The distribution and use of this limited or scarce water resource can create conflicts within a country. For example, the conflicts can exist between different regions of a country; e.g.,

regions that are more arid or have already exhausted their own supplies wishing to obtain water from more amply endowed areas. Perhaps, laws existing in that country may resolve these conflicts.

However, much of the world's freshwater supplies are located within basins and aquifers that cross international borders. There are some 260 international rivers, covering a little less than one half of the land surface of the globe affecting about 40% of the world's population (Wolf, 1998). Since water is vital for basic survival, industry, energy production and other fundamental components of a nation, sharing these transboundary waters between and among border nations can result in a myriad of conflicts.

The type and severity of conflict between the various states involved may vary depending on the region. In non-arid regions of the world conflicts or disputes are often based on environmental concerns resulting from development activities like dam construction etc., or transboundary pollution. On the other hand, in arid and semi-arid regions disputes and conflicts, although also possibly involving similar issues relating to development activities, usually center around the problem of water scarcity. The 280 or more treaties that have been signed between countries on water issues (Wolf, 2002) give evidence of the tensions that divided or shared basins engender. In spite of past negotiating efforts, conflicts linked to freshwater still exist at various international levels, and the risk for more grows as population and degradation pressures accelerate.

1.2 Nature of conflicts over water

Conflict is a natural disagreement resulting from individuals or groups that differ in attitudes, beliefs, values or needs. Conflicts in water management often involve interactions between various factors, water sub sectors and stakeholders in the water resources management process. Contemporary water resources management is a combined process of sharing water and resolving conflicts among stakeholders. A stakeholder in this context refers to an individual organization or institution that has a stake in the outcome of decision related to water sharing, because he, she or it is either directly affected by the decision or has the power to influence or block the decision.

Water resources management involves numerous uncertainties associated with the physical processes, available data and level of our knowledge. Its availability in a particular locality and point of time usually cannot be accurately predicted in advance. This uncertainties as well as scarcity are typically the reasons why conflicting scenarios arise among stakeholders, in sharing water and protecting their interests.

When the river basin traverses across multiple legal, political and international boundaries, the number of potential stakeholders and their specific interests increases, making the conflict resolution process increasingly complicated (Wolf, 1998).

1.3 Causes of water conflicts

Conflicts in water could be looked upon as consisting of three key spheres: water, economic and political (Le-Huu, 2001). Conflicts over water are often affected by problems in the economic and political spheres as much as those generated within the water sphere itself. Similarly, problems in the water sphere may lead to conflicts or disputes in the other two spheres.

Problems in the water sphere are mainly caused by various human and natural factors. These problems can normally be grouped into three major kinds in the water sphere: water quality, quantity and ecosystem problems. Increasing populations impose increasing demands for water supplies, often leading to unsustainable withdrawals. Activities of humans, industry, and agriculture generate wastes that are usually discharged into water bodies. Finally the environment and supporting ecosystems require water, and meeting those requirements often conflicts with meeting other demands.

The natural factors include the erratic natural distribution, extreme climatic events (such as floods, drought and cyclones), arid and semi-arid climate and local natural conditions. While human intervention may minimize the impact of these natural factors, lack of consideration and ignorance of the important roles of ecosystem functions, together with lack of consultation with stakeholders, may aggravate water conflicts.

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Global environmental change is also identified as a potential driver for water conflict. While there is insufficient evidence to support attributing recent trends of climate change and extreme events in water-related natural disasters (such as the more severe impacts of El Niño, the more frequent occurrence of extreme floods which affect many regions of the world) to global environmental change, these trends towards climate change and extreme events are on a global scale and need to be properly handled so as to prevent them from escalating into water conflicts.

The economic and political factors are treated as separate driving forces. Although these factors have a strong interaction with the key factors affecting the water sphere directly, they may originate independently from the water sphere. Often, the problems in the economic and political spheres are caused by the lack of detailed information on good management of water resources or by differences in the perception of a fair and equitable share of the water resources. Possible drivers for disputes in the economic and political spheres are identified in Figure 1.1.

1.4 Conflict resolution/Corporation potential

Conflicts resulting from water sharing problems may jeopardize economic and social order both within and between countries. Improved water management, conflict resolution and corporation could ameliorate such conflicts. Water management and conflict resolution process has been approached by many disciplines such as law, economics, engineering, political economy, geography, anthropology and systems theory. An excellent source of selected disciplinary approaches is available in Wolf (2002).

Conflicts should not be looked upon as always negative. It can be healthy when effectively managed. Healthy conflict management can lead to growth and innovation, new ways of thinking and additional management options. Understanding the conflict clearly is primary in that process. Then it could be effectively managed by reaching consensus that meets both stakeholders' needs. This may result in mutual benefits and strengthens the relationship. The goal is for all to "win" by having at least some of their needs met.

Natural and man-made factors

Industrial and agricultural outputs (pesticides, chemicals etc.)

Sewage and wastewater

Global environmental change (climate change, desertification, etc.)

Extreme climatic events

Arid and semi-arid climate

Unsustainable water withdrawal

Population pressure

Natural distribution

Local natural conditions

Water quality problems

Water quantity problems

FRESHWATER CONFLICTS

WATER SPHERE

Water ecosystem problems

Economic sphere disputes

Political sphere disputes

Territorial disputes

Extreme market forces

Trade issues

Economic disparity (poverty)

Ethnic rivalry

Nationalism

Regional hegemony

Chart adapted from that proposed by Paul Samson and Bertrand Charrier in "International freshwater conflict: issues and prevention strategies", Green Cross International, August 1997

Figure 1.1 Causes of freshwater conflicts (after Le-Huu, 2001)

One approach available for the successful management and resolution of conflicts (Watershed Information Network - Internet) is to follow the five steps: (i) analysis of the conflict, (ii) determination of the management strategy, (iii) pre-negotiation, (iv) negotiation, and (v) post-negotiation.

The first step, that is, the analysis of the nature and type of the conflict provides the stakeholders and mediator, if any involved, all the necessary details to proceed with the conflict resolution processes. Once a general understanding of the conflict is gained through that step, the group involved needs to analyze and select most appropriate strategy. The available conflict management strategies include, collaboration, compromise, competition, accommodation, and avoidance. In collaboration, compromise and competition a stakeholder has a high concern for his own group while concern over other party reduces from high, to

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medium and finally to a low concern. In accommodation stakeholder has low concern over his own interest and gives a high concern to the interests of other partners. Avoidance results from a low concern for his own interest coupled with a low concern for the interests of others. The third step, pre-negotiation sets the stage for effective negotiation or does the groundwork required. Initiation of the negotiation process, assessment of the resources and issues to be negotiated, agreeing on rules for communication, negotiation and decision making, gathering technical and social information needed are carried out at this step. At the negotiation stage, options that are of interest to stakeholders to resolve conflicts are invented and evaluated. Use of objective criteria for ranking ideas, making trade-offs among different issues, combining different options to form acceptable agreements are encountered in the process of evaluation. Once the negotiation is complete, the group will need to implement the decisions made. At this post-negotiation stage, the partners in the conflict must get the support from the organizations that have a role to play. Communication and collaboration should continue as the agreement is carried out. The partners will need to have a plan to monitor progress, document success, resolve problems, renegotiate terms and celebrate success.

As such, all water resources disputes do not end up with violent conflicts. Most of the time negotiations and discussions lead them to non-violent resolutions. However, every water resources dispute is unique and requires an individualized approach. The successful resolution of national as well as international water conflicts requires understanding of the nature of the conflict and then modeling and analyzing the inherent problems in it as discussed above. To reach a final agreement concerning how much of the shared water resource is allocated to each party or nation, assistance of procedures or methodologies acceptable to all the parties concerned is very much needed. Systematic study of the nature and conduct of conflict and corporation between parties involved based on new technologies and practices could assist the efficient management of water resources, and thereby reducing tension among parties in dispute over water.

As explained in an overview paper by Hipel (2001) and in articles contained within Theme 1.40 on Conflict Resolution in the Encyclopedia of Life Support Systems (EOLSS) (2002), a wide range of psychological, sociological, operational research, game theory, systems engineering and other kinds of models have been developed for systematically studying conflict and its resolution. Articles on conflict resolution published under Theme 1.40 include

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a number of systems engineering approaches to conflict resolution, such as the Graph Model for Conflict Resolution (Fang *et al*, 1993; Hipel *et al*, 1997b) and Drama Theory (Howard, 1999) with application to water resources and environmental conflicts.

2. Definition and Purpose of Systems Analysis

2.1 Systems approach – General comments

The art and science of systems analysis has evolved through developments in the separate disciplines of engineering, economics and mathematics. Rapid developments have taken place in this science and the availability of high-speed efficient and economical computers has contributed to its development. As the science of systems analysis had advanced over the last several decades and as the scale of modern water resource projects has grown, systems analysis has found extensive applications in water resources planning. The origin of the activity may be said to be in 1950s in the United States, and the pioneering work has been done by a group of engineers, economists and political scientists at Harvard University as reported in Maass *et al* (1962). Since then, the importance of systems planning has been increasingly recognized and continuous advances are being made (Fiering *et al*, 1971; Buras, 1972; Loucks *et al*, 1981).

A physical water resources system is a collection of various elements, which interact in a logical manner and are designed in response to various social needs, in the development and improvement of existing water resources for the benefit of human use. Haimes *et al* (1987) described water resources systems analysis as an approach by which the components of such a system and their interactions are described by means of mathematical or logical functions. In general, systems analysis is the study of all the interactions of the components. Very often systems analysis is concerned with finding that combination of components, which generates an optimum, i.e., a system, which consists of the best possible combination of elements for satisfying the desired objective. Thus, it involves in defining and evaluating numerous water resources development and management alternatives. This could be done in a very detailed manner representing various possible compromises among conflicting groups, values and management objectives.

Systems analysis may be used to find a "best acceptable" solution. But this is not its only purpose. Often it is applied for "structuring" a water resources project. By structuring it is meant that the systems elements are drawn into a block diagram and connected by means of

logical statements. When a system is represented in the form of such a diagram, it is easier to "see" how different components must interact for the system to perform properly, or how the system interacts with its environment. By isolating subsystems of the water resources system, their performance can be tested and analyzed separately. In this manner, the system approach gives transparency to the planning process and simplifies the discussion on all levels of the decision-making process; and it easily permits addition or deletion of different components or interactions.

The systems approach is especially useful when a project becomes so large that it cannot be considered as a unit, necessitating its decomposition. However, systems analysis is not an approach that can be used automatically and without thinking. Usually, the greatest effort of the analyst is to reduce the system to a manageable representation without destroying its essential features and relationships. The analyst may overlook important relationships because he may lack access to all necessary data, and usually time is not sufficient in an actual planning environment to develop the ideal model and test it to its fullest extent or to subject it to the scrutiny of several experts.

A prerequisite for a systems analysis is that all the elements of the system can be modeled either analytically or conceptually. It is important to distinguish between system and model. A model is the mathematical and/or physical representation of the system and of the relations between the elements of the system. It is an abstraction of the real world, and, in any particular application, the quality of the model and thus of systems analysis depends on how well the model builder perceives the actual relationship and how well he is able to describe their functional form.

Since models are abstractions of reality, they do not usually describe all features that are encompassed by a real world situation. A prerequisite for the systems analysis of a water resources system is the description of the system in terms of component models, which permit solutions to be obtained at reasonable cost and within a prescribed time frame. Therefore, the model builder should not attempt to model the reality of individual components as closely as possible, but only as closely as necessary to meet the overall accuracy requirements for his system.

2.2 Systems analysis -Definitions

Conventional engineering approaches following sectoral problem definitions and solutions appeared to be inadequate tools to tackle complex problems inherent in water resources management. Since the early sixties (Maass *et al*, 1962) serious attempts have been made to redefine the water resources development problems within the framework of systems analytical concepts. The analysis of the problems in this context implies the introduction of new terms and terminology as well as requiring the formulation of goals and aspirations to fit the new approach. The following description and definitions of system analysis related terminology are mostly adopted from Bogardi (1994).

In the broadest sense 'system' can be identified as the models of reality, consisting of a finite number of elements interrelated and interacting with each other in a regular interdependent way. While, a system is not related to any specific size, purpose or context, there are obvious limitations applied to identify a system. By using adjectives like social, natural, environmental, legal, or production the essence of the system considered becomes evident. Moreover these systems are not only limited by their scope but also by our ability to grasp, identify and also to characterize the interrelationships among the elements involved. By focusing only on the most essential or readily quantifiable interactions the system derived becomes itself a model of reality.

A system, following the above definition may be displayed in Figure 2.1. As shown in it system is carved out of its environment. Inputs and outputs substitute the severed interactions between elements of the defined system and elements left outside while feedback indicates a possible external interaction between outputs and inputs, which still can insert an impact on the system and its behaviour.

It is obvious, that this setup implies the factor 'time' in order to accommodate the time lag necessary for the feedback and corresponding adaptation, thus indicating the very dynamic nature of the system.
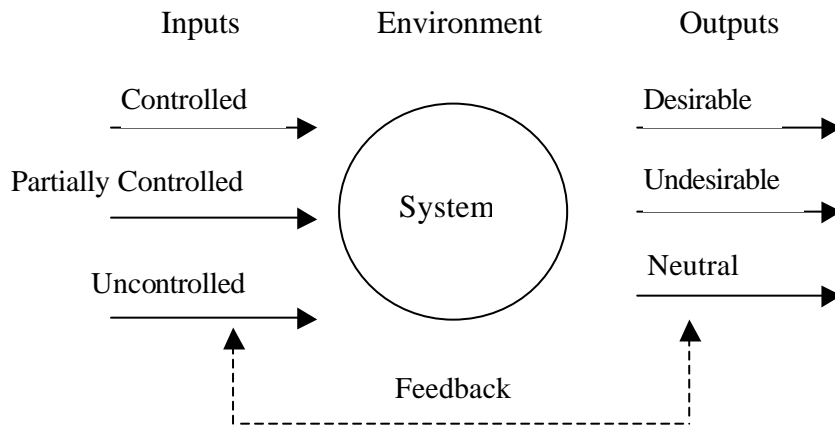
Figure 2.1 Model of the system (after Hall and Dracup, 1970)

From the point of view of the system analyst both inputs and outputs can be classified into different subsets. While the controlled and partially controlled inputs are described by **decision variables**, the uncontrolled input influence the state of the system without being subject to any direct influence. The set of feasible realizations of decision variables constitutes the **decision space**.

On the output side desirable and undesirable outputs are of particular interest. It is aimed to maximize the desirable and/or minimize undesirable output while selecting the course of decision.

The transformation of the system due to both decision variables and uncontrolled input are described by a set of variables called **state variables**, while the system response behaviour (rate of change of the state variables due to variable inputs) is characterized by **system parameters**.

Any expert involved in the task of water resources management would consider his/her system as the central one since the professional background biases the personal perception. It is appropriate to call those systems, subsystems by realizing their intricately woven interrelationships. Figure 2.2 presents several subsystems in a system. Also, the system concept does not prevent to divide even a subsystem further to subsystems for the sake of convenient analysis.

(SUB) SYSTEMS

political

administrative

legal

economic

social

INPUT   environmental   OUTPUT

financial

atmospheric

surface water

groundwater
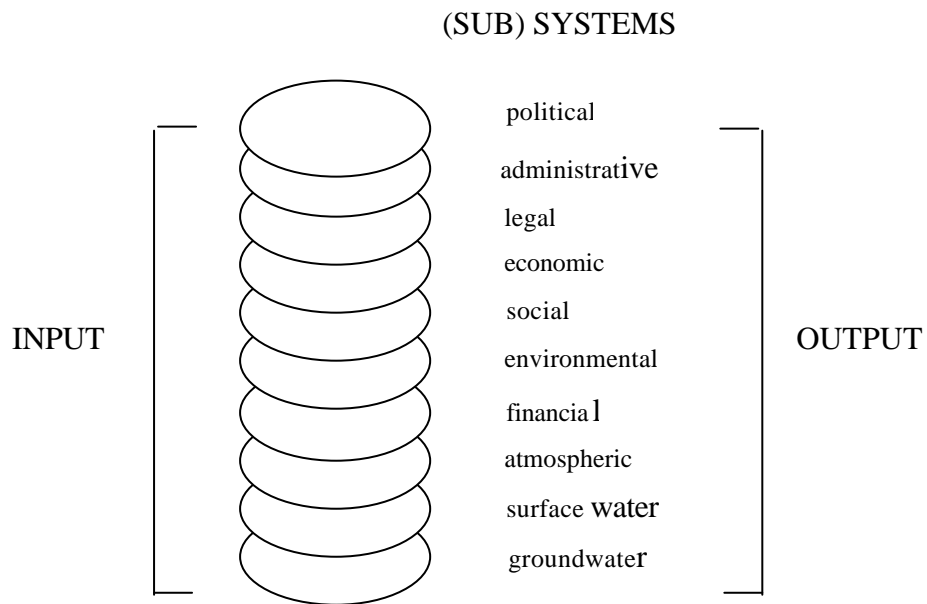
Figure 2.2 Subsystems composing a water resources system (after Bogardi, 1994)

Systems analysis (SA) in a very broad sense is concerned with the identification and description of models of reality and the study of system behaviour on these models under different aspects and conditions.

Furthermore, it can, but does not necessarily include the selection of a preferred course of actions to influence system behaviour. Consequently, SA might include the field known as operations research.

Systems engineering by its own virtue should include technical elements in this analysis. Clearly, the major tasks involved in systems engineering are the identification of the interrelationships, which should or/and can be controlled in order to influence system performance into a desirable direction, and to select the appropriate (technical) options to achieve the aimed goals. Thus in this context systems engineering implies a decision making process with respect to the controllable aspects of the system involved. Along with this definition, systems engineering is both an art and a science.

An excellent handbook on systems engineering was edited by Sage and Rouse (1999). Within the handbook, thirty articles on systems engineering written by well-known engineers and scientists cover virtually all aspects of the field. In Chapter 27, Hipel *et al* (1999) present an overview of operational research techniques, including conflict resolution and multiple criteria decision analysis, and the role they play in systems engineering.

It is an art how to define the system and to separate it from its environment, how to distinguish between essential and negligible aspects and interrelationships, and it is a science how to describe (mathematically or otherwise) the interrelationships, and how to select an optimal course of decisions out of the often vast array of possible course of actions.

The interconnections of the subsystems of Figure 2.2 either severed, or being considered as part of the subsystems simultaneously implied in the model impose constraints upon each other thus limiting the range, within which the individual inputs (decision variables) can assume numerical values. This results in the confinement of the decision space to a **feasible region**. Any set of decision variables situated within the feasible part of the decision space represents a **feasible policy**, which induces, under consideration of the actual values of the state variables and system parameters certain system outputs, desirable or/and undesirable. Both type of outputs are associated with certain **goals** to be attained. In order to gauge the impact of any feasible input policy upon the attainment of the present goals, the degree of goal attainments is expressed by **objective** criteria, which are preferably numerically quantifiable. Even by succeeding on this issue it can happen that several objectives cannot be measured on the same scale and thus cannot be expressed in the same units thus leading to noncommensurable objectives and resulting in a **multiobjective (multicriteria) decision making** problem.

However, following presentation assumes that a single unit can express all the objectives. Then, the remaining crucial part of the systems analysis is to define the relationships (or mathematical functions) by which the consequences or system out put can be determined in the selected unit of objectives, given the feasible decision policy, a certain constellation of state variables and system parameters. This function is called **objective function** and is expressed in general form as,

$$\text{min. or max.} \qquad \text{O.F.} \quad = f(\underline{x}, \underline{s}, \underline{p}) \qquad\qquad\qquad (2.1)$$

$$f \quad = \{f_n\} \ n....N \qquad\qquad \text{- objective function}$$

Where, $\qquad\qquad \underline{x} \quad = \{X_i\} \ i....I \qquad\qquad \text{- decision variables}$

$$\underline{s} \quad = \{S_j\} \ j....J \qquad\qquad \text{- state variables}$$

$$\underline{p} \quad = \{P_k\} \ k....K \qquad\qquad \text{- system parameters}$$

Subjected to a set of constraints, expressed here in general form as less or equal relationships;

$$gm \ (\underline{x}, \underline{s}, \underline{p}) \leq 0 \qquad m.....M \qquad\qquad\qquad\qquad (2.2)$$

The remaining problem, i.e., to select the **optimal** feasible decision policy, is to find the set of X_i (i....I) values to maximize (for benefits) or minimize (for losses) the objective function. While this is still a formidable task to be solved, it is even more fundamental to emphasize that the objectives and objective function, like the whole system, are rather a model than the expression of the real preference structure of the decision maker(s). Thus any optimal decision policy derived by maximizing (or minimizing) the objective function can only be considered optimal within the context of the given mathematical model. For the 'real world' decision it might be regarded only as a guideline being the conclusion of a mathematical analysis aimed solely to enhance the perception of the problem, rather than to surrender the decision sovereignty to the model and to consider it as a substitute decision maker.

The mathematical engineering core of the problem, i.e., the assessment of the system behaviour and the selection procedure of the most preferred course of action (policy) appear to be somehow unnamed. While it can be regarded as part of the systems analysis there is a distinct difference in the scope of the problems to be solved. This very fact, along with the mathematical approach involved warrant to distinguish it with a separate name: **operations research** (OR).

While OR is an 'independent' science originated from mathematical analysis of military operations in World War II, its definitions is still quite vague. Even Hillier and Lieberman (1980) were unable to formulate a definition. Some others try to use it as a synonym for systems analysis, yet this approach disguises the difference and hierarchical relationship between SA and OR.

OR might be described as the science of applied mathematics (or algorithms) developed to facilitate optimal planning, operation etc., briefly the management of resources, institutions, factories, etc.

2.3 Systems analysis tools

The tools of a systems analyst are many and varied in their usefulness. The type of solution procedure (or algorithm) most appropriate for any particular constrained optimization (or mathematical programming) model depends on the particular mathematical form of the objective function and of the constraint equations. There is no universal solution procedure that will solve efficiently all problems. However, available approaches fall into two categories: simulation and optimization. An extremely large number of simulation and optimization models providing a broad range of analysis capabilities for evaluating reservoir operations have been developed over the past several decades (Wurbs, 1993).

2.3.1 Simulation

Simulation is perhaps the most widely used method in water resources systems analysis due to its mathematical simplicity and versatility. Simulation is not an optimization procedure, so it does not identify optimal decisions. It only evaluates performance of a system under a given set of inputs and operating conditions. Simulation models permit very detailed and realistic representation of the complex physical, economic and social characteristics of a water resources system. The concepts inherent in the simulation approach are easier to understand and communicate than other modeling concepts. Simulation methods are able to solve water resources systems planning models with highly nonlinear relationships and constraints that cannot be handled by constrained optimization procedures.

A simulation may be deterministic or stochastic. If the system is subject to random input events, or generates them internally, the model is said to at least partially stochastic. If no random components are involved, the model is deterministic. A simulation may deal with steady state or transient conditions. The study of a water resources system during its initial

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years, perhaps involving one strategy for filling the reservoirs and one for diverting damaging floods, which occur before the structures are ready to receive them, lies in the area of transient analysis. Study of the operation of water resources system over a relatively long period of time during which no major changes in the system occur would be done with a steady-state analysis.

Simulation models have been routinely applied for many years by water resources development agencies in planning, construction and management of water resources projects. Many site-specific models have been developed. Colorado Reservoir Simulation System (CRSS) and Potomac River Interactive Simulation Model (PRISM) are two notable simulation models developed for particular water resource systems. Water resource system simulation models can be developed using readily available general-purpose commercial software such as Lotus 1-2-3, Quattro Pro, and Excel. Ford (1990) describes a reservoir simulation model called ResQ, which is designed to be used in combination with the user's choice of spreadsheet programme. An object-oriented-simulation modeling environment such as commercially available System Thinking Experimental Learning Laboratory with Animation (STELLA), a model designed to simulate dynamic systems, can also be used to simulate a water resource system.

Generalized simulation models designed to be readily applicable in analyzing water resource systems are also available. Acres model (Sigvaldason, 1976), HEC5 simulation of Flood Control and Conservation System (Mays and Tang,1992) and Interactive River System Simulation Model (IRIS) (Loucks, 1989, 1990) are a few examples.

The difficulty with the simulation approach is that there is often a frustratingly large number of feasible solutions or plans. However, when an optimization procedure can be constructed to efficiently solve an adequate approximation to the real problem, they can greatly narrow down the search with simulation for a global optimum by identifying plans that may be close to the optimum.

2.3.2 Optimization

The second category, optimization models, includes a diverse set of techniques or algorithms. The type of solution procedure (or algorithm) most appropriate for any particular constrained optimization (or mathematical programming) model depends on the particular mathematical form of the objective function and of the constraint equations. There is no universal solution procedure that will solve efficiently all constrained optimization models.

Application of optimization models in water resources systems analysis is extensive. Textbooks by Loucks *et al* (1981) and Mays and Tung (1992) cover many such models or techniques applicable in water resource system analysis. Yeh (1985) presented a comprehensive in depth state-of-the-art review of reservoir operation models, with a strong emphasis on optimization techniques. Most applications to water resources systems analysis involve linear programming (LP) and dynamic programming (DP). Various other nonlinear programming methods, particularly search algorithms have also been used. Optimization models are formulated in terms of determining values for a set of decision variables that will maximize or minimize an objective function subject to constraints. The objective function and constraints are represented by mathematical expressions as a function of the decision variables.

If the objective function, as well as the constraints is linear, then a very efficient procedure called linear programming, may be used. LP has been considered one of the most widely used techniques in water resources. Unlike most other optimization techniques, LP software packages are available. Dantzig presented an algorithm for solution of the LP problem called the "simplex method" in 1947. Since that time a series of revised simplex algorithms have been developed and computer codes programmed. Shane and Gilbert (1982) and Gilbert and Shane (1982) presented a model called HYDROSIM in which LP has been incorporated.

Though there are some limitations to the use of LP in a deterministic environment, numerous water resources studies have utilized it along with additional techniques in wide variety of problems (Houcks, 1982; Gryger and Stedinger, 1985; Simonovic and Burn, 1989; Reznicek and Simonovic, 1990). LP has been extensively used in stochastic reservoir system modeling

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as a main technique within different approaches such as chance constrained LP, stochastic LP for Markov process, stochastic programming with recourse and reliability programming.

Dynamic programming is an optimization procedure or an approach applicable in the study of multistage (sequential) decision problems. The stage or sequential characteristics of the problem often are time periods, however, the stages can also be space regions or physical entities such as reservoir sites or irrigation fields. It is based on the principle of optimality, which implies a sequential decision process in which a problem involving several variables is broken down in to a sequence of simple problems, each involving a single variable. DP is not restricted to any particular problem structure and it can handle non-linear objective functions and non linear constraints very easily. Applications of DP in water resources systems analysis are many (Young, 1967; Hall and Buras, 1961; Yeh, 1981; Allen and Bridgeman, 1986; Chung and Helweg, 1985; and others).

Many changes have been applied to the basic concepts of DP to make the technique more efficient for certain specific problems: differential dynamic programming, constrained differential dynamic programming, reliability constrained dynamic programming and stochastic dynamic programming.

Non linear programming (NLP) has not been popular among water resources system analysts. The main reason is that NLP techniques are slow, iterative and take up large amount of computer storage and time. On the other hand NLP offers a more general mathematical formulation of reservoir problems. NLP include search techniques, quadratic programming, geometric programming and separable programming. They can be used in conjunction with simulation as well as other programming techniques. The application of NLP has been reported by Hicks *et al* (1974), Haimes (1977), Rosenthal (1980), Simonovic and Marino (1980) and others.

Genetic Algorithms (GAs) introduced by Holland (1975) and developed by Goldberg (1989), is a powerful optimization approach, which has a potential in water resources system analysis and its applications are quite recent. McKinney and Lin (1994) applied GAs in the management of groundwater models. Simpson *et al* (1994) used GAs in optimization of pipe networks. Savic and Walters (1997) developed a computer model for least cost design of

water distribution networks. However, GAs have very little application in reservoir system optimization. East and Hall (1994), Kumari (1995), Oliveira and Loucks (1997), are a few applications of GA in reservoir operational problems reported in literature.

2.3.3 Multiobjective analysis

Water resources management very often encounters complex decision problems involving multiple objectives, which are addressed by multiobjective analysis approaches. Tecle and Duckstein (1994) presented the following terminology and notation that are found in the field of multiobjective decision-making.

 The process of modeling and solving a problem with two or more noncommensurable and conflicting objectives is known as **multiobjective decision making** (MODM). Objectives are **noncommensurable** if their level of attainment with respect to given attributes cannot be measured in common units. Objectives are **conflicting** if an increase in the level of one objective can only be achieved by decreasing the attainment level of another objective.

The characteristics, factors, qualities, performance indices or parameters of alternative management schemes or other decision processes are referred to as **attributes**. An attribute provides a means for evaluating the levels of an objective. It can be defined as a measurable aspect of judgment by which a dimension of the various decision variables or alternative management schemes under consideration can be characterized. A decision analysis problem consisting of more than two attributes is known as a **multiattribute decision problem** and may be solved using a multiattribute decision making (MADM) procedure. The procedure involves the selection of the "best" alternative course of action from a given number of alternatives described in terms of their attributes.

In decision-making theory, a **criterion** may represent either an attribute or an objective. In this sense, a **multicriterion decision-making** means either a multiattribute or a multiobjective decision problem or both. Multicriterion decision making (MCDM) is, therefore, used to indicate the general field of study which includes decision making in the presence of two or more conflicting objectives and/or decision analysis processes involving two or more attributes.

Decision variables are the vehicles used to specify decisions made by a decision maker. In mathematical programming, they represent the numerical variables (nonnegative), whose values are to be determined. During the problem formulation stage of a decision process, quantities to be treated as decision variables and fixed have to be decided. The quantities whose values are fixed are called **parameters**. There are restrictions on attributes and decision variables, which may or may not be expressed mathematically. **Constraints** describe restrictions or dependencies between decision variables and parameters and may be stated in the form of equalities, inequalities or probabilistic statements.

A multicriterion problem can be represented in vectorial notation as:

"Satisfice" $f(\underline{x}) = \{f_1(\underline{x}), f_2(\underline{x}), \ldots\ldots, f_I(\underline{x})$ (2.3)

Subject to $g_k(\underline{x}) \leq 0, k = 1, 2, \ldots\ldots, K$ (2.4)

$x_j \geq 0, \quad j = 1, 2, \ldots\ldots, J$

There are I objective functions $f_i(\underline{x})$, each of which is to be satisficed subject to the constraint sets. The region defined by this constraint set is referred to as the **feasible region** in the J dimensional decision space. It is important to note that the word optimum, which includes both the maximization of desired outcomes and minimization of adverse criteria is replaced by the word **satisfactum** and optimize is replaced by **satisfice** because when dealing with two or more conflicting objectives optimizing all objectives simultaneously is not possible as an increase in one objective usually results in a decrease of the others. In such circumstances **trade offs** between the objectives are made in order to reach solutions that are not simultaneously optimum but still acceptable to the decision maker with respect to each objective.

To find a final satisficing solution, an interaction between the analyst and decision maker is required. A **decision maker** (DM), is an individual or a group of individuals whose desires are supposed to be satisfied by the outcome of the multicriterion decision process. DM identifies the decision problem and specifies the objectives. **Analyst** is responsible for defining the decision model, conducting multicriterion decision process and presenting results to the DM. An important component of a MCDM process concerns the priorities often

attached to each one of the various criteria under consideration. These priorities may be represented as quantitative numbers usually referred to as **weights** or by means of ordinal expressions, which are denoted by **priorities**. The weights and priorities in the decision makers' view represent the relative importance of the objectives or utilities of a problem to one another.

Goals, aspiration levels and ideal points also reflect different aspects of DM's desire in dealing with a multicriterion problem. **Goals**, known as targets, are conditions desired by the DM and expressed in terms of a specific state in space and time. **Aspiration levels** are special cases of goals. The levels specified for goal points must be such that they cannot be achieved simultaneously for all objectives: the goal point is thus not in the feasible region. But when the goal point is in the feasible objective space, it is considered to be an aspiration level. If optimal values to a problem are determined for each objective without regard to the other objectives, the point having these optimal values as its coordinates in the objective space is called an **ideal point**. The ideal, point for a multicriterion problem must lie outside the feasible region in the objective space.

There are a number of possible solution types to multiobjective problems. The difference among the solution types are usually related to the type of problem and required solution, the type of techniques utilized to arrive at the solution and the number of decision makers involved in the process. The problem and technique selected for use, for example, may be decision analysis or mathematical programming and the solution required can be a preference ordering of alternatives or determining the magnitude of the value of each objective and selecting alternatives accordingly. Likewise the decision making unit may consist of a single individual or a group of individuals with conflicting interests. These kinds of differences in multiobjective problems can lead to different kinds of solutions.

Generating techniques is one of the multiobjective solution techniques. It provides a complete spectrum of nondominated solutions to a decision maker. Weighting approach, where each objective value is assessed, and combined using weights to offset noncommensurate units and to express relative importance of each objective is one approach in generating nondominated alternatives. Another technique is the constraint method. It assesses, or attempts to optimize each objective individually while restricting other objectives to maintain minimum standards.

The group of techniques known as multicriteria decision-making (MCDM) methods deal with selecting a discrete alternative from a list of options. The techniques developed for these types of problems are based on one of the following philosophies: (i) outranking, (ii) distance, and (iii) utility. Outranking techniques such as ELECTRE methods use indicators like concordance and discordance to make judgments in a search for a highly-rated alternative for most criteria yet are not completely unacceptable for any criteria. Distance-based methods use a notion of geometric best to determine the "closest" option to an ideal point. Multiattribute utility (MAUT) methods rely on values of relative objective satisfaction, where the alternative with the highest-rated utility is preferred.

In MCDM, a range of alternative solutions to a problem may be evaluated according to various kinds of criteria. When investigating combinations of alternative solutions to solve the problem under study, the number of possibilities can become very large. Hence, methods are required to "screen out" clearly inferior solutions that need not be considered for combination purposes and detailed analyses. Rajabi *et al* (2001) presented a method developed for screening out clearly inferior solutions for a large water policy subset selection problem. Moreover, Rajabi *et al* (1999) demonstrated how interdependence among alternatives could be taken into account when combining alternative solutions in water supply planning using a new procedure developed by Rajabi *et al* (1998).

Besides the above approaches, goal programming and compromise programming are two more techniques, which rely on prior articulation of preferences. Goal programming allows the decision maker to specify a target for each objective function and a preferred solution is then defined as the one that minimizes the sum of the deviations from the prescribed set of target values. The method of compromise programming first normalizes the objectives and then identifies solutions, which are closest to the ideal solution as determined by some measure of distance.

Exceptions to prior articulation are methods that employ progressive articulation of preferences. These are the true interactive conflict-capable multiobjective methods. Step method and sequential multiobjective problem solving (SEMOPS) are two techniques under this category. When progressive articulation methods are included within a comparison of

techniques, they are not usually rated highly because of the amount of information and time that is required by decision makers. They are based on an algorithmic approaches such as: (i) find a noninferior (nondominated) solution, (ii) modify the solution according to reactions of the decision makers, and (iii) repeat until satisfaction or termination.

Multiobjective techniques have been extensively explored in water resource planning and management (Keeney and Wood, 1977; Loucks *et al*, 1981; Gershon and Duckstein, 1983; Kindler, 1988; Simonovic, 1989; Hipel, 1992; Ko *et al*, 1992; Thiessen and Loucks, 1992; Bogardi and Nachtnebel, 1994; Hobbs and Meier, 2000).

2.4 A Systemic approach to conflict resolution

A human action disturbs a water system so that the interactions between physical, biological and/or social components are altered. This provokes some impact in the related systems. Usually, after trading off all impacts, those affected make an explicit or implicit judgment so that the net effect is either advantageous or disadvantageous to them. If those having rights in the area feel that they may be damaged then the conflict takes shape (White, 1986). Modification of the interaction among above components in the system motivates the application of systematic approach to conflict resolution.

A systemic approach has at least three roles in illuminating grounds on which conflict resolution may proceed. First, scientific investigation defines the systems that are affected, their structure (components), indicating where there is an established or assumed relationship among the various components. Definition of the system structure is fundamental because often conflicts arise where it has been assumed that the impacts were less-reaching than demonstrated in practice. Second, systemic approach help describe the characteristics of the various components, including the physical systems, the ecosystems, affected social groups and organizations with their preferences and modes of action. To identify the components is to deal with their interactions as they are established. Third, systemic approach offers means of estimating the significance of impacts not only in terms of physical quantities but also in terms of the way in which they are perceived by the people and organizations affected.

Table 2.1 presents some differences between traditional and systemic approaches in conflict resolution. A systemic approach is proposed as a powerful tool for deep inquiry and development of dialogues among stakeholders. Active participation of stakeholders and development of their skills to deal with conflicting situations is the driving force of a systemic approach.

Table 2.1 Traditional versus systems approaches to conflict

	Traditional Approach	Systemic Approach
Intention	Conflict resolution	Conflict resolution skill building
Time horizon	Short term	Long term
Point of application	After conflict becomes extreme	Before conflict becomes extreme
Stakeholder response	Defend position	Become reflective and open
Focus	Individual adversaries	System
Processing of complexity	Polarization	Powerful dialogue
Responsibility for conflict	Blaming of others	Own role in conflict

3. Types of Water Resources Management Conflicts and Models

3.1 General

Water is essential to sustain life in both human systems and ecosystems. In almost every region of the world, supply of water is becoming more difficult because of increasing demands associated with industrialization, increasing urbanization and growing population. Climatic conditions such as global warming may worsen an already critical condition in many years. Pollution from industrial, agricultural and urban wastes and groundwater quality degradation from over-pumping also limit the availability of water. Disputes resulting from water problems may jeopardize economic and social order both within and between countries. To ameliorate such conflicts, improved water management, conflict resolution and cooperation are essential.

In water resource systems, water stress lends itself to conflict or to cooperation. Postel (1999) described the roots of the problem at the sub-national level. Water, unlike other scarce resources, is used to fuel all facets of society, from biology to economy to aesthetics and religious practice. As such, there is no such thing as managing water for a single purpose – all water management is multi-objective and is therefore, by definition, based on conflicting interests. Within a nation these interests include domestic users, agricultuarists, hydropower generators, reactors and environmentalists – any two of which are regularly at odds and the chances of finding mutually acceptable solutions drop exponentially as more actors are involved.

As described conceptually and with case studies by Trolldalen (1992), these conflicting interests within a nation represent both a microcosm (a little world) of the international setting, and a direct influence upon it. He sidesteps the common trap of treating nations as homogeneous, rational entities, and explicitly links internal with external interests. Bangladesh is not just the national government of Bangladesh when it negotiates a treaty with India over Ganges flow, but it is its coastal population, inundated with saltwater intrusion; its farmers, dealing with decreasing quantities and increasing fluctuations; and its fishermen, competing for dwindling stocks.

This link between the internal and the external is critical when we look at violent international conflicts. Gleick (1993) is widely cited as providing what appears to be a history rich with violence over water resources. However, Wolf (1998) argues that what Gleick and others have actually provided is a history rich with tensions, exacerbated relations, and conflicting interests over water, but not violence, at least not between nations or over water as a scarce resource. He further states that there was one true water war in history, 4500 years ago, and seven cases of acute water-related violence - with the much richer record of explicit, legal cooperation (3600 water-related treaties). A scan of the most vociferous enmities around the world reveals that almost all the sets of nations with the greatest degree of animosity between them, whether Arabs and Israelis, Indians and Pakistanis, or Kyrgis and Uzbeks, either have a water-related agreement in place, or are in the process of negotiating one. The lessons of history turn out to be that, while water can act as an irritant, making good relations bad and bad relations worse, it rarely induces acute violence and often acts as a catalyst to cooperation, even between bitter enemies. Moreover those institutions that are created turn out to be extremely resilient over time, even as conflicts rage over other issues (Wolf, 1998).

