Negotiation Support for Cooperative Allocation of a Shared Water Resource: Methodology

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Abstract: The negotiation support system (NSS) proposed in this paper is designed to aid two parties in their negotiations for allocation of water from a shared water resource. The NSS has several components which are activated in a series of negotiating iterations: (1) creation/modification by each party of its utility function, using the analytic hierarchy process to structure and weight a set of objectives; (2) the water allocation system model for optimal economic allocation of water among districts and users in a specified territory, subject to physical, hydrological, legal, administrative and other constraints, which can be run by each party alone or by both jointly; and (3) a procedure for moving jointly in utility space toward efficient (Pareto) solutions in the current negotiation iteration, identification of the Nash equilibrium point on this frontier, and then seeking to move from this point beyond this temporary efficient frontier and create new values for both parties. The negotiation proceeds by alternating between individual analysis (each party in private) and joint problem solving by examination of alternatives in utility space. The NSS has been tested and evaluated in a series of simulations, which are the topic of a companion paper.

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Introduction

International or shared waters are surface and underground water resources whose watersheds are within the territory of more than one country. Many of the world's rivers cross or define international borders. According to Wolf [transboundary freshwater disputes database (TFDD)] there are 261 international river systems, which are home to about 50% of the world's population. Many of the world's aquifers are under the territory of two or more countries (Puri 2001).

Available quantities of the naturally renewable fresh waters are being exhausted in many parts of the world, and the problem of allocating and managing internationally shared water resources is becoming more acute. When dealing with water shortages, governments sometimes take unilateral actions, without considering the needs of their neighbors. Such policies alter the natural balance of quantities and qualities of water resources and can lead to international disputes and conflicts.

Management of international waters is difficult, since issues of control, jurisdiction, and sovereignty are extremely complicated. International law (United Nations 1997) does not provide unambiguous directives for allocation and management of international water resources (Shamir 1998). When claiming rights to shared waters, nations rely on their geographical position, historical rights, and often on their relative power. Conflicts over international waters are extremely complex because of the variety of interests involved and the meaning of water to human society: water is an issue of survival, of economic prosperity, of social implications, and of national political agendas. There are countries and regions where water bears important cultural and religious values. In many parts of the world, water resources are of strategic importance and, when scarce, they become a matter of a country's highest policy.

Within the boundaries of a country, allocation of water among neighboring political entities (states, provinces, counties, cities) is governed by national laws and institutes, and still similar allocation issues and conflicts arise here as well see for example Wolf, U.S. Domestic Water Compacts Data Base (Wolf 2007b). Thus, while the focus of this presentation is on the international context, the methodology is equally applicable to intranational cases of water allocation as well.

Characteristics of Negotiations over Internationally Shared Waters

Negotiations have been a common way to resolve disputes and avoid conflicts over shared water resources—more so than many people believe (Kliot et al. 2001a,b; Wolf 2007a). During the last two centuries, more than 400 treaties over international water resources have been signed, relating to water supply, navigation, flood control, hydroelectric power generation, industrial uses, pollution.

Negotiations over shared waters frequently last over long periods, sometimes several decades. Over this time, while management of the shared waters is not agreed, their quality and quantity may seriously decline and become inadequate for use by present

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and future populations and for maintenance of the ecosystems which they support (Gleick 1993).

The reasons for the extended duration of disputes and negotiations lie at the very heart of the issues at stake. Examples include: the Nile—between Egypt and the upstream riparian countries, negotiations ongoing from 1891 until recently; the Ganges-Brahmaputra-Meghna between India, Nepal, and Bangladesh from 1893 to 1996; the Jordan—between Israel, Jordan, and Syria from 1926 to 1995 and continuing (Wolf 2007a). More evidence for the length of negotiations over water are provided by Just and Netanyahu (1998) and Fisher et al. (2002, 2005). A country which depends on an international water resource places high priority on securing control over as large a share of that resource as possible. Since water is of high visibility and political importance, parties tend to conduct the negotiations as a zero-sum game on water quantities—even though water can produce many types of benefits when used wisely by the parties, and not merely divided between them. In the public arena, water is perceived and discussed in quantities only—the quantity that one party gains, the other loses. Bargaining in this manner leaves little or no space for exploring alternative solutions that will improve the benefits and better meet the objectives of both parties simultaneously. Concession on water quantities is perceived as a loss of value. When an agreement is reached, at least one of the parties may leave the table unsatisfied, sensing that it has lost some of the water that it considers to be its right. Furthermore, since international laws, regulations and institutions cannot enforce the countries to respect water agreements, there is a chance that if a party feels it lost too much water in the agreement it will not feel obligated to adhere to the agreement and will seek to exit.

The objectives which represent the value of water to a nation include both measurable ones (e.g., quantity of water, its cost, economic benefit) and subjective ones (e.g., internal politics, the religious significance of water, the effect of the negotiated agreement on social stability). The proposed negotiation support system (NSS) framework for negotiating allocations between neighbors therefore allows the parties to bring into consideration a wide variety of objectives, and provides each party with tools for comparing alternative outcomes in view of its own objectives. This framework is not based merely on multiobjective optimization; it recognizes that the process of moving toward a negotiated agreement is iterative and interactive between the parties, both in the space of decisions and the space of objectives.

Alternative Dispute Resolution

Management of international water resources and related conflicts have been a subject of interest in several fields, including hydrology and water resources management, international law, economics, game theory, multiobjective decision making, sociology, and psychology. Published works analyze the causes of successes and failures of international water negotiations from different aspects (Faure and Rubin 1993; Just and Netanyahu 1998; Delli Priscoli 2003). During the last 2 decades, there have been attempts to assess the potential of alternative dispute resolution (ADR) approaches in the specific area of environmental conflicts. The ADR approach includes a wide range of techniques with which the parties seek to achieve a joint settlement of issues. These techniques include dialogue and negotiation, and also mediation, facilitation, or arbitration. All these techniques are alternatives to simple bargaining processes that usually lead to "win-lose" solutions.

