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# SUSTAINABLE WATER RESOURCES MANAGEMENT IN A CONFLICT RESOLUTION FRAMEWORK[1]

*Jae H. Ryu, Richard N. Palmer, Sangman Jeong, Joo Heon Lee, and Young-Oh Kim*[2]

ABSTRACT: A decision support system for sustainable water resources management in a water conflict resolution framework is developed to identify and evaluate a range of acceptable alternatives for the Geum River Basin in Korea and to facilitate strategies that will result in sustainable water resource management. Working with stakeholders in a "shared vision modeling" framework, sustainable management strategies are created to illustrate system tradeoffs as well as long-term system planning. A multi-criterion decision-making (MCDM) approach using subjective scales is utilized to evaluate the complex water resource allocation and management tradeoffs between stakeholders and system objectives. The procedures used in this study include the development of a "shared vision model," a simulated decision-making support system (as a tool for sustainable water management strategies associated with water conflicts, management options, and planning criteria), and the application of MCDM techniques for evaluating alternatives provided by the model. The research results demonstrate the utility of the sustainable water resource management model in aid of MCDM techniques in facilitating flexibility during initial stages of alternative identification and evaluation in a basin suffering from severe water conflicts.

(KEY TERMS: conflict resolution; water conflict; simulation; drought; sustainable water resources management; multi-criterion decision making.)

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## INTRODUCTION

### *Water Conflicts*

Conflicts occur in water resources planning and management for a variety of reasons. Most simply, water conflicts occur when people and institutions disagree on the amount of water that is needed, required, or obligated at a specific location for a precise purpose at a particular time and of a given quality (Palmer *et al.*, 1999). Conflicts can be resolved in a variety of fashions: litigation, formal agreements, legislative orders, mediation, and informed discussions. Lord *et al.* (1979) notes that water conflicts tend to arise because of disputes associated with

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[2] Respectively, Hydrologist, School of Natural Resources, University of Nebraska, Lincoln, Nebraska 68588-0988; Professor and Head, Department of Civil and Environmental Engineering, 222 Marston Hall, University of Massachusetts, Amherst, Massachusetts 01003-9293; Professor, Department of Civil and Environmental Engineering, Kongju National University, Kongju, Korea; Associate Professor, Department of Civil and Environmental Engineering, Joongbu University, Geumsan, Korea; and Associate Professor, Department of Civil and Environmental Engineering, Seoul National University, Seoul, Korea (E-Mail/Jeong: smjeong@kongju.ac.kr).

perceived ownership, differences in how resources are valued, and differing interests. The goal of a negotiated agreement is to identify and evaluate alternatives that allow all parties to decrease their harm equitably (or equitably share their benefits), or agree upon the most accepted alternatives among those that are available. If multiple, mutually acceptable alternatives exist, alternative evaluation procedures can be used to select a solution that meets the goals of the parties in dispute. Computer-based models can identify areas of dispute and limit the range of alternatives to be considered to those that are Pareto-optimal (Cohon, 1978; ReVelle *et al.*, 2004). The concept of noninferior or Pareto-optimal solutions (also known as the efficient and nondominated solution) was first introduced by Pareto (1896) and is defined in this study as the state where no further improvements can be made to the system without disadvantaging a group or individual.

This study develops a sustainable water resources conflict-resolution model, using multi-criterion decision-making (MCDM) techniques, that evaluates the impact of water management alternatives in the Geum River Basin (Figure 1). The model supports decision making in the basin and provides useful insights into potential conjunctive operation of the two major dams in the watershed. Furthermore, the model illustrates tradeoffs to stakeholder groups and encourages decisions based on current and future needs and priorities.

### Computer-Based Conflict Resolution Model

Computer simulations and optimization techniques have been applied to water resources planning and management for decades. These models have been used in reservoir system studies associated with drought as well as water allocation studies. Many different optimization approaches, such as linear programming (Jenkins and Lund, 2000), nonlinear programming (Lund and Ferreira, 1995; Cai *et al.*, 2002; Barros *et al.*, 2003), and dynamic programming (Stedinger *et al.*, 1984; Kim and Palmer, 1997) have been developed for water management modeling. Multiobjective optimization techniques have also aided in decision making (Cohon, 1978; Mohan and Raipure, 1992). The advantages of multiobjective programming and planning include engaging stakeholders, generating a wide range of alternatives, and providing more acceptable solutions. Multiobjective programming approaches generate noninferior (Pareto-optimal) solution sets and create noninferior alternatives (Cohon, 1978). Other research has employed multiobjective approaches as a template for negotiation and conflict resolution (Lund, 1994).