Preventive diplomacy is a concept based on the premise that it is easier and cheaper to prevent disputes before they begin, than it is to resolve them after the fact (Spector, 2001). While seemingly self-evident, preventive diplomacy has proven difficult in practice, primarily because of the barriers within the international community of mobilizing crisis-level interest and resources before a crisis actually occurs. As Spector describes it, though, the concept is gaining momentum, particularly within the western defense establishment, and he offers cases for how it has been used effectively, as well as the processes of preventive negotiations for problem-solving.

Painter (1995) and Clark *et al* (1991) describe how the tools used by alternative dispute resolution (ADR) - mediation, facilitation, and arbitration - can be effective in resolving environmental disputes, an application termed EDR (environmental dispute resolution). The rationale for ADR and EDR are similar to those of preventive diplomacy -that is, it is cheaper and the solutions are more robust when issues are resolved through dialog rather than litigation (or combat), and Clark *et al* (1991) offer settings and cases to back the argument up.

Painter, offers a brief history of EDR from its roots in labor negotiations, suggests some problems with the approach, and concludes with 'post-structural alternatives.'

3.2 Disciplines and worldviews

Though water is a unifying resource, water education management and discourse is very much fragmented. To truly learn about water in its most holistic sense, it is necessary to understand the many aspects of the hydrologic cycle, from meteorology to surface hydrology, to soil science to groundwater to limnology to aquatic ecosystems, in its physical cycle. Also, it is needed to have an integral sense of the human dimensions, from economics to laws, to ethics to aesthetics to sociology and anthropology. Universities and management institutions are simply not organized along these lines; often they are fragmented to where even surface water and groundwater, quality and quantity, are separated out as if they were not inextricably interrelated.

However, each of these disciplines offers its particular perspective as conflict prevention and resolution (Wolf, 2002). Though each of these disciplines is rooted in their own topologies and terminologies, there are surprising similarities among them. Each discipline strives to provide a more structured framework for the often chaotic processes of conflict resolution: law (Bennett and Howe, 1998; Wescoat, 1996; McCaffrey, 1998) through its clear delineation of the terms, boundaries, and solutions; economics and game theory (Howe *et al*, 1986; Rogers, 1993) through the unifying concepts of rationality and efficiency; engineering (Lancaster, 1990; Bleed, 1990) by its description of present and future states, and how to get from one to the other; and political economy (Just *et al*, 1998; Allan, 1998) through its role between political and economic decision-making.

Each of the above disciplines brings its unique set of tools to help the parties prevent disputes, resolve disputes, or understand the problem in new ways to facilitate either prevention or resolution. Howe *et al* (1986) shows how market mechanisms can help with the problem of water allocations. Benefits might be equitably allocated across international boundaries through game theory (Rogers, 1993). Allan (1998) describes the concept of 'virtual water,' which is the water that moves between consumers and across nations

embedded within the products it was used to produce, as an argument against the limiting concept of water security. White (1986) shows geography's capabilities in interdisciplinary analysis. Further, he discusses about the coming information age and its effects on systems analysis, risk assessment, and societal responses. Simonovic (1996) brings the technology of the 21st century to bear on the issues, describing how new modeling tools, visualization techniques and information technologies can be packaged as decision support systems to aid parties in dispute in their decision-making.

3.3 Nature of conflicts over water

Most environmental conflicts, including water related, spring from three sources (White, 1986). First source is an actual or prospective human intervention in the environment, which provokes changes in natural and societal systems. The conflict arises when one or more of the stakeholder groups see the activity as disturbing the complex interaction between physical, biological and social processes. The second source is disagreement over the management of water supply at one location as it affects the use of it elsewhere. The third source is where climatic variability and change independent of any human activity places new stresses on the water resources and generates fresh adaptations to available resources.

In a river basin, which traverses across an international boarder, a political regional boundary or a general boundary of different jurisdiction, the basis of a conflict is the implementation of developments by a stakeholder concerned within its territory. Such implementation impacts at least one of its neighbors during water shortage conditions, and usually leads to a number of water conflicts. The key indicators or the water conflicts are related to a number of issues including water quantity, water quality, management of multiple use, political divisions, geopolitical setting, level of national development, hydro-political issue at stake and institutional control of water resources (Wolf, 1998).

Water quantity becomes an issue of conflict when the demand and supply curves approach each other. Greater upstream use and long-run changes in supply or demand could be the causes for water quantity related conflicts. Increasing water scarcity due to rise in population could lead to conflicts. On the other hand, water quality related conflicts might erupt due to

new source of pollution resulting from extensive agriculture development in the upstream. Return flows from agricultural, industrial and urban activities may also cause dissatisfaction among the downstream users and may end up in a conflict. In a large river basin water is generally managed for multiple uses such as power generation, food production, industrial development, municipal water supply, recreation, or a combination of them. Different user groups having different objectives may have conflicts in arriving at a common schedule of quantity and time of water distribution (Yoffe and Ward, 1999).

The human elements such as vulnerability of water quality and aquatic ecosystems to human activities, the failure to treat water as an economic resource, the desire for food security and importance of water to public health and economic development also creates conflicts over water.

Past history in different regions of the world indicates that shifting of political boundaries, which demarcate new riparian areas in the international river basins, has induced water conflicts. Wolf (1998) cites examples of conflicts in water bodies that became international when the British Empire dissipated in many countries. Geopolitical setting is another issue where the relative power and riparian position of a group play an important role. A group occupying the upstream area of a basin or that has more political power has more control over the others in implementing development projects (Lowi, 1993). The level of national development may be an indictor of potential water conflict in an international river basin. More developed nation may have better options for alternate sources of water, and may be less demanding over a conflict with a neighboring less developed nation. Mandel (1992) relates the intensity of a water conflict with the hydro-political issue at stake. Water conflicts resulting from human-initiated developments such as dams and diversions, are found to be more severe than those resulting from natural events like floods, droughts etc.

3.4 Conflicts resolution

Traditional conflict resolution approaches such as the judicial systems, state legislatures, commissions and similar governmental systems provide resolutions in which one party gains at the expense of the other. This is referred to as the 'zero–sum' or 'distributive' solution. In

water and environmental conflict resolution, a negotiation process referred to as the Alternative Dispute Resolution (ADR) is adopted. ADR refers to "a wide variety of consensual approaches with which parties in conflict voluntarily seek a mutually acceptable settlement". ADR generally seeks to move parties from 'zero-sum' solutions towards those in which all the parties gain, which are referred to as 'positive-sum' or 'integrative' solutions (Bingham *et al*, 1994). Negotiation, collaboration and consensus building are the key issues that facilitate ADR.

Prior to the negotiation, the pre-negotiation process in initiated by a person, the convener, who has sufficient authority and stature to capture the attention of stakeholders. The convener may contract a third party to conduct a preliminary review of the conflict. Review of this type reveals the background information on the conflict as well as identifying the stakeholders (Carpenter and Kennedy, 1988). If the preliminary review indicates that the negotiation process holds potential promise for improving the situation, the third party will conduct a conflict analysis (Moore, 1986; Schwarz, 1994). This activity composes a combination of data and personal interviews with parties concerned. The third party then designs an appropriate intervention strategy for bringing the stakeholders involved to the negotiation table. At this stage, the third party is referred to as mediator or facilitator. During the negotiation process, the parties must exchange information and share technical details. They should listen to other parties and the mediator. Above all, they should agree on creative options to seek mutually beneficial outcomes (Moore, 1986; Rothman, 1997).

The successful resolution of national as well as international water conflicts requires understanding of the nature of the conflict and then modeling and analyzing the inherent problems in it. To reach a final agreement concerning how much of the shared water resource is allocated to each party or nation, assistance of procedures or methodologies acceptable to all the parties concerned is very much needed. Systematic study of the nature and conduct of conflict and corporation between parties involved based on new technologies and practices could assist the efficient management of water resources, and thereby reducing tension among parties in dispute over water.

A systemic approach to conflict resolution is a new approach for water resources conflicts. It uses the disciplines of systems thinking and mental models to provide powerful alternative to

traditional approaches to conflict resolution, which often rely too much on outside mediation. By helping stakeholders explore and resolve the underlying structural causes of conflict, a systemic approach can transform problems into significant opportunities for all parties involved. A systemic approach to conflict resolution has been explored in the management science (Cobble and Huffman, 1999). Some elements of the systemic approach have been present in the work of Bender and Simonovic (1996) and Simonovic and Bender (1996) that proposes collaboration and collaborative process with active involvement of stakeholders that agree to work together to identify problems, share information and where possible, develop mutually acceptable solutions. Consensus building processes constitute a form of collaboration that explicitly includes the goal of reaching a consensus agreement on water conflicts. The indigenous approaches to water conflict reduction (Wolf, 2000) are also related to a systemic approach. Such methods include: (a) allocating time, not water; (b) prioritizing different demand sectors; (c) protecting downstream and minority rights; (c) ADR; and (e) practicing ritual ceremony of forgiveness.

3.5 Types of problems vs. Types of models

3.5.1 Conflict negotiation

Negotiation is a process where two or more parties with conflicting objectives attempt to reach an agreement. This process includes not only the presentation and exchange of proposals for addressing particular issues, but also the attempts by each party to discover the preferences, strengths and weaknesses of their opponents, and the use of that knowledge to help reach a satisfactory resolution. Negotiating parties may be individuals or teams representing their own interests or the interests of their organizations. Negotiation can be a constructive alternative to other means (e.g., physical violence, litigation, stalemate) of settling disputes (Holznagel, 1986; McDonald, 1988; Delli-Priscoli, 1988).

The main purpose of a negotiator is to try to identify alternatives that all parties in conflict will find acceptable. Negotiators must identify and explore the impacts of various decisions, and begin to understand the tradeoffs among these impacts. Various optimization and simulation models of water resource systems serve as "context" models for gaining such an

understanding. Negotiators must also determine, for each proposed solution to the conflict, what they, or whomever they represent, will gain, and what they will lose, and whether or not what they gain will be worth more than what they will lose.

A third-party mediator or facilitator may be included in a negotiation process to help manage the interactions and make suggestions for negotiating parties to consider. Alternatively, an arbitrator may be involved with the power to draft and perhaps dictate settlements for the parties (Anson *et al*, 1987). It is commonly recognized (e.g., Gulliver, 1979; Mastenbroek, 1989) that such disinterested parties can significantly help negotiators in their quest for an agreement.

Recent development in modeling negotiation processes is motivating work in the use of computer-based analyses of negotiation problems (Raiffa 1982). The complexity of many negotiation problems involving regional water resources development and use conflicts poses a challenge. This complexity motivates the development of computer models that today are beginning to be able to address many of these complexities with increasing effectiveness. These models and their supporting programs require that the issues of the stakeholders (those who are in conflict or who will be affected by any agreement) are adequately defined. But these issues can change. Hence, any analysis of negotiation problems must permit the updating of issues, preferences, and interested stakeholders as the negotiation process proceeds. This analysis must be sufficiently flexible to not constrain or limit the options and thinking of those negotiating, yet not overload them with information that may divert or distract them from reaching some mutually satisfactory agreement (Poole *et al*, 1991).

To resolve water resources disputes in the Washington metropolitan area, Las Vegas and the Kansas River basin a conflict negotiation model called Computer Assisted Negotiation (CAN) has been used (WRMI, Internet) successfully. The experience with the application of this model suggests that in multi-objective disputes with numerous parties a neutral outsider may have the broader perspective necessary to integrate the operations and actions of all parties. Often this allows the development of more acceptable, or even win-win alternatives.

3.5.2 The role of computer-based support in conflict resolution

At certain stage of conflict resolution, alternatives and proposals specific to stakeholders in conflict are analyzed for their technical feasibility and economic viability. Such analyses in water-based conflicts include among other processing of vast amount of hydrological and geophysical data, describing system structure, identifying system states by routing of natural and scheduled flows, mapping and graphing system operational strategies, and optimization and multi-criteria analyses of system components and operations. Therefore, a decision support tool that could assist the stakeholders with different technical aspects is vital for the success of a water conflict resolution process. Quite often, the stakeholders have limited or no technical knowledge relevant to water resources management. As a result, in a conflicting situation they generally stay firmly behind their positions irrespective of the technical difficulties associated with satisfying their criteria. It has been shown in the literature that in complex situations of this nature, the availability of computer-based support systems that could convey the technical information to stakeholders in an understandable form is one of the pre-conditions for finding mutually acceptable and sustainable resource management solutions (Simonovic, 1996).

3.5.2.1 Decision support systems
Use of computer-based support systems is the recent development in water conflict resolution (Raiffa, 1982). It is often a challenge, for everyone involved in handling the complex nature of water conflict on the regional or international scale. Such a complexity led the researchers around the world to develop computer-based decision support systems (DSS) that can provide considerable assistance in determining temporal and spatial distribution of water quantity and quality.

Decision Support Systems (DSS) are a specific class of computerized information system that supports decision-making activities. DSS are interactive computer-based systems and subsystems intended to help decision makers use data, documents, knowledge and/or models to identify and solve problems and make decisions.

Progress in computer software development and its implementation in water resources (Antrim, 1986; Fraser and Hipel, 1984; Anson *et al*, 1987; Jones, 1988; Kersten, 1988; Anson

and Jelassi, 1990; Foroughi and Jelassi, 1990; Meister and Fraser, 1992; Fang *et al*, 1993; Bender and Simonovic, 1996) provides different kind of negotiation assistance medium. Such tools are also referred to as Negotiation Support Systems. The basis for all these systems is group decision-making process (Lewis, 1993), which assists in solving disagreements among various stakeholders. Other water resources related decision support systems (Davis *et al*, 1991; Fredericks *et al*, 1998; Andreu *et al*, 1996; Reitsma, 1996; Dunn *et al*, 1996; Jamieson and Fedra, 1996; Arumugam and Mohan, 1997; Ford and Killen, 1995; Ito *et al*, 2001) with one or more tools for the analyses of water quantity and quality distribution, flood and environmental management, are also helpful in water conflict resolution.

Simonovic (1996a) defines a computerized decision support system as "a tool that 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 using all information available on request. They use quantitative models and database elements for problem solving. They are an integral part of decision-maker's approach to problem identification and solution. A decision support system for application in water resources management has the following characteristics: accessibility, flexibility, facilitation, learning, interaction and ease of use. Water resources problems are generally ill structured, lack data, associated with uncertainties, and include non-quantifiable variables (Landry *et al*, 1985).

A computerized decision support system should also have facilities for data management, data analyses and interaction (Bender and Simonovic, 1996). Such facilities are vital for problem identification, problem solving, and analysis of a decision consequences. Data management function may vary from simple statistical computation to the ability of calling up optimization and simulation models.

Presentation of data and results in a form that is easily recognized by the stakeholders is important. Participant's interaction in the process of evaluating alternative options and analyzing the impacts is regarded another important step in conflict resolution. Communication tools based on the natural language processing and artificial intelligence provide the support for interaction between the stakeholders during a conflict resolution process.

It is evident that decision makers could benefit from improved tools to assist them in making favorable decisions, especially when confronted with conflicting objectives and demands (Hipel, 1992). Jelassi *et al*, (1990) document a need for more rigorous research on the role computers can play in group decision making and in conflict resolution and on the impact computers can have on the outcomes of negotiation processes as well as on the participants' attitudes. The ultimate objective is to offer negotiating parties a means by which they, or a third party facilitator, could directly define and evaluate possible settlements. Achieving this objective would be a significant step toward improving the efficiency and effectiveness of the negotiation process.

Computer assisted negotiation models/software can be used to facilitate multi-party discussions of water-related conflicts. However, developers attempting to produce models to aid in trans-boundary negotiation often find it difficult to collect data from multiple jurisdictions regarding surface water use, groundwater use, groundwater recharge or climatic variables. Further, challenges arise in the reconciliation of regulations, operational policies, guidelines and legal doctrines affecting day-to-day management of a trans-boundary riverine system.

3.5.3 Negotiation support systems (NSS)

The current literature on interactive computer programs for multi-objective conflict resolution (e.g., Antrim, 1986; Fraser and Hipel, 1986; Anson *et al*, 1987; Jones, 1988; Kersten, 1988; Anson and Jelassi, 1990; Foroughi and Jelassi, 1990; Meister and Fraser, 1992; Fang *et al*, 1993) commonly uses the term Negotiation Support System. This term refers to the special type of Group Decision Support System designed for providing assistance in situations where there is disagreement among various parties as to what decisions to adopt. Research addressing group decision making in multi-objective situations is in its second decade (Nunamaker, 1989), yet the development and use of Negotiation Support Systems to facilitate and help guide multi-party negotiations is a relatively new field (Jelassi and Foroughi, 1989).

Figure 3.1 illustrates how Decision Support Systems have become more specialized during the last decade and where Negotiation Support Systems fit into this acronym timeline

(Thiessen *et al*, 1998). Negotiation Support Systems can be categorized according to their functions either as Negotiation Preparation Systems supporting a pre-negotiation strategic planning stage, or as Negotiation Information Management Systems (Gauvin *et al*, 1990) facilitating negotiations in real time.

Numerous development efforts are underway in each of the various kinds of negotiation support systems described above (e.g., Harvard, 1994).
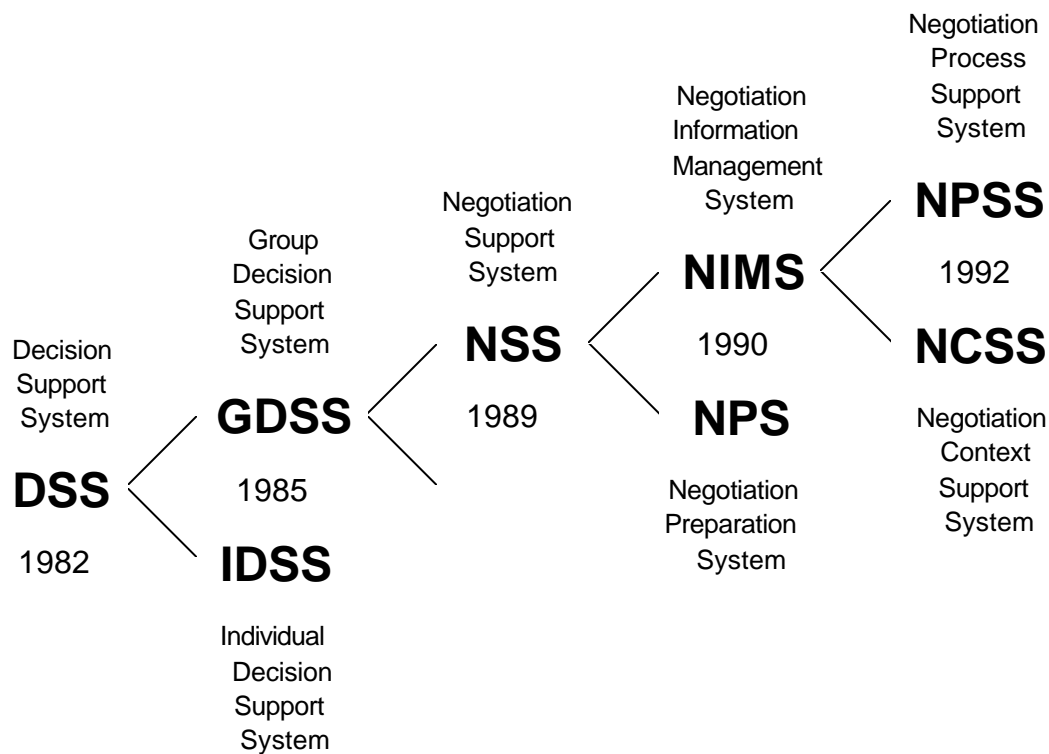
Figure 3.1 Negotiation Support System acronym timeline. The dates correspond to when the corresponding terms started to appear in the literature. (after Thiessen *et al*, 1998)

Negotiation Support Systems (NSS) cover a wide range of individual and group decision support techniques.

Kersten (1998) presented the development of a web-based NSS called INSPIRE (InterNeg Support Programme for Intercultural research). In the model, conjoint analysis technique has been used to construct utility functions that users employ in offer construction and evaluation. The system allows for the verification of compromise efficiency, provides graphical

representation of negotiation dynamics and has a message facility. Since many of the NSS based on decision and negotiation analysis are not used in real-life negotiations one could state that these types of systems have no practical potential. Kersten (1998) argues that this is not the case for the following four main reasons: (i) managers and professionals are becoming sophisticated users of decision support systems that embody many of the above methods and techniques, (ii) e-commerce, globalization of markets, and electronic communication lead to virtual negotiations, (iii) time pressure, vast amounts of data, and increasing problem complexity create new pressures that can possibly be partially alleviated with the use of DSS and NSS, and (iv) increasing user friendliness of NSS, and the employment of the data visualization and multimedia techniques as well as the integration with other systems.

There are many possible configurations in which a NSS can be positioned and Kersten (1998) presented three shown in Figure 3.2.
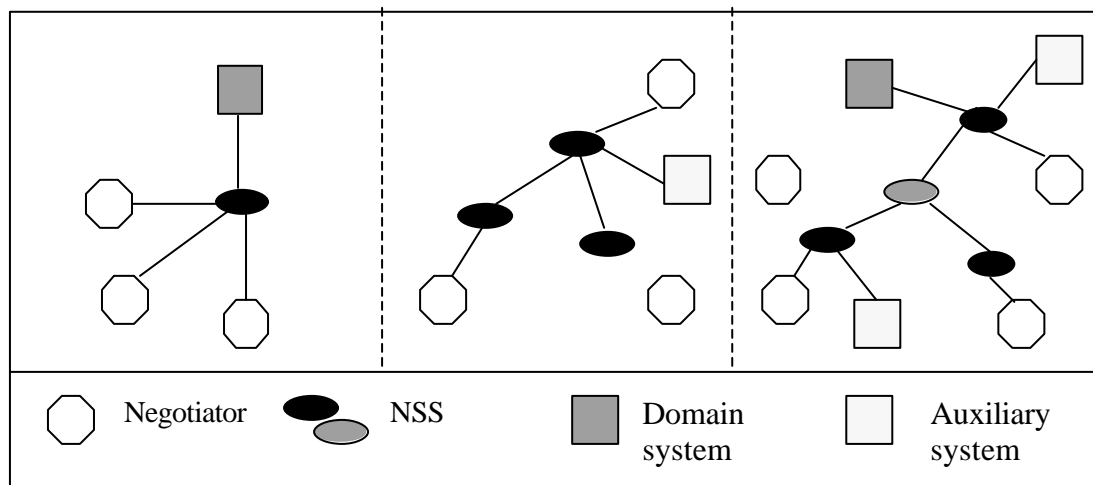
Figure 3.2 Three NSS configurations (after Kersten, 1998)

In configuration 1 there is only one NSS through which users negotiate and interact with other (typically remote) systems. This NSS would be under the control of a "third party" or the organization for which all parties work, and it would not be controlled by any of the negotiators.

Configuration 2 involves several NSS, each supporting and party and under the party's control. Parties communicate among themselves via individual NSS. An individual NSS may

use an auxiliary system that has access local databases and process proprietary information. This configuration assumed that there is no "third party" or impartial organization that can provide services to all the negotiators.

Configuration 3 also involves several NSS. One of them, however, supports the overall negotiation process: it may be used for the purpose of communication and common repository of messages and offers.

INSS (InterNeg Negotiation Support System) is a Web-based negotiation support system. It contains a facility for specification and assessment of preferences, internal messaging system and graphical displays of the negotiation progress (Kersten and Noronha, 1997). INSS can also act as an NSS and support and facilitate real-life negotiations. The system is designed so that two parties who can agree on the issues and the possible options for those issues can negotiate over the Web. This is an obvious advantage when the parties are widely separated and may have difficulty arranging meetings. Using INSS is also helpful when post-settlement improvement is likely.

3.5.4 Negotiation process systems (NPS)/ Negotiation process support systems

As shown in Figure 3.1 Negotiation Information Management Systems can be classified as either Context Support Systems or Process Support Systems (Thiessen *et al*, 1998). Context models focus on the behavior of the system being designed, managed or operated. Such models are used to answer questions about the performance of, or impacts resulting from, the system given any particular decision regarding its design, management or operation. Programs developed by the US Army Corps of Engineers' Hydraulic Engineering Center such as HEC-HMS, HEC-RAS, and HEC-5 are used to model runoff, create backwater profiles and analyze flood flows, and understand behavior in reservoirs. These models address the context of a water resources design, management, or operations problem: the system itself. They provide support necessary for understanding the physical system and evaluating proposed on-the-ground changes, and it was in this capacity that they were first incorporated into problem solving strategies. Generally, context support models are developed by experts and must be run by experts to provide output to the process. RiverWare and IRAS, are examples of context support modeling systems.

Process models are concerned with the dynamics or procedure of the negotiation process rather than with the performance or impacts resulting from the water resource system itself (Thiessen *et al*, 1998). Their goal is to identify solutions that are mutually acceptable, and possibly better than would have been found without their use. Process support can be designed for individual use, supporting either a mediator/facilitator, or a party in the negotiation. It is also possible for a process support system to assist all parties in a dispute, with the computer acting as a neutral facilitator of exchange among the interests. ICANS is an example of a process support system with application to water resource conflicts.

These systems are designed to assist the process of negotiation by increasing the likelihood of identifying one or more mutually acceptable proposals when a potential region of agreement exists. Sometimes they can help identify better solutions than would have been found without their use (Antrim, 1986).

The majority of current process support systems reported in the literature are still in the conceptual stage or are, at best, "backroom processors" playing a relatively passive role in the negotiation process (Foroughi and Jelassi, 1990; Anson and Jelassi, 1990; Jelassi *et al*, 1990). Nunamaker (1989) reports that most working systems are single workstations that support a professional mediator rather than the negotiating parties directly. Further work is needed before these models can substantially aid negotiating parties in a complex real-world setting (Jelassi *et al*, 1990; Teich *et al*, 1995).

A system designed to address a water resource conflict can contain elements of both context and process support. This combination produces a wide spectrum, ranging from dispute resolution systems that use context models as analysis tools, to modeling techniques with elements of both context and process and a supporting dispute system design. Examples of integrated systems include Shared Vision Modeling using STELLA®II as practiced by the University of Washington, USA, and flexible process design involving OASIS with OCL™, a product of Water Resource Management, Inc., USA.

ICANS, an Interactive Computer-Assisted Negotiation Support System, was developed specifically for use by professional mediators or facilitators to directly define and evaluate

possible settlements in multi-issue, multi-party negotiations (Thiessen *et al*, 1998). It can be used on a shared computer, or on a network, and identifies and evaluates alternatives based on confidential information on interests and values provided by each party.

3.5.5 Collaborative planning approach

Collaborative planning approach would help to alleviate conflicts over water resources if adopted in time. Bender and Simonovic (1996) presented a Decision Support System (DSS) for collaborative group planning of hydroelectric development projects. The approach considers systems analysis on a higher level as a driving principle of collaborative public decision making, which benefits from the conceptualization of stakeholder participation. This work illustrates the important conceptual role of formal systems analysis in public decision making. Systems involving human frailties will always be complex and that complexity will always be intimidating from a systems perspective. However, systems thinking is evolving into concepts that may help to understand how to approach complex technical problems that affect or involve people.

Bender and Simonovic (1996) discussed about two types of dynamic modeling paradigms understood by systems analysis. One is negative feed back, which forces system transformation toward an external goal. The second paradigm is the concept of positive feedback. Positive feedback behaves in a similar manner to many natural growth processes in which the system feedback instigates growth away from an external goal or reference point. Positive feedback systems approach initiates changes to a proposal away from an external goal, reference point of conflict, or disjoint value systems. Its direction and pace are flexible, which may desirable properties for group behaviour.

A framework for planning hydroelectric water management policy is demonstrated as a positive system feedback approach. The decision support system is designed for interaction and participation of a group of stakeholders with a project proponent. Planning within the group setting assumes an iterative, flexible, modeling posture. Stakeholders are able to interactively adjust the system to visualize changes, designed to improve understanding of system behaviour. Experimental alternatives are compared in terms of decision robustness relative to apparent issues and preference structures. Overall, the positive feedback

mechanisms of iteration and experimentation allow alternatives to be generated, assessed, and improved. Stakeholders are also able to explore their value systems, gain insight on potential impacts, and evaluate the collective judgments of participants. The reference point for pursuing collaborative planning is the state of conflict (or status quo) among stakeholders. Using the positive feedback process, the planning process dynamically searches for decisions, which are less conflicting than before. The process does not have an ultimate external goal, except the implicit goal of consensus. To model the dynamic processes of reinforcing and balancing feedback in public decisions (or public evaluation of decisions), we can learn from the tendencies of the traditional "reactive" approaches of accepting or rejecting proposals.

Balancing feedback, or stabilizing dynamic factors, are facilitated by knowledge transfer and empowerment of stakeholders. As stakeholders improve their understanding of the decision context, they have an opportunity to make a more informed proposal. The decision context includes the value systems of people, but also includes the relationship those value systems have with the chosen alternatives. Figure 3.3 shows the conceptual flow of information in the decision process: stakeholder input to the problem context and domain (scope of technical alternatives), and feedback in the decision process to the stakeholders.
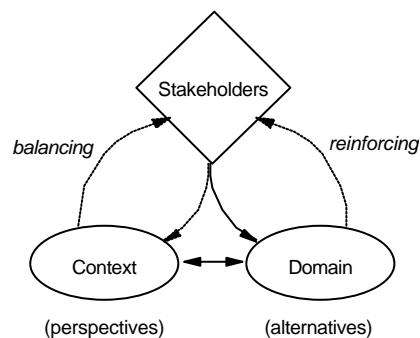
Figure 3.3   Sources of balancing and reinforcing feedback relationships (after Bender and Simonovic, 1996)

Providing balancing feedback, and facilitating the understanding of the various links that help define the problem context, is essentially a knowledge base problem. In the form of computer software decision support or in a human environment, knowledge bases are resources for

stakeholders with different technical backgrounds and different "technical languages" for describing their value systems.

The collaborative DSS presented by Bender and Simonovic (1996) uses a decision process, which contains three main modules: (i) criteria selection, (ii) alternative generation and (iii) decision evaluation. The inputs by stakeholders to the DSS are values, technical options or impressions of alternative performance. The output to the stakeholders mirrors the above inputs (i) problem context, (ii) alternative behaviour, or (iii) decision robustness.

The criteria selection module acknowledges that the choice of judgment criteria is variable. Individuals may differ greatly, and they may also (unknowingly) be redundant. The choice of judgment criteria and their relative weight in assessing alternatives can be delicate. Figure 3.4 illustrates the process of feedback to stakeholders as they explore choices in criteria.
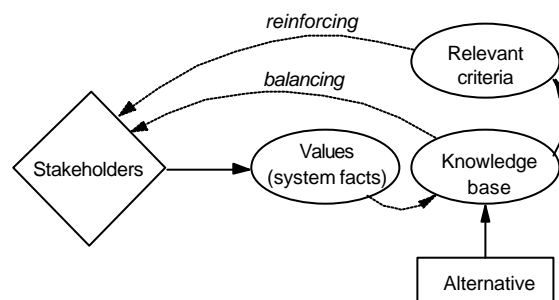
Figure 3.4 Feedback in the criteria selection process (after Bender and Simonovic, 1996)

Feedback in the criteria selection process is both balancing and reinforcing. The choice of criteria may "reinforce" the opinions of stakeholders. However, the description of reasoning by the knowledge base acts to "balance" subsequent changes by explaining degree of importance and potential impact on valued facts.

Alternative generation within the group setting assumes an iterative, flexible, modeling posture. Stakeholders are able to specify technical options from the problem domain. Knowledge bases are then used to determine appropriate model analysis, which in turn, describes the behaviour of the alternative as shown in Figure 3.5.

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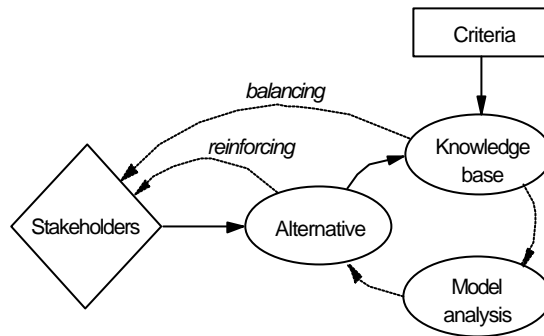
Figure 3.5 Feedback in the alternative generation process (after Bender and Simonovic, 1996)

Alternative behaviour is likely to "reinforce" the direction of subsequent choices in technical options. Knowledge bases must "balance" the behaviour of the stakeholders by explaining how the models reach their conclusions.

Decision evaluation examines tradeoffs and explores the sensitivity of decisions to uncertainties in alternative behaviour. In the process of multiobjective analysis shown in Figure 3.6, experimental alternatives are ranked in terms of decision robustness relative to apparent issues and preference structures.
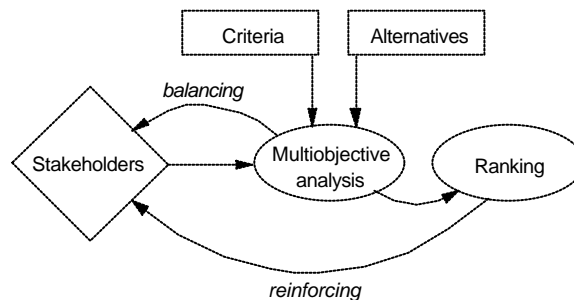
Figure 3.6 Feedback in the decision evaluation process (after Bender and Simonovic 1996)

The formal multiobjective approach provides a framework designed to "balance" the "reinforcing" implications of seeing which alternatives are ranked higher. It provides structure and a specific form of expressing both judgments and degree of subjectivity.

Implementation of collaborative decision support for public decisions is limited by several factors such as acceptance, trust by participants, learning time for using decision support tools and accumulation of domain knowledge. However, if these limitations can be

overcome, the risks of proposal rejection and costs of planning will be reduced, and that more creative solutions will emerge. The motivation for pursuing this form of approach is the potential of discovering creative solutions from combining the disjoint aspects of stakeholder perspectives.

3.5.6 Consensus approach

Consensus, a general agreement in opinion, among interested parties or stakeholders can help to alleviate conflicts in water. It describes the level in which stakeholders are satisfied with a solution to a question. Degree of consensus, calculates the level of agreement between affected stakeholders about the judgment of rank for alternatives they have. Bender and Simonovic (1997) presented a process, which this measure promotes and may also provide insight into specific issues on which to focus the planning of water resources use or development. Consensus assumes that an appropriate group of stakeholders is able to collaborate in assessing proposed solutions to environmental problems or development initiatives. It also assumes that the collective best, which a group of stakeholders has to offer implicitly, provides insight to the needs of future generations. As presented, a consensus approach may not be capable to giving a correct answer, instead, consensus measures provide sources of feedback designed to assist in; (i) whittling down the number of appropriate alternatives, (ii) identifying sources of disagreement, (iii) tracking progress of negotiations, and (iv) adding additional insight to the perceived degree of robustness.

In a consensus-based approach for achieving sustainability through decision-making, the decision process becomes iterative, using an extra step to evaluate progress in discussions among decision makers. The commonly used distance metrics can be used to assess degree of consensus among decision makers. The following are 5 measures for a degree of consensus (Kuncheva, 1994; Bender and Simonovic, 1997).

$$\boldsymbol{g}^1 = 1 - \min_{i \neq j} \left| w_i x_i - w_j x_j \right| \qquad i,j = 1,.......,n \tag{3.1}$$

$$\boldsymbol{g}^2 = 1 - \max \left| w_i x_i - w_j x_j \right| \qquad i,j = 1,.......,n \tag{3.2}$$

$$g^3 = 1 - \frac{1}{n} \sum_{i=1}^{n} |w_i x_i - u| \qquad\qquad (3.3)$$

$$g^4 = 1 - \frac{2}{n(n-1)} \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} |w_i x_i - w_j x_j| \qquad\qquad (3.4)$$

$$g^5 = 1 - \max |w_i x_i - u| \qquad i,j = 1,\dots\dots,n \qquad\qquad (3.5)$$

with $\quad u = \frac{1}{n} \sum_{i=1}^{n} w_j x_j$

and where n is the number of decision makers, x_i is the distance metric value for decision maker i, w_i provides parametric control and possible weighting of a decision maker, and $\gamma^k \in$ [0 1] is the degree of consensus measure for an alternative, indexed by $k \in$ [1.5]. Of course, some care must be taken to preserve a consistent and meaningful mathematical form in γ^k. That is, distance metrics (x) and weights on decision makers (w) must be set appropriately. To be of use, γ^k must operate on the range [0,1], with due regard to the sensitivity of selecting nonequal weights for decision makers. Weights would normally be set at $w_i = 1$.

The *highest coincidence measure* (γ^1) checks, for each alternative, whether any decision makers agree on the tank (distance metric value here). $\gamma^1 = 1$ if at least two decision makers agree on the tank (actually, the value of the distance metric).

The *highest discrepancy measure* (γ^2) checks whether ant decision makers disagree on the distance metric value of an alternative. The two decision makers who disagree most vehemently are chosen to represent the consensus measure. $\gamma^2 = 1$ if all decision makers are in agreement.

The *integral mean coincidence measure* (γ^3) records the (average) variability of disagreement among decision makers, using the average distance metric value (u) as the basis for summation. $\gamma^3 = 1$ if all decision makers are in complete agreement.

The *integral pairwise coincidence measure* (γ^4) cycles through comparisons of every possible pair of decision makers, measures any discrepancy, and computes and average value. $\gamma^4 = 1$ of all decision makers are in complete agreement. γ^4 is very similar to γ^3, but provides slightly different information about the same general aspect about consensus. Instead of expecting an average distance metric value and focusing on decision makers with extreme views (such as with γ^3), γ^4 gives a better indication of relative grouping of decision makers.

The *integral highest discrepancy measure* (γ^5) focuses on the single most extreme perspective, using an average distance metric value as the basis for judging extremes. $\gamma^5 = 1$ if all decision makers are in complete agreement.

Each measure for degree of consensus illuminates or captures a different aspect of consensus. The three coincidence measures focus on identifying common ground. The two discrepancy measures are focused on identifying sources of disagreement. Besides the provision of numerical feedback to the decision process, decision makers can be identified as supportive or otherwise, including identification of significant pairs of decision makers.

The degree of consensus indicates the relative strength of ranking. That is, the worst alternative may have a high degree of consensus because everyone agrees that it is the worst alternative. The result is weak ordering of alternatives, and complete transitivity may not be achieved. Bender and Simonovic (1997) illustrated the consensus approach through an example in water resources planning in the former republic of Yugoslavia.