Delli Priscoli (2003) outlines the advantages of ADR to water resources management in general, and to international water disputes in particular. The aim of all ADR techniques is to move the disputing parties from a position-based to an interest-based dialogue. In disputes over water resources (as in many other fields), parties' positions (in particular the opening positions) do not necessarily represent their true interests, nor do these positions engender a productive dialogue toward resolution and agreement. As an example, a country's needs for fresh agricultural produce may be better served by allowing a neighbor that has a better water productivity to use more of the shared water, produce the necessary goods, and then trade. ADR is based on the premise that there often is more than one way to satisfy interests. Delli Priscoli (2003). concludes that when parties concentrate on positions then getting less water is perceived as a loss, while if they concentrate on interests they often find different ways to meet their interests, rather than just fighting over the quantities.

We propose a collaborative NSS to assist parties in searching for feasible and satisfying solutions to allocating and managing shared water resources (Kronaveter and Shamir 2006; Kronaveter 2005). The NSS is designed to improve communication and information exchange between the parties, to assist them in recognizing and formulating their own interests and objectives, and in exploring and evaluating alternative solutions to the allocation issues. The NSS is designed to support bilateral negotiations, although the basic principles embedded in the system can be applied to multilateral situations.

Water Scarcity and Economic Solutions

Water disputes often stem from water scarcity. However, scarcity may be the result of inefficient use or of preference being given to certain demand sectors, frequently to agriculture, without proper consideration of the economic value of water. According to some agricultural economists, a large fraction of water allocated to agriculture is producing little if any value net of cost. Low water prices contribute to overuse and deterioration of natural water resources, resulting in water shortages (Becker and Zeitouni 1998). Nevertheless, agriculture carries benefits beyond the economic. In many countries it helps to protect open spaces against excessive urban sprawl, adds green and healthy environments, maintains population distribution, and, significantly, is an important component of the national ethos that farmers are the nation's builders. These benefits express themselves in subsidies to farmers, often through water prices. The view of water economy that is embedded in our NSS recognizes such public/national benefits, and allows parties to express them in their willingness-to-pay functions.

The economic approach requires that the price of water to consumers should include, beside the costs of capital, extraction, and delivery, the scarcity rent of water at the source. This holds true for consumptive use of surface and groundwater, as well as to any nonconsumptive uses that reduce the benefit to other users. Scarcity rent takes into account the user cost due to scarcity (Fisher et al. 2002, 2005). Tietenberg (1992) and Jordan (1999) go even further by arguing that the scarcity rent should reflect not only the existing but also the potential future scarcity of water that results from today's extractions.

Supporters of the economic approach relate to water as an economic good, and propose allocation of water through a market mechanism, treating water as an ordinary economic good, and seeking to balance the marginal cost of the supply of water with the marginal willingness to pay. However, there are serious

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objections to imposition of a pure market mechanism in both domestic and international water allocation problems, the main argument being the inequity which causes the poorer parties to end up with less water. Opponents to the purely economic approach argue that water is a public good and a basic need which should be available at reasonable levels to everyone. Perry et al. (1997) state that water satisfies different needs, has properties that make it both a private and a public good, and therefore water policy must be formulated in terms of multiobjective decision making. We adopt this philosophy in the design of our NSS, and incorporate some concepts of a water market system to help in determining an optimal allocation of an international water resource. At the same time we allow the negotiating parties to introduce other objectives into their preference structure.

Overview of Negotiation Support Models

Kersten (1985a) defines group decisions and negotiations as situations that engage participants in two types of activities: communication and decision making. Negotiation support techniques are aimed at assisting the participants to form, represent, and analyze arguments, exchange information (including offers), and make compromised decisions.

Formal methods and models for group decisions and negotiations evolved from decision analytic methods for individual decision making (Kersten 1985a). Computer based tools and aids have been developed to assist the participants in group decision making and negotiations. NSSs are computer programs for interactive multiobjective conflict resolution (Kersten 1988; Thiessen and Loucks 1992). They can be categorized according to their functions as systems which assist one party only in preparing for negotiation, and systems used by the parties during the negotiation process itself. Nyhart and Goeltner (1987) further divide the second type into: (1) context support systems, which are used in negotiations over design, management, or operation of a system, and for the analysis of the performance of that system under various circumstances; and (2) process support systems, which are concerned with the dynamics of interaction between the negotiating parties. Both are aimed at increasing the likelihood of identifying mutually acceptable solutions when a space of such solutions exists, and at identifying solutions better than those that would have been found without their use (Thiessen and Loucks 1992).

Negotiation support systems have been developed for use in practice, as well as in training and research, in fields that cover various instances of human interaction. Examples of systems which model and support the dynamics of negotiations are PERSUADER (Sycara 1993) and International Communication and Negotiation Center (ICONSnet 2000) ⟨http://www.icons.umd.edu⟩ for support of multiple parties; MEDIATOR (Jarke et al. 1987); and NEGO (Kersten 1985b) which provide assistance to (or as) a third party—the mediator. The graph model for conflict resolution (GMCR) (Hipel et al. 1999) is a standalone decision support system (DSS) designed to aid one party in the negotiation-preparation phase and/or in determining a successful course of action during the negotiation process. NEGOTIATOR (Bui 1996), and GENIE (Wilkenfeld et al. 1995) are systems that can be used for individual decision support in multiparties negotiations.

In water resources management, computer programs that provide simulations of hydraulic and hydrologic processes can also be used as negotiation context support systems. Such are the programs developed by the U.S. Army Corps of Engineers' Hydraulic Engineering Center HEC-HMS (Hydrologic Modeling System), HEC-RAS (River Analysis System), and HEC-5 (The U.S. Army Corps of Engineers 2008) used to model runoff, analyze flood flows, and understand the performance of reservoirs, RiverWare, for river and reservoir modeling (Zagona et al. 2001), and Interactive River-Aquifer Simulation (IRAS) (Loucks et al. 1995). These models provide support for understanding the physical system and for evaluation of the system's behavior under options and alternatives proposed in a negotiation process. Interactive Computer-Assisted Negotiation Support System (ICANS) (Thiessen and Loucks 1992) is an example of a negotiation process support system with application to water resource conflicts. Based on information provided to the program, in confidence, by each party, it assists the parties in identifying feasible alternatives, if any exist, that should be preferred by each party in the absence of a negotiated agreement. If such alternatives do not exist, the program can help parties develop counterproposals. Through a series of iterations in which each party's input data, assumptions, and preferences may change, ICANS can aid the parties in their search for a mutually acceptable and preferred agreement. Examples of systems that integrate both context and process support include the Conflict Resolution Support System (CRSS) (Rajasekaram et al. 2002), a computerized technical support system developed to aid conflict resolution through five functional activities: communication, problem formulation, data gathering and information generation, information sharing, and evaluation of consequences. The basic tools included in the CRSS are for multipurpose reservoir operation, river flow routing, multicriteria decision making, and spatial data analysis. Shared vision modeling (Palmer et al. 1993) is an approach based on the premise that "models must reflect the effected parties' perspective of their water resources system." It requires identification of the stakeholders involved in the system and recognition of their primary concerns. The approach is combined with Systems Thinking for Education and Research, High Performance Systems, Inc. (STELLA II 2008), which is an object-oriented, graphical modeling environment that can simulate any water system. The stakeholders receive training in STELLA II, and develop a model of the physical system, with which they perform simulation of proposed alternatives and examine the outcomes and consequences of each. The model is considered joint property of all stakeholders, and is available during the process of negotiation and conflict resolution. OASIS (2008) (HydroLogics, Inc.) is a tool that enables parties with diverse and often conflicting goals—such as cities, power utilities, environmentalists, and agriculturalists—to work together to develop operating policies and solutions that best satisfy their diverse objectives.

The common features of these models which provide both context and process support of negotiations related to water resources are as follows:

1. They enable simulation of physical water systems and thus provide means for exploring proposed alternatives;
2. They require a joint definition of the problem by the parties, and agreement on the constraints imposed on each alternative solution;
3. They do not require that each party formulate and structure its preferences;
4. They focus on the physical feasibility of analyzed alternatives and do not provide an "objective" measure for the "quality" of these alternatives; and
5. They do not provide a structural framework for moving toward efficient (Pareto) solutions.

The NSS proposed below fills some of these deficiencies.

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Principles of NSS

The NSS combines tools of individual decision-making analysis, ADR techniques, game theory models, and principles of free market theory. These are combined in a way that recognizes notions of equity, fairness, efficiency, and stability. The NSS is designed to aid in the search for an outcome that will be perceived as the "best compromise" by the parties, given the state of their mutual trust and other negotiations conditions ("the state of the world"). Joint management of the shared resource is not mandated by the NSS; if the outcome includes elements of cooperative or even joint management it is because the parties have so decided according to their individual criteria.

ADR techniques, including joint analysis of the effects of proposed solutions, brainstorming, joint search for mutually preferred solutions, and techniques for solving the problems of fair division (game theoretic models), are used to decrease the effect of the power politics mechanism on the outcome, and increase both parties' feeling of fairness. The notion of equity is introduced by offering the same set of decision support tools to both parties, but also by implementing a game theoretic model to seek an equitable division of scarce resources.

The notion of efficiency is introduced with a double meaning. In bargaining theory, the term "efficiency" is used to qualify the outcome of a bargaining process. A solution is considered efficient if it is not possible to move from it in a direction that increases the gain of both parties simultaneously: moving from an efficient solution to increase the gain of one party results in a decrease of the gain of the other party. Solutions that are efficient in the sense of the bargaining theory are referred to as Pareto optimal or nondominated solutions. A rational compromise solution should be chosen among the efficient solutions, since if the solution is not efficient it is possible to move from it in a way that improves the outcome for both parties. Usually, it is up to the negotiating parties to use their cognitive skills to recognize and select a single outcome from the set of outcomes. This will, however, also depend on the quality of communication and the level of mutual confidence between the parties. In bargaining, it may happen that the parties reach an agreement that "misses" some of the possible joint gains, and "leaves something on the table," a solution that would make all of the parties better off (Raiffa 1982). The game theoretic algorithm for selecting equitable bargaining solutions ensures that solutions satisfy the efficiency criterion.

An additional meaning of the notion of efficiency in the NSS is that of economic efficiency, which relates to the way water resources are utilized. Efficiency of water use is expressed by a system of prices at which consumers buy water, shadow prices of water, and supply costs. The NSS incorporates a water allocation optimization model, Water Allocation System (WAS) (Fisher et al. 2002, 2005) which enables an "on-line" analysis of the effects that each proposed solution has on the system of prices. According to the principles embedded in the model, water resources are used in an efficient manner when the prices for consumers equal to the sum of supply costs and the shadow value of water in the source.

Stability of the agreed solution means that the parties do not seek to move away from it, i.e., they are satisfied that they have attained the best outcome possible under the circumstances.