3.5.7 Scenario analysis

GLOBESIGHT (GLOBal fore SIGHT) is a reasoning support tool, (Sreenath, 2002) useful for understanding the past, evaluating the present and looking into different feasible (not probable or just possible) futures through scenario analysis as presented in Figure 3.7. The user represents the subjective and qualitative aspects of the issue at hand, whereas, known data, procedures, models are inherent in GLOBESIGHT. Together with the "human-in-the-loop-with-the-computer" one could explore different futures or scenarios.
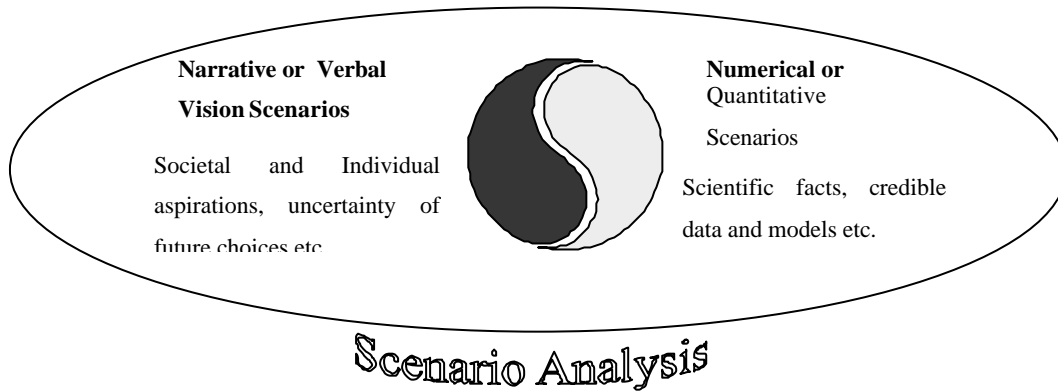
Figure 3.7 Relationship between verbal and quantitative scenarios (after Sreenath, 2002)

GLOBESIGHT consists of four modules as shown in Figure 3.8: (i) Information Base: Contains credentialed quantitative, and verbal, (or qualitative) data and information. (ii) Models Base: Consists of models of sub-systems such as population/demographics, economics, water supply, demand and use, energy generation and demand, other resource availability and use, etc. The hierarchical set of models are scientifically based on the principle of "model only what is modelable" and created using a dominant relationship modeling approach. (iii) Issues Base: Using the models base as basic building blocks one can construct systems to study specific issues in detail. (iv) Functionalities Base: The functionality deals with three issues basically – input, output, and process. Broadly, input consists of data import and model management utilities. Output formats include geographical information system (GIS), multi-axis graphs, X-Y plots, batch output, etc. Process includes specific procedures such as data interpolation, extrapolation etc.
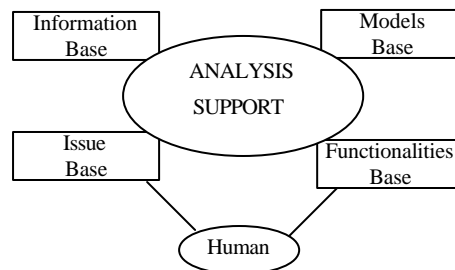
Figure 3.8 GLOBESIGHT architecture (after Sreenath, 2002)

Case studies conducted using GLOBESIGHT pertaining to water resource conflict analysis include: Nile Basin Problematique (development of Egypt and Ethiopia – present to 2050);

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Aral Sea Basin countries vision validation; Limpopo River Basin countries development; China, Sub-Saharan countries and world food trade (see genie.cwru.edu). GLOBESIGHT reasoning support software has been available on SUN hardware as well as PC hardware for a number of years. SUN Solaris and LINUX version are available. Currently only Microsoft Windows 98/2000 and XP are supported.

3.6 Scales issue in conflicts

Water conflicts may have a wide range of scales which usually reflect the true scales of water management problems in water utilization resulting from water shortage, water-related disasters and water pollution (Le-Huu, 2002). Water conflict may have a larger scale resulting from different perceptions of needs, such as ecosystem needs for environmental protection, economic opportunities from water resources development, social equity and future demands for water. Large-scale water conflict may result from different perceptions of local natural phenomena that affect the interests of the stakeholders owing to the lack of information or communication. Water conflicts can be seen at three geographic levels: global, regional and upstream-downstream (Le-Huu, 2002). Geographic scale and intensity of conflict are found to be inversely related (Wolf, 1998). Conflicts can occur based on the purpose it is to be used and the user. Uneven distribution in time can also bring water conflicts.

3.6.1 Global scale of water conflicts

According to the World Water Vision report (Cosgrove and Rijsberman, 2000) the world population has tripled in the past 100 years, but water use for human purposes has increased six-fold. It pointed out that about half of all available freshwater was being used for human ends, the trend continued to increase and there was a water crisis today. Thus rising population is leading to an increase in demand for water, which does not match the supply leading to water scarcity. Scarcity of water is however not just related to supply but also to the inequitable access to these supplies. The crisis has becoming more alarming because of its inequitable distribution between rural and urban areas or poor and rich as well as among nations sharing water resource. Hence water conflicts become a frequent occurring in such

cases. Water is important for life on earth. Though, its importance does not rely on economic barriers, a distinction does exist mainly due to availability. The rich get water resources much easily than the poor and hence poverty is a cause for their lack of availability, which may lead to conflicts. In fact, poverty is one of the major influential factors related to the sustainable provision of basic water requirements of a society on global scale. The lack of availability of basic services is a primary measure of poverty and poverty is the primary obstacle in the provision of very basic services of a society, such as their water needs.

Water scarcity, which could lead to conflicts, is further exacerbated by weather and climate variability. Global climate changes could significantly affect the hydrological cycle, altering the intensity and temporal and spatial distribution of precipitation, surface runoff and evapotranspiration with various impacts on different natural ecosystems and human activities. For example, greenhouse warming is likely to increase the number of intense precipitation days and flood frequencies in northern latitudes and snowmelt-driven basins. Also the frequency and severity of droughts could increase in some areas as a result of a decrease in total rainfall, more frequent dry spells, and greater evapotranspiration. These impacts on water resources could be sufficient to lead to conflicts among users, regions, and countries.

Cosgrove and Rijsberman (2000) in their World Water Vision report argued that the crisis was not due to having too little water to satisfy human needs, but mainly due to managing water so badly that billions of people, and the environment, suffered greatly. The root cause of the global scale of water conflicts is due to the poor management of water resources and the increasing disparity in the economic and social conditions between areas, countries and regions. There were three major groups of global-scale water conflicts resulting from the following three issues: (1) lack of accessible water, (2) increasing environmental concern, and (3) the economic value of water.

3.6.1.1 Lack of accessible water

According to recent WMO/UNESCO estimates, the total volume of accessible water is less than 0.3 per cent of the global water resources. The lack of accessible water is caused by the shortage of water in terms of both quantity and quality. This is largely as a result of poor water allocation, wasteful use of the resource and lack of adequate management action.

3.6.1.2 Increasing environmental concerns

Water resources ecosystems are increasingly recognized for the environmental goods and services they provide through healthy catchments. This trend has built up into global concerns for water quality protection and biodiversity conservation through a series of conservation programmes, including the establishment of natural reserves and protected areas.

In many countries, specially in developing countries, these movements have often been seen as obstacles to the economic development of river basins. The tension tends to increase when opportunities for development are severely constrained by these environmental concerns.

3.6.1.3 Economic value of water

The scarcity of freshwater in the global system has been recognized as a major global concern with respect to food security and therefore, to the well-being of humankind. Water is therefore seen not only as a social good but is increasingly recognized as having economic value. It is the scarcity of water and not merely its importance for existence that gives it its value. Where water is not scarce, it is not valuable (Fisher, 2001). However, water is a basic commodity and therefore, obtaining it through markets is one way of tackling the scarcity (Howe *et al*, 1986) though it possesses both desirable and undesirable attributes. Besides more emphasis should be given for the allocation of existing water supplies more efficiently to minimize the burden to the poor.

3.6.2 Regional scale of water conflicts

Water conflicts on a regional scale may come from three main categories: differences in water resources endowment, transboundary pollution and disputes in the management of international river basins. While water conflicts in the first two categories are less common, those in the third category are more frequent.

The different levels of water resources endowment have always been the main reason for the disparity in the distribution of population among areas of a country or in a region. People tend to settle in areas with rich water resources where urban settlements continue to grow. Within a country, various measures, including economic incentives and development action,

can be taken to minimize the impact of the differences in water resources endowment on the social and economic conditions between regions, although such measures may lead to other issues in water management. For an international region, options are usually limited and the discrepancy in resources can easily be conceived as better opportunities for development. This perception could lead, on the one hand, to explosive political issues, such as illegal activities to make use of the rich water resources, including the diversion of water resources or illegal fishing, and, on the other, to undue pressure to share those resources by using different control measures based on monopolistic market opportunities or transit control.

Transboundary pollution is becoming more and more frequent with higher levels of development intensity. Among the prominent issues of transboundary pollution are those related to acid rain caused by industrial development or the construction of major coal-fired thermal power plants. Intensive agricultural development and different industrial waste disposal schemes may lead to severe pollution of groundwater aquifers that extend beyond national boundaries. As in most cases, transboundary pollution also affects the country of the source and this leads to better opportunities to find suitable solutions to control and resolve the problems.

With respect to the third category of conflicts, on the regional scale, there are about 260 major river basins and a number of the major groundwater aquifers cross national boundaries. These river basins comprise about 40% of the total land area of the world, which includes more than 60 per cent of the area on the continents of Africa, Asia and South America. Most of these river basins are areas of potential conflict, especially in the large river basins and those shared by several countries. Examples of conflicts on a regional scale of varied intensity can easily be found among these international river basins.

3.6.3 Upstream and downstream relationship

The relationship between upstream and downstream states is usually the principal root cause of water conflicts in the management of international river basins. While water is a resource flowing from one place to another, it carries the impact of human intervention between places. Furthermore, the variability in time of water quantity and quality adds complexity in the management of international water resources and confusion to the perception of changes

from human intervention. This is especially true when a river flows between areas of different climate conditions, such as dry and wet regions of a river basin. Depending on the relative importance of the impact of the changes on the economic and social conditions, water conflicts may develop from a bilateral issue into a river basin problem.

While it may be difficult to forecast the flow conditions with accuracy and to achieve good understanding on the part of the public about the river regime under different conditions, it is necessary to ensure accessibility to accurate information to all and to provide the public with a complete picture of the river system; only on the basis of equal access to information can mutual understanding and trust be developed to form the basis for conflict prevention.

3.6.4 Conflicts between purposes and users

Water is a vital resource for human survival and economic development. Multi-interests of water resources include its utilization in water supply and sanitation, agriculture, industry, urban development, hydropower generation, fisheries, transportation, recreation, low and flat lands management and other activities. As populations and economies grow, water demand for diverse interests increases while the availability of the resource remains constant, which may engender water use conflicts. Specially, when water is used from a common source for conflicting interests such as water supply for irrigation purposes and industrial requirements, dispute can erupt among users.

3.6.5 Conflicts in time

Freshwater availability, both in the forms of precipitation and runoff, is very unevenly distributed throughout the year in almost all regions of the world. About 60-70% of runoff is generated during flood periods and therefore values for renewable water resources vary noticeably during a year. Unevenness in the distribution of river runoff during a year may result in crisis situations. Further, year-to-year water variability within the regions can be quite significant. This is especially so in the arid and semi-arid regions where the actual values are small. Here, water availability for individual years can be 1.5 to 2 times less than the averages over a long period, whereas for wet regions this difference is in general, within 15 to 25%.

This temporal variation of water availability may be over come by creating reservoirs. Water could be stored in reservoirs when available in excess during high flow periods and used when it is needed during droughts. Besides reservoirs facilitate reducing damages due to floods, by temporarily storing the high flood flows.

3.7 Integrated water management: Multi-sectoral

Integrated water resources management has been too often ignored in the past, and solutions to water management related problems have been sought through largely technical means. Integrated means socio-technical; not merely taking into consideration socio-economic factors or technical factors individually, but integrating both aspects in the process of the management of water resources in a basin. Equally, we must take into account not only human water needs in setting our goals, but also the maintenance of the required ecosystem balance.

Integrated water management takes into account all inputs, all forms of utilization, and all protection needs as well as political, legal, institutional, economic, social and cultural aspects associated with water resources development. The term "integrated" most commonly refers to integration across use sectors, such as agriculture and urban water supply. However, it can also encompass a number of other divisions, including the following: administrative jurisdictions; ground and surface water; upstream and downstream reaches; environmental and human uses; supply and demand management; water quantity and quality; land and water use; and transboundary uses. The approach seeks a solution to the water management problem by promoting integration across all the relevant sectors given above. It provides a framework to manage competition for limited water resource and the potential conflicts and inefficiencies. Further, it recognizes a more participatory approach to development and management of water resources and the economic value of water. Further, integrated water resources management guarantees the maintenance of essential forms of water utilization over long periods of time or sustainable use of water.

Conflicts in the water management of international river basins can be perceived as interaction of management issues in the following interdependent processes: integrated water resources management, international cooperation, and conflict management processes. Conflicts may appear in many forms as part of the integrated water resources management process, at different scales in the context of international cooperation, and in varying intensity in terms of conflict management.

Conflict management requires partnerships among all the stakeholders involved in a water resources development activity. The multi-sectoral partnerships ensure the essential understanding of the multiple dimensions of a specific conflict and ensure adequate capacity building required. It will create lasting forms of conflict prevention. Included in multi-sectoral partnerships are governments, international organizations, NGOs, local and tribal groups, business and industry, academia and other actors. It is doubtful that sustainable solutions can be built upon anything but a multi-sectoral foundation.

3.7.1 Water conflicts in the integrated water resources management process

Water management is becoming more and more complex along with the increasing complexity of economic and social development process. As integrated water resources management is itself a process, conflicts in water management evolve with the scope and intensity of the interaction between human beings and nature, among individuals and between communities. Conflicts in the integrated water resources management process can therefore be seen from different perspectives: environmental, economic and social or political. The effectiveness and efficiency of the integration of water resources management into the economic and social development process of the countries can be measured through the following four aspects: social context, economic aspects, legal and institutional framework and development perspectives.

3.7.1.1 Social conflicts of water use: equitability and ecosystem efficiency
Water has long been perceived as a social good, and interaction between human beings and nature has, until recently, been based mostly on the sectoral perception of water resources ecosystems. This has resulted in various forms of water conflicts, which reflect different

perceptions from the sectoral needs for water or from different concepts of water-use priority in the process of social and economic development.

In terms of an integrated water resources management process, these social conflicts of water management form the most important obstacle to the achievements of water-use efficiency of a water resources ecosystem. The social perception of water and water rights varies from one country to another and even from one community to another. These human factors have contributed to the inefficient division of a natural hydrological unit and to the complexity of the integrated water resources management of these natural hydrological units. Integrated water resources management requires the adoption of integrated river basin management, for which water resources must be considered an integral part of a given river basin, aquifer or watershed as a unitary resource. In the management of this unitary resource, the tendency towards unilateral exploitation of water among neighbours would need to be avoided so as to provide a cost-effective way to increase freshwater supplies.

These human factors, together with the cultural perception of water use have aggravated institutional obstacles to integrated water resources management. Social and institutional obstacles to integrated water resources management will be greater for international river basins when different cultures, and countries with even historical animosities, are involved. In such a context, it will be necessary to prevent social conflicts through the prioritization of the social and ecosystem needs for water by the formalization of historic patterns of use among all parties, as part of short-term goals and through the establishment of a shared vision for integrated river basin management as part of long-term goals for ecosystem efficiency.

3.7.1.2 Economic conflicts in water use: market efficiency
Apart from satisfying basic human needs and health, water resources are essential for food production, energy and the restoration and maintenance of ecosystems, and for social and economic development in general. While agriculture accounts for a major part of global freshwater use and is necessary to ensure food security, the high economic growth expected in the developing countries calls for better value-added utilization of water resources. It is imperative that freshwater resources development, use, management and protection be planned in an integrated manner, taking into account both the short- and long-term needs of

the social dimension and the stability and sustainability of the social and economic development process.

Competition for limited water resources increasingly occurs among agricultural, rural, urban, industrial and environmental uses. At the same time, disparity in the economic conditions between the urban and rural areas in a country and among countries continues to increase. Questions of economic efficiency in water use will eventually grow and assume greater significance in conflict management in water resources development. Effective use of the market mechanism could contribute to conflict prevention in water management by making use of increased opportunities and incentives to develop, transfer and use a resource in ways that would benefit all parties. On the other hand, the inability to integrate water resources management into the economic and social development process will lead to the aggravation of conflicts in water management. These conflicts are known as economic conflicts of water management. In order to avoid them, it is necessary to create conditions for an efficient environment for the economic use of water, including a well-defined legal and institutional framework for water utilization and conditions for a fair and equitable sharing of the beneficial use of the water resources.

3.7.1.3 Legal conflicts: rules in water utilization and principles for water allocation

Application of the integrated water resources management concept to international river basins usually faces the most difficult obstacle: the legal context of water use. From an ecosystem point of view, the legal aspect of international river basins is the main source of inefficiency and conflicts in water management. These conflicts reflect the multitude of problems in the legal aspects of water resources management, which may come from issues related to the allocation of water resources within a country or the management or sharing of water among the riparian countries of an international river basin.

The lack of a universal system of water rights in the management of international river basins continues to be a major obstacle to the efficient and optimum utilization of shared water resources and to the resolution of water conflicts.

3.8 Stakeholder participation – Shared vision approaches

Shared vision modeling is a disciplined approach to developing water resources models for conflict resolution. Shared vision modeling requires both the use of time-tested planning procedures and the active participation of those likely impacted by a water resources plan. In simple terms, shared vision models are computer models developed by stakeholders, water managers, and water planners that incorporate planning objectives and performance measures into a framework that allows the generation and evaluation of alternatives in a manner that facilitates conflict resolution. These models typically contain social, economic, and environmental impacts as well as hydrologic and hydraulic analysis.

Implementing integrated water resources management (IWRM) and resolving conflicts through stakeholder participation is not an easy task. It requires the active support of all stakeholders and especially a will to implement on the part of governments. Commonwealth Knowledge Network reports a successful application of stakeholder participation in water conflict resolution in Barbados. Users and suppliers of water in Barbados came together to discuss water related conflicts and recommended ways to integrate stakeholder concerns into the existing water management strategy. A decision support system was used to assist decision makers in testing different policies and scenarios, conducting sensitivity analysis and making optimal choices and was found very useful.

Water resources planning and management involves numerous stakeholders (Loucks, speech at Valencia). Each stakeholder or interest group has its' own objectives, interests and agendas. The decision-making process is one of negotiation and compromise, but from it come the decisions that have the best chance of being the most effective, i.e., the right, decisions. So, the model should meet the information needs of all these different stakeholders to get them to believe in and accept these models and their results to reach a common - shared – vision.

Involving stakeholders in model building accomplishes a number of things. It gives them a feeling of ownership and a much better understanding of what their model can do and what it cannot do. If they are involved in model building, they will know the assumptions built into their model. While there may be no agreement on the best of various assumptions to make,

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stakeholders can learn which of those assumptions matter and which do not. In addition, just the process of model development by numerous stakeholders will create discussions that will lead toward a better understanding of everyone's interests and concerns. Though such a model building exercise, it is just possible those involved will reach not only a better understanding of everyone's concerns, but also a common or 'shared' vision of at least how their environmental system (as represented by their model) works. Experience in stakeholder involvement in model building suggests such model building exercises can also help multiple stakeholders reach a consensus on how their real system should be developed and managed.

Shared vision modeling/conflict resolution appears to be more promising when applied to relatively new or low intensity conflicts before legal or political alternatives have been considered or for higher-intensity conflicts where agreements have been made or incentives have been imposed to maintain broad dedication to the process (Lund and Palmer, 1997).

In the US, one of the major advocates of shared vision modeling is the US Army Corps of Engineers. They have applied an interactive general-purpose model-building platform called Stella II^{TM} in a number of exercises where conflicts existed over the design and operation of water systems. Each of these model-building 'shared-vision' exercises included numerous stakeholders together with experts in the use of Stella II.

Palmer *et al* (1993) reported the development and application of a "shared vision model" during the national study of water management during drought and applied extensively in the ACT-ACF basin-wide study. The model uses graphically based computer simulation to develop easily understood analyses of the systems under study and facilitates the testing and collaborative use of the model by all those involved in the process. The advantage of these "shared vision models", as the name implies, is that consensus in the model and in the computer results can be reached, since all parties participated in the development of the model.

Understanding the stakeholders of a certain water conflict is fundamental to successful resolution of it. However, in most cases getting the less affected stakeholders participated in the negotiations processes have been difficult. In general, only the most affected parties are interested in involving in discussions and negotiation procedures. Shared vision modeling

like other consensus building processes, requires that there be a strong motivation among the stakeholders to develop a consensus. This usually occurs only when the parties believe they can achieve a desirable goal through consensus building that can otherwise not be achieved. In some conflicts the number of stakeholders involved in a conflict may be high and therefore, participation of all of them in resolution processes such as public hearings would be difficult. In such cases different techniques may be required to obtain their views like questionnaires.

3.8.1 International Joint Commission in water resource conflict resolution

Many rivers and lakes lie along, or flow across, the border between Canada and the United States. The development and continued use of these water resources by both countries has given, and continues to give rise to disputes as well as problems of mutual concern for those who live along the common frontier. The *International Joint Commission (IJC; Commission)*, a unique international organization established by Canada and the United States under the *Boundary Waters Treaty of 1909 (Treaty)*, has played an important role in preventing and resolving disputes in the transboundary region of these two countries (Clamen, 2002). The history of the IJC is rich in experiences derived from almost 100 years of operation by dealing with over 120 issues.

3.8.1.1 The Canada - United States Boundary Region
The Canada-United States boundary extends from the Gulf of Maine westward across the continent to the straits of Juan de Fuca off the coast of British Columbia and then northward to the Beaufort Sea. This expansive region is extremely diverse in climate and ecology. Throughout most of its length, the boundary crosses or bisects natural drainage basins. Boundary waters or waters which are followed by the boundary make up almost 43% of the total length of the boundary.

3.8.1.2 The IJC and the 1909 Boundary Waters Treaty
Clamen (2002) presented a description of the IJC and the role it played in water resource conflict assessment and resolution in detail. The IJC was established pursuant to Article VII of the 1909 Boundary Waters Treaty between Great Britain and the United States. In 1909 Canada had not yet fully acquired an international personality and Great Britain still acted for

Canada in its formal relations with other countries. Today, as a fully independent country, Canada has succeeded to Great Britain's rights and obligations under the Treaty, which remains a cornerstone of the relationship between Canada and the United States with respect to transboundary water and environmental issues.

From the beginning, the Commission's fundamental role has been to prevent and resolve transboundary environmental and water-related disputes between the United States and Canada through processes that seek the common interest of both countries. It not only offers the two countries a flexible set of mechanisms to help them manage their relationship in the transboundary region, but also provides them with the assurance that it will reflect the shared system of principles and values recognized in the Treaty.

The Commission has two primary responsibilities under the Treaty. First, the IJC acts as a quasi-judicial body to consider applications for approval to build and operate certain works in boundary waters and rivers that flow across the boundary. Secondly, at the request of the governments, the Commission examines and provides non-binding recommendations on transboundary issues with a view to preventing and resolving transboundary conflicts.

The IJC's Rules of Procedure allow Commissioners to appoint a Board composed of equal number of qualified persons from each country to conduct necessary studies and to report. When a Board submits a final report the Commission typically makes it available to governments and interested persons prior to holding public hearings. The Commission's Boards have proven to be highly effective mechanisms for impartial, joint fact-finding and their reports have provided the basis for Commission decisions and recommendations.

Examples of projects falling under IJC jurisdiction include hydropower structures at the outlets of Lakes Superior and Ontario, water control facilities on the Niagara River, and dams on the Kootenay, Columbia, Pend d Oreille, Okanagan, Rainy, St. Croix, and St. John Rivers. The IJC also advises the United States and Canadian Governments on other environmental and natural resource matters and administers the apportionment of the waters of the St. Mary and Milk Rivers (which flow through Saskatchewan, Alberta and Montana), and the Souris River (which flows through Saskatchewan, Manitoba and North Dakota). All these ongoing

projects are vast potential sources of conflict, which have been essentially transformed by the Commission into models of bi-national environmental cooperation.

The IJC also has critical duties under the revised 1978 Great Lakes Water Quality Agreement to monitor progress and coordinate activities associated with this Agreement. The Commission evaluates programs and measures designed to improve water quality in the Great Lakes and reports biennially to the Federal, State, and Provincial Governments and the public on achievements and shortfalls under the Agreement. The IJC's emphasis on direct access for, and contributions from, citizens of both nations have not only helped shape policy recommendations, but also enhanced the governments' efforts to restore the Great Lakes ecosystem.

Other, separate treaties and conventions permit the IJC to deal with emergency water level conditions in the Rainy Lake and Lake of the Woods watershed (Minnesota, Manitoba and Ontario); approve diversions of water from the Lake of the Woods (Minnesota, Manitoba and Ontario); oversee the operation of control works that distribute water over the crest of the Niagara Falls (New York and Ontario); and resolve disputes regarding the use of the Columbia River (Washington and British Columbia.)

The Treaty provides for six commissioners, three from each country, who serve in their personal and professional capacities and do not receive instructions from their governments. The IJC acts as a unitary body and acts to achieve the best long-term interests of the two countries.

3.8.1.3 Case study: Great Lakes - St. Lawrence River

The following case study constitute a representative account of occasions in which the Commission's contribution has been or is currently evident and illustrate how transboundary reservoir management conflicts are managed by the IJC.

The Great Lakes - St. Lawrence River basin is the largest system of fresh surface water on the globe, stretching 3,840 km from the middle of the North American continent to the Atlantic Ocean. The five interconnected lakes - Superior, Michigan, Huron, Erie and Ontario - contain approximately 20% of the world's freshwater with about 16,000 km of shoreline. A large

number of Americans and Canadians live within the boundaries of the Great Lakes basin. Fluctuating water levels affect adversely most persons either directly or indirectly.

In its Great Lakes *regulatory role* the IJC has issued Orders of Approval for control works at two locations (Lakes Superior and Ontario) and remedial works at one location (Niagara River). Although the outflows of Lakes Superior and Ontario are regulated by the IJC, since the inflows are not, the levels of the lakes vary seasonally and also with long-term climatological trends and instantaneous hydrometeorological events. Many studies have indicated that these, and other human interventions, have relatively minor impacts on water level fluctuations in comparison with natural forces, and that storms can induce some of the most dramatic changes in local levels.

In its *advisory role* the IJC has been asked to conduct studies of Great Lakes water levels and flows on numerous occasions. During record-breaking high levels in 1985 and 1986 riparian communities petitioned governments to reduce the effects of high levels throughout the system. Governments in turn referred the matter to the Commission. In 1993, the Commission completed a comprehensive study of fluctuating water levels in the Great Lakes-St. Lawrence River basin that produced a series of recommendations on which both governments and the Commission itself are still acting.

Lake Ontario: In 1952 the IJC approved the construction of hydropower facilities in the international reach of the St. Lawrence River, which extends from Lake Ontario to Cornwall, Ontario and Massena, New York. Changes in water levels and flows on Lake Ontario and in the St. Lawrence River often create conflicts among several interests. These interests fall into five categories: riparian, hydropower, commercial navigation, recreational boaters and the environment.

Overall, Lake Ontario regulation has resulted in substantial benefits to interests around the Lake and along the St. Lawrence River. With an agreed set of criteria and a flexible regulation plan, the Commission and its Board represent a model of co-operation for regulation of a complex system and for investigating improved conditions for the interests sharing that system. Nevertheless even successful water management regimes need review and adjustments from time to time. In December 2000 the Commission began a review

through a bi-national Study Board to take into account developments that have occurred since the 1950s. To get public participation in it commission formed a 24-member Public Interest Advisory Group made up of interested citizens in both countries, which illustrates the Commission's commitment to public participation in its studies.

Lake Superior: Lake Superior has been regulated since 1921 when construction and operation of the compensating works structure just above the head of the St. Marys Rapids was approved by the IJC. The approval included several conditions recognizing interests on Lake Superior. Later, in 1979, following a ten year Commission study of Great Lakes water levels, the IJC recognized the need to broaden the scope of interests and issued a Supplementary Order to take into account downstream interests in the St. Marys River and Lakes Michigan and Huron.

The present plan for regulating Lake Superior is Plan 1977-A, which came into effect following the 1979 Order. The plan considers conditions on Lakes Superior, Michigan and Huron when specifying outflows. It specifies minimum allowable flows in the St. Marys River to prevent excessively low levels downstream, ensures water for power production, maintains adequate flows in the Rapids for fish habitat, and limits winter flows to a specified maximum to prevent ice jams. Plan flows are set monthly. Conflicts between users, when they arise, are typically resolved through the forum of this international board and the use of an agreed-upon regulation plan based on the Commission's Order.

Currently, due to continued low levels in the upper Great Lakes and growing grass roots support for re-evaluating Regulation Plan 1977-A (largely from citizens on Lake Michigan who believe that a Amore equitable@ regulation plan is possible and desirable) the Commission is considering initiating a review of its Orders of Approval for the regulation of Lake Superior, similar to that just started for Lake Ontario and the St. Lawrence River. If undertaken, this project would represent another opportunity to review whether a long-standing means of resolving conflicts is in need of amendments in the light of changed circumstances in the watershed.

3.8.1.4 International watershed boards

In 1997, in response to a request from governments on providing greater assistance in meeting future transboundary environmental challenges, the Commission developed several proposals, the most important one being the establishment of international watershed boards in major transboundary watersheds that extend across the Canada - United States boundary, or some regional combination of these watersheds. In the past, transboundary water issues were often seen as localized but, experience with the Great Lakes Water Quality Agreement and the ecosystem approach changed that perspective and the Commission recognized that transboundary water issues must be addressed in an integrative manner, including both biophysical and human aspects.

The Commission found that demographics, climate change and technologies are combining to increase the potential for conflict over water resources and other environmental concerns. Resolution of these issues is often made more difficult by changing governmental responsibilities at all levels and by demands from many interests to be involved in decisions that affect them. The IJC boards could deal changes in jurisdiction and governance, which are not always the same on both sides of the border, in an integrative and non-adversarial way.

IJC boards would provide a mechanism for avoiding and resolving transboundary disputes by building a capacity at the watershed level to anticipate and respond to the range of water related and other environmental challenges that can be foreseen for the 21st century. This mechanism includes effective co-ordination of government institutions at various levels, acquisition and fostering of expertise, knowledge and information about the ecosystem of the watershed, consultation with and involvement of the full range of interests concerned, including the public, and above all the flexibility to identify and deal with unforeseen developments. Finally, this improved mechanism could be implemented without substantially affecting existing institutions.

Governments have approved the watershed boards proposal in principal and the Commission is now pursuing its implementation by, as a first step, amalgamating existing IJC Boards in watersheds where such amalgamation is most easily accomplished, and revising the Boards' mandates to reflect an ecosystem approach to their work. The Commission believes that the introduction of a system of permanent IJC international watershed boards from coast to coast

will increase the Commission's capacity to provide the governments with an even stronger and more flexible mechanism for dealing with transboundary water issues.

3.8.1.5 Conflict resolution

IJC has been successful in preventing and resolving transboundary water resource conflicts. The Boundary Waters Treaty established a framework, within which IJC developed a process that has provided the basis for much of the success of the bilateral environmental relationship. This process can be characterized by six main elements.

<u>Consultation and Consensus Building</u>   The Treaty provides that a majority of the Commissioners can reach a decision but the Commission's Rules of Procedure call for the concurrence of at least four Commissioners to ensure that at least one Commissioner from each country agrees. In practice, most Commission decisions are taken by consensus and the Commission requires some keyboards to refer matters to the Commission for decision if board members are unable to achieve consensus. Thus the Commission and its network of advisory and regulatory boards strive for consensus as a means of reflecting the common interest.

<u>Providing a Forum for Public Participation</u>   Article XII of the Boundary Waters Treaty requires the Commission, in any proceeding, inquiry or matter within its jurisdiction, to assure that "all parties interested therein shall be given convenient opportunity to be heard." In practice, the Commission has always emphasized the importance of public participation and advice.

<u>Engagement of Local Governments</u>   The Commission invites and facilitates the engagement of state, provincial and municipal governments and other authorities in transboundary environmental issues. At the same time, the IJC brings bi-national and national resources and considerations to bear on the resolution of local and regional matters.

<u>Joint fact finding</u>   This is a foundation of Commission practice. The Commission recognizes that bi-national joint fact-finding build an important and often essential foundation for the achievement of consensus on appropriate actions.

<u>Objectivity and Independence</u>   The authors of the Treaty built into the IJC an expectation that its members would seek to find solutions in the common interest of the two nations. They are expected to serve the Commission in their personal and professional capacities. This allows board members to explore all options, which helps promote the development of novel solutions and consensus.

<u>Flexibility</u>   One of the most important features of the Commission's work has been the flexibility inherent in its mandate and process to be able to adapt to the circumstances of particular transboundary issues or conditions.

All the above elements have become a fundamental part of the relationship between the parties in boundary areas. They have kept difficult issues from the diplomatic agenda of the parties and helped to ensure the continued health of the environmental relationship. The Commission believes these practices will increase in importance as the basis for a successful transboundary relationship in future.

3.8.1.6 Summary

The United States and Canada have demonstrated the possibility for two sovereign nations to effectively cooperate in managing the waters they share. The keys to successfully resolving issues include establishing a forum for jointly determining the facts, building trust and giving both parties an equal voice, and focusing on the best interests of the watershed as a whole. The *International Joint Commission* (IJC) provides an example of how neighbouring countries can structure such a forum.

The Commission's fundamental role of preventing and resolving disputes has contributed to a successful transboundary environmental relationship between Canada and the United States throughout most of the 20th century. The 1909 Boundary Waters Treaty established a framework for the Commission's role and the flexibility of the Treaty and of the Commission itself has enabled the IJC to respond to changing times. Within this framework, the IJC has developed a process that has provided the basis for much of the success of the bilateral environmental relationship. This process is characterized by six main elements: consultation and consensus building; providing a forum for public participation; engagement of local governments; joint fact-finding; objectivity and independence; and flexibility. The

Commission sees its most recent proposal, the creation of international watershed boards, as a refinement that can assist the parties greatly in addressing new challenges.

4. Case Studies Illustrating Applicability, Success and Limitations of Systems Analysis

Concepts of systems analysis have been applied in the resolution of many conflicts over water as presented in this section. The first study shows a collaborative approach presented by Bender (1996) that could be used in conflict resolution. The method has been demonstrated through its application to resolve a conflict related to the Manitoba Hydropower in Manitoba, Canada. The presented decision support system, dubbed a Collaborative Planning Support System, demonstrates the possible implementation of integrated support for planning sustainable water resources systems alleviating conflicts.

In general no solution exists, which simultaneously satisfies all objectives related to economic development and environmental preservation in water resources development. Nachtnebel (1997) presented a methodology based on techniques related to compromise programming that could assist in conflict resolution among different interest groups or countries via its application to water related conflicts along Danube River in the next study.

For transboundary water problems between Canada and the USA, the two governments under the Boundary Waters Treaty of 1909 to thoroughly study the conflict and make recommendations often call upon the International Joint Commission. The third case study demonstrates a flexible and efficient decision support tool developed by Hipel *et al* (2002) for investigating strategic conflicts through its application to the Flathead River international water resource dispute.

The last case study presents various water related conflicts observed in the Aral Sea basin. It presents a discussion by Sokolov and Dukhovny (2002) on the importance of concentrating future activities within the basin in the directions of institutional strengthening, creating a legal framework, establishing a financial mechanism and technical perfection and capacity building for the integrated water resources management and sustainable development within the context of system analysis. Vali *et al* (2002) explored different future development scenarios for the Aral Sea basin countries based on the GLOBESIGHT reasoning support tool.

***4.1 Collaborative approach in conflict resolution – Manitoba Hydropower example,
Manitoba, Canada***

4.1.1 Introduction

Successful completion of a water resources project is directly related to the active involvement of stakeholders (affected parties and agencies) in its planning process. Their involvement is vital to formulate alternatives since they carry knowledge and experience necessary. Besides, their involvement will help minimizing conflicts over water related development activities. This study presents an objective oriented decision support system (DSS) approach developed in empowering stakeholders enabling them to participate within a collaborative framework for water-resources planning. Applicability of the approach is demonstrated through its application to a project involving the development of hydroelectric-power generation.

The DSS has been built integrating Geographic Information Systems (GIS) and an expert system as tools. This integration of GIS and expert system will enable easy visualization of project alternatives, designation of field studies and ultimately the inclusion of stakeholders in the planning process for a development proponent, who pursues more effective means for stakeholder participation and conflict resolution.

Following the conceptual systems approach of managing feedback, the task of data management in the DSS takes on a new role. System data, or physical data, includes:
- Description of problem domain
- Characteristics or properties of region
- Measurements from field studies (both included and missing)
- Model outputs
- Technical options
- Experience (with technical options, similar problem domain, site characteristics, etc.)

Experience, especially, is a key component to providing appropriate feedback to participants, although it may also be implicit in the organization of the other data.

Decision data is the complementary set of data to be recognized in the integration of tools. It tends to be more abstract, such as:

- Value systems

- Technical background of participants

- Preferences, opinions

Management of this data can take on various forms, including relational databases. Some data are more appropriately stored in an object-oriented data management scheme, or within a spatial database. The different forms of data management offer unique benefits, based on implementation, but they are quite similar. Relational databases are organized into tables, records, and fields. Object-oriented databases are organized into classes, objects, and properties. One of the benefits of object-oriented databases is that they typically are able to access methods or models and take advantage of properties such as inheritance and polymorphism.

Access to models through the concept of attaching methods to a class of objects (polymorphism-like) allows seamless connection of translation models to convert from one unit to another, aggregation models to combine components into more abstract measures or indicators, and simulation models to investigate the behaviour of complex processes.

The following case study example uses object-oriented data management to define alternatives, connecting the technical option objects to GIS models.