Water Allocation System as Used in NSS

Economically optimal allocation of water is the basis of the WAS model (Fisher et al. 2002, 2005). The area in question, covering the territory of one or more political entities, is divided into "districts." Each has sources, consumer sectors (urban, agriculture, industry, nature), and is connected to other districts and/or to a central conveyance system. Physical and economic data are given for the sources, consumer sectors, and the conveyance system. Economic data include supply costs and water demand functions (willingness-to-pay functions) defined for each consumer sector in each district, which represent the private value (to the consumers) of water (Fisher et al. 2002, 2005; Draper et al. 2003; Jenkins et al. 2004). The demand functions for all consumers in a consumer sector of a district are aggregated into a single demand curve. They can be augmented (raised) by the public willingness to pay, which represents the additional value (above the private one) that the district or country assigns to the use of water (for example, a subsidy on water price for agriculture). The local supply costs are subtracted, resulting in a net demand (private plus public) function for each sector of each district. The model maximizes the total net benefit (the aggregate area under all net demand functions) by allocating water among all districts and sectors, subject to physical, political, administrative, and any other imposed constraints. The model can also include the use of recycled wastewater from the urban sector in agriculture. In its current form, WAS is a single-year model; a multiyear version is under development.

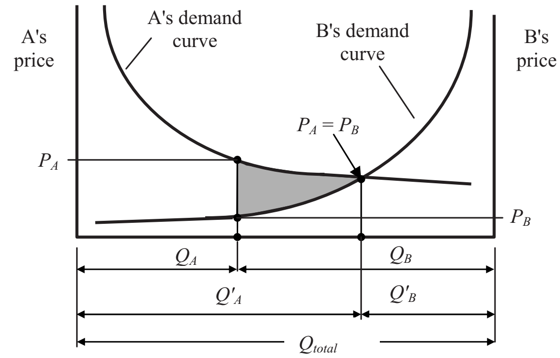

Fig. 1. Water transfer: creating "new" value

The principles of economically optimal water allocation, which underlie the NSS, are depicted in Fig. 1. Suppose that a total annual quantity Q_{total} is available in the shared resource. The net demand functions $P(Q)$ of negotiating parties A (from left to right) and B (from right to left) represent their willingness to pay for water and are shown one opposite the other. Recall that these net demand functions embody both the private value of water to the consumers and the public/national value expressed by the negotiating parties A and B and are after supply costs have been deducted. Next, suppose that water from this source is allocated to the two parties in quantities Q_A and Q_B ($Q_A+Q_B=Q_{\text{total}}$). The total net benefit to A and B from this allocation equals the sum of areas below the two demand functions to this point. If a unit of water were transferred from party B to party A, the sum of the areas, i.e., the total net benefit, would increase. By transferring additional units of water from B to A, we continue to increase the total net benefit, reaching the maximum at the point at which the two values, P_A and P_B, are equal. Hence, if we wanted to allocate the total quantity Q_{total} of water to A and B so as to maximize the total net benefit, the optimal quantities for allocation would be Q'_A and Q'_B. Relative to the starting allocation (Q_A and Q_B), the transfer of water from B to A to the optimal point increases the total value by the shaded area in Fig. 1. This optimal allocation shown

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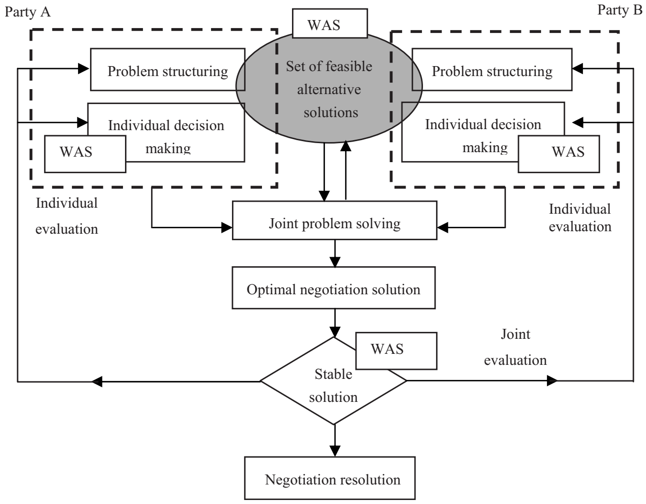

Fig. 2. Negotiation support system

above is free of any constraints. In reality, the allocation is subject to a set of constraints: physical (e.g., capacities of the conveyance systems), legal, and administrative (e.g., quantities guaranteed to consumers), and political considerations (the range of allocations acceptable to a party in the negotiations). Therefore, the constrained optimal allocation may be to the right or to the left of the unconstrained one. WAS maximizes total net benefit to both parties subject to all constraints.

Regardless of the parties' claims for ownership of water in the shared resource, they may agree to allocate for use (subject to constraints), and then negotiate over the allocation of the extra benefit that would accrue from so doing. This changes the negotiations from allocation of water quantities to allocation of water benefits—a central premise of the WAS philosophy.

WAS can be run in a countrified version, where the area in question is a single country, with water allocation from the shared resources to a country defined a priori. In this mode, a party to the negotiation can analyze—in private—its own options and those proposed by the other party. The party can select to charge consumers prices that are fixed a priori, independent of the cost of supply ("fixed-price policy") or allow the prices to be determined by WAS, such that they reflect the cost of supply. WAS can also be run for the whole region of two or more countries (the regional version), in which case shared water resources are treated as common pools. This can be done by each party alone, or jointly by both as part of the negotiation. The objective of using WAS in the NSS is to ensure that whatever the constraints imposed by the parties during the negotiation process, the remaining domain of feasible allocation is utilized optimally, so that no economic gains are left on the table.

WAS output data include the optimal allocations, total net benefit from water use, shadow prices of water for the consumers and districts, and shadow values of constraints, including scarcity rents for water in the sources.

Negotiation Support System

The NSS (Fig. 2) is designed to support bilateral negotiations, although the same concepts can be extended to negotiations with more than two parties. It is based on symmetry between the parties and provides each with an identical set of tools. The negotiation is modeled as a combination of two processes: individual decision making conducted by each party in private (top part of Fig. 2, on both sides) and joint problem solving (center of Fig. 2). Individual decision support is aimed at assisting the parties in structuring their systems of preferences related to the water allocation problem. Each party establishes its utility for negotiated alternatives, using the analytic hierarchy process algorithm (Saaty 1980) to weight and combine its different objectives, the economic objective being just one of them, into a single utility figure. Joint problem solving is modeled as an interaction, supported by tools from game theory, in which the parties have the opportunity to design and select jointly preferred solutions.

WAS serves as a basic element of the NSS. It is used in two ways: first, each party uses WAS by itself—in private—to examine various water-allocation scenarios, to generate information about the implications of such scenarios on its country's domestic water economy and consequently on its own objectives. This is seen on both sides at the top of Fig. 2, and can be done for the party's own territory with its own data, or for the combined area of the two parties, with the data for the other party assumed to be known.

Second, the parties can agree to perform a WAS analysis jointly, as seen in the top center of Fig. 2, to search for joint gains. While exploring scenarios for resolving the allocation of the joint water resources and negotiating "around" the WAS model, the parties have an opportunity to improve communication, evaluate each other's expectations and goals, and interact in a manner that is less competitive and more integrative. This is represented in the block "Joint decision making" in Fig. 2. The top part of the figure represents an iterative process of moving from individual (private) evaluations to joint decision making.

Once this iterative process leads to a degree of agreement (not necessarily final) it results in a temporary "optimal negotiation solution," which is not considered final until it has gone through a stability analysis (lower part of Fig. 2, explanation to follow). WAS can again be used in this step.

The negotiation process is thus modeled as an alternating sequence of individual and joint activities in which the parties manipulate the set of alternative solutions, designed to enlarge the negotiation space by creating and proposing new alternatives, and narrowing it by removing nonefficient ones. An alternative can be designed by a single party, by a mediator, or by the two parties jointly. Removal of nonefficient offers is determined according to the individual preference structures and utility values of both parties, and by a game-theoretic device based on the Nash bargaining solution (explained later), which operates within the joint "utility space." Enlarging and narrowing the set of alternatives are repeated in an iterative manner regulated by a "protocol of interaction."

The iterative nature of the negotiation process enables the parties to revise their preference structures during the negotiations and develop a dynamic set of the alternative solutions. The design of the NSS is based on conclusions drawn from a number of real-world cases of international water disputes. It recognizes the usual absence of confidence between the parties, and assures a level of confidentiality in the manipulation of revealed information. Also, the approach does not assume that agreement between the parties has to be based necessarily on cooperation in the management of the shared water resources. It searches for the "best outcome" as perceived jointly by both parties, given their level of mutual trust, and given the present "state of the world."

Negotiation Protocol (Protocol of Interaction)

Negotiation is a joint problem solving process during which the parties have to communicate and interact. The NSS includes an interaction protocol, designed to assist the parties in problem solving. Parties who claim rights to the same water resource frequently assume that they have mutually conflicting interests, and are therefore inclined to bargain in a competitive manner. The negotiators may find themselves locked in a difference which seems impossible to overcome, and at least one of them prefers to break off the negotiation process. The protocol of interaction is designed to reduce the probability that this will occur. It is motivated by normative (prescriptive) models of interaction, taken from game theory.

A negotiation protocol specifies the rules and steps of interaction. In zero-sum negotiations it is typically an alternating sequence of offers and counteroffers. In contrast, our NSS prescribes a combination of two procedures, alternative generation and alternative evaluation, aimed at searching for negotiated solutions that improve the achievements for both parties. A new alternative solution may be offered by one or both parties, or by a mediator, disregarding who offered the previous one. Generation of alternatives is supported by the WAS model which enables analysis of various inter- and intracountry water allocation scenarios. Each of the parties then conducts its own evaluation, using the AHP tool and possibly its own version of WAS. These two processes, alternative generation and alternative evaluation, are repeated in a sequence of iterations, which is designed to terminate when a stable solution is reached.

Design of Alternatives

The parties design alternatives while using, individually or jointly, the WAS model. Each party can analyze the effects of an alternative using the complete set of WAS outputs. However, there are only a few results of the WAS output that are relevant on the public level and that figure in the bargaining process. Let: Q_{DS}=average annual renewable quantity of water in the shared resource; $Q_i(a)$=quantity of water allocated to party i, $i=\{A,B\}$, in alternative a; $q_i(a)$=WAS-optimal quantity of water to be supplied to party i, given $Q_i(a)$ ($q_i(a) \leq Q_i(a)$); and $q_i(a)$ can vary as a function of intracountry water allocation arrangements; and $V_i(a)$=annual net economic benefit to party i from the use of water as a result of alternative a. This is the net benefit from the total annual consumption of water in i, with $q_i(a)$ as one component: $V_i(a)=V_i(Q_i'+q_i(a))$, where Q_i'=quantity of water available to i from sources other than the shared one. Like $q_i(a)$, $V_i(a)$ varies as a function of the domestic water utilization scenarios.

Q_{DS} can be allocated in one of the following ways: (1) it can be allocated a priori to the parties in quantities $Q_A(a)$ and $Q_B(a)$ (so that $Q_A(a)+Q_B(a)=Q_{DS}$), and each party analyzes the intracountry water-allocation scenarios a posteriori, given $Q_i(a)$, $i=\{A,B\}$; and (2) Q_{DS} can be defined as a common pool; in this case, the regional version of the WAS model determines the optimal allocation so as to maximize the joint net benefit from the annual use of water in both countries—without any restrictions or prejudgment on the final allocations. The allocated quantities of the shared resource ($Q_A(a)$ and $Q_B(a)$) and the net benefit from water use in the two countries will be different for different regional scenarios.