4.1.2 Case study - Manitoba

A case study selected to apply integration of technologies for collaborative alternative generation at the proposed hydroelectric development site of Wuskwatim Lake, Manitoba. Wuskwatim Lake is on the Burntwood River system in northern Manitoba, west of the city of Thompson (Figure 4.1) in Canada. Flow along the Wuskwatim reach of the Burntwood River is augmented by the diversion of water from South Indian Lake via the Rat River into Threepoint Lake (upstream of Wuskwatim). Proposed development sites in this area include Wuskwatim Lake at Taskinigup Falls, at Early Morning Rapids on the Burntwood (immediately upstream of Wuskwatim Lake), and at the Notigi control structure (upstream of

Threepoint Lake). Two communities may be directly affected by development. Thompson is a city with a population of 14,000 people that live downstream of any development in the region. Nelson House is a First Nation community (population 1,500), upstream of Wuskwatim Lake on Footprint Lake near Threepoint Lake. They live in potentially flooded areas. Manitoba Hydro has identified the area as having a generating capacity of 360 MW of power (Manitoba Hydro, 1987).
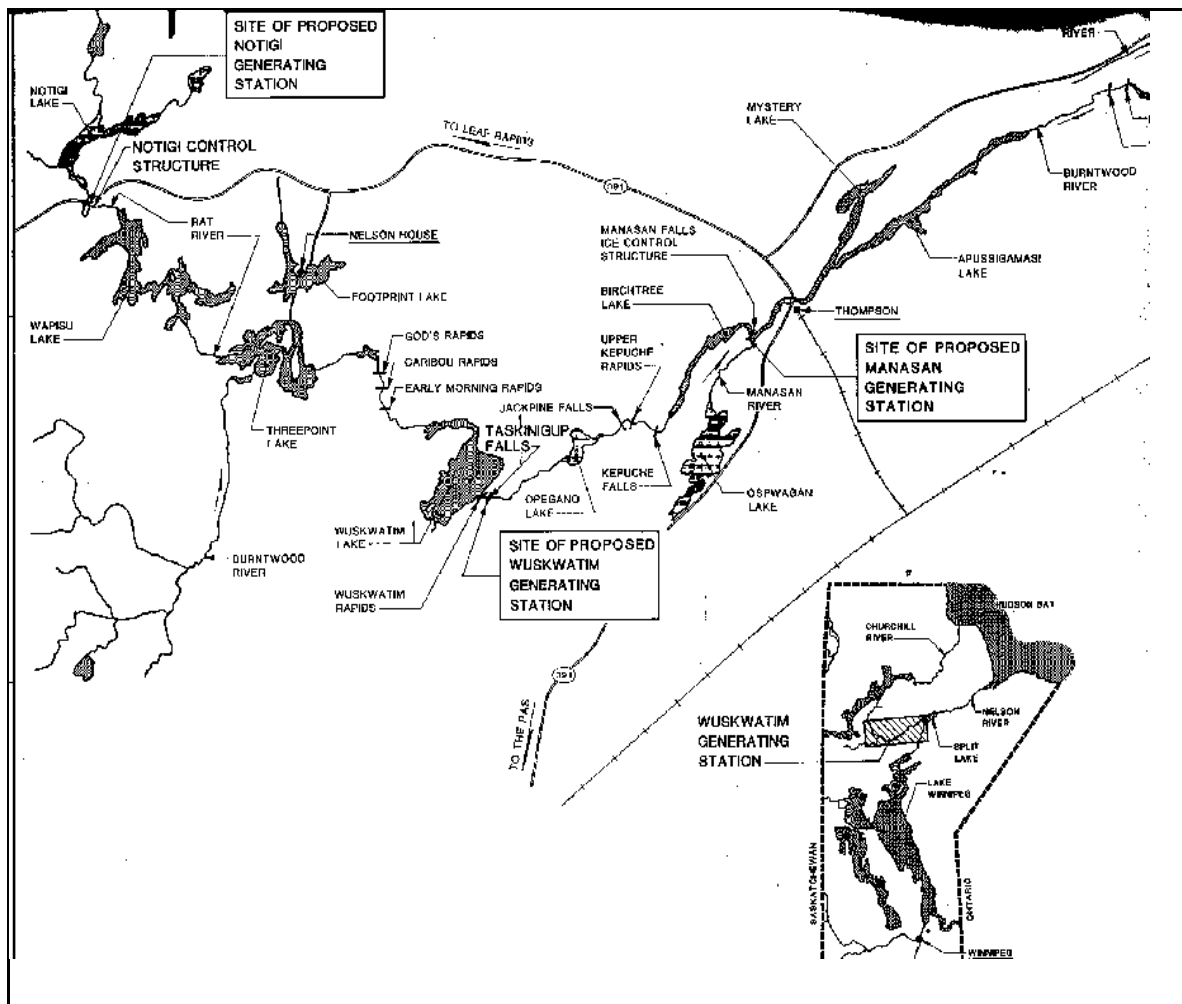
Figure 4.1 Case study area (after Bender, 1996)

4.1.3 Development proponent

Manitoba Hydro is an electric utility in the province of Manitoba. It manages, as a crown corporation of the province, a large system of regulated reservoirs, hydroelectric generating stations, thermal generating stations, transmission links throughout the province, and external

transmission links to Manitoba. Manitoba Hydro operates from its mandate outlined in the Manitoba Hydro Act, which states:

The intent, purpose, and object of this Act is to provide for the continuance of a supply of power adequate for the needs of the province, and to promote economy and efficiency in the generation, distribution, supply, and use of power (Manitoba Hydro, 1989).

Using this Act as a guideline, Manitoba Hydro evaluates the energy needs of Manitoba in terms of consumer demand, and assesses the efficiency in which a reliable supply of energy is supplied. The achievement of Manitoba Hydro's mission, in the fulfillment of the Act, is described as the pursuit of several strategic objectives (Manitoba Hydro, 1989):

1. To provide a safe, adequate, economical and reliable supply of electricity to meet customer requirements.
2. To provide all customers with excellent service with particular focus on individual customer satisfaction.
3. To promote conservation of electricity when it can be achieved more economically than supply.
4. To develop and maintain a workforce with a high level of motivation, productivity and job satisfaction.
5. To improve productivity and quality in all segments of the business on a continuing basis.
6. To be recognized as a good corporate citizen which deals sensitively and fairly with the effects of its activities on communities and individuals.
7. To conduct all corporate activities in accordance with the principles of sustainable development.
8. To assure the Corporation's long-term financial integrity.
9. To secure beneficial extra-provincial agreements.

All activities of Manitoba Hydro may be described in terms of their role in satisfying one or more of these strategic objectives. The scope of this work is primarily concerned with strategic objectives 1,6,7,8, and potentially 9. Strategic objectives 1,8,9 are relatively straightforward to comprehend and pursue. However, objectives 6,7 are extremely subjective. Without stakeholder participation in making choices that affect these objectives, Manitoba

Hydro can only guess whether they made the proper choices before moving through a licensing process.

Manitoba Hydro has prepared 2 initial design alternatives for the Wuskwatim Lake area. One option is to fully develop Wuskwatim with a high dam at Taskinigup Falls. Another option is to develop 2 low head generating stations, one at Taskinigup Falls, the other upstream of Wuskwatim Lake at Early Morning Rapids on the Burntwood River. A final design has not been chosen.

Manitoba Hydro would like to involve various stakeholders in the planning of environmentally sensitive features of development such as:

- Generating station option.
- Reservoir elevation.
- Operating mode for the generating station.
- Forebay clearing.
- Location of the permanent access road to the project site.
- Location of Birchtree station.
- Location of transmission lines.
- Mitigation, compensation, and enhancement programs.
- Monitoring.

4.1.4 Identification of stakeholders

Manitoba Hydro has historically chosen to generate electricity primarily from the flow of water instead of using other sources of power such as nuclear power, or fossil fuels. The province of Manitoba is rich in hydroelectric potential and is sparsely populated in many areas. Some of North America's largest lakes exist in Manitoba. The Nelson River drains a large portion of North America into Hudson's Bay in Manitoba's north. Most of the generating capacity is in northern Manitoba where there are few people and many natural resources. Mining and forestry are the major industries of the region. Many areas are pristine wilderness and many communities have subsistence economies that are dependent on local hunting and fishing. Some generating capacity is already realized in northern Manitoba. A significant project is the Churchill River diversion, which diverts water from the Churchill

River system to existing generating stations in the Nelson River basin. Another proposed project, which will not be built in the near future, is the Conawapa generating station on the Nelson River.

There are several treaties and agreements in place to regulate the development of northern Manitoba water resources for hydropower. The most significant agreement, in terms of relevance for this case study, is the Northern Flood Agreement. It specifies constraints on development, with particular interest in South Indian Lake and the Churchill River diversion through the Rat River and Burntwood River systems to the Nelson River. The Northern Flood Agreement is a contract between the Government of Manitoba, Manitoba Hydro, and First Nations communities in the north. It includes Wuskwatim Lake and areas upstream and downstream of proposed hydro development in the area.

There are many potential planning participants identified as stakeholders for development near Wuskwatim Lake. They include the city of Thompson (downstream of Wuskwatim Lake), Nelson House First Nation (upstream of Wuskwatim Lake), and the Department of Fisheries & Oceans as a regulatory agency for fisheries interests. Any development near Wuskwatim Lake may impact the flow regime, water quality, and many geomorphological characteristics near Thompson. Nelson House may be subject to either direct flooding or increased water levels from backwater effects. Impacts associated with flooding may also affect Nelson House such as erosion and water quality problems.

The Department of Fisheries & Oceans, in an effort to address fisheries concerns, may consider impacts in terms of reservoir habitat, riverine habitat, and fish passage. Reservoir habitat may be altered from previous reservoir habitat and/or created from traditionally riverine habitat. Riverine habitat both upstream and downstream may be impacted. Most changes are assumed to occur downstream of the development site, but altered flow characteristics upstream of the site are caused by backwater effects.

Obstruction to fish migrations, to either upstream or downstream movements, may alter local populations of fish. Some species may disappear, while others may dominate. Changes or disruptions in species composition may alter ecosystem links. Changes in fish population may also impact local commercial and recreational fisheries at Nelson House or Thompson.

4.1.5 Project licensing

There are also outstanding issues to be resolved between Manitoba Hydro and Nelson House First Nation, related to the Churchill diversion project which augments flow past Wuskwatim Lake. This complicates an already complicated procedure for project licensing. Presently, the federal environmental assessment and review process of pursuing development of a hydroelectric generating station can be described in 9 steps (FEARO, 1986):

1. Submission of a proposal, listing potential environmental issues and stakeholders (*a priori* environmental assessment investigations are encouraged and quickly becoming mandatory).

2. Screening of proposals to determine the need to mitigate environmental impacts or to modify the proposal.

3. Further investigation. Projects, which pass screening, may need further clarification of impacts before public hearings.

4. Referral to the Minister of the Environment for panel review.

5. Preparation of an environmental impact statement.

6. Public hearings on the environmental impact statement.

7. Report on proposal impacts and recommendations to address impacts.

8. Publication of report.

9. Licensing decision by the Minister of the Environment.

4.1.6 Integration of GIS tools

In an attempt to avoid conflicts with stakeholders through the project licensing process, a collaborative planning process can be implemented to include relevant participants in the conceptual design stage. Decision support tools to experiment with different technical options can be a powerful visualization and knowledge transfer tool. GIS, as a viable and popular spatial analysis tool, is well suited to be integrated with hydraulic and hydrologic processes.

4.1.7 GIS database

Two digital NTS maps were selected for use in GIS applications (they are 63o09, and 63o10). They are 1:50000 scale UTM grid maps, in zone 14, using the GRS80 ellipsoid. The maps are adjacent to each other. Each map is approximately 30km x 30km. Map 63o10 contains areas upstream of Wuskwatim Lake, but not Notigi control structure or the Nelson House community. It also contains the majority of Wuskwatim Lake and the Rat River release point. Map 63o09 contains a portion of Wuskwatim Lake, and downstream areas of the Rat River, although not as far as Thompson.

A digital elevation model (DEM) has been developed from contour lines, a small set of available point elevation values, and known lake levels for some of the larger lakes. The accuracy of the DEM is not questioned at this point. It is discretized at 1m (vertical scale) intervals for 30m by 30m cell sizes, and is meant to be representative overall.

Other data in the database includes boundaries between land and surface water areas, wetlands, streams, rapids, and roads. A number of structures have also been digitized for possible inclusion in flooding experiments, including both the proposed Wuskwatim and Early Morning generating stations.

4.1.8 Flood inundation visualization

GIS exploration of flooding scenarios is one aspect of visual demonstration that may contribute to improved participation and understanding between various stakeholders.

The task of flood inundation is a complex task if hydraulic behaviour such as backwater effects is taken into account. Unfortunately, the determination of backwater demands a substantial amount of data. Backwaters are usually generated by the standard step method, using cross-section data for each reach. A typical procedure calculates the effect with external models, and simply displays the results using GIS. That procedure works fine for a river basin where the flooding is mainly on the flood plain of the river. For cases where a flood will inundate a variety of areas and land types, the cross-section data requirements become expensive and unmanageable.

For the purpose of visualizing a flooding scenario, especially for a large case study region (over 1000 km^2 in this case), it is relatively simple and straightforward to generate a flood without backwater. The results will not be completely accurate, but will be representative.

To generate a flood, the following procedure is used:

1. Combine the selected hydraulic structures (dams) as bitmap images with the digital elevation model (DEM). Hydraulic structures are treated as an area with a specified elevation.

2. Identify the upstream side of the hydraulic structure.

3. Specify an elevation for flooding.

4. Generate clumps of areas below the flood level.

5. Choose the appropriate clump as the reservoir.

6. Change the DEM and topographic maps appropriately.

A graphical interface has been developed in OpenWindows using SmartElements from Neuron Data to allow experimentation with different flooding scenarios. Structures such as dams or dykes can be added and removed. Reservoir levels can be adjusted. The size of the flooded area, and the added storage volume are also calculated.

4.1.9 Development of alternatives

Generally, the experimental process of developing alternatives is iterative according to the sequence below:

1. Choose technical options (such as dam, reservoir stage).

2. Update model analysis.

3. Present results (save alternative).

4. Return to 1.

Figure 4.2 shows the results of selecting technical options updating the model analysis, and presenting the results for a possible design proposal. The example in Figure 4.2 shows the interactive selection of 1 dam icon and 2 dyke icons on a small picture of the case study area. The selected dam location, Wuskwatim (at Taskinigup falls), is then set to a reservoir stage of 240m by the participants. This simple input defines the basic requirements for a technical

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alternative. Not visible in Figure 4.2 is the alternate approach of selecting from a previously defined list of alternatives (remember Manitoba Hydro already has conceptual designs being considered).
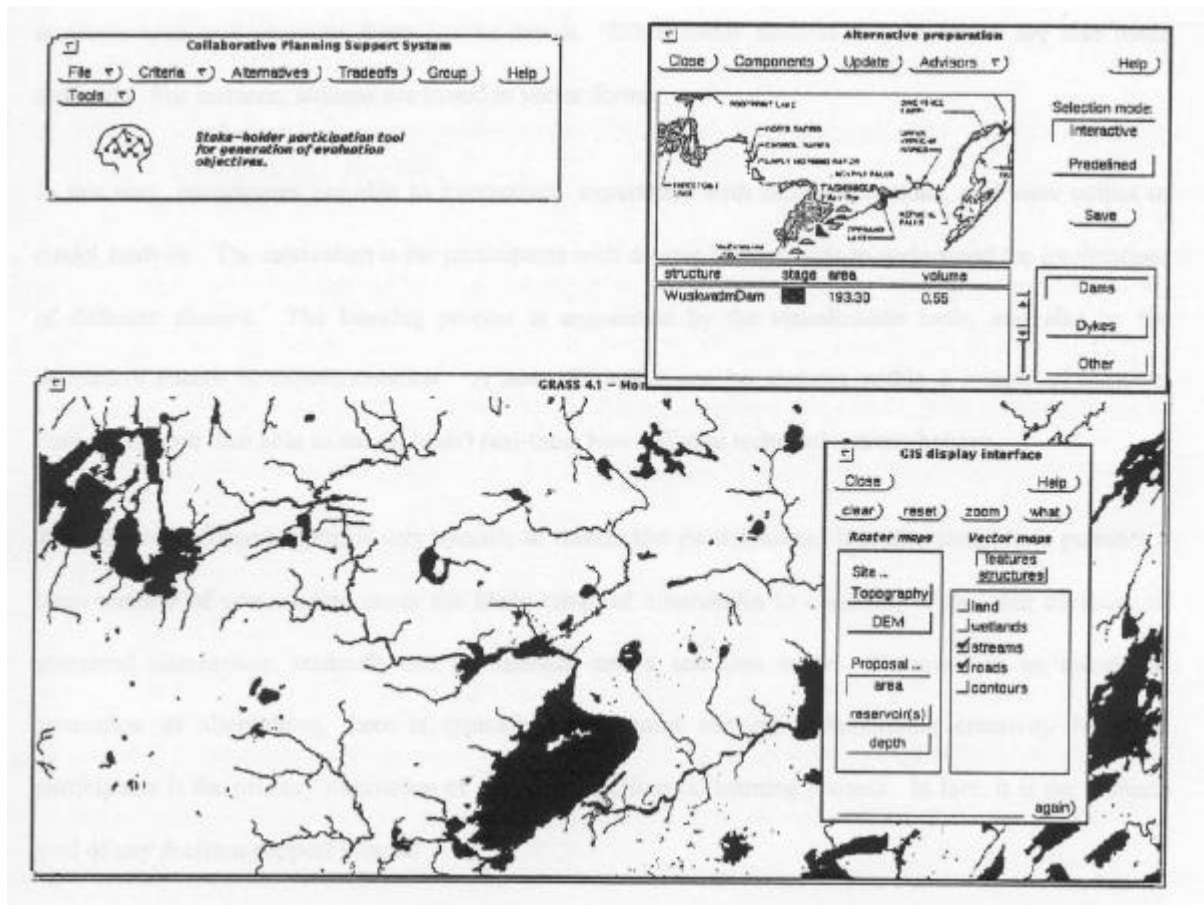
4.2 Example display for alternative generation decision support (after Bender, 1996)

An update (clicking the *Update* button atop the window in the top right corner of the display) triggers the object-oriented database to collect the selected technical options, and submit them to relational database tables. The necessary GIS analysis tools are invoked, providing updates in the form of GIS maps of the flooded region. Other properties are also calculated, such as reservoir area (193.3 km^2) and reservoir volume (0.55 km^3).

The GIS display has also been automated with a custom interface. Original topography or the DEM can be displayed at any time to compare with the current flooded scenario. The new topographic area, the reservoir area, and reservoir depth can be shown. Other vector features and structures are also made available. For instance, streams are stored in vector format.

In this way, participants are able to interactively experiment with technical options, and view output of model analysis. The motivation is for participants with diverse backgrounds to understand the implications of different choices. The learning process is augmented by the visualization tools, and also by the interactive nature of experimentation. A new alternative can be updated within a couple of minutes. Participants are then able to see, in (near) real-time, how different technical options behave.

The form of decision support is very specific to stakeholder participation. It is also possible to generate a large number of scenarios to cover the likely range of alternatives to consider. From that database of generated alternatives, tradeoffs can be assessed and a selection made. However, in an automated generation of alternatives, there is typically one element missing. Facilitating creativity from the participants is the primary motivation of using an experimental learning process. In fact, it is the ultimate goal of any decision support system.

The selection of technical options shown in this example in no way reflects the position of Manitoba Hydro. Manitoba Hydro is interested in the creative contribution of stakeholders. Predefined alternatives may be under consideration, but they have not been presented in any detail in this description.

4.1.10 Application of expert systems

4.1.10.1 Expert systems

Expert systems are a branch of the artificial intelligence community that specializes in the mundane task of encoding experience and processes for making decisions. Knowledge is encoded in Boolean logic and accessed by searching mechanisms called inference engines. Five phases in expert system design are: identification, conceptualization, formalization, implementation, and testing. Describing expert systems this way tends to cloud the essence of expert system application. Most computer programs can handle the IF-THEN-ELSE architecture that expert systems use to encode knowledge. The unique advantage is derived by the inferencing capabilities of expert systems. Two types are used: backward and forward chaining. Backward chaining searches for information if it is required while forward chaining is directed to the relevant information. In general, backward chaining uses IF statements as search mechanisms, and forward chaining acts on THEN statements. The unique power that

backward chaining brings to expert systems is the modularity in knowledge dissemination. Each rule in a knowledge base may be given a very specific scope and aspect of a knowledge domain, and does not need to address its place in the broader problem scope. Consistency in language is necessary for the expert system to function.

The use of expert systems in describing operating policies for reservoirs and other water management problems is an approach that easily adapts to system simulation and experimentation of decision rules. Simonovic (1991) outlines general areas of application applicable to expert system technologies. One example is the use of interest satisfaction relationships, defined within an expert system, to describe regulatory decision-making on Lake Ontario (Eberhardt, 1994). An expert system application for a water resource design problem for fish passage can be found in Bender *et al* (1992). Like many design problems, rules of thumb are popular for facilitating choices. Fish passage is no exception. Bender *et al* (1992) encodes rules of thumb within the Boolean architecture, and integrates the knowledge, in the typical expert system manner, with both backward and forward inferencing mechanisms. Other examples of expert systems in water management problems can be found in Simonovic and Savic (1989), and Simonovic (1992). Applications for environmental screening of alternatives have also used expert systems. An example is Fedra *et al* (1991).

4.1.10.2 *Prototype expert system for choosing the design of a hydroelectric generating station*

As an example expert system (ES), a prototype hydropower development construction planning expert system has been developed. The hydropower construction ES encodes some basic hydropower design engineering experience at Manitoba Hydro, from a cooperative expert: Per Stokke, P.Eng. The purpose of the ES is to suggest a technical option such as a dam, along with its various components such as reservoir and powerhouse, and provide expert advice as to the type of dam and potential improvements that might be required such as water energy dissipation requirements, reservoir operating policy, and water intake positioning.

If a dam is to be created, an object is created within the Dam class, inheriting all the properties and behaviour associated with a dam. In turn, four components are also created as sub objects to the dam. They are:

- Reservoir

- Spillway

- Powerhouse

- Release

Each of these sub objects is in turn attached to relevant classes. For example, the spillway belongs to a class of objects called *Spillways*. The new spillway, in turn, inherits the properties and behaviour associated with spillways. In this way, an object-oriented model is built to describe the relationships between the dam and its surroundings. Other, nonstructural objects can also be associated with the dam.

4.1.10.3 Knowledge base

The rule base of the expert system attempts to specify many of the design elements of the dam. For instance, a dam may be earth fill or rock fill if an embankment type of dam is chosen. An example rule is:

IF   the dam is an embankment type AND

        site excavation rock is not available AND

        a site borrow area is easily accessible

THEN design the dam as earth filled

WHY   earth fill cost is low due to accessibility, compared to quarrying rock

In order to assign "earth fill" to the embankment type of dam, however, we must ensure that embankment is chosen or at least feasible. Backward chaining is used by the inference engine to search for rules to assign the dam to the embankment class of dams, such as the following:

IF   there are no frost concerns AND

        the experience of the planners has been with embankment dams AND

        the cost of earth fill (borrow material) is low

THEN recommend an embankment type of dam

WHY   embankment dams are feasible (cost of earth fill) and preferred

Other rules are used to determine the relative cost of earth or rock fill for embankment dams. Likewise, rules attempt to determine properties and design requirements for the dam sub objects (*reservoir*, *release*, *spillway*, *powerhouse*), for instance:

IF   the experience of planners has been with either/both overflow and orifice spillways AND

the potential siltation in the reservoir is not high

THEN recommend an overflow type of spillway

WHY experience has been with overflow spillways, and flushing of sediment is not a factor

IF   the available hydraulic head to the powerhouse is less than 25m

THEN recommend a close couple type of powerhouse

WHY close couple systems work well for low head stations

IF   the available hydraulic head to the powerhouse is less than 15m AND

the powerhouse turbine unit capacity is less than 65MW

THEN recommend a bulb turbine design

WHY both head and turbine capacity are relatively low

Figure 4.3 shows the results of a consultation with the expert system through the Collaborative Planning Support System (CPSS) interface. There are two active windows. The left window displays the recommended properties for design of the dam and hydroelectric generating station. Radio buttons provide access to properties of the different aspects of design. The right window is the *Session Control* window. Relevant questions are posed by the expert system. Subsequent recommendations are documented to the left in the *Property Display* window. Figures 4.3 and 4.4 show some of the recommendations for design based on an example consultation.
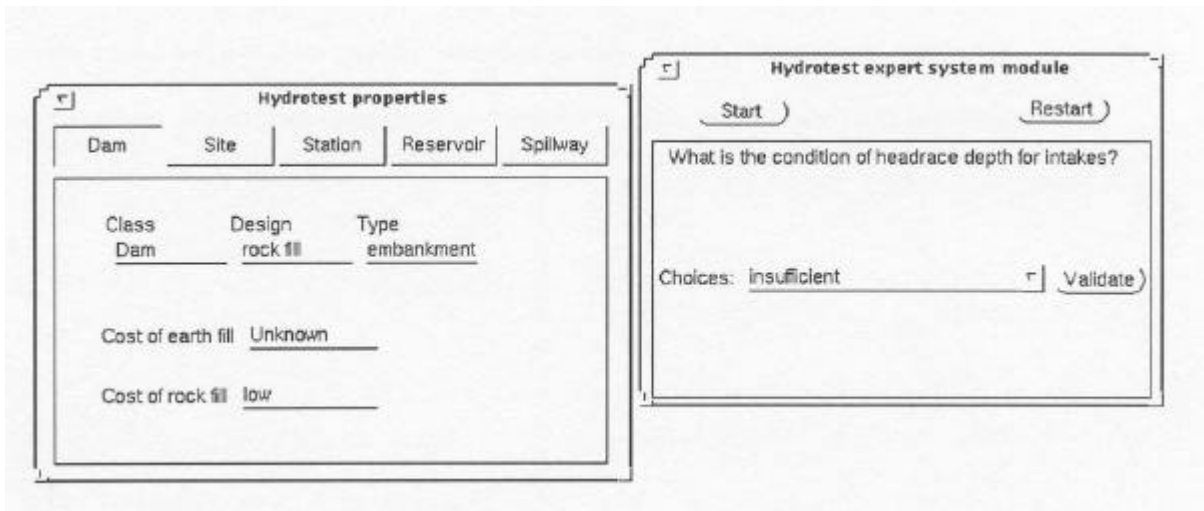
Figure 4.3 Expert system module interface (after Bender, 1996)
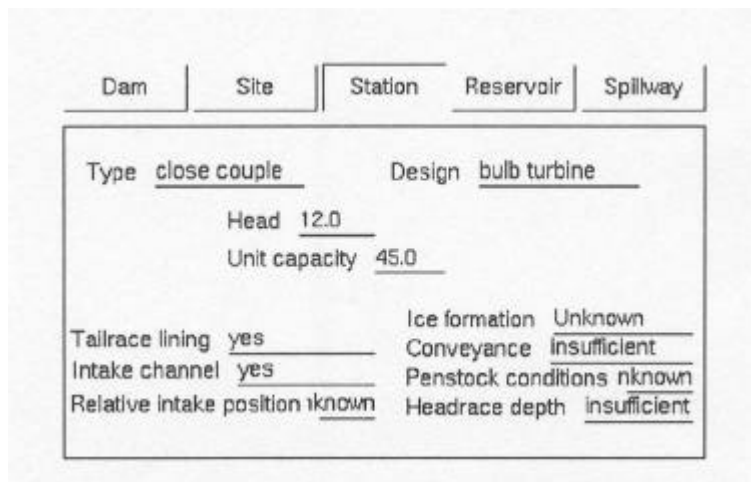
Figure 4.4 Example recommendation for a generating station design (after Bender, 1996)

The hydropower construction expert system provides an example for the type of experience, which can be provided by expert systems within a DSS. It is a sample utility, available for the specific (conceptual) design of technical options. Expert systems do not replace experience, but provide consistency and accessibility to knowledge. They may also provide decision-making participants with the tools to generate realistic alternatives without being experts in multiple disciplines.

4.1.11 Summary

The decision support system, dubbed a Collaborative Planning Support System, demonstrates the possible implementation of integrated support for planning sustainable water resources

systems alleviating conflicts. It shows the potentials of the integration of tools such as GIS and ES within a collaborative group-planning framework in better decision- making. By exploring development alternatives using online support from GIS and ES, users of the CPSS are able to experiment and visualize marginal differences between different technical options. Its' decision-making process is iterative, and experimental and is driven by different forms of feedback of the stakeholders/participants in the process.

4.2 International water conflicts: Danube River application

The Danube river basin has an area of 817,000 km2 and includes to a larger extent the territories of thirteen riparian countries. In addition, it collects the runoff from small catchments located in four other countries. Thus the Danube, although neither the longest nor the largest river in Europe, is the most international river of Europe. The main water uses are domestic water supply, irrigation, hydropower generation and navigation. More than 40 large dams and barrages have been constructed on the main river and its tributaries, utilizing the hydropower potential. Further, several hundred smaller reservoirs have been built along the tributaries to serve for irrigation.

Due to major political and economic changes in Central and Eastern Europe, the Danubian countries asked for support to implement accepted environmental standards and to establish a new institutional structure. The main environmental problems refer to surface water quality, riverine ecosystems and nutrient load into the Black Sea.

In the last decades several bilateral agreements between neighbouring riparian countries have been signed, while a few international agreements are nearly finalized. The objective of the Environmental Programme for the Danube River Basin (EPDRB) together with the Strategic Action Plan (SAP) is to improve the environmental state, especially water quality, in the basin. The programme is designed to assist the treaty, which is already agreed upon among the riparian countries.

A drafting group composed of experts from the World Bank, United Nations Development Programme (UNDP), the Programme Coordination Unit (PCU), and four participating Danube countries (Romania, Bulgaria, Hungary and Austria) developed the Strategic Action Plan (SAP). An intensive consultation process ensured that the viewpoints and objectives of the riparian countries were properly considered. The joint goals for environmental management were defined as sustainable and equitable water management, the preservation of unique habitats and wetlands with emphasis on the Danube Delta, the control of hazardous and toxic spills, and enhanced regional co-operation. To achieve these goals a Task Force supervising the activities of the drafting group and the Environmental Programme was

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established. A detailed action plan, including a list of hot spots, was prepared in order to improve water quality.

To improve collaboration and harmonize water management, the countries agreed on general principles and criteria for formulating strategies and establishing a priority list of implementation measures. Also, nonstructural measures, such as institutional strengthening and capacity building, were emphasized. These measures were considered important for countries that had newly established legislation and administrative structures.

Funding for entire programme is to be covered by the Danube nations themselves, with support from international sources provided only for selected projects.

In recent implementation of the Convention, the EPDRB and the SAP did not prevent conflict, the roots of which date back to the time before these joint activities were initiated. One example of an unresolved conflict is that over a hydropower plant located on the border between Hungary and Slovakia. Although jointly started and planned, the different political developments in the respective countries resulted in different preferences and objectives. To date, no solution could be obtained, and this case is currently before the International Court of Justice in de Hague.

Hydropower development is of great economical value for some Danube countries and it has also some additional effects such as flood protection and improved navigation. Nevertheless, adverse environmental effects can be observed. Thus, no solution exists which simultaneously satisfies all objectives related to economic development and environmental preservation. Nachtnebel (1997) presented a methodology that could be used to assist in conflict resolution among different interest groups; either among interests within a society or between two different states with distinct preference structures. The methodology is based on techniques related to compromise programming. The compromise solution is identified in two steps. First, a ranking is performed for each country and then an alternative is identified that is as close as possible to the countries' favoured alternatives. A generalized distance measure was introduced to define the distance between individual solutions for each country and the compromise solution. In addition, an overall viewpoint is also considered, whereby the project impacts are assessed without considering the national borders. The water conflict

resolution procedure summarized above is explained in detail below as presented by Nachtnebel (1997).

4.2.1 Identification of goals for the section of the Danube studied in this work

The main goals of water-related development involve support of navigation, utilization of hydropower potential, preservation of water resources for domestic requirements and environmental preservation because of the unique characteristics of the flood plain area. Subsequently, these goals are specified and criteria are developed to quantify the goals.

4.2.1.1 Hydropower

Governmental statements in both countries underlined the importance of hydropower utilization but simultaneously in country 2, some environmental groups asked for planning steps to establish a national park in the flood plain area of Danube.

Goals related to power generation and energy management are included in energy reports issued regularly by the ministries of the countries and in international studies (Equipe Cousteau, 1993; Kovacs, 1986; IUCN, 1994). The principles of governmental energy and environmental policies include the following set of guidelines:

- reduction of primary energy consumption,
- increased utilization of renewable resources, especially of hydropower,
- minimization of environmental impacts related to power generation and consumption.

4.2.1.2 Navigation

The Danube section from Braila (170 km) to Kehlheim, FRG (2414,7 km) is classified as category IV according to the European Waterways Standards (Fekete, 1990; Danube Commission, 1988). This requires a minimal depth of 2.50 m and a width of 40-180 m for navigation in un-impounded sections. In impounded sections, the minimal prescribed depth is 3.5 m. For the respective stretch of the Danube, the recommendations of the Danube Commission indicate a minimum depth of 2.5 m and a width of 150 m. During low flow periods, several fords with a depth of 2 m or less restrict economical navigation, and frequent dredging works are required to maintain the waterway. All the Danube countries have adopted these recommendations and their governments declared it an important goal to

guarantee at least the minimal requirements for navigation throughout the year. Recent programs and recommendations (ECE, 1994) even propose a navigable depth of 3.2 m for international European waterways.

4.2.1.3 Drinking water supply

One of the goals of the regional water management is the protection of the extended alluvial aquifers bordering the Danube. This resource partly serves the regional drinking water supply, including some villages in the vicinity of the Danube. In this context, the emphasis is also on the protection of springs, which are supplied from a karstic aquifer located close to the Danube. It is worth noting that 80-95% of the domestic water requirements in the basin are covered by groundwater.

4.2.1.4 Environmental preservation

In 1978 and 1979, major areas of the flood plain forests were legally protected. Due to the unique ecological characteristics o this area, planning activities were initiated in the last years to delimit a natural preserve worthy of becoming a national park. Obviously, the preservation of the flood plain forests and of the riparian wetlands constitutes an important objective for this region.

4.2.1.5 Social objective

The social objective refers to satisfying drinking water requirements, increasing employment opportunities, and increasing facilities for water-related recreation. The increase of employment opportunities is important for both countries, especially the creation of long-term jobs.

4.2.2 Definition of criteria

Hydropower development as a critical environmental intervention will be considered in the context of sustainable development. Sustainable water resources development aims to identify economically attractive, technically feasible, socially acceptable and ecologically sound water resources projects that will "meet the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). This raises the questions regarding the kinds of tools and methodologies available that can consider these

four key issues simultaneously in the planning process. Although it has become evident that multiple criterion decision making, risk analysis, and conflict resolution techniques are appropriate tools for this purpose (Hartman, 1986; Higler, 1986; Loucks, 1994; Haimes, 1994; Nachtnebel *et al*, 1994), the specific elements for identifying sustainable water resources projects were unknown, particularly to the engineering practice. Evidently, acceptable levels of high reversibility, low risk and high equity are the conditions necessary for the development of sustainable water resources.

Reversibility can be measured by the degree to which an engineered natural resource system such as a contaminated groundwater system can be remedied to its original, un-engineered state. It may take a long time and considerable effort to clean up a contaminated aquifer; thus, the reversibility level of the original groundwater development would be quite low. Here, reversibility is expressed by the degree to which specific habitats are preserved. Flood plain forests require at least one hundred to two hundred years to develop their typical plant composition and spatial pattern. Specifically, the preservation of river morphology and flood plain forests and the diversity of fauna species are used as indicators of reversibility.

Risk can be defined as possible adverse consequences of uncertainties facing water resources development. Risk occurs when planning criteria such as economic benefits or reversibility in the planning horizon of water resources development are estimated with a certain degree of uncertainty. Various types, such as economic, social or ecological risks should be defined and then combined to select sustainable water resource alternatives under minimum risk. Risk is not considered explicitly in this paper but it is obvious that any major loss in typical habitats would increase the probability of irreversible changes in the riverine ecosystem. Many ed-list species, already endangered by extinction, are found to only in the remaining flood plain forests. Therefore, the preservation of species can be seen as a risk-reducing objective, which might be achieved by natural protection of large areas of the river corridor.

Equity can be defined as the degree of fair distribution of benefits and losses among various parties influenced by water resources development, or it can refer to perception of long-term impacts. The latter, for instance, refers to equity between present and future generations or equity among social parties that have quite different preference structure. Here in this paper,

equity is seen as the outcome of a trade-off procedure between two different countries and simultaneously between ecological and economical interests within each country.

A list of criteria for characterizing the economically, ecologically and socially - related goals in the context of sustainable water resources development given Nachtnebel (1997) are presented in Table 4.1. These criteria are one of the outcomes of an expert work group's analysis of a hydropower conflict at a national level.

The two countries share a joint resource but have different preferences. To support a comparison of the two evaluation procedures, the set of criteria given in Table is used for both countries. The 33 criteria (C_i) are grouped with respect to sub goals such as preservation of aquatic habitats or preservation of riverine flood plain forests. The sub goals (SO_k) express targets of either economic or ecological objectives, named O_1 and O_2. Given this information an impact assessment study can be carried out independently for each country. A certain number of points (or a sum of weights) are assigned to the various sub goals to consider the different number of criteria for the goals and to avoid any artificially introduced bias in the preferences. A balanced preference structure would be reflected by the allocation of an identical number of points or weights to different objectives, for example, economical development and ecological preservation. The aggregated weights are given in Table 4.2, reflecting the different preference structure of the two involved countries, and someone in an independent position, such as a referee, completes the table.

Table 4.1 Goals, criteria and units (after Nachtnebel, 1997)

Goals	Sub goals	Criteria	Units
Maximization of Economical utilization ATS of resources	Maximize power generation Minimize costs	Annual power output Investment costs Maintenance costs	GWh Mrd Ordinal
Increase social welfare	Increase of employment rate Increase of recreational opportunities Improved navigation Protection of the medicinal spring	Create jobs during construction Recreational facilities Duration of restricted navigation risk	Man-years Ordinal Days/yr ordinal
Preservation of the specific ecosystem in this region	Preservation of the flood plain forest Preservation of typical Faunistic populations Preservation of the morphometric variability of riverbanks Improvement of water quality Preservation of the groundwater system	Losses due to construction Area of initial vegetation Losses of inundated area Area of flood plain forests Forest edges Timber galleries Impact on water fowl Impact on other populations Compatibility with national park requirements Ratio of impoundment to km Free flowing section Length of remaining riverbanks Length of water-bank line at low flows Length of water bank line at mean discharge Shallow water zone at low flows Shallow water zone at mean discharge Gravel banks at low flows Gravel banks at mean discharge Connectivity between mean river and oxbows Rate of degradation of the river bed Saprobic scale Change in groundwater quality Length of impervious dams Area with changes in the mean groundwater table (>0.5m) Area with changes in the groundwater dynamics (0.5-1.0m) Area with change in the groundwater dynamics (>1m)	ha ha % ha km km ordinal ordinal ordinal km km km km km ha ha ha ha number ordinal ordinal ordinal km qkm qkm qkm

Table 4.2 Countries' preferences expressed by the weights of the main objectives (after Nachtnebel, 1997)

Participant	Economy	Ecology
Country 1	140	60
Country 2	80	120
Referee	100	100

4.2.3 Multicriteria approach for group decision making

Here, a sequential evaluation procedure based on composite programming (Bardossy and Duckstein, 1992) is applied to rank the alternatives. First, each country assesses and evaluates the impacts with respect to its preference structure, elaborates a plan evaluation table, and achieves a ranking of alternatives. If both countries would rank the same alternative as the best one then there would be no conflict among countries. Otherwise, in a second step, the alternatives that are as close as possible to both favoured alternatives can be seen as compromise solutions for the parties in conflict. These identified alternatives needn't be non-dominated solutions. The multicriterion approach, which is applied for each country, tries to identify compromise solutions by a simultaneous trade-off at several levels. At the beginning, as in many other multicriterion techniques, the elements of plan impact matrix (C_{ij}), which express the output of alternative A_j with respect to criterion c_i, are scaled to obtain the plan evaluation matrix (x_{ij}).

$$x_{ij} = \left(c_{i,best} - c_{ij}\right)/\left(c_{i,best} - c_{i,worst}\right) \tag{4.1}$$

The performance indicators x_{ij} are allocated to sub goals SO_k, which reflect instance the preservation of aquatic habitats, which are in turn allocated to economy and ecology related objectives O_1 and O_2. Compromise programming identifies solutions by a simultaneous tradeoff at the level of performance indicators, sub goals and main objectives, expressed by a distance measure or Lp-norm. Considering alternatives j the outputs are obtained for each level by,

$$L_j(P_k) = SO_{jk} = \left(\sum_i w_j \left(x_{ij}\right)^p_k\right)^{1/p} k \qquad I \in \{G_k\} \tag{4.2}$$

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$$w_k = \sum_i w \qquad with \sum w_i = 1 \qquad\qquad (4.3)$$

$$L_j(Q_1) = O_{11} = \left(\sum_k w_k (SO_{jk})^{qi} \right)^{1/qi} \qquad k \in \{H_m\} \qquad (4.4)$$

$$w_1 = \sum_k w_k \qquad\qquad (4.5)$$

$$L_j(r) = O_{j=} \left(\sum_{1=i}^{2} w_1 (O_{j1})^r \right)^{\frac{1}{r}} \qquad\qquad (4.6)$$

Where the set $\{G_k\}$ defines the binary relationship between criterions I and sub goal SO_k and respectively the set $\{H_m\}$ describes the binary relationship between the sub goals and the two main objectives. Here, $\{H_m\}$ consists of two sets, namely an economy related objective with the sub goals 1-4, as given in Table 2. The ranking from a country's perspective is achieved simply by arranging the values of the L(r)-norm in ascending order. The preferred alternative is obtained by

$$Min\{L_j(r)\} = Min\{O_j\} = O* \qquad\qquad (4.7)$$

The distance Dj of alternative j from O* is expressed by

$$D_j = \left(\sum w_1 |O_{j1} - O_1*|^r \right)^{\frac{1}{r}} \qquad\qquad (4.8)$$

Considering the two countries, the final goal is to select an alternative that minimizes the generalized distance measure

$$L_j(s) = \sum_{1=i}^{2} \left({}_1w_1 |{}_1O_{j1} - {}_1O_j*|^s + {}_2w_1 |{}_2O_{j1} - {}_2O_1*|^s \right)^{\frac{1}{s}} \qquad (4.9)$$

${}_1O_1^{\#}$ components of the preferred alternative in country 1

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$_2 O_1^{\#}$ components of the preferred alternative in country 2

Where the prefix index refers to the country. Weights are assumed to be equal for the countries.

This approach is supplemented by an evaluation of the alternatives from an overall viewpoint, irrespective of any national preferences. The project impacts are integrated and assuming equal weights for the two main objectives, the methodology is repeated by applying equations 1-8.

The metric of distance measure L(.) is defined by the exponent (.), which is here either p_k, q_1, r or s. Assuming a value of one would imply that losses in one performance indicator $x_{i,j}$ can be compensated by high performance levels in another indicator $x_{i,j}$. As the value of the exponent increases, the lower performance levels define the distance L(.) and for (.) = ∞ the worst outcome defines the distance. In other words, the exchange among different performance indicators decreases as the exponent (.) increases.
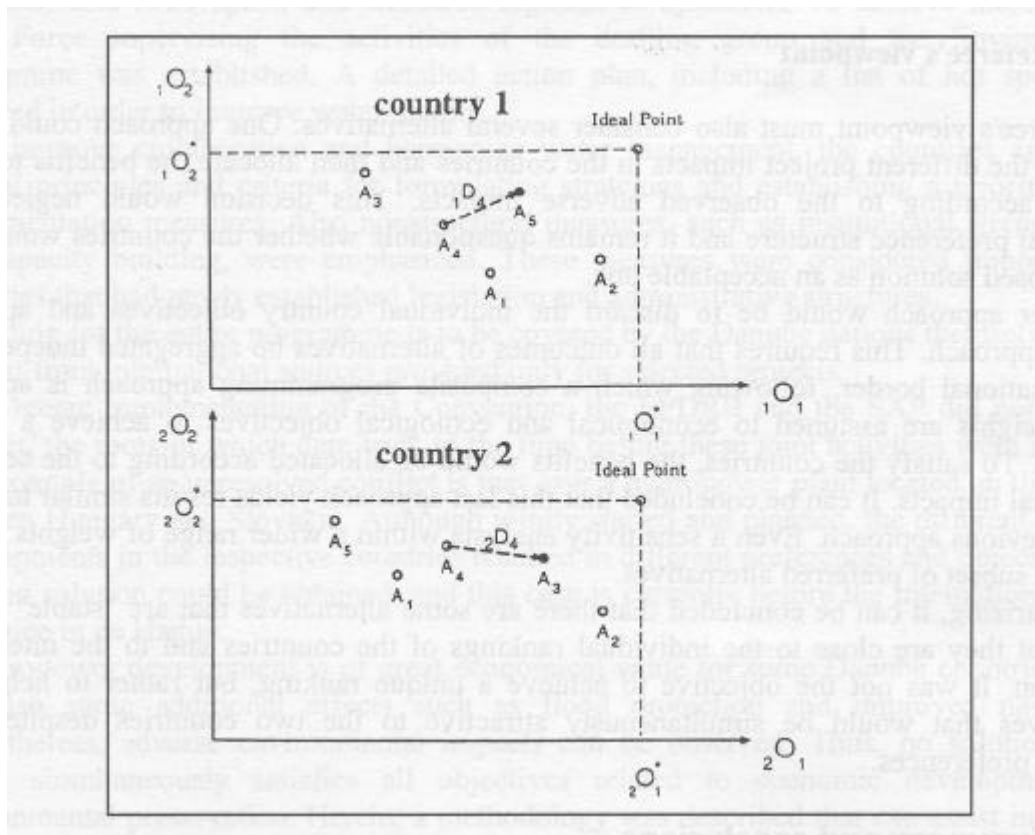
Figure 4.5   Schematic representation of the performance of the alternatives within a bi-objective framework for both countries (after Nachtnebel, 1997)

4.2.4 Conflict resolution among the countries

Now the goal is to identify an alternative that is acceptable to both countries. Such an alternative should be as close as possible to both of the individually preferred alternatives. The two distances have to be expressed according to the national preference structure.

$$_1L_j(s) = {}_1D_J = \sum_{1=i}^{2} \left({}_1w_1 \left| {}_1O_{j1} - {}_1O_1 * \right|^s \right)^{\frac{1}{s}} \tag{4.10}$$

$$_2L_j(s) = {}_2D_J = \sum_{1=i}^{2} \left({}_2w_1 \left| {}_2O_{j1} - {}_2O_1 * \right|^s \right)^{\frac{1}{s}} \tag{4.11}$$

$$L_j(s) = \left({}_1D_j{}^s + {}_2D_j{}^s \right)^{1/s} \tag{4.12}$$

The above given distance can be understood as a generalized distance because it expresses the L(.)-norm in a non-orthogonal system.

4.2.5 Referee's viewpoint

The referee's viewpoint must also consider several alternatives. One approach could be to compare the different project impacts in the countries and then allocate the benefits to each country according to the observed adverse impacts. This decision would neglect the individual preference structure and it remains questionable whether the countries would see the proposed solution as an acceptable one.

Another approach would be to discard the individual country objectives and apply a unified approach. This requires that all outcomes of alternatives be aggregated independent of any national border, following which a composite programming approach is applied. Equal weights are assigned to economical and ecological objectives to achieve a sound trade-off. To satisfy the countries, the benefits would be allocated according to the severity of national impacts. It can be concluded that this last approach yields results similar to those of the previous approach. Even a sensitivity analysis within a wider range of weights yields the same subset of preferred alternatives.

Summarizing, it can be concluded that there are some alternatives that are "stable" in the sense that they are close to the individual rankings of the countries and to the integrated evaluation. It was not the objective to achieve a unique ranking, but rather to help find alternatives that would be simultaneously attractive to the two countries despite their different preferences.

Nachtnebel (1997) stated that the main result of the application is in the selection of a reduced set of alternatives, which satisfies to a large extent the expectations of both countries. Both the overall approach and the compromise approach between the countries yield similar results. This reduced set of alternatives would provide a basis for a more focused discussion and negotiation process. The disadvantage is in the somewhat arbitrary definition of distance and in the possibility that dominated solutions might be obtained.

4.3 Resolution of Water Conflicts between Canada and the United States

4.3.1 Introduction

There have been no wars between Canada and the United States of America (USA) since the War of 1812-14, when invading forces failed to wrest control of Upper and Lower Canada from Great Britain. For more than a century, citizens of these two friendly neighbors have been proud to proclaim that they share the world's longest unguarded border, stretching almost 5000 km across the middle of North America from the Atlantic to the Pacific. The peaceful status of this border is in part a result of certain well-conceived treaties that encourage cooperation and minimize frictions. For example, Canada, the USA, and Mexico have formed NAFTA, the North American Free Trade Association, to regulate trade among the three countries and resolve trade disputes.

Among the agreements between Canada and the USA, the greatest jewel may well be the Boundary Waters Treaty of 1909. Under this treaty, the International Joint Commission (IJC) was established to study and recommend on water allocation, water quality, and other environmental problems that cross the Canada-US border. The IJC's numerous recommendations on the solution of complex water and environmental problems, have been remarkably free from bias. The Boundary Waters Treaty constitutes an excellent model for other countries considering international agreements about shared water resources.

Hipel *et al* (2002) used the Graph Model for Conflict Resolution, a comprehensive approach to conflict analysis, to illustrate the strategic aspects of international water conflicts. The decision support system GMCR II facilitates the application. The conflict to be analyzed is a multi-party water dispute that concerned development along the Flathead River, which crosses from British Columbia into Montana. The elements of the graph model, and the design of GMCR II, are outlined. Subsequently, the Flathead River conflict is described and then systematically modeled and analyzed using GMCR II. As demonstrated using this example, water disputes can be resolved fairly and equitably within the purview of the Boundary Waters Treaty.

4.3.2 The Graph Model for conflict resolution and GMCR II

In a graph model of a conflict (Fang *et al*, 1993), the decision-makers (DMs) and the possible states of the conflict are specified, along with the state transitions controlled by each DM. A graph model also includes each DM's ordinal ranking of all possible states as resolutions of the conflict.

When a graph model is analyzed, each state is assessed for stability from the point of view of each DM. A state is stable for a DM if that DM would choose not to depart from it, should it arise. Solution concepts are models of the DM's thinking processes in deciding what would be the likely outcome of a move away from a given state. Note that a state may be stable under some solution concepts but not others. Of course, different DMs may have different solution concepts. A state that all DMs find stable is equilibrium, and constitutes a possible resolution of the conflict model. The value of the graph model as an analysis tool for negotiation problems was demonstrated by Kilgour *et al* (1995, 1996).

In Table 4.3, different solution concepts imply different levels of foresight, or measure a DM's ability to consider possible moves that could take place in the future. A DM with high foresight thinks further ahead. Nash stability (R) has low foresight, and the level of the foresight increases from low at the top to high at the bottom. Nonmyopic stability (NM) has the highest foresight and limited-move stability (L_h) has variable foresight level given by the parameter h. Some solution concepts, such as L_h and NM, allow strategic disimprovements, which occur when a DM (temporarily) moves to a worse state in order to reach a more preferred state eventually; other solution concepts, such as R and sequential stability (SEQ), never allow disimprovements; still others, general metarationality (GMR) and symmetric metarationality (GMR) permit strategic disimprovements by opponents only. Different solution concepts also imply different levels of preference knowledge. Under R, GMR and SMR, a DM need only know its own preferences, while a DM must know the preference information for all DMs for solution concepts SEQ, L_h and NM.

Table 4.3 Solution concepts and human behavior (after Hipel *et al,* 2002)

Solution Concepts	**Stability Description**
Nash stability (R)	DM cannot unilaterally move to a more preferred state.
General metarationality (GMR)	All DM's unilateral improvements are sanctioned by subsequent unilateral moves by others.
Symmetric metarationality (SMR)	All DM's unilateral improvements are still sanctioned even after a possible response by the original DM.
Sequential stability (SEQ)	All of the DM's unilateral improvements are sanctioned by subsequent unilateral improvements by others.
Limit-move stability (L_h)	All DMs are assumed to act optimally and (h) a fixed number of state transitions are specified.
Nonmyopic stability (NM)	Limiting case of limited-move stability as the number of state transitions increases to infinity.

The decision support system GMCR II implements the Graph Model for Conflict Resolution within a Windows environment (GMCR II, 2000; Hipel *et al*, 1997b). The structure of GMCR II is shown in Figure 4.6.

The modeling subsystem of GMCR II allows users to enter conflict models conveniently and expeditiously. Users input DMs and options, patterns of infeasible states, allowable transitions and preference information. Then GMCR II will generate the required input for stability analysis, including

- Feasible states,
- Allowable state transitions, and
- Ranking of states from most to least preferred, allowing ties, for each DM.
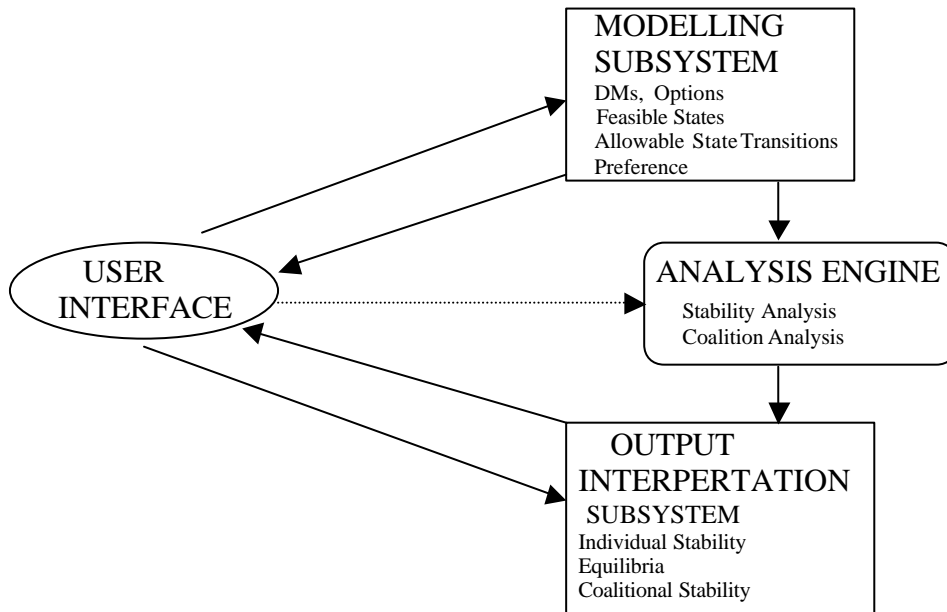
Figure 4.6 GMCR II structure (after Hipel *et al*, 2002)

Based on the information generated at modeling stage, the analysis engine performs a thorough stability analysis on the conflict model. The analysis engine can produce a large amount of output data, including the stability results for every state, and for each DM, under the wide variety of solution concepts listed in Table 4.3.

The output interpretation subsystem presents the results from the analysis engine in a user-friendly manner. Information about individual stability, equilibria, and coalition stability is easily identified and compared.

4.3.3 Case study: Flathead River conflict

The Flathead River flows from the southeastern part of the Canadian province of British Columbia into the US state of Montana, then into Flathead Lake, and eventually into the Columbia River, which flows into the Pacific Ocean. In 1910, coal was discovered in the Flathead valley in British Columbia. Sage Creek Coal Limited was formed in 1970 to develop this area. After Sage Creek finished its first stage development plan, British Columbia granted an approval-in-principle for Stage II of the Sage Creek's proposal in February 1984.

Understandably, the governments of the USA and Montana were concerned about the potential effects of Sage Creek's proposed mine on the Flathead River system, Glacier National Park, and Flathead Lake. In response to these concerns, the US and Canadian governments requested that the IJC examine the possible impacts of the proposed mine on water quality and quantity, fisheries, and other water uses associated with the Flathead River, and make recommendations.

Under the Boundary Waters Treaty, the IJC is composed of three members from Canada and three members from the USA. When called upon to make a recommendation, the IJC summons experts from both countries across a range of disciplines to form a Board to thoroughly study the situation and arrive at an unbiased and sound set of recommendations. Based upon the Board's report, the IJC then puts forward a summary of the study and final recommendations to the two federal governments. IJC reports regarding the Flathead River Conflict are available from its Ottawa and Washington offices (International Joint Commission, 1988a, b).

4.3.4 Modeling: Putting the problem into perspective

GMCR II can be systematically employed for modeling the Flathead River Conflict (Hipel *et al*, 2002). The main components required for constructing a conflict model are listed under the Input Data Subsystem in Figure 4.6. Below, the Flathead River Conflict is modeled for the point in time just before the IJC made its recommendations in December 1988.

The Flathead River conflict was studied using an earlier version of GMCR by Hipel *et al* (1997a). Here, a somewhat different model of the conflict is developed and more detailed modeling and analytical results are presented and explained.

4.3.4.1 Decision makers and options
  a. *Sage Creek Coal Limited (Sage Creek).* Sage Creek Coal Limited was the developer of the proposed mine. As of 1988, Sage Creek already had substantial financial and other commitments to the Flathead River Development project. Therefore, Sage Creek hoped that the IJC could recommend the continuation of the development proposal, which

would encourage the provincial government of British Columbia to issue a full Stage II license.

b. *Province of British Columbia (BC).* The provincial government could issue the license for the mining on its own but it had to consider the potential environmental impact assessment. In addition, pressure from the federal government of Canada and from the USA also had to be taken into account.

c. *State of Montana (Montana).* The Montana government worried about the potential pollution and environmental degradation that might be caused by the proposed mining development. Environmental groups and the US Department of the Interior agreed fully with the Montana State government on this issue.

d. *International Joint Commission (IJC).* The IJC appointed the Flathead River International Study Board to examine the Flathead problem (IJC, 1988a), and based upon the Board's findings made its recommendations to the governments of Canada and the USA (IJC, 1988b).

Other DMs, such as the federal governments of Canada and the USA, were not considered in this model because they were not directly involved in the dispute at this stage. In addition, environmental groups from both the USA and Canada were included with Montana as a single DM because they had similar viewpoints.

The DMs and their options are displayed in Table 4.4. As of December 1988, Sage Creek could *continue* the original project, *modify* it to reduce environmental impacts, or stop it by not selecting either the option to *continue* or to *modify*. The provincial government of British Columbia (BC) could issue a license to support the *original* development, or a project with suitable *modification*, or it could force Sage Creek to stop its development by not granting any license. Montana could continue to *oppose* any development or withdraw its opposition by not *opposing*. The IJC could recommend either the *original,* or a *modification*, or *no* project at all.

In Table 4.4, a "Y" opposite to an option indicates "Yes" the option is selected by the DM controlling it, whereas an "N" corresponds to "No", the option is not taken. A *strategy* for a given DM is any feasible combination of its options. For example, in the state shown in

Table 4.4, BC is selecting the option "Original" and rejecting the option "Modification". Similar explanations can be applied to the other three DMs in Table 4.4.

Table 4.4   The decision makers and options of the Flathead River conflict (after Hipel *et al,* 2002)

DMs and Options	Status Quo		
Sage Creek			
1. Continue: *Continue* original development	Y	⎫	Strategy for
2. Modify: *Modify* to reduce environmental impacts	N	⎭	Sage Creek
BC			
3. Original: Support *original* project	Y	⎫	Strategy for
4. Modification: Require *modification*	N	⎭	BC
Montana			
5. Oppose: *Oppose* any development	Y	⎬	Strategy for Montana
IJC			
6. Original: Recommend *original* project	N	⎫	Strategy for
7. Modification: Recommend *modification*	N	⎬	IJC
8. No: Recommend *no* project	N	⎭	

A *state* is formed when each DM selects a *strategy*. As an example, Table 4.4 shows the status quo state existing in 1988. Written horizontally in text, the status quo state (YN YN Y NNN) is created by Sage Creek, BC, Montana, and the IJC following strategies (YN), (YN), (Y), and (NNN), respectively.

In GMCR II, users go to the main menu "Conflict" to enter the description of the conflict model. Under this menu, users can input the title of the conflict, the date of analysis for the model, and a brief introduction of the conflict. Then they input information about DMs and their options by going to "Modeling -> States -> Generate Possible …". A pop-up window appears to guide users adding the DMs and their corresponding options in the form of "full title" and "short title".

4.3.4.2 Feasible states

In the Flathead conflict model, there are 8 options in total. Because each option can be either selected or rejected, $2^8 = 256$ states are mathematically possible. However, many of these states are infeasible in the real world, for a variety of reasons. For example, the two options controlled by Sage Creek are mutually exclusive because Sage Creek cannot continue the original project and simultaneously modify it. The options controlled individually by BC and the IJC are also mutually exclusive. In some cases, some option combinations can occur only if another pattern of options is selected. In the Flathead conflict model, Sage Creek's decision must conform to the license issued by the BC government. If BC refuses to issue any license, Sage Creek will have to stop its project. In addition, because the IJC is mandated to conduct an independent investigation, it must make its own recommendation to this end.

In GMCR II, four types of infeasibilities are available to specify infeasible patterns: "Mutually Exclusive Options," "At Least One Option," "Option Dependence," and "Direct Specification." Users go to "Modeling -> States -> Remove Infeasible…" to specify the three types of infeasibilities in the Flathead conflict model. Figures 4.7 - 4.9 display the infeasible patterns using GMCR II screens. Figure 4.7 indicates that the DMs Sage Creek, BC and IJC can only choose at most one option from the set of options each DM controls. Figure 4.8 gives two cases of necessary conditions in the lower box for the upper patterns to occur. The first condition states that Sage Creek can proceed with its original project only if BC issues a full license, whereas the second pattern implies the IJC must come up with a recommendation except for the status quo situation when the IJC is still carrying out its study of the problem. Figure 4.9 directly specifies the infeasible pattern "2&(-3&-4)", which means that Sage Creek cannot proceed with any development plan unless BC issues a license to support either the original or modified proposal. In the direct specification window, "&" means "and," "-" stands for "not," and the numbers are option numbers. After removing all infeasible states, 37 feasible states remain; they are listed in Figures 4.10a and 4.10b.

4.3.4.3 Allowable state transitions

After a recommendation is made, it is impossible for the IJC to change its mind and support another option that it controls. Therefore, it is reasonable to assume that movement with respect to Options 6, 7 and 8 is one way — only transitions from "N" to "Y" are allowable. Figure 4.11 shows how to define these one-way transitions for the IJC in GMCR II, using the

menu "Modeling -> Transitions -> Single Option Based." Double-clicking on the default two-way arrows changes their directions.

4.3.4.4 Relative preference ranking

Before carrying out a stability analysis, GMCR II requires that the feasible states be ranked from most to least preferred for each DM, where ties are allowed. GMCR II possesses two flexible approaches, called Option Weighting and Option Prioritization, for conveniently specifying preference information in terms of options for each DM. An internal algorithm then automatically orders the states for the DM based upon this preference information. Option Weighting allows users to assign a number or numerical weight to each of the options from the viewpoint of each DM, where a positive or negative number means the DM likes or does not like the option, and the magnitude of the number reflects the degree of preference. Option Prioritization provides an intuitive specification based on preference statements listed from most important at the top to least important at the bottom. In addition to these two means to specify the ranking of feasible states for each DM, GMCR II also allows users to fine-tune the preference ranking by directly re-ordering states, joining two or more states into an equally preferred group, and splitting an equally preferred group apart. Option Prioritization along with Direct Ranking is employed to come up with the preference ranking for the DMs in the Flathead River Conflict. Table 4.5 lists the preference statements using option numbers in order of priority for each DM.

Table 4.5 Preference statements for the decision makers (after Hipel *et al,* 2002)

Sage Creek	BC	Montana	IJC
1	3 IF 6	-1	6|7|8
2	4 IF 7	-2	
3	-3&-4 IF 8	8	
4	6	-6	
6	7	-7	
7	-5	-3	
-5	3	-4	
-8	4	5 IF 1	
	1	5 IF 2	
	2	-5	

Both conditional and unconditional preference statements are acceptable in GMCR II, and two types of conditions, "IF" and "IFF (if and only if)", are permitted. The symbols "-", "&", and "|" represent "not," "and," and "or, " respectively. From Table 4.5, one can easily interpret the preference statements given in order of priority from the top of the column to the bottom for each DM. The option number 1 given at the top of the left column indicates that Sage Creek most prefers to proceed with its original proposal. As indicated by the option number 2 written below the 1, Sage Creek's next preference is a modified project. In order of decreasing preference, Sage Creek would like to see BC approve the original project (option 3), BC ratify the modification (option 4), the IJC recommend the original project (option 6), and the IJC select the modification (option 7). The least important preferences for Sage Creek are that Montana does not oppose the project (-5) and the IJC recommends no project (-8).

The second column from the left lists BC's preference statements. As can be seen, BC most prefers supporting the original project (option 3) if the IJC recommends it (option 6). Next, BC prefers to recommend the modification (option 4) if the IJC recommends it (option 7). The third preference statement from the top means that BC prefers not to support the original project (-3) and the modified one (-4) if the IJC recommends no project (8). Hence, the first three preference statements for BC mean that BC wants to follow whatever the IJC recommends. In decreasing order of preference the remaining preference statements in the second column mean that BC would prefer IJC recommending the original project (6), IJC choosing the modified project (7), no opposition from Montana (-5), BC supporting the original project (3), BC a modification (4), Sage Creek continuing with the original development (1) and Sage Creek building a modified one (2).

The preference statements for Montana can also be easily interpreted from the prioritized list given in the third column in Table 4.5. As can be seen, Montana most prefers that Sage Creek not build the original development (-1). Finally, the IJC prefers to recommend the original project, a modified one, or no project (6|7|8). The IJC must make an unbiased recommendation, which is modeled by equal preference for each possible recommendation.

In order to invoke the preference ranking windows, one can click "Modeling -> Preference …." Then the window in Figure 4.12 pops up to prompt the user to select preference eliciting methods and the DM whose viewpoint is to be described.

Figure 4.13 shows how to input the preference statements for BC. The default statement type is unconditional. To specify a conditional statement, users can pull down the arrow to select "IF" or "IFF" from the list. After all preference statements are entered, GMCR II will generate the resulting preference ranking. The screen is similar to that of Figure 4.10 except that the order of the states reflects the preference statements. At this stage, direct ranking permits users to fine-tune the preference ranking over the states.

Following the procedures in Figures 4.12 and 4.13, users select different DMs and separately enter each one's preferences from Table 4.5. Table 4.6 displays the preference ranking of states from most preferred at the top to least preferred at the bottom for each DM, where the numbers represent states. For the IJC, the states bracketed are equally preferred, which would be highlighted in a single color on the screen.

4.3.5 Analysis and results: Deciding what to do

In a stability analysis, GMCR II calculates the stability of every feasible state for each DM for all of the solution concepts listed in Table 4.3. If a state is stable according to a given solution concept, for all DMs, it constitutes an equilibrium under that solution concept. It is therefore a compromise resolution, since no DM has an incentive to unilaterally move away from it. By going to "Analysis -> Run," the equilibria list in Figure 4.14 is derived. (The acronyms for the solution concepts are as in Table 4.3).

Figure 4.14 indicates that states 10, 22, 25, 26, and 34 are equilibria for all solution concepts. Among these equilibria, states 10, 25, and 26 correspond to the three possible recommendations from the IJC. In these cases, the BC government tries to alleviate the potential pressure from both the USA and Canadian federal governments by conforming to the IJC's recommendations. However, if the BC government becomes more aggressive and focuses only on its own economic benefits, states 22 and 34 are more likely to occur, whereby the IJC recommends a partial project or no project at all, but BC insists on its original approval-in-principle for the full project. Moreover, at these equilibria, Sage Creek always takes the same strategy as BC. This behavior pattern also demonstrates that Sage Creek is ready to develop a plan as big as the license that BC allows.

Table 4.6 Preference ranking for DMs (after Hipel *et al*, 2002)

Sage Creek	BC	Montana	IJC
4	4	26	19
10	5	32	2
16	3	30	3
22	10	36	4
28	11	27	5
1	9	33	6
34	19	14	7
5	18	20	8
11	25	18	9
17	24	24	10
23	26	15	11
29	1	21	12
35	32	2	13
7	28	8	14
13	29	6	15
19	27	12	16
25	31	3	17
31	30	9	18
37	34	37	37
3	35	31	20
9	33	35	21
15	37	29	22
21	36	25	23
27	16	19	24
33	17	23	25
6	15	17	26
12	14	13	27
18	22	7	28
24	23	11	29
30	21	5	30
36	20	34	31
2	7	28	32
8	6	1	33
14	2	22	34
20	13	16	35
26	12	10	36
32	8	4	1

Historically, state 26 was the final outcome of the Flathead River conflict. The IJC recommended stopping the project, and the BC government cancelled its original approval for the full project, and Sage Creek was forced to abort its development. Subsequently, Montana withdrew its opposition petition. Reading from left to right, Table 4.7 shows the sequence of state transitions from the status quo state 1 to the final equilibrium state 26, where arrows indicate the location and direction of option changes during the evolution of the conflict. Table 4.7 also points out that if BC were aggressive enough, it would be very likely that the state transition process would have been stuck at equilibrium 34. In addition, state transition from 34 to 32 involves both DMs BC and Sage Creek, which means that the cancellation of the license from BC forced Sage Creek to stop its project.

Table 4.7 State transitions from status quo to final outcome (after Hipel *et al,* 2002)

Sage Creek			
Continue	Y	Y → N	N
Modify	N	N N	N
BC			
Original	Y	Y → N	N
Modification	N	N N	N
Montana			
Oppose	Y	Y	Y → N
IJC			
Original	N	N N	N
Modification	N	N N	N
No	N → Y	Y	Y
State Numbers	1	34 32	26

Coalition analysis, which investigates the potential gain for two or more DMs through their cooperation with each other, is also programmed into GMCR II. In the above stability analysis, a state is an equilibrium if no individual DM has the incentive to move away from it unilaterally. However, if the possibility of coalition among two or more DMs is considered, a group of DMs might have both the motivation and ability to depart from an equilibrium so

that they can arrive at a more preferred equilibrium for each DM in this group. If this possibility exists, the equilibrium from which the group moves to a more preferred one is deemed to be coalitionally unstable.

Clicking on the box beside "Coalition Stability" in Figure 4.14 causes GMCR II to distinguish the coalitionally stable equilibria by displaying them in different colors. In this particular model, all equilibria are coalitionally stable. However, if we remove the restrictions on the allowable transitions for the IJC in Figure 4.11, the strong equilibria are the same five states, 10, 22, 25, 26 and 34, but only state 34 of the five equilibria is coalitionally stable. As an example, one can look at the potential coalition at the historical outcome state 26. If the IJC changes its position from recommending no project to supporting a modified proposal, BC issues a partial license, and Sage Creek therefore proceeds with a reduced development plan, this coalition will lead the conflict to state 19. State 19 is more preferred than state 26 for BC and Sage Creek, and equally preferred for the IJC. However, this coalition would hurt Montana because state 19 is much less preferred than state 26 for Montana.

4.3.6 Conclusions

GMCR II presented by Hipel *et al* (2002) is a flexible and efficient decision support tool for investigating strategic conflicts. Such conflicts inevitably arise in a host of river basin management problems such as water pollution, water allocation, and water conservation. For a transboundary water problem between Canada and the USA, the IJC is often called upon by the two governments under the Boundary Waters Treaty of 1909 to thoroughly study the conflict and make recommendations. As demonstrated by the Flathead River international water resource dispute described in the previous sections, GMCR II can provide practitioners with decision advice, structural insights and a deeper understanding of the conflict under consideration. With this enhanced understanding, practitioners can better understand the strategic relationship among the DMs, which can enable analysts to seize the opportunity to direct the conflict to a more favorable resolution.
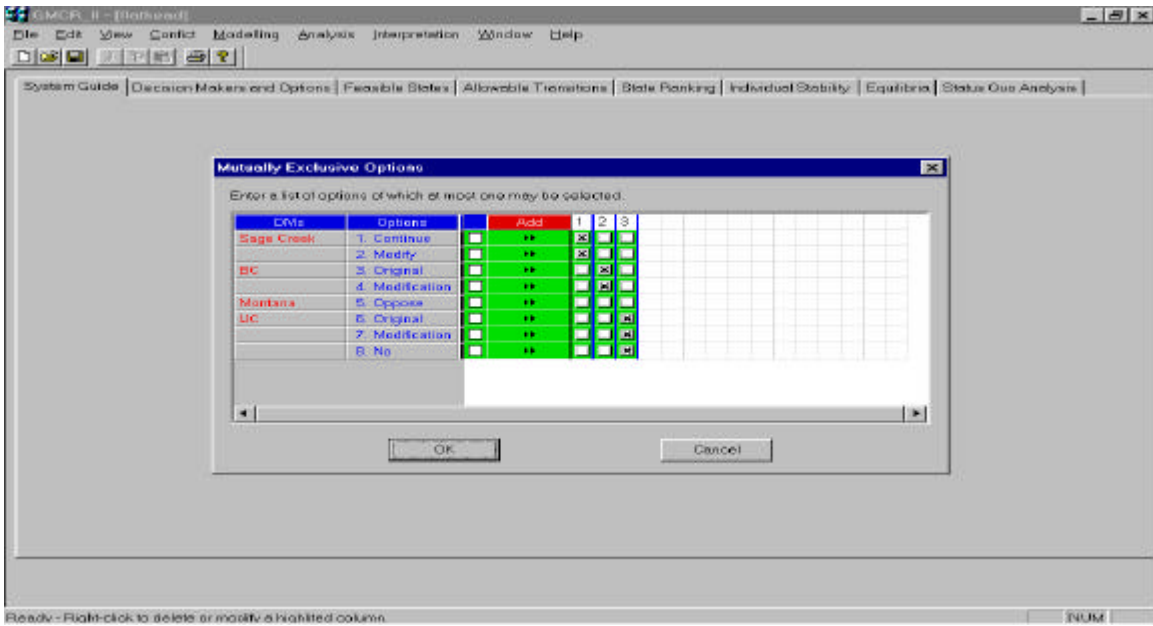
Figure 4.7 Mutually Exclusive Options (after Hipel *et al*, 2002)
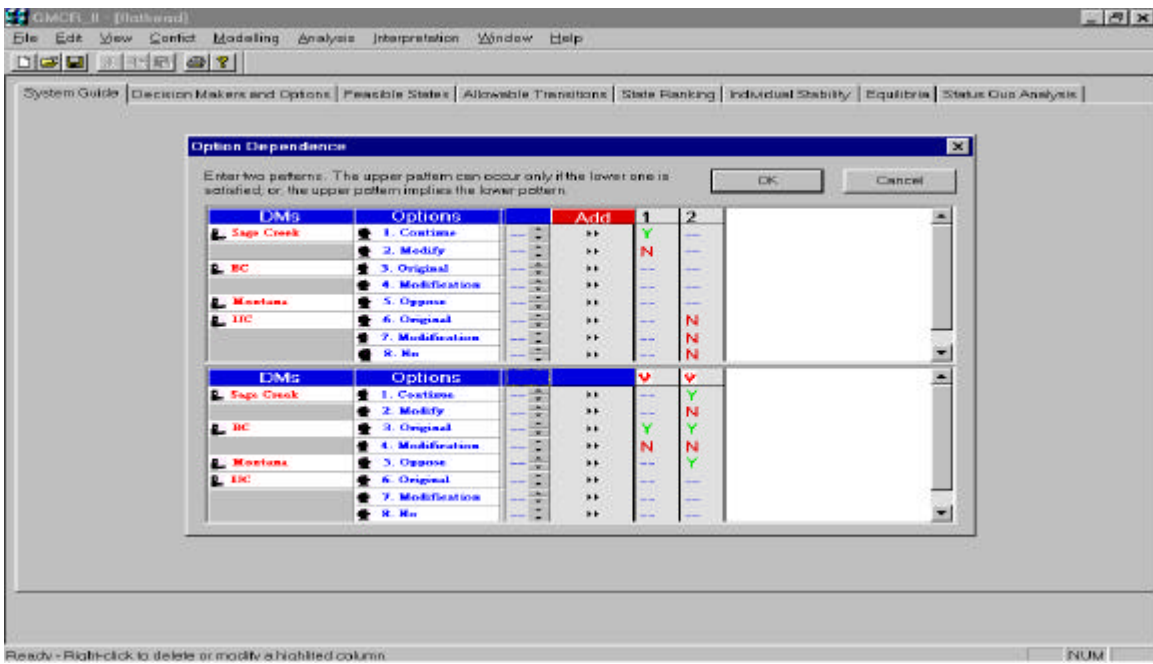
Figure 4.8 Option Dependence (after Hipel *et al*, 2002)
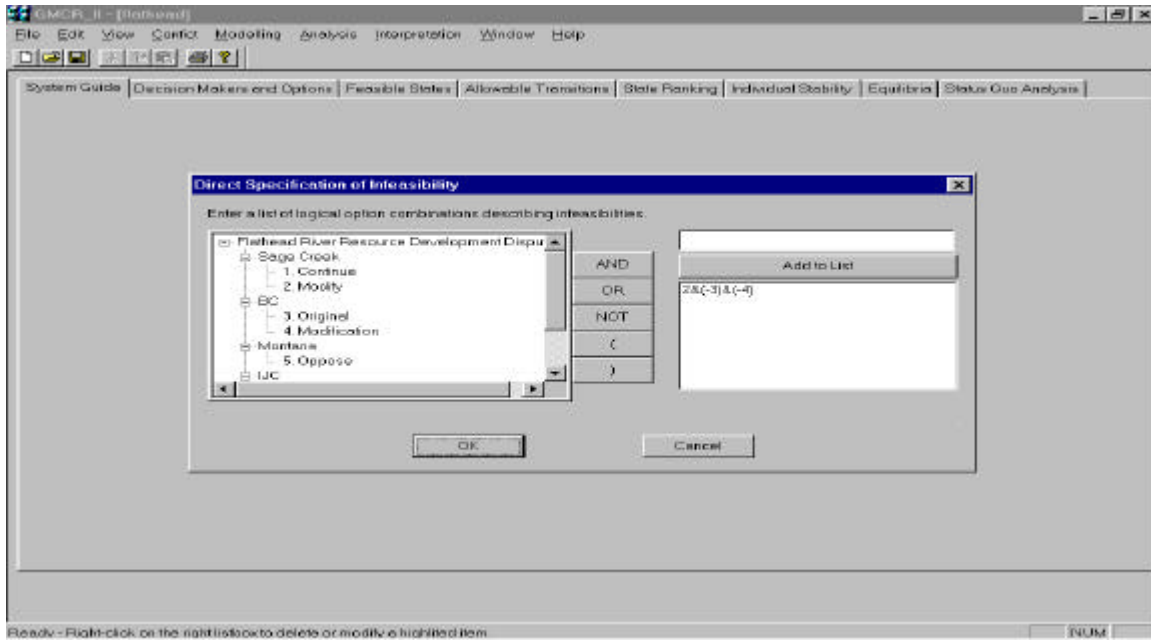
Figure 4.9 Direct specification (after Hipel *et al*, 2002)