On the public level (in terms of shared information), the parties negotiate the allocation of two commodities: water and an economic value. From the perspective of party i, $i=\{A,B\}$, alternative a is represented by the allocated quantity of water from the shared resource, $Q_i(a)$, measured in units of volume, and a monetary value $v_i(a)$. The sum of the quantities allocated to the two parties, $Q_A(a)+Q_B(a)$, is constant over all alternatives. Since water sources are always subject to random variability, this is often set to be an agreed upon average annual renewable potential of the water source.

Denote by $v_i(a)$ the net economic gain to party i from alternative a, relative to some reference alternative, a_r, which is assured to party i ($v_i(a)=V_i(a)-V_i(a_r)$). If, for example, alternative a reallocates the shared water resource so that party A gains an additional quantity of water, the economic value of the total quantity of water available to A increases according to its demand curve. Correspondingly, party B loses the same quantity of water, so that the economic value of its available water decreases according to its own demand curve. If the gain to A is greater than the loss to B then they may agree to share in some manner the net total gain. In order to make such an alternative attractive to party B, A can offer B a "side payment" $v_A(a)$ and $v_B(a)$ are then the net economic values that the two parties gain by selecting alternative a over the reference alternative a_r. The sum $v_A(a)+v_B(a)$, varies over the alternatives. If alternative a is (economically) efficient, this sum will be equal to the change in the total annual economic value of water in the two countries, achieved by selecting alternative a over a_r.

On the private level (in terms of confidential information), each party evaluates the efficiency of an alternative according to a set of its own criteria, its own objectives. The set of criteria of one party is independent of that of the other party. Party i expresses the "quality" of the alternatives by assigning each of them a vector of "scores" in the following way: if $u_i^j(a)$ is a subjective measure (score) of the degree to which alternative a satisfies objective j, $j=1,\ldots,n$ then alternative a represents for party i the n-tupple $[u_i^1(a),\ldots,u_i^n(a)]$, with n being the number of party i's objectives (criteria). The subjective measures, $u_i^j(a)$, result from an evaluation of alternative a, as part of i's individual decision making process, as explained next.

Individual Decision Support

The NSS allows dynamic evaluation of the objectives, which reflect the party's interests, goals, and perceptions—dynamic in the sense that it can change during the negotiation process and depends on what is stated by the other party, by new information or by a simple change of mind. Generally, the objectives (criteria) can be of the two types: (1) quantitative objectives, which can take values measurable in their characteristic units, for example water quantity and net benefit from water use; and (2) qualitative objectives that cannot be measured by any standard units, for example national security or social stability or any other nonquantifiable political or social objective, as well as constraints resulting from in-country allocations. The timing of allocations during the year, which is often an important consideration, can be discussed and negotiated after the annual quantities have been considered.

For given negotiation conditions, a "state of the world" and a set of L alternative solutions, party i, $i=\{A,B\}$, creates a subjective utility function, U_i, which assigns a score to every n-tupple $[u_i^1(a_l),\ldots,u_i^n(a_l)]$, $l=1,\ldots,L$. This score is a real number from the interval $[0,1]$, which expresses the level of overall satisfaction that party i accords to each of the L alternatives. The model for

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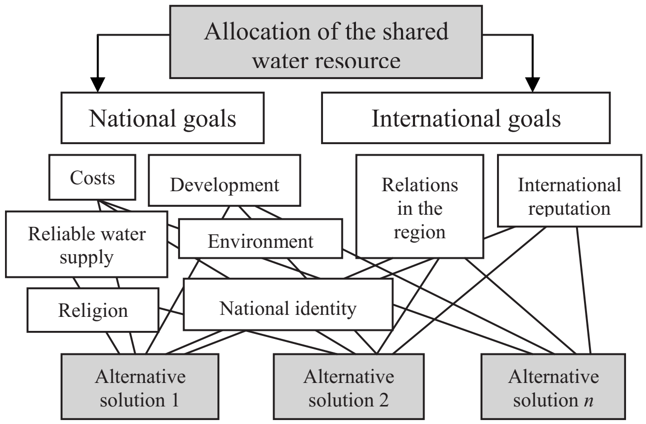

Fig. 3. Individual preference structure

creating the utility function utilizes the AHP (Saaty 1980). AHP is a multiobjective decision support designed to select the best out of a number of alternatives evaluated according to a set of several criteria. For our purpose it proceeds in three steps: (1) assigning (a vector of) weights to the objectives, based on pairwise comparisons among them; (2) assigning (a matrix of) weights to the alternatives vis-à-vis each objective, again using pairwise comparisons; and (3) a combination of the two sets of weights to compute the relative ranking of the alternatives with respect to all objectives. Each of the first two steps can be broken into a hierarchy of levels, to reflect the way in which objectives are structured. AHP has been used in creating a policy for Israel's water sector (Shamir et al. 1985).

Within the framework of the NSS, each party's preference structure is organized into a multilevel hierarchy, as shown by an example in Fig. 3. The upper level is the water allocation issue. The second level contains the objectives ("costs," "reliability," "environment," which here are shown to be divided into two groups), and the third level consists of the negotiation alternatives.

The top and bottom levels are common to both parties. The elements of the middle levels, the sets of criteria, and weights assigned to them by the party, are separate and confidential. The middle level can be divided into sublevels, as shown in Fig. 3, to elucidate the AHP weighting process (Saaty 1980). It may be clearer and easier to first weight the objectives under "national goals" with respect to each other, do the same for those under "international goals," then weight "national" versus "international," and come up with the relative weights of the all the objectives, in both groups ("costs," "environment," "relations in the region," etc.), against which the alternatives are measured (weighted). This process can be broken into more than two hierarchical sublevels.