Figure 4.10a Feasible States (#1-#19) (after Hipel *et al*, 2002)
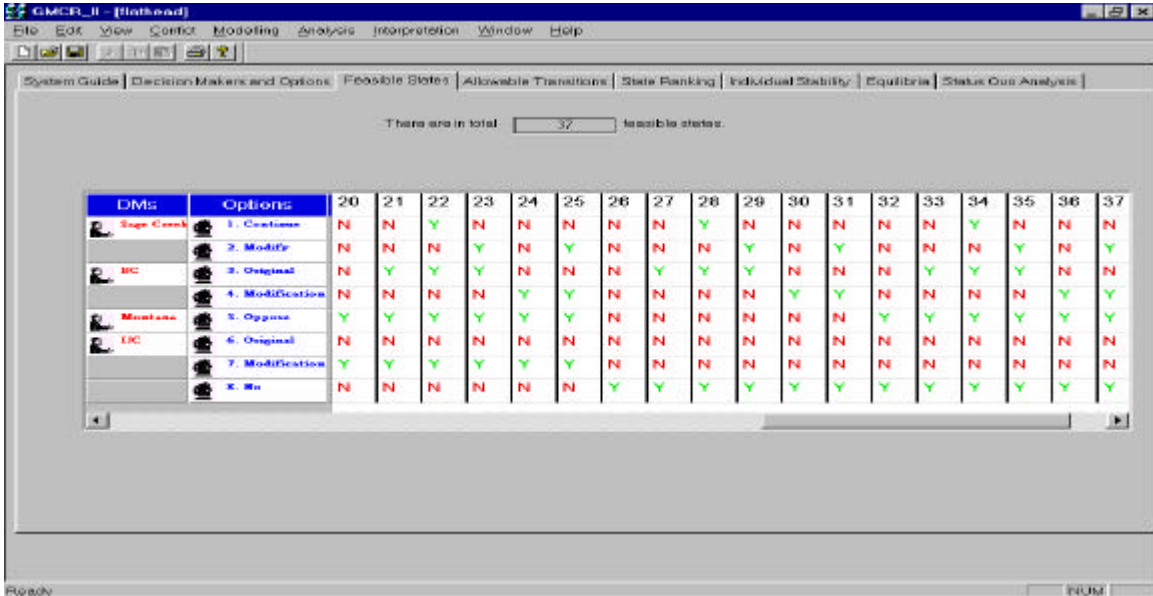
Figure 4.10b Feasible States (#20-#37) (after Hipel *et al*, 2002)
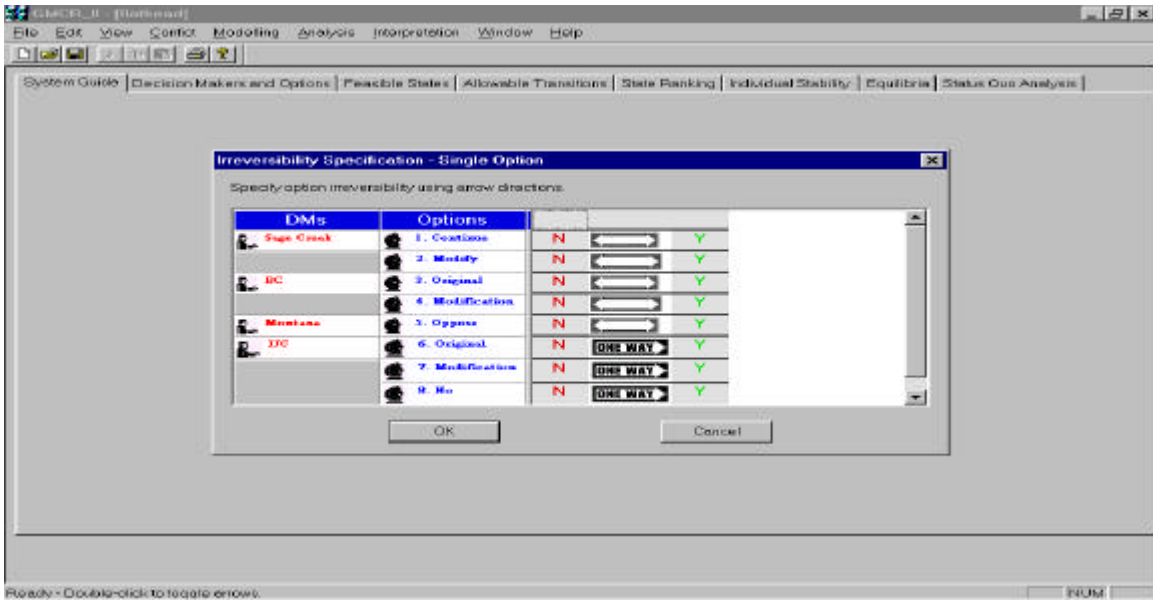
Figure 4.11 Allowable Transitions for the IJC (after Hipel *et al*, 2002)
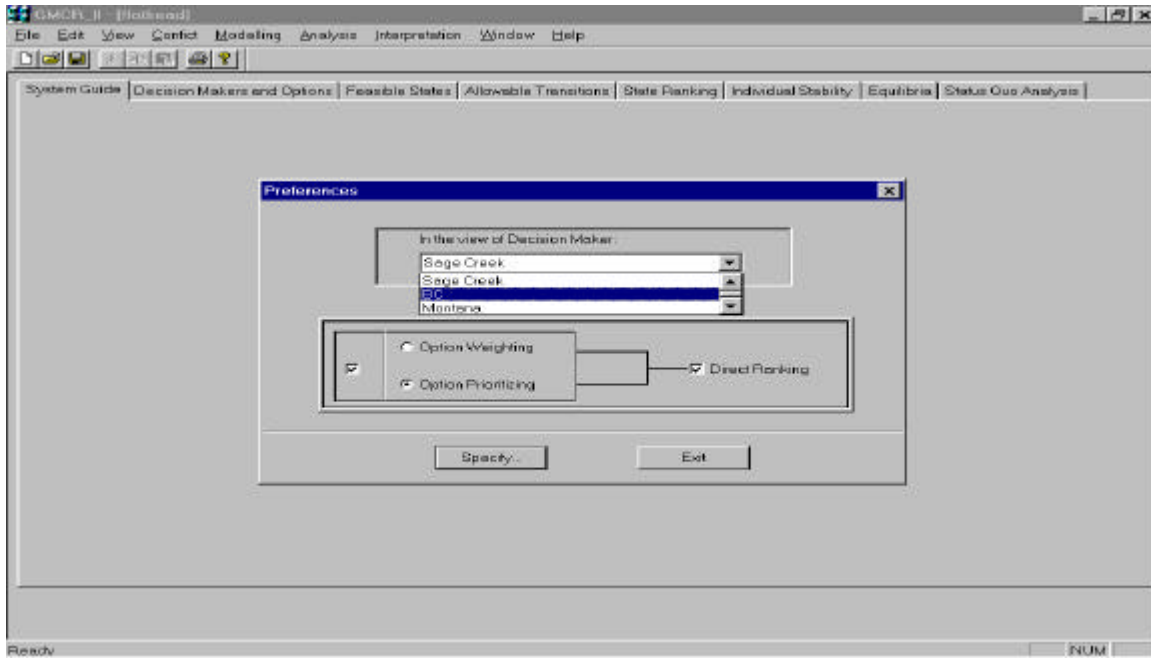
Figure 4.12 Preference Ranking Methods (after Hipel *et al*, 2002)
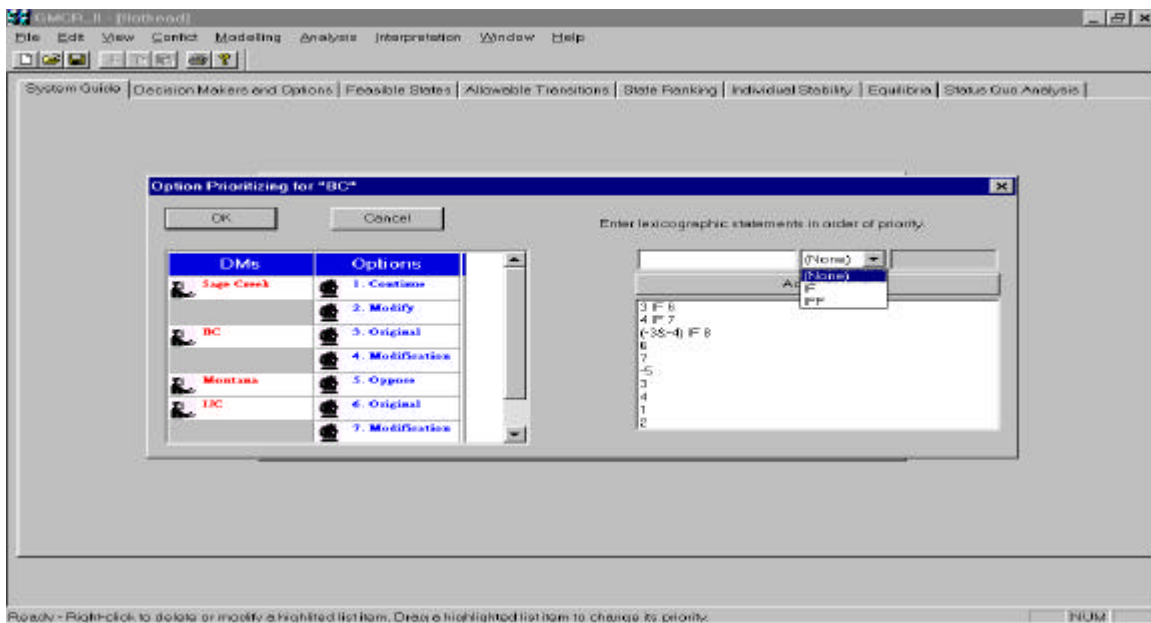
Figure 4.13 Preference Statements for BC (after Hipel *et al*, 2002)

Figure 4.14 Equilibria List for Flathead River Conflict (after Hipel *et al*, 2002)

4.4 Aral Sea Basin - Conflicts

4.4.1 Aral Sea basin

The Aral Sea Basin is located in the heart of the Eurasian continent, at the crossroads of ancient routes from Europe to Asia and from the Middle East to the Far East. It is shared by five countries of the Former Soviet Union as shown in Figure 4.15 (southern Kazakhstan, southern Kyrgyz Republic, most of Turkmenistan, and all of Tajikstan and Uzbekistan, which together account for 86.6% of the basin), Afghanistan, Iran and China. Its total extent is about 1.79×10^6 km^2, largely in the catchments of two major rivers that flow to the Aral Sea: those of the Amu Darya (0.95×10^6 km^2 or 53% of the basin) and Syr Darya (0.45×10^6 km^2 or 25%). The balance (0.39×10^6 km^2 or 22%) is shared by catchments of rivers that disappear in the desert sands, including the Zerafshan, Kashkdarya, Kafirnigan, Murgab and Tejen.
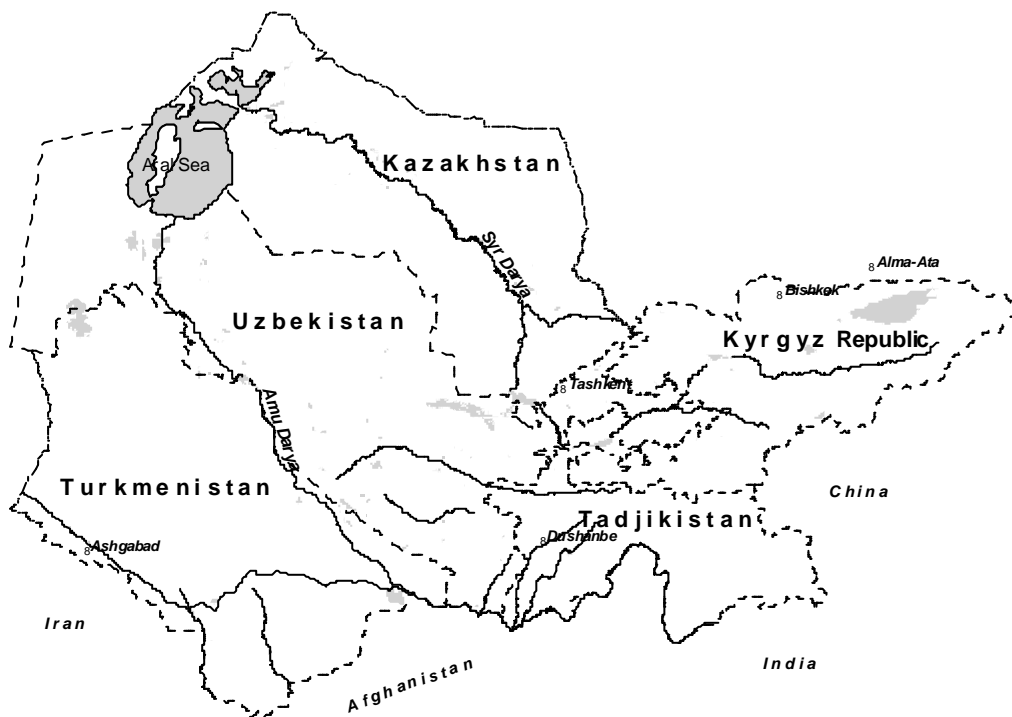
Figure 4.15 The Aral Sea Basin (after Sokolov and Dukhovny, 2002)

4.4.1.1 Hydrological characteristics

A specific feature of the region from hydrological point of view is the division of its territory into three main zones of surface runoff: (a) the zone of flow formation (upper watersheds in the mountain areas to the southeast), (b) the zone of flow transit and its dissipation (central part), and (c) the delta zones (to the northwest). For water resources management and operational purposes each river basin is sub-divided into water management units (planning zones) and as such there are totally 45 planning zones over the region.

The climate in the region is sharply continental, mostly arid and semi-arid. Average precipitation concentrated in the winter and spring is about 270 mm with deviation between 600 and 800 mm in mountain zones and 80 and 150 mm in deserts.

4.4.1.2 Water resources

Two main rivers cross the Aral Sea basin from the southeast to the northwest, fall into the Aral Sea (inland lake). Before 1960, the Aral Sea was the world's fourth largest lake. But since 1960 the sea declined precipitously. The Amu Darya is the biggest river (in terms of water availability) in the region. The Syr Darya is the longest river. The Zerafshan River is located between the Amu and Syr, and it is former tributary of the Amu Darya. The total available surface water resources in the basin are estimated to be 116.5 km^3 per year as presented in Table 4.8.

Table 4.8 Total natural river flow in the Aral Sea basin (multiyear flow, km^3/year) (after Sokolov and Dukhovny, 2002)

State	River basin		Aral Sea Basin	
	Syr Darya	Amu Darya	km^3	%
Kazakhstan	2.426	-	2.426	2.1
Kyrgyz Republic	26.850	1.604	28.454	24.4
Tajikistan	1.005	51.578	52.583	45.2
Turkmenistan	-	1.549	1.549	1.2
Uzbekistan	6.167	5.056	11.223	9.6
Afghanistan and Iran	-	19.593	19.593	16.8
China	0.755	-	0.755	0.7
Total Aral sea basin	37.203	79.280	116.483	100

Renewable resources of groundwater located in 339 aquifers with total reserves of 43.49 km^3, of which 25.09 km^3 are in the Amu Darya basin and 18.4 km^3 in Syr Darya basin. The actual (2000) water abstraction from aquifers is 11.04 km^3/year, though in 1990 it acceded 14.0 km^3.

Return waters are additional source of available water, but due to high mineralization they are also source of pollution. About 95% of this water is collector-drainage water and rest is municipal and industrial waste water. Along with irrigation development, return flow increases and it was most intensive during 1975-1990. Since 1990 it stabilized and within the period of 1990-1999 it varied between 28.0-33.5 km^3/year, of which 13.5-15.5 km^3 formed in the Syr Darya basin and 16.0-19.0 km^3 in the Amu Darya basin. More than 51% of this water is released back to the rivers and 33% into the depressions. Due to its pollution, only 16% of this water is used for irrigation.

4.4.1.3 Land use

The prosperity of Central Asia, as an agrarian region from ancient times, was always very closely interrelated with land use. From this point of view the fertile soils formed the framework for prosperity for the rural population. Out of the total land resources of about 154.9x10^6 hectares some 59.4x10^6 hectares are considered as cultivable, of which only about 10.1x10^6 hectares are actually used. Half of the actually cultivated lands are located in oasis's (they are naturally drained, with fertile soils). The other half of the land requires for their use a complicated and expensive set of reclamative measures, including not only drainage and levelling, but also improvement of soil structure. The total irrigated area is about 7.9x10^6 hectares.

4.4.1.4 Ecosystem dynamics

The large-scale development of water resources mostly for irrigation has changed the hydrological cycle in the region and created serious environmental problems in the Aral Sea Basin. The most dramatic effect has been the shrinking of the Aral Sea and it's ecosystem disruption. Other impacts include: (1) the loss of fish species in the sea, due to increasing salinity and toxic contamination, (2) soil degradation as a result of water logging and salinization of irrigated land in the catchment areas of the Aral Sea Basin, (3) crop diseases and insect infestation, due particularly to the cotton mono-culture agricultural development,

(4) adverse health effects from the poor water quality and wind-blown chemicals from the exposed sea bottom, and (5) local climate changes.

The riparian states have agreed that the Aral Sea coastal region (deltas of the Amu Darya and Syr Darya) will be considered as an independent water user whose demands will be specified jointly by all of them. These demands are to be set on the basis of an approved strategy for improvement of the environmental situation in the coastal region, taking into account the year-to-year variability of river flows. At the same time, all the riparian states recognize the importance of environmental water requirements concerning both water quality and preservation of biodiversity and bio-productivity of natural rivers and reservoirs.

4.4.1.5 Social and economic characteristics

The total population within the Aral Sea Basin was 41.8×10^6 in 2000, of which almost 63.6% were rural as shown in Table 4.9. During last five years the average annual population growth was 1.5%; ranging from 2.2% in Uzbekistan to 0.4% in Kazakhstan. Independence after the Soviet Union collapse (August - September 1991) was accompanied by a big social threat for the majority of the population in the region. Thus, Central Asia, despite a high level of human development and social services, now has poverty levels comparable to some African countries and is on the same level as in Pakistan and India.

Table 4.9 The basic parameters of water-land resources development in the Aral Sea basin
(after Sokolov and Dukhovny, 2002)

Indicator	Unit	1960	1970	1980	1990	2000
Population	10^6 Inhabit.	14.6	20.3	26.8	33.6	41.8
Irrigated area	10^3 ha	4510	5150	6920	7600	7896
Irrigated area/capita	ha/capita	0.31	0.27	0.26	0.23	0.19
Total water diversion	km^3/year	60.61	94.56	120.69	116.27	105.0
Incl. Irrigation	km^3/year	56.15	86.84	106.79	106.4	94.66
Specific diversion /ha	m^3 /ha	12450	16860	15430	14000	11850
Specific diversion /capita	m^3 /capita	4270	4730	4500	3460	2530
GNP	Bln.$	16.1	32.4	48.1	74.0	55.3
Including agricultural Production	Bln.$	5.8	8.9	18.3	22.0	15.0

4.4.1.6 Ethnicity, languages, religion

Taking into account the fact that the Soviet Government established administrative boundaries between the countries mostly artificially in the beginning of the Soviet era (1920s), the ethnic composition in the Aral Sea basin is very comprehensive. However, during the past years after Soviet Union collapsed the national structure in the countries changed considerably due to migration of the population resulting in the reduction of many non-native groups. About 70% of the people leaving were skilled manpower and that factor had a negative effect on the regional economy.

4.4.2 Water related conflicts

Conflicts in water management within the Aral Sea Basin can be perceived as disagreement of interests, ideas and principles. Conflicting issues in the integrated water resources management process could be listed as social, economic, legal and prospective variables.

4.4.2.1 Social conflicts

Water has been perceived as a social good and interaction between human beings and nature. Unfortunately, up to date priority has been given to the basic water needs of human beings in the region. As a result Aral Sea has lost about 70 % of its volume, 60 % of its surface area and water salinity has increased from 8 % to 60 % since 1960. There are huge processes of desertification (on an area of about 1.6×10^6 hectares). Losses of biodiversity occurred – common quantity of species, which disappeared from the water fauna and flora, exceed 80 types.

The second problem is salinization and water logging on the irrigated area (approximately 5.0×10^6 hectares require artificial drainage). Irrigation creates return flow as a source of environment threats. This polluted water constitutes more then 30 % of totally available water resources in the region. As a result, there is growth of river water salinization, sometimes up to 1.5 to 2.5 g/l. Worsening of ground water quality, especially under actions of chemical industry is also observed. Above-mentioned factors resulted in growth of different diseases and degree of mortality in downstream reaches of the Syr Darya and Amu Darya rivers.

4.4.2.2 Economic conflicts

Use of water resources in Central Asia, mainly for drinking needs and irrigation, began more than 6000 years ago. Intensively water resources began to be used in 20th century, especially after 1960, that was caused by fast growth of the population, intensive development of an industry and, mainly, irrigation (see Table 4.9). As it is visible from the submitted data, total water diversion in 1960 in the Aral Sea Basin was $60,610 \times 10^6$ m^3, and by 1990 it has increased up to $116,271 \times 10^6$ m^3, or by 1.8 times. For the same period the population in the specified territory has increased by 2.7 times, the irrigation area have increased by 1.7 times, agricultural productions by 3 times, gross national product almost by 6 times as presented in Table 4.9.

After disintegration of the Soviet Union in 1991, total use of water in the region began to reduce due to general economic degradation. After 1994, as a result of the coordinated water saving policy accepted by Interstate Coordination Water Commission (ICWC) of the states of Central Asia, the decrease of common water intake became the target tendency. In the year 2000 the general water intake was about 11.2 km^3 less than that in 1990.

During the last three decades of the Soviet era (1960 -1990), the irrigated agriculture and the sectors of economy related to water management (processing of the agricultural production, hydropower, construction and some others), contributed more than 50 % to the GNP. The collapse of the former USSR and the unified currency (Russian Rouble) zone created shocks for economy of Central Asian countries. The sharp disruption of production, trade and financial relations were the main reasons for the drop of general output and agricultural output especially (see Table 4.10).

It is necessary to underline, that in all countries agricultural output fell less than GDP and much less than industrial output (except Kazakhstan and it does not apply for Uzbekistan). As a whole, in Central Asia, changes in agricultural production related to an increased share of food crops output (again except Kazakhstan). Further development of reforms with more price incentives to the farmers, and a better legal framework for land and water use are important to promote labour productivity and the living standards of farmers and rural population in general, i.e., the majority of population (63%) of all countries within the Aral Sea Basin. Despite the relative decline of agriculture's share, it still plays a significant role in

the Aral Sea Basin, especially in Kyrgyz Republic, Tajikistan and Uzbekistan. It is rather important in Turkmenistan (cotton and wheat) and Kazakhstan (grain) as well.

Table 4.10 Changes in the economic situation during the transition period (after Sokolov and Dukhovny, 2002)

Country	GNP per Capita US$		By Sectors of Economy, %					
			Industry and Construction		Agriculture, Forestry and Fishery		Services Sphere	
	1990	2000	1990	2000	1990	2000	1990	2000
Kazakhstan	2310	1493	36.1	34.2	28	21.3	35.9	44.5
Kyrgyz Republic	1240	365	35.9	30.4	34.6	34.1	29.5	35.5
Tajikistan	910	321	33.7	27.9	27.1	23.8	39.2	48.3
Turkmenistan	1490	820	33.6	35.1	28.6	17.9	37.8	47
Uzbekistan	1700	985	32.5	19.9	31.3	34	36.2	46.1

There are 60 reservoirs with useful volume of water more than 10 million m^3 each in the Aral Sea basin. Total complete capacity of reservoirs makes 64.8 km^3, of which useful volume is about 46.8 km^3 (20.2 km^3 in the Amu Darya basin and 26.6 km^3 in the Syr Darya basin). On the basis of these reservoirs 45 hydroelectric power stations with capacity 34.5 GW are constructed. The largest hydroelectric power stations are Nurek (in Tajikistan on the Vakhsh river), with capacity 2,700 MW, and ???togul (in Kyrgyz Republic on the Naryn river) with capacity 1,200 MW. The hydraulic power makes 27.3 % of total general consumption of energy in the Aral Sea Basin. Tajikistan is the biggest producer of hydropower (about 98 % of total national electric agriculture generation) and Kyrgyz Republic (about 75 %). The least hydropower is generated in Turkmenistan (1 % of total national electric generation). The region can satisfy more than 71 % (150 GW) of needs in energy through hydropower.

Competition for limited water resources occurs among agricultural, rural, urban, industrial and environmental uses in the region. Irrigated agriculture is a major source for food security and the biggest water consumer (about 90 % of total water resources used for irrigation). Also, there is growth of ecological requirements, industrial and municipal needs. From this point of view there are a few conflicts of water management in the region:
- Among countries in water sharing – for quantity, delivery schedule and shares of expenses to cover water management costs within basin.

- Upstream and downstream relations concerning water allocation, schedule of water release from reservoirs and quality of water.

- Among sectors (irrigation, power generation and environment) – for water allocation, use of water reservoirs and water sharing for the Aral Sea coastal zone, rivers itself (sanitary and ecological flows).

To avoid these conflicts, it is necessary to create efficient framework for use of water, including legal and institutional basis for a fair and equitable sharing of the beneficial water use.

4.4.2.3 *Legal conflicts*

There is a lack of universal system of water rights and legal instruments in the management of transboundary river basins in the region. The main reason is the lack of trust among riparian countries, because doctrine of absolute territorial sovereignty dominates within the Aral Sea basin. The water specialists recognized necessity to adopt the integrated water resources management concept into actual water management and use. Already some steps have been made towards to implementation of the new doctrine – absolute territorial integrity.

4.4.3 Conflict resolution

4.4.3.1 *Water conflicts in perspective*

Water is limiting factor (both quantitatively and qualitatively) for some zones in the Aral Sea basin already. Therefore, future sustainable development is under some stress. Besides, there is unclear impact of global climate change to availability of water resources in the region. In this context, conflicts in water management could appear as a result of different national approaches to the planning of national development scenarios. It is desirable to establish proper interstate cooperation to promote universal conduct of planning process.

There are some limiting factors to conduct conflict resolution in the region. Among them are the lack of information transparency and lack of proper communication system between different levels of water related players:

- On the inter-sector level in each country and in region.

- On the interstate level between water specialists and water users;
- Between water organizations and NGOs.

To establish proper mechanism for the above-mentioned conflict prevention and resolution it is necessary to concentrate future activities on the following directions: (a) institutional straightening at the national and regional levels; (b) creation of a legal framework; (c) establishment of the proper financial mechanism; (d) technical perfection and capacity building.

4.4.3.2 Institutional aspects

The necessity to achieve the integration of water resources management at the basin level was fully understood in the period before independence. Understanding the importance of having a single water management organization for the whole basin in 1986 two Basin Water Organizations were established – BWO "AmuDarya" and BWO "SyrDarya". Such a basin-wide organization could operate water in the rivers in accordance with the rules and schedule agreed among the republics. Ministry of Water Resources provided the financing of BWOs from the federal budget for operations, maintenance, rehabilitation and development.

Concerns to create a mechanism for regional collaboration in organization and financing of water resources management has arisen after independence. Based on the principles of equal rights and responsibility for rational water use agreed since 1992, a number of interstate agreements, documents and decisions have been signed, which regulate collaboration in the sphere of joint water resources management, conservation and use.

The first interstate agreement (1992) was related to the establishment of the Interstate Commission for Water Coordination (ICWC), which became responsible for joint water resources management. ICWC took on responsibilities for water management in both basins directly from former Soviet Ministry of Water Resources.

Later, in 1993, with the Aral Sea Basin Program extension, two new organizations were established. Those were: The Interstate Council for the Aral Sea (ICAS) with the purpose of the Program coordination; and the International Fund for Saving the Aral Sea (IFAS) with the

purpose of accumulating finances and their control. In 1997 ICAS and IFAS were combined and re-established into a new IFAS.

The existing structure of the interstate organizations responsible for water resources management was created during a long period (1991-1999), and distribution of their obligations was confirmed by the Head of States in Agreement dated April 9, 1999, which was signed in Ashgabad (Turkmenistan). The structure is presented in Figure 4.16.

International Fund for Aral Sea Saving (IFAS) is the highest political level of decision-making before approval by the Heads of State (if appropriate) and IFAS Executive Committee is a permanent body, which implements the IFAS Board decisions through the IFAS National Branches. Besides, the EC IFAS on behalf of the Board could establish agencies for various regional projects and programs implementation.

Interstate Water Coordination Commission (ICWC) is a collective body managing transboundary rivers responsible for water allocation among countries, monitoring; preparing preliminary assessment of proposals on institutional, ecological, technical and financial approaches, based on mutually agreed decisions by all sides. The two Basin Water Organizations (BWOs) (Amu Darya and Syr Darya), the Scientific Information Center (SIC) and ICWC Secretariat are executive bodies of this Commission. The Commission was established in accordance with "Agreement on collaboration in sphere of joint water resources management within interstate water sources" dated February 18, 1992, and then approved by the Head of States on March 23, 1993.

The 1992 agreement provided that water allocations should be based on *"existing uses of water resources"* and that the two river basin agencies (BWOs) should continue to perform basin management functions subject to control by ICWC. Subsequently, the ICWC agreed that the 1992 agreement should remain in force until a *Regional Water Management Strategy* had been formulated which responded to new realities and which outlined more objective mechanisms and principles for water allocation and rational use.

Figure 4.16 Structure of international fund of Aral Sea (after Sokolov and Dukhovny, 2002)
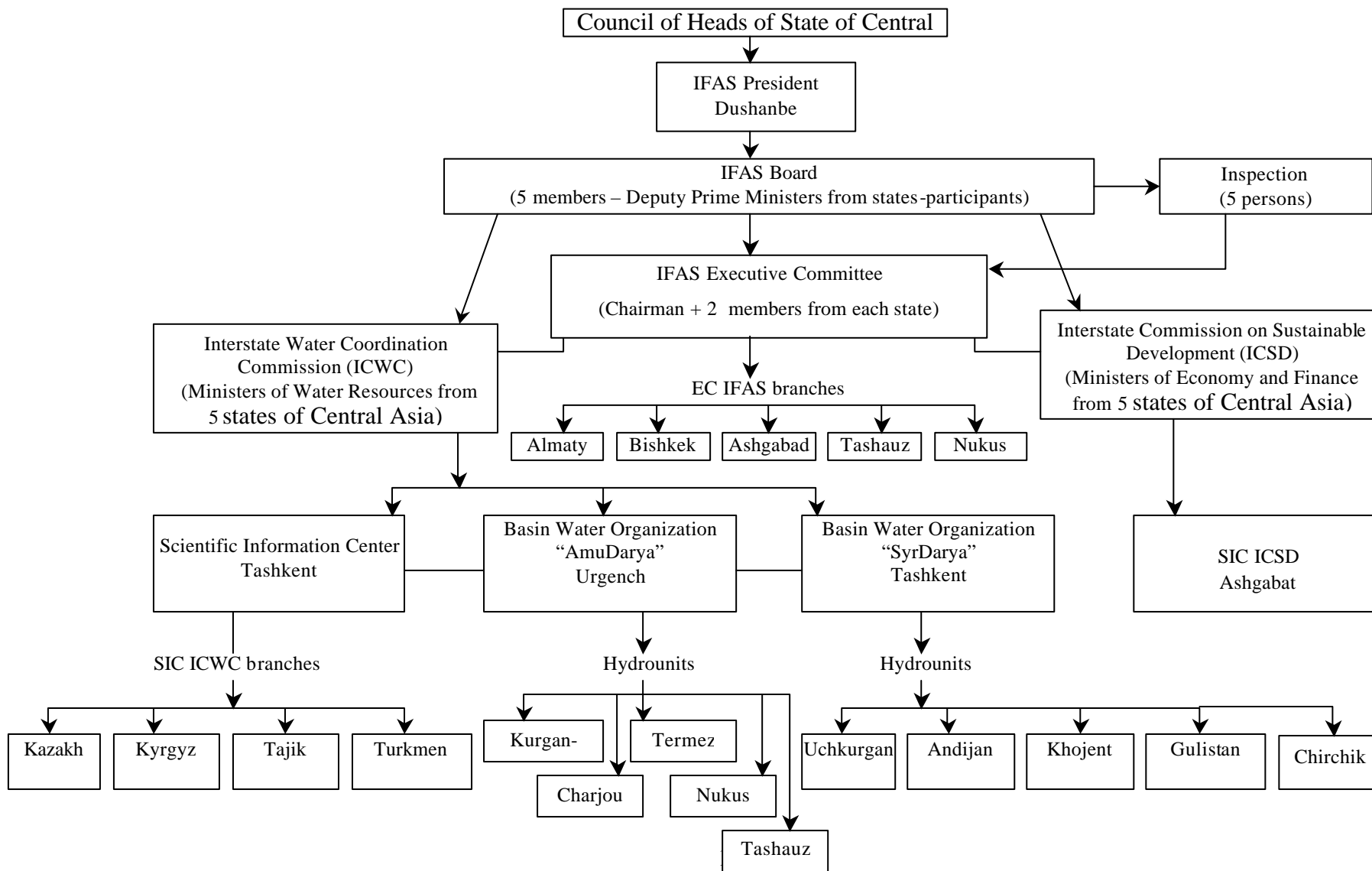
In January 1994, the Presidents of the five Central Asian countries met in Nukus (Karakalpakstan) and approved a Program of Concrete Actions for the improvement of the environmental situation in the Aral Sea Basin and for its social and economic development. The Aral Sea Basin Program (ASBP) included eight thematic sub-programs, the first of which addressed to formulation of a general strategy of water distribution, rational use, and protection of water resources. The first stage of this work was finished in 1997 by presentation of the fundamental provisions of the water resources management strategy. As a further step, in 1998 new GEF Project consisting of five components was started.

A comprehensive description of the objectives and mandates of IFAS and BWOs along with their advantages and disadvantages are included in the report by Sokolov and Dukhovny (2002). It further gives institutional management at the national levels in detail.

4.4.3.3 Legal basis

Water relations needed a new legal basis, because the rivers in the region became transboundary. This requires new approaches to interstate negotiations in the sphere of water allocation and water use. Central Asian states responding quickly to the need for a new legal basis for water allocation and management, in 1991 declared the establishment of a joint water resources management on the basis of equity and mutual benefit.

To overcome the inherited inter-regional water problems and minimize ethnic tensions, the five Central Asian countries signed an interstate water agreement on February 18,1992, according to which water allocation should be based on the existing uses of water resources and the two river basin authorities should continue to perform basin management under the control of the Interstate Commission for Water Coordination (ICWC).

Existing documents do not ensure proper water use and control. Water flows to the Aral Sea are not ensured, emergency conditions are created, and water use is still inefficient. Therefore, legal documents should be developed to improve joint water use in the Aral Sea Basin. In 1996 the establishment of the legal basis began the process of joint management, use, development and conservation of transboundary water resources in the region.

Achievement of a consensus between States in the creation of a strong regional legal framework is a long-term process and work on this is being carried out (Sokolov and Dukhovny, 2002).

4.4.3.4 Financing

Water management activity in the Central Asian states is performed at expense of state budget as well as payments for water services. The amount of charge is different in different countries. It depends on state policy and its participation in water management sector support and development, water resources conservation, pricing policy for agricultural production, etc. The payment for water as a resource exits for all kinds of water users except agricultural ones. Water users who pay for water are industrial enterprises, power stations, material enterprises, etc. Water services for irrigation water are payable in Kazakhstan, Kyrgyz Republic and Tajikistan.

Paid water use solves not only economic problems of water organizations, but facilities perfectioning of management, rational water use and water saving in all branches of economy. Trade rights should be provided to water-related organizations promoting their investments in water saving measures and additional water resources involvement.

Gradual reduction of state subsidies for agricultural producers and other users for water delivery; transfer of all categories of water users from stable tariff to tariff with respect for water used volume and competition system for water saving introduction are a few measures that should be implemented. Incentives should be created for all states and water users to conserve water and to free it for environmental needs.

4.4.3.5 Technical issues

The most important issue is rehabilitation and modernization of irrigation and drainage systems in the region through: (a) improvement of the state of irrigated lands and (b) improvement of irrigation technique.

The SIC ICWC, BWOs "Syr Darya" and "Amu Darya" with assistance of CIDA prepared a Feasibility study "Water Resources Management and Control Systems for the Amu Darya and Syr Darya Basins" to provide the region countries with water in accordance with quotas

established by ICWC and to develop plans for water reservoirs and water intakes operation, developing systems of management, communication and information.

SIC ICWC elaborated the program for development of models system. This programme consists of a set of models including: (a) River basin models; (b) Models for national water policy which satisfy water demands of each State, depending on their socio-economic development. These models will support for future development at the regional and national levels as a tools in the preparation of Regional and National Water Strategies. They will further support for multiyear flow regulation by ICWC and for BWO multiyear planning, for annual planning of water allocation and correction of this planning in interests of BWO and for operational tasks of water management by each BWO.

The elaboration of basin modeling for future development at the regional level, and modeling of planning zone and operation work for BWO, was began by SIC ICWC together with the Water Management Authorities of all states. Also, It is necessary to develop training system for water specialists with NGO involvement.

4.4.4 Future work

Sokolov and Dukhovny (2002) suggested that the existing shortcomings in water management can be eliminated and water use effectiveness can be achieved via real regional partnership and integration of efforts in following six directions including the following.

- Integration of the countries efforts in water basin management and conservation through the partnership at interstate (regional) level.
- Integration of water management system hierarchic levels through vertical partnership in the chain: "state-water system-territorial water and administrative bodies-water users and water consumers".
- Integration of water users and water management organizations through water users involvement at all levels to water management hierarchy as well as partnership between governmental and non-governmental bodies.
- Integration of knowledge and practice through partnership of science with water users and water organizations (using such tools as base of knowledge, training, consultation, extension service).

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Preparation of water partnership in the region is suggested in the effort of integration. Taking into account existing regional problems, they suggest creating four thematic groups relevant to ICWC working groups.

- Technical aspects
- Legal questions
- Institutional issues
- Financial aspects

Successful development and coordination of the regional and national water strategy and its monitoring can be realized using existing scientific potential.

4.4.4.1 Proposal for Integrated Water Resources Management

Dukhovny (2002) proposed the use of a set of models for the Aral Sea basin as a tool for integrated water resources management and sustainable development within the context of system analysis. Since the Aral Sea basin system is a very complex one, development of a decision support system is not simple. A large number of models to adequately describe processes of water use, water development and water funds, a database, a knowledgebase and a forecast system, a set of criteria, constraints and links is needed. Such a system is absolutely necessary for conflict free management of water resources within this basin, integrating the different administrative and political entities, various sectors of economy etc.

Systems analysis and modeling as a whole can help to all society because along with their utilization by water specialists as tools and mechanisms of planning and control, they can serve as a prove for politicians to find most rational decision and create political and socio-economic climate for rational water resources used and win public confidence.

The interlinked set of models fall into two categories; hydrologic and socio-economic. The different models include, Hydrologic model of annual planning, Perspective planning hydrological model, Multiyear regulation model, Socio-economic sub-model and National planning model. Dukhovny (2002) presented the detailed description of the models development, their linkages etc., in detail.

4.4.5 Scenario Analysis in future development of the Aral Sea Basin countries

The Governments of the Aral Sea Basin countries, in cooperation with UNESCO came up with a vision for the region till 2025. This section presents a study carried out to examine different scenarios to achieve the vision goals using GLOBESIGHT reasoning support tool described previously (Vali *et al*, 2002). The tool, which is useful for understanding the past, evaluating the present and looking into different feasible futures through scenario analysis with its "human-in-the-loop-with-the-computer" approach could assist water conflict resolution via the exploration of different futures or scenarios.

4.4.5.1 Signs and symptoms

The problems seen arising in the Aral Sea Basin are twofold. The first problem is that of the depletion of the Aral Sea and the consequent environmental problems. However, economic and social development is a priority for the countries in the basin over saving the Aral Sea itself. If the people in the region continue to live at the current standards, earning less than $1000 per person per year it is safe to assume that they will not be too concerned about the depletion of the Aral Sea, and would be more concerned about their own livelihoods.

As Figure 4.17 shows, the population of the region is expected to grow to about 70 million in 2025 according to the UN low projections. The biggest hurdle the region faces is the transition from being part of the centrally-planned Soviet Union to independent and economically viable countries.
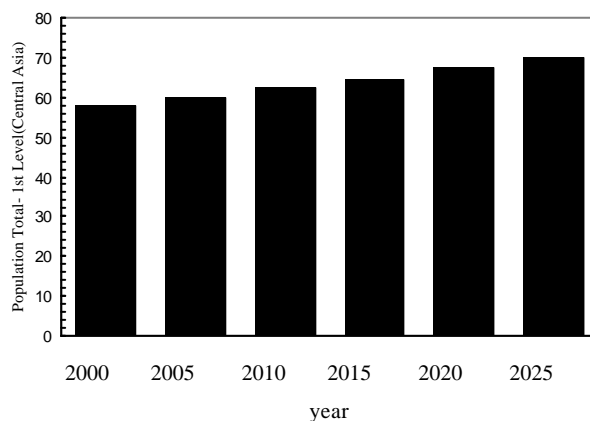
Figure 4.17 Population Projections (UN Low) (after Vali *et al*, 2002)

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Currently, average income per capita is $900 per year for the region. Based on their current water demand, 80% of which goes to irrigate cotton and grain fields, less than 10km^3 is flowing into the Aral Sea. Any increase in population, no matter how slight, will require that agricultural production increase at the same rate as the population. Grain trade among the countries in the region does currently exist. Grain imports to the region, however, are negligible and the countries will want to continue this policy; relying on inter-country grain-trade. Assuming no change in agricultural productivity, overall land quantity will have to be expanded, which means more water will be needed leaving even less water flowing into the Aral Sea. In fact by 2025 there will be no water flowing into the Aral Sea.

Figure 4.18 shows the different levels of industrial production that will be required in order to achieve the different levels of per capita income shown assuming high increases in agricultural productivity given in Table 4.11. Even to achieve a slight increase in per capita income to $1000 it can be seen that the economy would have to grow at an average rate of over 1% over the next 25 years, which is not necessarily high. This is well within the realm of possibilities considering that the development over the last decade the economy of the Central Asian Republics has shrunk – a decline triggered by the fall of the Soviet Union.
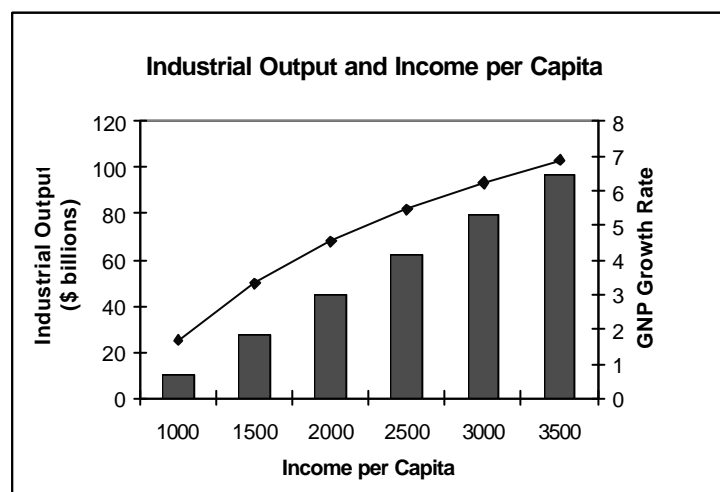
Figure 4.18   Industrial output necessary to reach various levels of income per capita (after Vali *et al*, 2002)

In the area basin countries, the disparities in incomes are high. A significant majority of the population is living on less than $900 per year. The region has enough land and water to feed its people and could still have enough water left over for environmental purposes. But

because of poor management a lot of water is wasted in getting from the rivers to the fields. Currently almost 26 km^3 of water is lost or unaccounted for.

Table 4.11 Increase in agricultural productivity (after Vali *et al*, 2002)

Future (2025)	Yield
Food Crops (irrigated/rainfed)	4.6/1.8 ton/ha
Industrial Crops	3.3 ton/ha
	Water use/ha
Food Crops	5500 m^3/ha
Industrial Crops	6000 m^3/ha

The region also has tremendous wealth in the forms of natural gas and oil resources but poor management has held these countries back from utilizing their resources for the betterment of people.

This study took a detailed look at the Aral Sea Basin countries, in terms of their economic and social development based on the Aral Sea Basin Sustainable Development Model that looked at the interactions between population growth, economic development, food self-sufficiency, water use and water flowing into the Aral Sea. In order to look at the prospects for the region a vision was formulated as in the process described in the following section. The model was used with the Globesight (UNESCO GENIe Coordinating Center, 2000) software. In order to study the long-term development of Aral Sea basin countries Mesarovic's "Conjunctive Approach" of scenario analysis that combines the narrative or verbal vision scenarios with numerical scenarios (Sreenath, 2001) is followed. The processes of generating the narrative are not distinct but intertwined.

The steps adopted are as follows: Study the issue background understanding the present status and the past trends. Form consistent mathematical models supported by science and available data of the various components of the system. These models are useful in numerical simulation. Using GLOBESIGHT and a time stepped interactive human-in-the-loop reasoning support approach generate scenarios.

4.4.5.2 Formulation of vision and scenario analysis

The process of developing a water-related Regional Vision for the Aral Sea Basin (ASB), for the second World Water Forum held in the Hague in March, 2000, was coordinated and facilitated by UNESCO over a period of 1½ years, though the UNESCO began work in the Aral Sea Basin countries much earlier after request from the Central Asian republics during October 1997 (UNESCO, 2000).

The water-focused vision for the development of Central Asian Republics is a direct result of two initiatives. The first was UNESCO's *Aral Sea Initiative.* National commissions were formed for each of the five republics staffed with local experts and stakeholders. These national commissions held consultative exercises in their own countries to establish scientific and political consensus. The UNESCO constituted Scientific Advisory Board on Aral Sea Basin (SABAS) that was represented by the scientists from the region also provided input. Input from International Fund for Aral Sea (IFAS) was also solicited for the vision. Follow up meetings were held with National Commission representatives, SABAS and IFAS representatives facilitated by UNESCO personnel.

The vision represents a desirable future. Although the focus was on water a much broader perspective had taken that involved a range of developmental dimensions—from population growth, economy, and agriculture (both food and industrial crops), to development indicators on individual well-being such as life expectancy, child mortality, access to safe water, etc. The results of the lengthy considerations involving members of the working groups of all five ASB countries, experts from the region, as well as foreign experts, are summarized in terms of some key indicators as shown in Table 4.12.

Recognizing that the complexity of the situation requires a trade-off between different dimensions of development, the vision targets are given in terms of thresholds (desirable, minimal, or maximal levels), i.e., the problem is recognized as being multi-objective, while the approach has been holistic.

Table 4.12 Possible goals for the water-related regional vision for the Aral Sea basin used in the testing of the feasibility of the vision (UNESCO,2000)

Possible goals in the water-related Vision for the Aral Sea Basin	Targeted thresholds for 2025
Health	
Child Mortality Rate (Children below 5 years of age per 1000 births)	<30
Life expectancy at birth in years	>70
Nutrition	
Average availability of food calories per inhabitant per day	>3000
Environment	
Water available for the environment in km^3 per year	>20
Wealth	
Increase of income per person in purchasing power in urban areas as a factor since the year 2000	>2.5
Increase of income per person in purchasing power in rural areas as a factor since the year 2000	>3.5
Agriculture	
Average water use in cubic meters per ton of wheat	<1000
Average water use in cubic meters per ton of rice	<3400
Average water use in cubic meters per ton of cotton	<1900
% of irrigated area salinized (middle and highly salinized)	<10
Drinking Water supply	
Coverage of piped water supply in urban areas, in % of people	>99
Coverage of piped water supply in rural areas, in % of people	>60
People served good quality water by biological standards, urban, in %	>80
People served good quality water by biological standards, rural, in %	>60

In order to lead to the desired progress in reality, the vision has to be shown as feasible and not only as desirable. This was taken as the task of the scenario analysis. The results of the scenario analysis are expected to identify demographic, economic, technological, management, etc., changes needed to reach the vision goals. The feasibility of the changes implies the feasibility of the vision. Feasibility here is described as not violating any "physical constraints". The required changes indicated by this approach to scenario analysis are policy targets. For example, a scenario indicates a required increase in water use efficiency but the policies that would lead to such an increase are in the domain of government and private sector decision-making. One important question would then be

regarding the availability of technology to implement/realize this water use efficiency. Thus, in general this refers to a subsequent testing of realism.

Scenario analysis is not expected to predict the future. Rather, it is only to outline at least one path of future development that is consistent with constraining realities, technological, managerial and economic progress, etc. There could be many other paths leading to the vision goals. The role of government and private sector decision-makers is to steer the development along a socially acceptable path.

4.4.5.3 Implementation

To test the feasibility of these goals and generate a set of policy targets necessary to realize the vision, the GLOBESIGHT reasoning support (decision making) tool was used, custom-tailored by the GENIe team (Global-problematique Education Network Initiative) at Case Western Reserve University, Cleveland, USA, for the occasion as presented in Figure 4.19. Its main component is a multi-level model of sustainable development, *Aralmod* as shown in Figure 4.20. The model contains a number of sub-models, but some of its features are briefly indicated here. A description of each sub-model used in the overall Aral Sea Basin Sustainable Development Model follows.
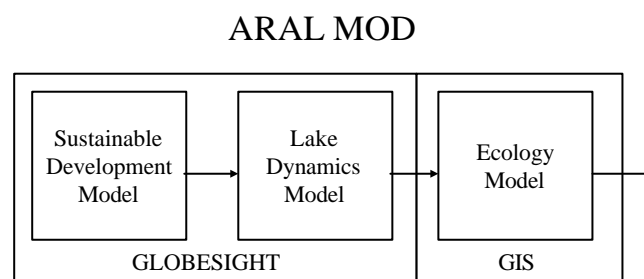
ARAL MOD

Figure 4.19 Aralmod block diagram (after Vali *et al*, 2002)

Population: The population sub-model is described using a simple first order difference equation (UNESCO GENIe Coordinating Center, 2000). The population in any given year is computed as the population in the previous year plus any growth in population, which may be negative, resulting in a decrease in population. The growth in population is computed as the growth rate times the population in the previous year. If the growth rate is negative, then there will be a decline in population. If the growth is zero, there will be no change in

population (equilibrium population) and if the growth rate is positive then there will be an increase in population.
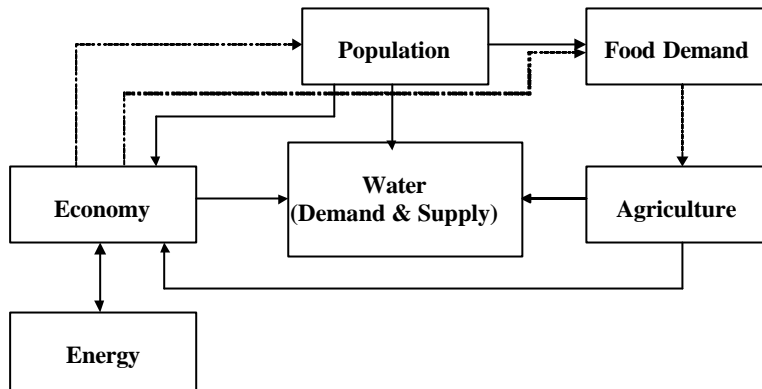
Figure 4.20 Structure of the Aral Sea basin sustainable development model (after Vali *et al*, 2002)

Agriculture: Two types of crops – industrial and food crops – are tracked separately. In the case of the Aral Sea Basin, the only industrial crop considered is cotton since this is the primary industrial crop. Food crops include cereals, roots, tubers and pulses. The land for the food crops (irrigated and rainfed) and industrial crops are computed individually as first order difference equations. The yields for the food crops (irrigated and rainfed) and industrial crops are also computed as a first order difference equation. The total food production is the product of land for food crops (irrigated and rainfed) and its yield (irrigated and rainfed) and the total industrial crop production is the land under industrial crops times yield for industrial crops. All industrial crops are irrigated. Industrial crops are fully exported with the exports in monetary terms being the price of cotton times the total cotton production.

Food: The food sub-model has two components – food demand and food supply. Food demand is computed in terms of calories and is the product of population and the calorie demand per capita per day times days of the year. The calorie demand per capita per day is assumed to increase proportionately to an increase in income per capita; so as the people get richer their diets will change and they would like to consume more meat in place of roots and tubers (Brown, 1995). Even if calorie demand per capita were to remain constant, as population increases so does food demand. Food supply is the total food production me asured

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in terms of calories. Food production is multiplied by a coefficient, which translates food in terms of tonnage into food in terms of calories.

Economy: The economy sub-model is further divided into four sub-models: agriculture, service, energy and industry non-energy. The agricultural output is the sum of the industrial crops times their price on the international market and food crops times its price plus any investments into the agricultural sector from export earnings (see Energy sub-model). The GNP for the other three sectors is computed as first order difference equations. Industry has been divided into energy and non-energy because the Aral Sea Basin has a lot of oil and natural gas, which gives the region a greater growth potential in terms of the energy sector. The Industry – Non-Energy sector includes manufacturing, mining, transportation, etc. The growth rates for the three sectors are computed as the basic growth rate plus the investments from export earnings into the sector divided by the GNP of that sector times the capital-output ratio of that sector plus any foreign investments into that sector divided by the GNP of that sector times the capital-output ratio of that sector. In other words, any reinvestment of export earnings or any foreign investment into a sector would increase its basic growth rate.

Energy: The energy production is computed as a first order difference equation, with the rate of growth equal to the rate of growth of the energy sector of the economy. The energy intensity is also computed as a first order difference equation. The energy demand is then the product of energy intensity and total GNP. If energy demand is greater than the production, then the total energy consumption is equal to the production; otherwise it is equal to the demand. Any excess production is then exported. The energy exports in monetary terms is the price of energy times the energy exports. Total export earnings are then the sum of the earnings from energy exports and cotton exports. The total earnings are then reinvested into the four different economic sectors

Water Supply: The water supply is the sum of the supply from the two rivers, Amu Darya and the Syr Darya, and the ground water and recycled water, which are all taken to be constant for the region.

Water Demand: The total water demand is the sum of the domestic, industrial and agriculture water demand. The domestic water demand is the product of population and water demand

per capita. The industrial water demand is the product of industrial GNP times water needed per dollar of industrial output. The agriculture water demand is the product of water needed per hectare for industrial crops times land under industrial crops added to water needed for food crops under irrigation times land under food crops under irrigation.

Aral Sea: The difference between water supply and water demand less any water losses is then the balance that flows into the Aral Sea. The surface area of the Aral Sea is computed by using look-up tables that were created using past data. The surface is a linear function of the volume of the Aral Sea. The evaporation and precipitation are also computed from look-up tables and they are both linear functions of the surface area. The current year's volume is then the previous year's volume plus the inflow into the Aral Sea plus precipitation less evaporation. The level is computed as a function of the volume and the surface area.

4.5.4.4 Scenario Analysis

First, a regional scenario is formulated to achieve the vision goals. This spells out the policy alternatives required to achieve the vision. Implications of these policy alternatives are discussed. Next, an optimistic but realistic scenario is formulated with the regional implications being the end result.

The first vision goal studied is economic development. This calls for a threefold increase in per capita income for the region as shown in Figure 4.21.
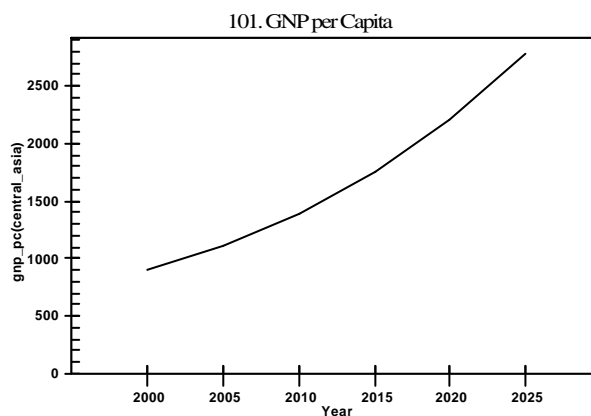
Figure 4.21 GNP per capita (vision goal) (after Vali *et al*, 2002)

The population currently is 58 million and the average annual income per person is approximately US$900. The population is projected to grow to about 70 million in 2025 (UN

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low projection). This means that the GNP of the region will have to grow approximately three and a half times in the next twenty five years as shown in Figure 4.22.

As there isn't much scope of increasing agricultural land and as the price of cotton, which is the major industrial crop produced in the region, is highly unlikely to increase (World Cotton Outlook) most of the growth will have to be in the industrial sector (energy and non-energy) of the economy. Under these assumptions the energy sector will grow from $11.3 billion in 2000 to $61.4 billion in 2025 and the non-energy sector will grow from $3.8 billion in 2000 to $20.6 billion in 2025. Since the service sector is already almost 45% of the total economy we assume service will continue to be 45% of the economy. Even though agricultural output doubles from $11.4 billion in 2000 to $22.7 billion in 2025, as a percentage of the economy it falls from 21.7% to 11.5% as shown in Figure 4.23.
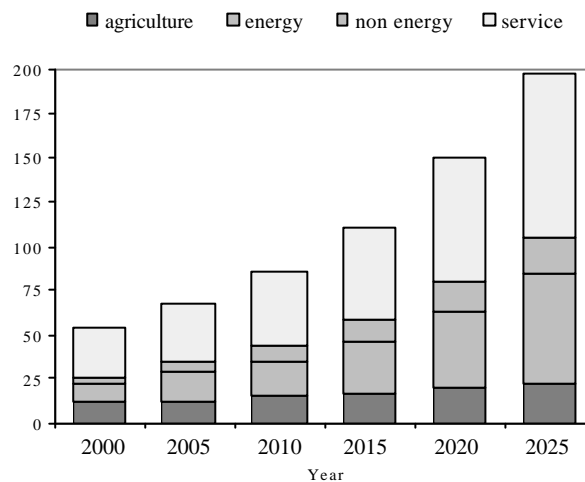
Figure 4.22 GNP by sectors (after Vali *et al*, 2002)

Industrialization, however, is not an overnight process so there will be a time lag between implementation of policies geared toward industrialization and realization of results. In the next five to ten years a lot of emphasis will still be on increasing agricultural efficiency and productivity with a shift toward more aggressive industrialization after that. The study assumes that yields for industrial crops (mainly cotton) will increase from 2000 to 2010 and remain constant from thereafter. After 2010, almost all of the increase in economic output will come from the industrial sector. Central Asia has a lot of oil and natural gas reserves so this is something that could be achieved, but to what extent is debatable.
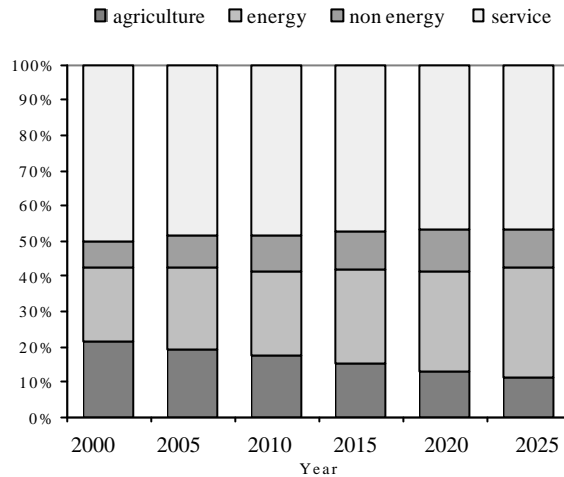
Figure 4.23 GNP by sectors (% of the economy) (after Vali *et al*, 2002)

Another goal that is looked at is that of food self-sufficiency. Currently, as a region, Central Asia produces all of its food requirements. The current demand is about 2800 calories per capita per day. As economic prosperity increases there will be a shift in diet patterns. As the poorest become wealthier their diets tend to become more complete and there is a shift from eating more vegetables and grain to more meat. As the population itself is also increasing there will be a substantial increase in food demand (from 19.7 million tons in 2000 to 29.2 million tons in 2025). The calorie demand per capita per day is assumed to grow proportional to the increase in income to about 3500 in 2025 (Vision goal).

In order to achieve food self-sufficiency there will have to be an increase in food production. As land for food crops, irrigated and rain-fed, is kept constant this will have to be done through a substantial increase in both rain-fed and irrigated food crop yields. Since the emphasis on increase in agricultural productivity is over the next ten years most of the increase in yields will occur by 2010, after which yields will be almost constant till 2025. Irrigated yields will increase from 2.2 tons per hectare in 2000 to 4.1 tons per hectare in 2025 and rain-fed yields will increase from 0.7 tons per hectare in 2000 to 1.1 tons per hectare in 2025.

All of these goals are to be achieved while increasing the inflow into the Aral Sea from the Syr Darya and Amu Darya rivers that flow through the region to over 20 km^3. The study assumes that the domestic per capita water supply remains constant throughout the period and

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also that the industrial water supply per dollar of economic output remains constant. All the increase in water efficiency will come from the agricultural sector. Currently, the water intensity (m^3 per hectare) for food crops is 13,400 and that for industrial crops is 10,000. Water intensity will have to be decreased by more than 40% in order to achieve our goal for water inflow into the Aral Sea. Also the vision goals of how much water should be required (drop per crop) to produce one ton of wheat, rice and cotton (1000, 3400, and 1900 respectively) are met.

Making improvements to the infrastructure by which water is transported to the fields can decrease water intensity. Also, there is almost 20km^3 of water that is unaccounted for, which by itself could achieve the desired inflow into the Aral Sea.

In order to achieve the various vision goals the study outlines the different measures that will have to be taken in terms of increasing yields and increasing water efficiencies and industrial output. While there is scope for improvements in yields and water efficiencies and increase in industrial output, the levels of increases that are required make these goals highly unlikely to achieve. This notion is made even more apparent when the scenario formulation is carried out at the national level. It is important to realize that even if each individual country could meet these targets, achieving the vision goals at the regional level requires total cooperation amongst the nations and equal distribution of income as well as food between the nations; this makes the regional vision highly unlikely. Consequently, the vision is felt as not likely to be achievable and therefore another scenario that is also optimistic but more realistic is formulated.

This scenario assumes the level of yield increase that could take place in each country based on projections by International Water Management Institute (IWMI, 2000). This results in an increase in irrigated and rainfed food crop yields for the region as a whole in 2025 as compared with the vision scenario.

The economic growth for the four different sectors is assumed for each country and the resulting growth for the region is shown in Figure 4.24. This scenario also assumes the UN low projections for population growth. This results in an increase in per capita income for the region to be two-fold as opposed to a three-fold increase in the vision scenario.

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The calorie demand per capita is increased in the same proportion as income as in the vision scenario but since income doesn't increase the calorie demand per day per capita only increases to 3000. Despite this smaller increase in food demand, the criterion of food self-sufficiency is not met. There is still a deficit of almost 10%.
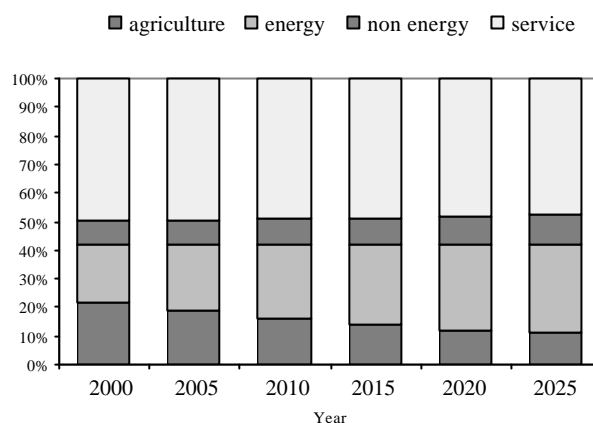
Figure 4.24 GNP by sectors – New scenario (after Vali *et al*, 2002)

Water intensities for the three different sectors (agriculture, industry and domestic use) are given in Table 4.13 assuming only a 25% reduction in agriculture water intensity for all the countries. Also it assumes that the water losses will be reduced from 20km^3 to about 15km^3. This results in an inflow into the Aral Sea of about 25km^3, which is one of the vision goals.

Table 4.13 Water intensity by sectors (after Vali *et al*, 2002)

Category	Year - 2000	Year - 2025
Agriculture – food crops (m^3/hectare)	13,400	10,250
Agriculture – indcrops (m^3/hectare)	10,000	7,000
Domestic (litres/person/day)	300	300
Industry (km^3/$billion)	0.2	0.16

4.5.4.5 Conclusions

The study presented shows the applicability of the human-computer interactive tool GLOBESIGHT in the scenario analysis that may support in water related conflict resolution in exploring different development futures or scenarios.

The analysed optimistic but realistic scenario shows that though not all the vision goals are likely to be met over the next 25 years the inflow into the Aral Sea can be increased to over 20km^3. This would require better management of the water resources and greater cooperation amongst the nations to minimize wastage of water. There is scope for economic betterment keeping in mind the vast amount of natural resources available in the region. Whether the Central Asian countries can achieve an improvement in their standard of living depends very much on their governments' ability to utilize these resources in the most beneficial way and for them to be able to distribute the income in a highly equitable manner.

5. Treatment of Uncertainty in Negotiation and Agreements

There are many sources and types of uncertainty encountered in water resources management. Mays and Tuan (1992) defined uncertainty as the occurrence of events that are beyond our control. The uncertainty of water resource systems is an undeterminable characteristic and during the design and management of them, decisions are made under various kinds of uncertainty.

Moral-Seytoux (1976) listed several uncertainties encountered when dealing with water projects. Some uncertainties are governed by laws of chance, for example, uncertainties such as hydrologic uncertainty, economic uncertainty, population growth etc. There are uncertainties that are apparently not governed by laws of chance such as, uncertainties of a social origin, including revolutions and wars.

In water management uncertainty can be caused by inherent hydrologic variability (data and observation), uncertainty due to fundamental lack of knowledge of hydrologic processes and uncertainty involved in the modeling process. However, in a water related conflict resolution process, uncertainties can occur due to the decision-makers involvement in the procedure. The decision makers and/or the stakeholders will have uncertainty regarding their preferences on diverse alternatives. There may be uncertainty in the weights given to various alternatives, too. While the uncertainties related to hydrology could be handled by probabilistic approaches, due to the ability to handle both objective (hydrology related) as well as subjective (decision maker related) uncertainties, the use of theory of fuzzy sets is observed to be very much suitable in handling uncertainty in conflict analysis.

Naturally, conflicts over water take place among two or more stakeholders and each of them can have multiple objectives associated with array of uncertainties. This chapter presents a multicriteria decision making (MCDM) approach that would be useful in resolving multi-party, multi-objective conflicts over water when various kinds of uncertainties are involved in the decision-making processes.

Complex decision problems involving multiple objectives encountered very often could be addressed by multiobjective analysis approaches, such as compromise programming, ELECTRE etc. Though many of these traditional multicriteria decision making (MCDM) techniques are a very valuable strength for decision makers, extensive sensitivity analysis is necessary to propose any kind of recommendation with confidence. By combining Fuzzy sets with a MCDM technique, the evaluation of the performance of discrete alternatives with uncertainties could be modeled as imprecise and vague. A model comprising concepts of fuzzy and compromise programming is presented in this chapter, which addresses many of the lacking qualities in many MCDM techniques, where uncertainties and subjectivity are concerned.

5.1 Modeling uncertainty

Uncertainty is a source of complexity in decision-making, which can be found in many forms. Typical types of uncertainty include uncertainty in model assumptions, and uncertainty in data or parameter values. There may also be uncertainty in the interpretation of results. While some uncertainties can be modeled as stochastic variables in a simulation, other forms of uncertainty may simply be vague or imprecise.

Traditional techniques for evaluating discrete alternatives such as ELECTRE (Benayoun *et al*, 1966), AHP (Saaty, 1980), Compromise Programming (Zeleny, 1973; Zeleny, 1982), and others do not normally consider uncertainties involved in procuring criteria values. AHP inherently includes linguistic subjectivity, and has been applied to water resources problems (Palmer and Lund, 1985; Lund and Palmer, 1986).

Sensitivity analysis can be used to express decision maker uncertainty (such as uncertain preferences and ignorance), but this form of sensitivity analysis can be inadequate at expressing both the probabilistic and imprecise forms of uncertainty. There have been efforts to extend traditional techniques, such as PROTRADE (Goicoechea *et al*, 1982), which could be described as a stochastic compromise programming technique. A remaining problem is that not all uncertainties easily fit the probabilistic classification.

There are typically three main forms of imprecision identified in fuzzy decision making (Ribeiro *et al*, 1995). They are,

- incompleteness, such as insufficient data,
- fuzziness, where precise concepts are difficult to define, and
- illusion of validity, such as detection of erroneous outputs (Tversky and Kahneman, 1990).

5.2 Fuzzy decision making

Fuzzy system descriptions have been applied in water resources planning decisions (Haimes, 1977; Slowinski, 1986). Fuzzy approaches attract a lot of attention in water resource management mainly due to uncertainties in discrete decisions that are affected by continuously variable inputs and also because of empirical and poorly-defined goals for water supply, water quality, or other indirect measures such as recreational accessibility. Water supply problems entice fuzzy applications to be combined within multiobjective decisions for expert system decision support (Bardossy and Duckstein, 1992). Zimmerman (1987) presented frameworks and applications of decision-making with expert systems in a fuzzy environment.

Fuzzy decision making techniques have addressed some uncertainties, such as the vagueness and conflict of preferences common in group decision making (Blin, 1974; Siskos, 1982; Seo and Sakawa, 1985; Felix, 1994; and others), and at least one effort has been made to combine decision problems with both stochastic and fuzzy components (Munda *et al*, 1995). Application, however, demands some level of intuitiveness for the decision makers, and encourages interaction or experimentation such as that found in Nishizaki and Seo (1994). Leung (1982) and many others have explored fuzzy decision making environments. This is not always so intuitive to many people involved in practical decisions because the decision space may be some abstract measure of fuzziness, instead of a tangible measure of alternative performance. The alternatives to be evaluated are rarely fuzzy. However, their perceived performance may be fuzzy.

An intuitive, and relatively interactive, decision tool for discrete alternative selection, under various forms of uncertainty, would be a valuable tool in decision making - especially for applications with groups of decision makers. This chapter presents the application of fuzzy sets in conjunction with a standard MCDM technique, compromise programming.

5.3 Displaced ideals

Multicriteria decision analysis techniques can approach the analysis of multiobjective problems in a number of ways. They are generally based on: outranking relationships, distance metrics and utility theory. The concept of the displaced ideal was used by Zeleny (1973,1982) to form compromise programming, a multicriteria technique which resolves criteria into a commensurable, unitless, distance metric measured from an ideal point (for each alternative). The result is a direct ranking (strong ordering) of alternatives, valid for the selected weights and the chosen form of distance measurement. The following can be used to calculate a discrete compromise programming distance metric (L), otherwise known as the Minkowski distance:

$$L = \left[w_i^p \left(\frac{f_i^* - f_i}{f_i^* - f_i^-} \right)^p \right]^{1/p}$$

(5.1)

f_i is the value for criteria i ; f_i^*, f_i^- are the positive and negative ideal values for criteria i, respectively; w_i is a weight, indicates relative importance of a criteria; L is the distance from an ideal solution; and p is the distance metric exponent. It is assumed that $\sum w_i = 1$. Typically, the Euclidean distance (p=2) is used to penalize large deviations from the ideal. However, the exponent can also carry an economic interpretation. The Hamming distance (p=1) results in a case of perfect compensation between criteria. For the Chebychev distance (p=α), there is no compensation among criteria - the largest deviation from the ideal dominates the assessment.

Many of the traditional MCDM techniques, including compromise programming, attempt to preserve some level of transparency to problems. This is a valuable strength for decision

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makers. However, compromise programming (like most MCDM techniques) only makes use of a limited amount of information. Extensive sensitivity analysis is necessary to recommend any kind of recommendation with confidence. The marriage of a transparent technique such as compromise programming with fuzzy sets is an example of a hybrid decision making tool available to future planners.

5.4 Existing applications using fuzzy ideals

Leung (1982) used the fuzzy ideal concept in multicriteria conflict resolution. Leung defines a fuzzy ideal solution, generates a membership function for each alternative (based on relative satisfaction or closeness to the ideal) and ranks alternatives based on the relative closeness to the ideal using distance metrics. In Leung's method, no weights are used, and the decision space is not defined by the criteria values, it is defined by the fuzzy membership (relative satisfaction) values. For this to occur, fuzzy sets representing level of satisfaction must be used to translate the criteria values. In order to accommodate conflict resolution, the decision space is treated as continuous - connecting the discrete (fuzzy) alternatives and searching for a location with the shortest distance to the fuzzy ideal.

Lai *et al* (1994) used distance metrics and the concept of a displaced ideal to reduce a multiobjective problem to a two objective problem. They are to (i) minimize the distance to an ideal solution and (ii) maximize the distance to the worst solution. Membership functions are assigned to the ideal and worst solutions to fuzzify the problem, weights are used to resolve the two remaining objectives. Decisions are reached by formulating the problem as a fuzzy linear programming problem, and solved in the standard Bellman and Zadeh (1970) approach.

An example of fuzzy compromise decision making can be found in Bardossy and Duckstein (1992), where a MCDA problem is evaluated using a distance metric with one of the criteria being qualitative and subjective. A codebook, a set of membership functions used to describe categories of subjective information, is established which translates a cardinal scale selection of the subjective criteria into a fuzzy set. Application of the extension principle to combine the single fuzzy criteria with other, quantitative, criteria is demonstrated graphically.

Bardossy and Duckstein (1992) and a similar paper by Lee *et al* (1994), who provide examples of using a fuzzy displaced ideal.

5.5 *Fuzzy arithmetic operations*

The theory of fuzzy sets, initiated by Zadeh (1965), defines a fuzzy set, *A* by degree of membership, $m_A(x)$, over a universe of discourse, *X*, as

$$m_A : X \rightarrow [0,1] \qquad (5.2)$$

Fuzzy sets are indications of a level of possibility, as opposed to probability. Figure 5.1 provides an example of a triangular fuzzy set, which is also normal and unimodal. Normality is satisfied by at least a single value with a possibility $m(x)=1$. Figure 5.1 shows a unimodal set because there is only one peak. The function which defines $m(x)$ is piecewise linear, but can be any function which satisfies the above equation.
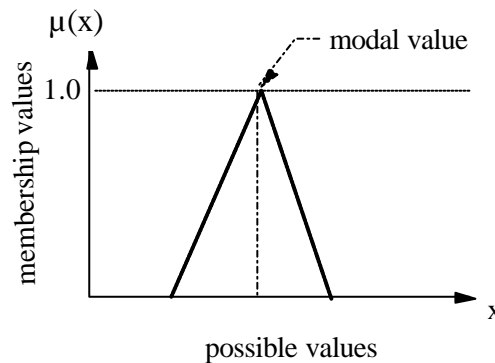
Figure 5.1 A fuzzy set

One of the important characteristic properties of a fuzzy set is its degree of fuzziness. As the range of valid *x* values increases, the degree of fuzziness increases. Also, as more valid *x* values become more possible (higher membership values), the degree of fuzziness increases.

Many operations on fuzzy sets use connectives called triangular norms: t-norms and s-norms. t models the intersection operator in set theory. Likewise, s models the union operator. The min and max operators are commonly used for t and s respectively, although the family of

valid triangular norms is very large. Composition operators are also used to connect fuzzy sets. They include sup and inf. The sup operation is the supremum or maximum of its membership function over a universe of discourse. Likewise, inf refers to the minimum. The combination of composition operators and connectives produces a powerful framework for many operations. Sup-t compositions (max-min), and inf-s compositions (min-max) are examples used in fuzzy operations. There are many texts on fuzzy sets, including Dubois and Prade (1978), Zimmerman (1987), Mares (1994) and Sakawa (1993).

Fuzzy arithmetic is made possible by Zadeh's extension principle, which states that if f : $X \circledR Y$ is a function and A is a fuzzy set in X then $f(A)$ is defined as

$$\boldsymbol{m}_{f(A)}(y) = \sup_{x \in X \,;\, f(x)=y} \boldsymbol{m}_A(x) \tag{5.3}$$

where $f : X \circledR Y, \; y \; \hat{\boldsymbol{I}} \; Y$

From this extension principle, fuzzy arithmetic operations such as addition, subtraction, multiplication, division and exponentiation can be described.

5.6 Fuzzy compromise approach

5.6.1 Fuzzy distance metrics

Changing all inputs from crisp to fuzzy and applying the fuzzy extension principle can accomplish (Bender and Simonovic, 2000) the transformation of a distance metric to a fuzzy set. Measurement of distance between an ideal solution and the perceived performance of an alternative can no longer be given a single value, because many distances are at least somewhat valid. Choosing the shortest distance to the ideal is no longer a straight forward ordering of distance metrics, because of overlaps and varying degrees of possibility. The resulting fuzzy distance metric, as the following approach will attempt to demonstrate, contains a great amount of additional information about the consequences of a decision and the effect of subjectivity.

The process of generating input fuzzy sets is not trivial but there are many available techniques for encoding information and knowledge in a fuzzy set. The process of generating appropriate fuzzy sets, accommodating available data, heuristic knowledge, or conflicting opinions, should be capable of presenting information accurately. Appropriate techniques for fuzzy set generation should be considered to be specific to the type of problem being addressed, the availability of different types of information and the presence of different decision makers.

Fuzzification of criteria values is probably the most obvious use of fuzzy sets. There is a long history of published articles demonstrating decision problems with qualitative or subjective criteria. Fuzzy sets are able to capture many qualities of relative differences in perceived value of criteria among alternatives. Placement of model values, along with curvature and skew of membership functions can allow decision makers to retain what they consider degree of possibility for subjective criteria values.

Selection of criteria weights is an aspect, which is typically subjective, usually with a rating on an interval scale. As a subjective value, criteria weights may be more accurately represented by fuzzy sets. Generating these fuzzy sets is also a subjective element. It may be difficult to get honest opinions about degree of fuzziness from a decision maker. It might actually be more straightforward to generate fuzzy sets for weights when multiple decision makers are involved. Then, at least, voting methods and other techniques are available for producing a composite, collective, opinion. Regardless, more information can be provided about valid weights from fuzzy sets than from crisp weights.

Ideal values for criteria may also be very subjective. Certainly, the ideal solution may be significantly more subjective than the perceived performance of an alternative. For example, if profit is a criterion, what is the ideal amount of profit?

The distance metric component, p is likely the most imprecise or vague element of distance metric calculation. There is no single acceptable value of p for every problem and it can be easily misunderstood. Also, it is not related to problem information in any way except by providing parametric control over interpretation of distance. Fuzzification of the distance metric exponent, p, can take many forms but in a practical way it might be defined by a

triangular fuzzy set with a mode of two. Larger or smaller (fuzzy) values of p may also be valid but fuzzy exponential operations for large exponents results in difficult interpretation of the distance metric due to a large degree of fuzziness (range of possible values).

The benefits of adopting the general fuzzy approach compromise programming are many. Probably the most obvious is the incorporation of subjective uncertainty. Expressing possibility values with fuzzy inputs allows experience to play a significant role in the expression of input information. The shape of a fuzzy set expresses the experience or the interpretation of a decision maker. Conflicting data or preferences can also be easily expressed using multimodel fuzzy sets, making the fuzzy compromise approach a candidate for application to group decision-making.

Nonfuzzy distance-based techniques measure the distance from an ideal point, where the ideal alternative would result in a distance metric, $L : X \rightarrow \{0\}$. In a fuzzy compromise approach, the distance is fuzzy, such that it represents all of the possible valid evaluations, indicated by the degree of possibility or membership value. Alternatives that tend to be closer to the ideal may be selected. This fuzzified distance metric is analogous to a sensitivity analysis for the nonfuzzy case.

5.6.2 Selecting acceptable alternatives

The fuzzy compromise approach is further able to support decision analysis exercises by ranking the alternatives according to perceived performance. As an attempt to standardize a procedure for judging, which L is best among a set of alternatives, desirable properties can be defined. The most important properties are:

- Possibility values tend to be close to the ideal, x=0, distance.
- Possibility values have a relatively small degree of fuzziness.