The function, which describes the overall utility assigned by party i to alternative a, is of the linear additive form

$$U_i(a) = w_i^1 u_i^1(a) + \dots + w_i^n u_i^n(a), \quad \sum_{j=1}^{n} w_i^j = 1 \tag{1}$$

where $w_i^1, \dots, w_i^n$=weights of n objectives (criteria); and u_i^j, $j=1, \dots, n$="performance" of alternative a with respect to objective j. Once party i has established its overall utility function, its decision becomes a standard optimization problem: find alternative a for which $U_i(a)$ is maximized.

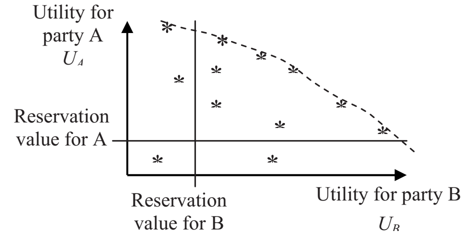

Fig. 4. Joint utility space

Joint Consequence Space

When parties have opposed interests, the solution, which maximizes the utility function of one party, will be unacceptable by the other. A negotiation agreement will be achieved only if the parties manage to find a jointly acceptable solution. Within the framework of the NSS, a game theory model is included, which, in each negotiation iteration, assists the parties in selecting an efficient and equitable alternative, among the set of known, feasible alternative solutions to the problem.

Selection of the "best" negotiation solution is performed by accounting for the utility functions of both parties. Once the parties have evaluated their utility functions for a given set of alternatives, their options can be presented in a joint utility space (Fig. 4).

The reservation values in a joint utility space mark the utility values assured to the parties in case they break away from the negotiations. In negotiation theory, this threshold value of the "no agreement" alternative is called the best alternative to a negotiated agreement (BATNA). In other words, a rational party, who acts to maximize his utility function, will not accept an alternative which gets him a utility lower than his BATNA.

Another consideration for selection of the "jointly best" alternative arises from the concept of efficiency. Of all feasible alternatives, the efficient ones are those from which one cannot move to improve the utility of one party without decreasing the utility of the other. These lie on the efficient (Pareto) frontier. However, in the case of negotiations the efficient frontier is not known. The parties successively generate alternatives that map to discrete points in the joint utility space. At each iteration of the negotiation process one can identify those points which form the (temporary) efficient frontier (seen in Fig. 4) and the challenge is to move to the "north-east" beyond this frontier in the next iteration (this will be considered in the next section).

Given the BATNA values and the (current) efficient frontier, the problem is reduced to selection of one of the efficient alternatives, which are beyond the BATNA values. This is a difficult task, since by moving along the efficient frontier, improvement of one party's gains can be achieved only at the expense of the other's loss. Of the game theory models which propose solutions for such difficulty, we have adopted the Nash bargaining solution (Raiffa 1982). According to the Nash solution, the best alternative is the one that belongs to the efficient frontier and maximizes the product of utility values of the two parties. According to the rationale of the Nash point (Fig. 5), the parties should move from the point (V, U) on the efficient frontier to point $(V\text{-}\Delta V, U+\Delta U)$ if $\Delta U/U$ is greater than $\Delta V/V$ (the proportional gain for one player is larger than the proportional loss for the other). They should continue to move along the frontier, up to the point at which $\delta U/U = -\delta V/V$, i.e., the point at which the product UV is maximized (Raiffa 1982).

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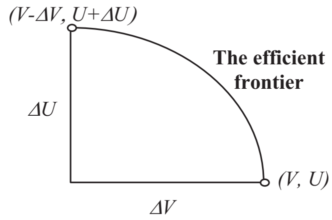

Fig. 5. Nash rationale for selection of best alternative: find point which maximizes product *UV*

Iterative Progress of Negotiations

A basic premise of our NSS is that parties are allowed to modify their sets of objectives and/or the associated weights during the negotiation process. This means that alternative which mapped in a previous iteration to a specific point in joint utility space, can now map to another point if the utility function(s) changed. This may redraw the efficient frontier and define a different Nash point. The real challenge is to move beyond the current efficient frontier (which, as stated, is merely a temporary one) and improve the utilities of both parties. The dynamic evolution of the set of alternative solutions can be shown as a progression in the joint consequence/utility space (Fig. 6). The NSS is designed to assist the parties in advancing toward solutions which (jointly) improve their overall satisfaction.

The NSS allows the parties to change their sets of objectives and systems of preferences, and hence the utility evaluations, in response to changes in the negotiation conditions. After each iteration the parties can change their set of the objectives by adding and/or removing objectives, and/or by changing their relative weights.

In Fig. 6, U_A^t and U_B^t are utility values of parties *A* and *B*, in negotiation iteration *t*. In each iteration the parties negotiate over a set of alternatives with the aim of (eventually) selecting a single alternative as "the best"; we propose that this be the Nash bargaining solution, but the parties need not accept this, and can use any alternative as the "best." Note, however, that the procedure for relaxing the weights, to be presented below, does depend on using the Nash point. The alternative selected as "best" in one iteration becomes the reference alternative for the next iteration. This means that alternatives negotiated in iteration *t* are compared relative to one another, as well as to the reference solution selected as "the best" in iteration $t-1$. In a general case, utility scores of a reference solution selected in iteration $t-1$, U_A^{t-1} and U_B^{t-1}, can be different from the utility scores of that same alternative in iteration *t*, U_A^t and U_B^t, since the utilities are reevaluated for each iteration. The reference alternative of the first iteration is the "no agreement" alternative, which corresponds to (U_{A_BATNA}; U_{B_BATNA}). If no alternative in iteration *t* has a better performance than the reference alternative a_r^{t-1}, then this solution is proposed as the final negotiation resolution.