Some other performance indicators might favour model values close to the ideal, or possibility values, which tend to be far from poor solutions.

An aspect of comparing fuzzy distance metrics is the possible occurrence of points of indifference between fuzzy sets. If the rising limb of a fuzzy distance metric (the arc which is closest to the ideal distance of zero) were to intersect the rising limb of another fuzzy distance

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metric (i.e., equal membership values for two or more alternatives at some distance from the ideal) – a point of indifference would exist. The concept of indifference may vary. Interpretation of "best" depends on which side of the indifference point is considered to be interesting in the evaluation of comparative best. In the special case where the modes are equal, while the rising and falling limbs vary drastically, selection of the mode as the point of interest in ranking the sets will result in equal ranking. Awareness of these indifference points may not be directly evident when ranking alternatives, but indifference points (depending on their bcation) cause ranking orders to change when different levels of risk tolerance are specified. The ability to express risk tolerance will be explored further.

Relative performance of alternatives may be visually intuitive when looking at the fuzzy distance metrics but in cases where many alternatives display similar characteristics, it may be impractical or even undesirable to make a visual selection. A method for ranking alternatives can automate many of the visual interpretations – and create reproducible results. A ranking measure may also be useful in supplying additional insight into decision maker preferences, such as distinguishing relative risk tolerance levels.

Selection of ranking method is subjective and specific to the form of problem and the fuzzy set characteristics, which are desirable. A taxonomic examination of existing methods can be found in Bortolan and Degani (1985). There exists an assortment of methods ranging from horizontal and vertical evaluation of fuzzy sets, to comparative methods. Some of these methods may independently evaluate fuzzy sets, while others use competition to choose among a selection list. Horizontal methods are related to the practice of defuzzifying a fuzzy set by testing for a range of validity at a threshold membership value. Vertical methods tend to use the area under a membership function as the basis for evaluation, such as center of gravity. The comparative methods introduce other artificial criteria for judging the performance of a fuzzy set, such as a fuzzy goal. The following methods are vertical and comparative, respectively. A discussion of their properties follows.

5.6.3 Weighted center of gravity measure

Given the desirable properties of a ranking method for the fuzzy compromise approach, one technique which may be qualify as a candidate is the centroid method, as discussed by Yager

(1981) in terms of its ability to rank fuzzy sets on the range [0,1]. The centroid method appears to be consistent in its ability to distinguish between most fuzzy sets. One weakness, however, is that the centroid method is unable to distinguish between fuzzy sets which may have the same centroid, but greatly differ in their degree of fuzziness. The weakness can be somewhat alleviated by the use of weighting. If high membership values are weighted higher than low membership values, there is some indication of degree of fuzziness when comparing ranking from different weighting schemes. However, in the case of symmetrical fuzzy sets, weighting schemes will not distinguish relative fuzziness.

A weighted centroid ranking measure (WCoG) can be defined as follows:

$$WCoG = \frac{\int g(x)\,m(x)^q\,dx}{\int m(x)^q\,dx} \qquad (5.4)$$

where $g(x)$ is the horizontal component of the area under scrutiny, and $m(x)$ are membership function values. In practice, WCoG can be calculated in discrete intervals across the valid universe of discourse for L. WCoG allows parametric control in the form of the exponent, q. This control mechanism allows ranking for cases ranging from the model value $q = (\infty)$ – which is analogous to an expected case or most likely scenario, to the center of gravity ($q = 1$) – which signifies some concern over extreme cases. In this way, there exists a family of valid ranking values (which may or may not change too significantly). The final selection of appropriate rankings is dependent on the level of risk tolerance from the decision maker.

Ranking of fuzzy sets with WCoG is by ordering from the smallest to the largest value. The smaller the WCoG measure, the closer the center of gravity of the fuzzy set to the origin. As a vertical method of ranking WCoG values act on the set of positive real numbers.

5.6.4 Fuzzy acceptability measure

Another ranking method, which shows promise, is a fuzzy acceptability measure, Acc, based on Kim and Park (1990). They derived a comparative ranking measure, which builds on the method of Jian (1976) using the possibility measure to signify an optimistic perspective, and supplements it with a pessimistic view similar to the necessity measure (Nec).

The possibility measure, formally known as the degree of overlap between fuzzy sets, can be described as the possibility of something good happening and can be stated mathematically as:

$$Poss(G, L) = \sup_{x \in R} T\left(\mathbf{m}_G(x)\,\mathbf{m}_L(x)\right) \tag{5.5}$$

where T is a t-norm, L is the fuzzy set defined by $L{:}X \rightarrow[0,1]$ and G is a fuzzy goal, defined by $G{:}X \rightarrow[0,1]$.

The necessity measure gives a pessimistic view, formally known as the degree of containment, described as the necessity for ensuring something bad does not happen. Nec can be expressed mathematically as,

$$Nec(G, L) = \inf_{x \in R}\left(\mathbf{m}_G(x)\,s\,\overline{\mathbf{m}}_L(x)\right) \tag{5.6}$$

where, $\overline{\mathbf{m}}_L$ is the complement $(1 - \mathbf{m}_L)$ membership value.

These two measures, Poss and Nec, can be combined to form an acceptability measure (Acc):

$$Acc = \alpha Poss(G,L) + (1 - \alpha)\,Nec\,(G,L) \tag{5.7}$$

Parametric control with the acceptability measure (Acc) is accomplished with the α weight and the choice of the fuzzy goal, G. The α weight controls the degree of optimism and degree of pessimism and indicates (an overall) level of risk tolerance. The choice of a fuzzy goal is not so intuitive. It should normally include the entire range of L, but it can be adjusted to a smaller range for the purpose of either exploring shape characteristics of L or to provide an indication of necessary stringency. By decreasing the range of G, the decision maker becomes more stringent in that the method rewards higher membership values closer to the ideal. At the extreme degree of stringency, G becomes a nonfuzzy number requiring the alternatives be ideal. As a function, G may be linear, but can also adapt to place more emphasis or less emphasis near the best value ($x = 0$ for distance metrics).

Ranking of fuzzy sets using Acc is accomplished by ordering values from largest to smallest. That is, the fuzzy set with the greatest Acc is most acceptable. Acc values are restricted on the range [0,1] since both the Poss and Nec measures act on [0,1] and α reduces the range of possible values by a factor of 2.

5.6.5 Comparison of ranking methods

Comparison of ranking methods WCoG and Acc with those reviewed by Bortolan and Degani (1985), suggested both to be superior to the methods given in the review, given the desirable properties of L. The problem with many available methods is that, although most are able to correctly identify the best fuzzy set, they may not be capable of distinguishing both degree of dominance and provide an ordinal ranking for more than two fuzzy sets. Many methods supplied ranking values, for example as {1,0,0} for three fuzzy sets. Very little decision information is returned by those methods. Relative dominance among fuzzy sets is an important aspect for distinguishing between fuzzy distance metrics. Both WCoG and Acc provide information of this type.

WCoG is conceptually simple and visually intuitive. It's weakness in discerning between fuzzy sets with the same shape and model value, yet with different degrees of fuzziness is offset, somewhat, by the unlikely event of having distance metrics with those properties. Fuzzy distance metrics may have very similar shapes considering that all alternatives are evaluated for the same fuzzy definition of p. They may also have similar modes, depending on criteria values. Degree of fuzziness, or at least some discrepancy in shape, provides the means by which the weighting parameter q is able to distinguish indifference points. In general, though, interpretation of difference points is not usually very sensitive to the choice in q.

Acc provides more comprehensive and possibly more relevant parametric control over the interpretation of results. Acc is able to explore the "surface" of fuzzy distance metrics with a meaningful interpretation of the variables used for parametric control (α, G). However, the parameters for the Acc measure are difficult to justify if some combination is used to recommend an alternative. The appropriate use of Acc is strictly to determine sensitivity, if any, of alternative rankings to different attitudes displayed by a decision maker.

Regardless of the combination of characteristics for fuzzy distance metrics, both the WGoC and Acc methods produced similar results, which correspond with visual interpretation of fuzzy distance metrics. Both may prove to be useful in a decision-making problem with

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multiple alternatives. Choosing just one of these methods or a completely different method (of which there are many), should be dependent on the desirable ranking properties of the given problem. In some cases, it may be advantageous to use more than one method as a form of verification.

5.7 Application of the fuzzy compromise programming

The Tisza River in Hungary was studied by David and Duckstein (1976) for the purpose of comparing alternative water resources systems for long-range goals. They attempt to follow a cost effectiveness methodology to choose from five alternatives, but many of the twelve criteria are subjective as shown in Table 5.1. Eight criteria are subjective and have linguistic evaluations assigned to them. Six of these subjective criteria are considered on a scale with five linguistic options {excellent, very good, good, fair, bad}. Two criteria are judged by different linguistic scales {very easy, easy, fairly difficult, difficult} and {very sensitive, sensitive, fairly sensitive, not sensitive}. David and Duckstein (1976) provided numeric differences along an interval scale are given so that a discordance index can be calculated for the ELECTRE method.

Table 5.1 Original values used in David & Duckstein (1976)

Criteria	Alternative				
	I	II	III	IV	V
Total annual cost	99.6	85.7	101.1	95.1	101.8
Probability of water shortage	4	19	50	50	50
Energy (reuse factor)	0.7	0.5	0.01	0.1	0.01
Land and forest use (1000ha)	90	80	80	60	70
Water quality	Very good	Good	Bad	Very good	Fair
Recreation	Very good	Good	Fair	Bad	Bad
Flood protection %	Good	excellent	Fair	Excellent	Bad
Manpower impact	Very good	Very good	Good	Fair	Fair
Environmental architecture	Very good	Good	Bad	Good	Fair
Development possibility	Very good	Good	Fair	Bad	Fair
International cooperation	Very easy	Easy	Fairly difficult	Difficult	Fairly difficult
Sensitivity	Not sensitive	Not sensitive	Very sensitive	sensitive	Very sensitive

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David and Duckstein (1976) provided criteria weights to calculate the concordance index of ELECTRE. Weights were supplied from the set of {1,2}. The technique used by ELECTRE somewhat alters the weighting issues in its use of a concordance index, and weights are not needed to calculate a discordance index, but it is not known what effect uncertainty in the weights has on assessing alternative tradeoffs.

As a conclusion, David and Duckstein (1976) suggest that a mix of systems I and II would be appropriate since they appear to somewhat dominate the other alternatives and show no overall domination over each other. Duckstein and Opricovic (1980) reached similar conclusions for the same system, using a different artificial scaling for subjective criteria. A sensitivity analysis is implied by David and Duckstein (1976) to be the next logical step in the planning of the Tisza River basin. Changes to the data, weights and time horizon are suggested. Although changes to the data may have probabilistic implications, criteria weights and certainly the impact of the time horizon are more vague because many may be possible and entirely valid. Bender and Simonovic (2000) showed that the treatment uncertainties as fuzzy as a useful improvement in evaluating water resource systems such as the Tisza River.

Figure 5.2 shows the fuzzy definitions for linguistic terms used in assessing subjective criteria. Quantitative criteria are also fuzzified, but generally are less fuzzy.

Other fuzzy inputs include the expected ranges of criteria values as presented in Figure 5.3a and the form of distance metric or degree of compensation among criteria for different alternatives as shown in Figure 5.3b. Criteria weights are fuzzified on a range of [0,1] by simple scaling of the weights used by David and Duckstein (1976) as {1,2} $\rightarrow$ {0.33,0.66} (Figure 5.3c).
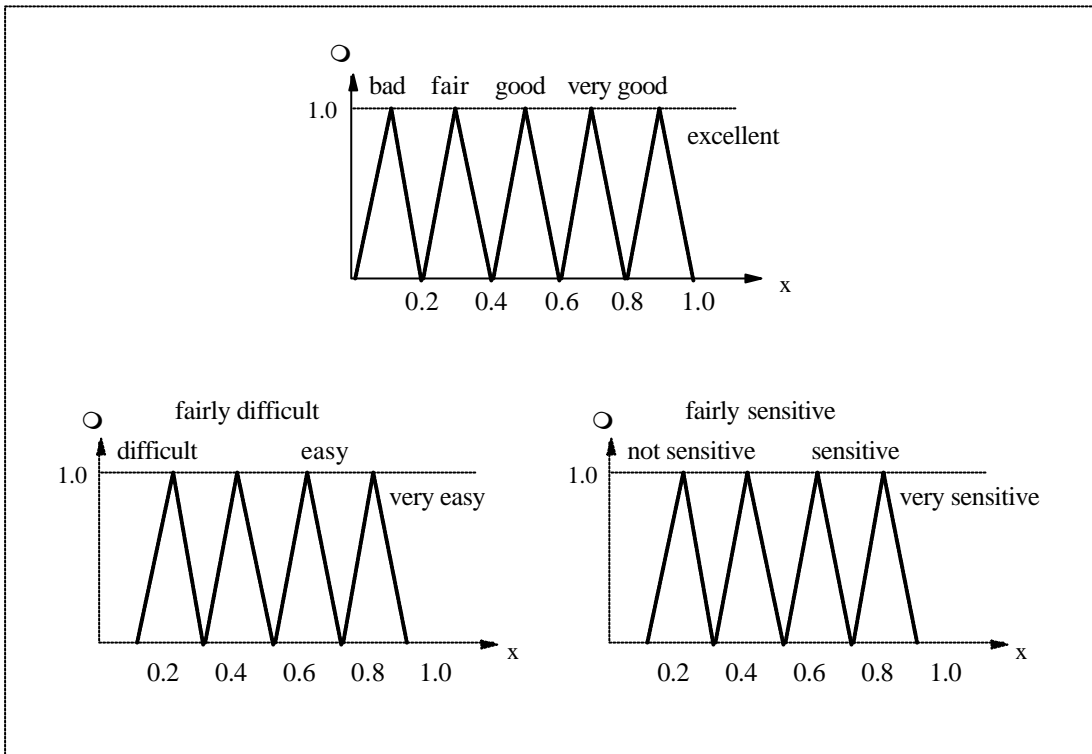
Figure 5.2 Fuzzy subjective criteria interpretation for the Tisza River problem (after Bender, 1996)
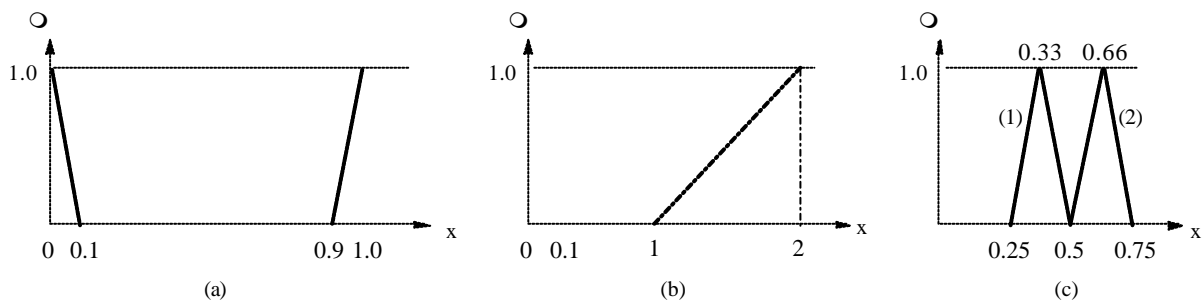
Figure 5.3 Fuzzy input for the Tisza River problem (after Bender, 1996)

Assuming the fuzzy definition for the distance metric component (p), and knowing the form of criteria values and weights to be triangular, the resulting fuzzy distance metric (L_i) poses the characteristic shape (Figure 5.4) of near linearity below the mode and a somewhat quadratic polynomial curvature above the mode. Although the degree of fuzziness is similar for all five alternatives, some of the alternatives are clearly inferior.
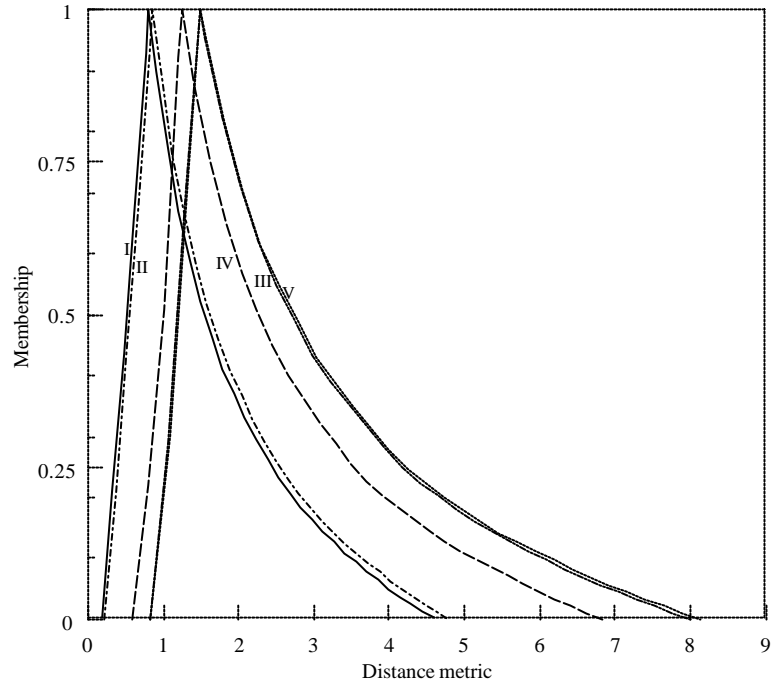
Figure 5.4 Distance metrics for the Tisza River problem (after Bender, 1996)

Ranking of these alternatives is reasonably straightforward because of the simplicity of the shapes and similarity in degree of fuzziness. Both WCoG and Acc measures produced expected results given in Table 5.2 for arbitrary parameter settings on both methods. Rankings were insensitive to changes in levels of risk aversion as would be expected from visual inspection. The resulting ranks confirm the findings of David and Duckstein (1976), that alternatives I and II are dominant.

Table 5.2 Tisza River alternative rankings from WCoG and Acc measures (after Bender, 1996)

Rank	Alternative	WCoG (p = 1)	Acc (G:[0,8], α=0.5)
1	1	1.49	0.81
2	2	1.59	0.80
3	4	2.38	0.75
4	3	2.83	0.72
5	5	2.85	0.71

In a live case study with multiple decision makers, there are opportunities for a group emphasis to collectively adjust the fuzzy inputs. The rankings may change considerably because the values defined for this experiment are predominantly simple triangular membership functions, given the form of nonfuzzy input data. Adjustments to relative fuzziness and the presence of conflicting opinions will significantly alter the shape of the fuzzy distance metric, particularly within the vicinity of the model value.

5.7.1 Collaborative decision-making

Group decision-making involving stakeholders are important in conflict resolution processes. A fuzzy compromise approach facilitates more collaborative exploration of available alternatives and their associated risks. Increasing or decreasing the fuzziness of the inputs and by locating ranges or multiple points of opinion incorporates collective opinions. Fuzzy sets are able to process this kind of information and are also able to present it effectively and intuitively.

In the approach, by allowing direct control over the definitions of fuzzy sets, stakeholders are able to experiment with different fuzzy definitions for parameter uncertainties. This promotes a better understanding of consequences for changes in accuracy when viewing the resulting rankings Each stakeholder brings a unique flavour to the planning process, in terms of their level of risk aversion and their interpretation of uncertainties in alternative performance. The interactive feedback to stakeholders about potential changes in ranking from different perceptions of uncertainty (i.e., level of risk aversion) may explain many idiosyncrasies in the opinions of different stakeholders.

Overall, the role of fuzzy evaluation of alternatives is to promote stakeholder understanding of relative performance of alternatives, given multiple source of uncertainty. The fuzzy compromise approach presented here is an example of a technique, which can be relatively transparent and intuitive and allows direct control by stakeholders.

6. Future Outlook

6.1 General

In many places in this world water is a stressed resource. Population and regulatory pressures, political and economic instabilities and variation of climate can all contribute to further pressure to extract more out of existing sources and also to move further away from where the demand is to tap additional sources. This brings neighbouring political entities into a situation of potential conflict.

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). In the past, many different tools have been used for simulation and optimization of complex water resources systems in order to provide improved basis for decision making. To offset the pressure on water in the future, water management will rely more and more on sophisticated information management technology. The continuing evolution of information technology creates a good environment for the transition to new tools. Some current trends are indicating stronger future reliance on computer networking, easily accessible databases, decision support systems, object oriented programming and system dynamics simulation.

6.2 Tools for future water management

Complexity and uncertainty are two paradigms that will shape the tools for future water management (Simonovic, 2000). The first one is focusing on the complexity of the water resources domain and the complexity of the modeling tools in an environment characterized 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.

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6.2.1 Complexity paradigm

Water related problems in future are going to be more complex. Domain complexity is increasing as shown in Figure 6.1. In the past water resources development works were created to satisfy quantity requirements of smaller communities. However, with the population growth, large-scale water resource development projects were required over larger spatial scales. Besides the concern over the environmental and social impacts of water resource management is also increasing. Along with the above factors, the climate variability and regulatory requirements are increasing the complexity of present water resources management problems and complexity will continue to rise in future. When several parties share a single water resource, satisfaction of these diverse interests of stakeholders involved may affect others leading into conflicts. Complexity of the conflicts will naturally increase with the complexity nature of future water management activities.
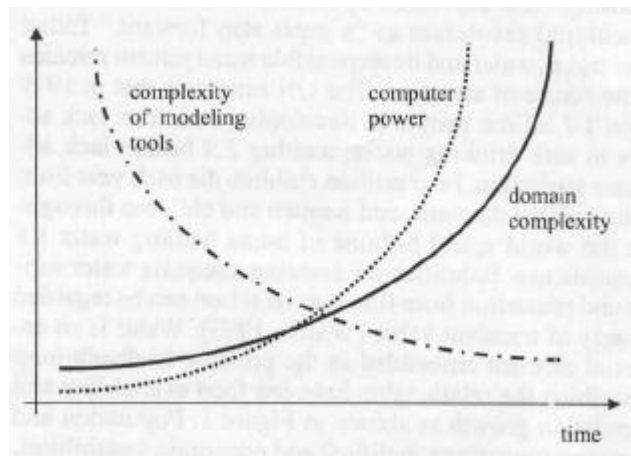
Figure 6.1 Schematic presentation of the complexity paradigm (after Simonovic, 2000)

Rapid increase in the processing power of computers is the second complexity paradigm as presented in Figure 6.1. Since 1950, use of computers in water resources management has steadily grown. Computers "the machines that changed the world" have moved out of data processing into information and knowledge processing. Computer has become a "silent partner" for more effective water resources decision-making (Simonovic, 1996a, 1996b). 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).

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The third component of the complexity paradigm is the reduction of complexity of tools used in water management (Figure 6.1). Introduction of systems analysis is the most important advancement made in the field of water management in the last century (Friedman *et al*, 1984; Yeh, 1985; Rogers and Fiering, 1986; Wurbs, 1998). Simonovic (2000) defined systems analysis as an approach for representing water-related problems using a set of mathematical planning and design techniques that are solved using computer. System analysis techniques, which are often called "operations research", "management science" and "cybernetics", include simulation and optimization techniques that are used in water resources development and management. Systems analysis is particularly promising when scarce resources must be used effectively.

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. However, simulation models developed for the management of water in the early stages were complex. Most generalized models were 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 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, 1995; 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.

Application of optimization techniques in water management is popular. Linear programming (LP) is applied to problems that are formulated in terms of separable linear objective functions and linear constraints. However, neither objective functions nor constraints are

linear in most practical water management applications. With the use of different schemes for the linearization of non-linear relationships and constraints, LP has been used to tackle non-linear problems.

Non-linear programming (NLP) is an optimization approach used to solve problems when the objective function and the constraints are not in the linear form. Though a few successful applications are reported in literature, NLP is not very popular in water resources management. The inability to distinguish between a local optimum and a global optimum may be one reason for that. 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 and water network distribution problems. However, the main problem of global optimality remains an obstacle in practical applications for NLP.

Dynamic programming (DP) can handle non-linear objective functions and constraints and therefore, has been very frequently used in water resources management. To overcome the limitations in DP known as "curse of dimensionality", DP with some modifications has been used in water management. These include discrete differential dynamic programming, differential dynamic programming.

Evolutionary algorithms, which shows a high efficiency and ability in finding global optimum has gained much recognition among researchers in water management sector (Simonovic, 2000). 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 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 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". This group of algorithms

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includes, among others, evolution strategy (Back *et al*, 1991), evolutionary programming (Fogel *et al*, 1966), genetic algorithms (Holland, 1975), simulated annealing (Kirkpatric *et al*, 1983) and scatter search (Glover, 1999). Evolutionary algorithms are becoming more prominent in the water management field. Work of Goldberg and Kuo (1987), Wang (1991), Murphy *et al* (1993), Simpson *et al* (1994), McKinney and Lin (1994), East and Hall (1994), Fahmy *et al* (1994), Davidson and Goulter (1995), Franchini (1996), Dandy *et al* (1996), Oliveira and Loucks (1997), Savic and Walters (1997), Wang and Zheng (1998), Wardlaw and Sharif (1999), Ilich and Simonovic (1998) are some examples. 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.

6.2.2 Uncertainty paradigm

The first component of the uncertainty paradigm is the increase in all elements of uncertainty in time and space as presented in Figure 6.2. Simonovic (2000) suggested that the uncertainty in water management could 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 labeled 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. In water resources management variability is mainly associated with the spatial and temporal variation of hydrological variables.
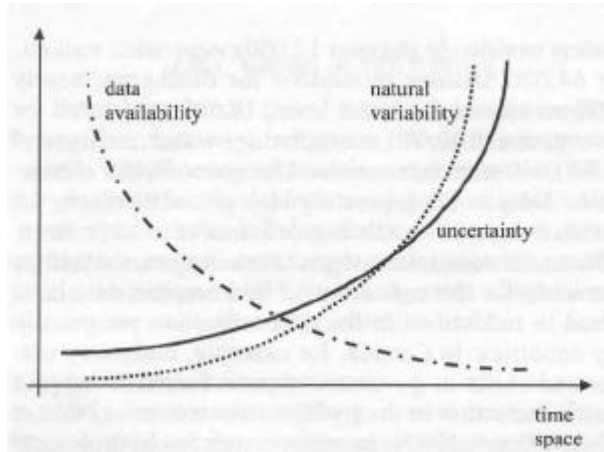
Figure 6.2 Schematic presentation of uncertainty paradigm (after Simonovic, 2000)

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 shown in Figure 6.3.
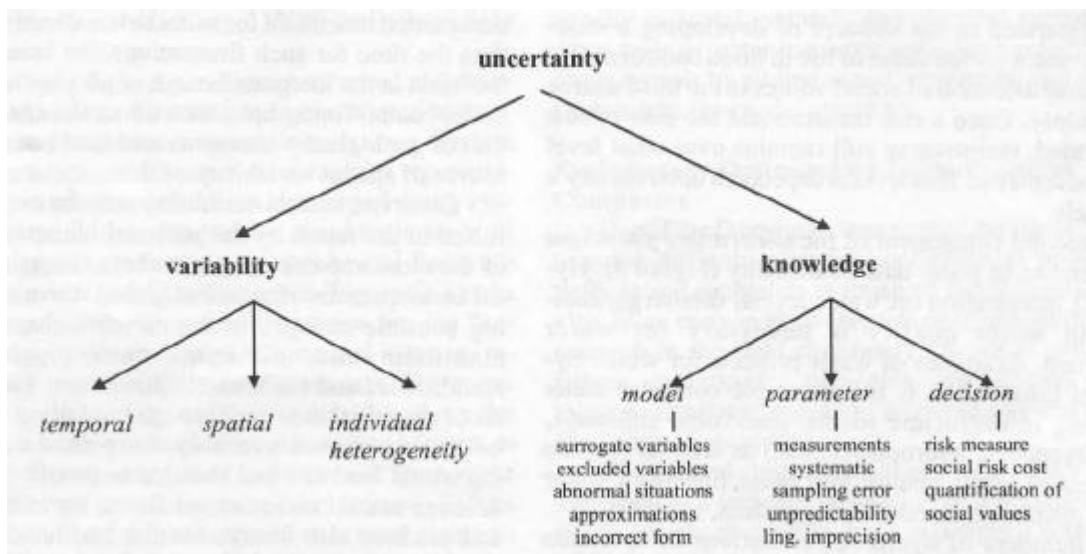
Figure 6.3 Sources of uncertainty (after Simonovic, 2000)

Model uncertainty refers to the knowledge of a process. Models are simplified representations of real world processes and model uncertainties can arise from

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oversimplification or from the failure to capture important characteristics of the process under investigation. The major sources of this type of uncertainty are shown in Figure 6.3.

The next general category of uncertainty is parameter uncertainty. It is the fine-tuning of a model and cannot cause the large variations found in model uncertainty. The third type 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 decrease in water data availability is the second component of the uncertainty paradigm as shown in Figure 6.2. Hydrological information is indispensable for water management. Though the number of hydrological stations in operation worldwide as reported by WMO (1995) is very impressive, their distribution is not uniform, being scarce over large areas. Further, financial constraints of governments have resulted in reduction in the data collection programmes all over the world.

The third component of the uncertainty paradigm is the increase in natural variability of water availability. Water flow exhibits considerable temporal and spatial variation. This variation is not detected if the selected time scale for water balance analyses is longer than the time for such fluctuation. Observed natural variability may be even further affected by the potential climate change.

6.3 *Future tools for water management*

Based on the two paradigms described above Simonovic (2000) presented four main directions in which future water management tools will be developed. They are (a) object oriented simulation, (b) evolutionary optimization, (c) integration of fuzzy set analysis with simulation and optimization tools and (d) integration of spatial analysis with simulation and optimization tools.

6.3.1 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.

The power and simplicity of use of objective 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

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allows enhancement of water models by adding social, economic and ecological sectors into the model structure.

6.3.2 Evolutionary optimization using powerful computers

Use of Darwinian "survival of the fittest" approach to solve difficult numerical optimization problems in various different forms such as genetic algorithms, evolutionary strategies, evolutionary programming or simulated annealing, 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 solutions that are selected as "parents" are capable of producing better "offspring." A termination 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

6.3.3 Integration of fuzzy analysis with simulation and optimization tools

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 (2000) 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 favourable. 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.

6.3.4 Integration of spatial analysis with simulation and optimization

Most of the simulation and optimization tools used in 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.

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.

6.4 Use of virtual databases

Collection of data or information and sharing them among stakeholders is very vital in the water conflict resolution process. The advancement of computer sciences and information technologies provides improved measures in handling data and information. The present Internet technology is mature enough to support the development of virtual databases for a complex domain such as water related conflict resolution. This mode of support has many advantages when compared to more traditional centralized database models. The virtual database (VDB) is an Internet based data catalog that facilitates search by data type, custodian, location, and other attributes from a distributed confederation of data holding organizations.

The data required in water conflict management consists of a variety of data sets, each of which is used for specific purposes. The type of data related include:

- Topographic data (elevations, land use, soils, vegetation, hydrography, etc.)
- Imagery (satellite images, aerial photographs, etc.)
- Administrative data (political boundaries, jurisdictional boundaries, etc.)
- Infrastructure data (roads, levees, wells, utilities, bridges, hydraulic structures, etc.)
- Environmental data (threatened and endangered species, critical aquatic and wildlife habitat, archeological sites, water quality, etc.)
- Hydrometeorologic data (flood plain delineation, stream flows, precipitation, temperature, wind, solar radiation, soil moisture, etc.)
- Economic data (industries, etc.)
- Emergency management data (emergency plans, census data, organizational charts, etc.)

There is a large amount of relevant data that is usually maintained by various agencies, each with different levels of complexity. In general, each data series may consist of several data sets. Each data set may contain several features. A data base system is a combination of one or more databases and a database management system. A database is a collection of data, and a database management system is a collection of programmes that enable users to create and maintain a database.

The Internet technology can be used to support data collection, processing and dissemination. At present, the Internet can be accessed through the local area network (LAN), telephone line, cable, or wireless (mobile) technology. Convenience that the Internet provides includes information browsing, database access and file transfers at any time and from nearly anywhere.

Two approaches can be considered in building an internet-enabled database system: centralized approach involves collecting data from different sources and storing them in a single dedicated database at one location. A web site connecting to this database is necessary to supply query interfaces to web clients. Distributed approach does not require centralized data storage. Instead, the data can be stored in the database of data provider and accessed through the Internet. This type of database solution relies on more advanced Internet and computer science technology and is known as the Virtual Database.

6.4.1 Evaluation of user data needs

At the beginning of VDB development it is necessary to communicate with all the stakeholders involved in the conflict to capture all the relevant data and (numerical and descriptive) information, aspirations, proposals, modeling tools etc.

6.4.2 Virtual database architecture

To present a conceptual architecture of a VDB, one developed for Red River basin in Canada for a flood management study (Simonovic, 2002) is presented in Figure 6.4, as an example. It shows the general configuration in terms of communication and data accessibility across a distributed or remote network of sites. Data providers have several options for providing access to data sets. These include:

a. Data Provider 1 stores its metadata on an external web server, but then retrieves information from within its firewall from internal operational systems. Data can be retrieved from this data provider online through a transactional system.

b. Data Provider 2 stores its metadata on an external web server and replicates relevant public data also to the external web server. No access through the firewall is permitted. The replication is intended to synchronize internal data sources with the external data

store. Data can be retrieved from this data provider online via an application of FTP service.

c. Data Provider 3 stores its metadata on an external web server and posts static public data to an FTP site on the external server. Data can be retrieved from this data provider online via an FTP service.

d. Data Provider 4 stores its metadata only on an external web server and provides no access to internal or external data sources. Data cannot be retrieved from this data provider on line. A formal request for required data may be fulfilled in an offline process.
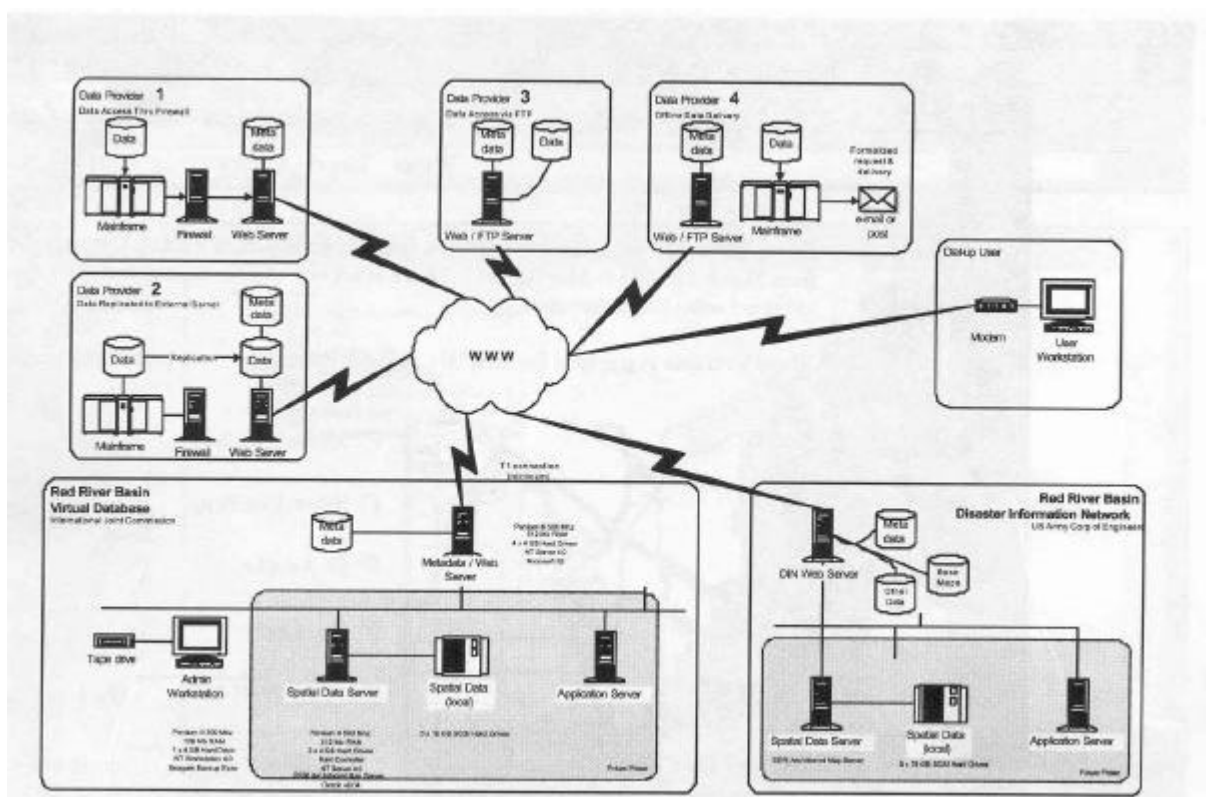

Figure 6.4 Schematic presentation of the virtual database concept (after Simonovic, 2002)

Simonovic (2002) discussed architecture and technical requirements of a virtual database in detail based on the virtual database developed for the management of floods of the Red River in Canada.

6.5 Decision support systems

A decision support system is envisioned as a tool for analyzing diverse development and management alternatives in water resources project. It makes decision-making process more transparent and efficient, which will aid in reducing future probable conflicts among different stakeholders.

Development of decision support systems (DSS) is closely related to computers. An acceptable definition in the context of water resources management is: " A Decision Support System allows decision-makers to combine personnel 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, semi-structured 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", (Simonovic, 1996, 1996a).

A DSS provides assistance to decision-makers, including database access, descriptive and predictive models, geographic information systems, methods to involve stakeholders in the basin and other tools and services.

6.6 Web Interaction

The World Wide Web (WWW) is a truly global communications vehicle and as such it plays an important role among the international water resources community. The Internet has exploded within the global development scenario as email and the WWW are finding many practical applications (Anderson, 1999). Environmental related information and activity are quite abundant on-line and water resources related websites and information have experienced a dynamic evolution in a relatively short timeframe.

In water resources management, specially in water related conflict resolution, providing all the stakeholders involved in the conflict with access to data, analysis tools and other relevent information is vital. It enables each interested party or stakeholder to investigate probable

solutions to the conflict by themselves and then negotiate with a better understanding of the consequences of the alternative solutions. Web can provide this opportunity of giving all the stakeholders the access to the tools developed to analyse the conflict and a common database, which is having data and information relevent to the water conflict.

An online database common to all stakeholders provides them easy access to the latest water resources information. The database should be easily accessible for both information retrieval and information updating. It allows the user community to update information themselves, distributing the maintenance workload and enhancing accuracy. The inclusion of relevant information from multiple subdisciplines under water resources (engineering, economic, social, environmental etc.) would be vital in conflict analysis processes.

Stakeholders should not only have access to the databases, but also should be able to use the decision support system developed to analyse the conflict from their own computer. Also they can use various web based decision support systems applicable in analysing their problem via Internet.

Web-Based DSS (internet) deliver decision support information or decision support tools to a manager or business analyst using a "thin-client" Web browser like Netscape Navigator or Internet Explorer that is accessing the Global Internet or a corporate intranet. The computer server that is hosting the DSS application is linked to the user's computer by a network with the TCP/IP protocol. Web-Based DSS can be communications-driven, data-driven, document-driven, knowledge-driven, model-driven or a hybrid. Web technologies can be used to implement any category or type of DSS. Web-based means the entire application is implemented using Web technologies; Web-enabled means key parts of an application like a database remain on a legacy system, but the application can be accessed from a Web-based component and displayed in a browser.

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