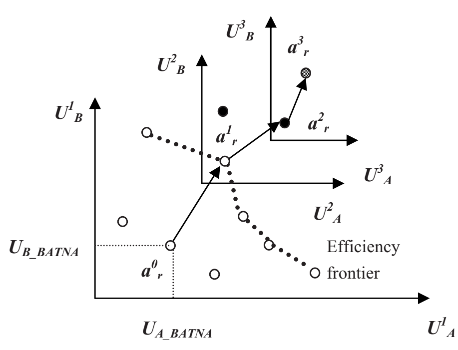

Fig. 6. Iterative progress of negotiations in joint utility space

Relaxing Weights of Criteria

For a given alternative *a*, which is supposed to challenge the last reference alternative a_r, the parties are allowed to relax the weights of their objectives, by assigning an upper and lower limit on the weight of each objective. The final weights of the objectives are then obtained by a maximization procedure.

Let $w_A^i i=1,\ldots,n$ and w_B^j, $j=1,\ldots,m$ be the weights of the vectors of objectives of parties *A* and *B* in iteration *t* (note that the number of objectives need not be the same for the two parties). Next, let $u_A^i(a)$ and $u_B^j(a)$, $i=1,\ldots,n$ and $j=1,\ldots,m$, be the scores of alternative *a* with respect to *n* objectives of party *A* and *m* objectives of party *B*. Then, the product of the overall utilities of the two parties resulting from alternative *a*, is

$$U_A(a)\cdot U_B(a)=(w_A^1u_A^1(a)+\ \ldots\ +w_A^nu_A^n(a))\cdot(w_B^1u_B^1(a)+\ \ldots \\ +w_B^mu_B^m(a)) \qquad (2)$$

or, in vector-matrix form

$$U_A(a)\cdot U_B(a)=\frac{1}{2}[w]^T[C_1][w],\quad [C_1]=\begin{bmatrix}0 & [C]\\ [C]^T & 0\end{bmatrix} \qquad (3)$$

where $[w]$=vector of weights of the two parties $[w]^T=(w_A^1,\ldots,w_A^n,w_B^1,\ldots,w_B^m)$, and C=matrix obtained by multiplication of the vectors of the scores of alternative *a*

$$[C]_{n\times m}=[u_A(a)]\cdot[u_B(a)]^T=\begin{bmatrix}u_A^1(a)\\ \ldots\\ u_A^n(a)\end{bmatrix}[u_B^1(a)\ \ \ldots\ \ u_B^m(a)] \qquad (4)$$

The search for optimal weights of the objectives of both parties is a quadratic maximization problem

$$\underset{[w]}{\mathrm{Max}}\ \tfrac{1}{2}[w]^T[C_1][w] \qquad (5)$$

subject to:

The weights are within the prescribed ranges

$$w_{A\ \min}^i\leqslant w_A^i\leqslant w_{A\ \max}^i,\quad i=1,\ldots,n\quad w_{B\ \min}^j\leqslant w_B^j\leqslant w_{B\ \max}^j, \\ j=1,\ldots,m \qquad (6)$$

The weights sum to 1

$$\sum_{i=1}^{n} w_A^i=1\quad \sum_{j=1}^{m} w_B^j=1 \qquad (7)$$

The overall utility to a party is greater than or equal to the utility which that party obtains by the reference alternative

$$\begin{bmatrix}[u_A(a)]^T & 0\\ 0 & [u_B(a)]^T\end{bmatrix}[w]\geqslant\begin{bmatrix}U_A^{\mathrm{reference}}\\ U_B^{\mathrm{reference}}\end{bmatrix} \qquad (8)$$

If there is a feasible solution to this optimization problem, then *a* becomes the new reference alternative; if there are no further proposed alternatives, it is then the final negotiation resolution.

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Experimental Evaluation

The efficacy of the NSS cannot be established in an objective way, i.e., by proving that it reaches by itself a "good" solution to a negotiation; it must be put to the test in simulations. Two types of simulation experiments have been conducted. The first were with real actors—groups of students and of negotiation trainers—who played a "negotiation game" based on a synthetic case study. Half of the participants in each group performed the exercise with the NSS and the other half without, and the results were compared and analyzed statistically. These exercises were somewhat limited by the duration of the "game" and by the computer skills of the participants, so only some parts of the NSS features could be assessed in these simulations.

The second type of experiment was performed with "simulated actors." The initial preference structures were elicited from selected participants in the previous simulation set, while the remaining dynamics of the negotiation process were generated by us. The aim of these experiments was to test and explore the role and capabilities of WAS within the framework of the NSS in detail, which was not possible in simulations with real actors.

Length limitations of this paper do not allow presentation of this part of the work, which will therefore be included in a companion paper.

Summary and Conclusions

The negotiation support system is designed to assist two parties that share a scarce international water resource, who wish to find and adopt a mutually attractive allocation. It utilizes an economic perspective as a rational criterion for management of the scarce resource. The NSS introduces an economically based water allocation optimization model (WAS) into negotiations, with the aim of emphasizing the potential gains to both parties that can be obtained. Water is evaluated in terms of values, not merely of quantities. We believe that the WAS model, by which the parties can explore the effects of various domestic and international water allocation schemes, contributes to their creativity in searching for alternative negotiation solutions.

The NSS includes tools (AHP, Nash equilibrium) from multicriteria decision making and game theory that help the parties to explore a wide range of individual objectives (besides economic efficiency), evaluate their systems of preferences, and recognize the opportunities for tradeoff between different objectives.

The protocol of interaction and the iterative negotiation process are aimed at improving the communication and understanding between the parties and in assisting them to advance gradually from a competitive win-lose stance to alternatives which bring joint gains. The combination of the AHP model for individual decision support and the Nash bargaining solution enables the parties to recognize mutually preferred alternatives, which might otherwise be overlooked.

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