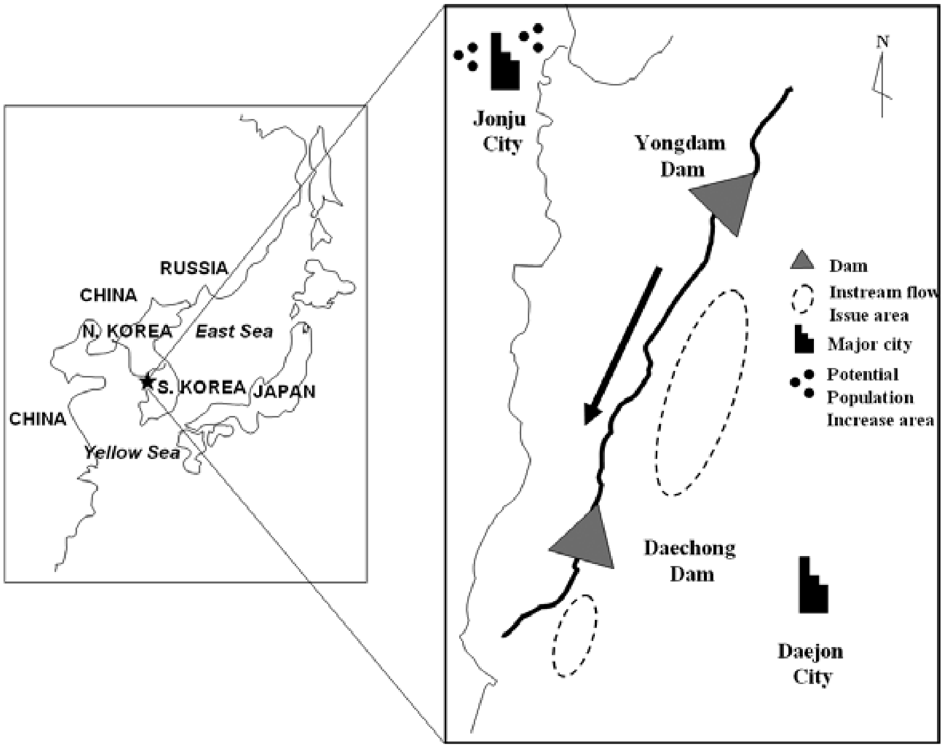

FIGURE 1. Map of Water System in Geum River Basin.

There are, however, weaknesses in these methods. Careful screening of alternatives may be needed to reduce the solution space. Furthermore, these methods may not provide stakeholders with a means to make a final selection between alternatives.

Alternatively, shared vision modeling arose from the computer-aided negotiation approach. During the 1990s, Palmer *et al.* (1993) introduced "shared vision planning," a procedure that allows interested participants to achieve consensus by forming a shared vision of a system or process. The goals of shared vision planning are to (1) provide insight into questions and concerns that generate conflicts, (2) include information that represents the interests and perspectives of all participants, (3) obtain equitable benefits for all participants, and (4) provide the opportunity for a high level of involvement by all stakeholders. A key element in this planning process is the creation of a shared vision planning model, a highly interactive computer simulation model that allows participants to visualize the impacts of their planning decisions.

The shared vision planning approach was applied during the National Drought Study to water supply in Boston, Massachusetts; reservoir management on the Green River in Tacoma, Washington; water supply in Norfolk, Virginia; recreation and hydropower on the Kanawa River in West Virginia; and an interstate conflict between Kansas and Missouri (Palmer *et al.*, 1993; Werick and Whipple, 1994). Unlike classic multiobjective programming, the use of shared vision planning uses interactive models in a group setting to support joint fact finding, policy dialog, and alternative evaluation (Keyes and Palmer, 1992). This approach was considered appropriate for application to the Geum River Basin to resolve water conflicts. Other types of computer-based negotiation procedures are also widely used in water resource conflict resolution (Lord *et al.*, 1979; Karpack and Palmer, 1992; Werick and Whipple, 1994; Keyes and Palmer, 1995; Meo *et al.*, 2002), and other applications areas are listed in the literature (Thiessen and Loucks, 1992; Lund and Palmer, 1997).

### *Multi-Criteria Decision Making*

Several studies have used an MCDM approach, derived from stakeholders' preferential matrix, to evaluate management alternatives. However, studies have seldom examined the relative extent of individual alternatives associated with sustainable water management options in conflict resolution settings (Thiessen and Loucks, 1992; Cai *et al.*, 2004; Rajasekaram and Nandalal, 2005). Cai *et al.* (2004) have evaluated alternatives with some stakeholder involvement using an MCDM's output similar to that used in this paper, but with somewhat different analytical methods. We adopt a relatively simple approach for integrating conflict resolution, sustainable water management, and decision support framework with evaluation processes. This approach improves negotiation capabilities between stakeholders. We also refer the reader to Thiessen *et al.* (1998) and Fang *et al.* (1993) for a discussion of the effectiveness of a proposed system for conflict resolution. These papers offer a description of how stakeholders used the models to decide which management approach best addressed their concerns. In applications, the iterative processes and collaboration between competing groups to manipulate computer models are addressed in order to assess successful completion of the primary objective, namely conflict resolution.

In the remainder of this paper, a brief review of water conflicts in the basin is presented. Next, a description of potential management options is presented with a description of a simulated decision-making exercise. Evaluation of alternatives (a set of management options) for a conflict resolution framework is then presented through the MCDM technique, concluding with a summary and discussion of future work. We anticipate that the results of this study will contribute to promoting long-term water sustainability in facilitating flexibility during initial stages of alternative identification and evaluation in a basin dominated by severe water conflicts.

## WATER CONFLICT IN THE GEUM RIVER BASIN, KOREA

The Geum River Basin (Figure 1) is 9,810 km$^2$ with a main stem length of 396 km. The water resources of this basin depend largely on the precipitation that occurs during the summer monsoon season (June to August/September). More than 60% of the annual precipitation occurs during this period, and annual average temperature and precipitation are about 20°C and 1,200 mm, respectively. Heavy rainfall, accompanied by tropical cyclones in the region, creates flooding and can have significant impacts (dam failures, loss of human life, loss of livestock, etc.). The quantity of precipitation that occurs during the monsoon season essentially defines drought or flood conditions.

Two major dams are located on the Geum River. Daechong Dam creates a reservoir of approximately 1,500 million cubic meters and provides water to several major cities, including Daejon, Chongju, and Chonan. Yongdam Dam creates a reservoir of approximately 815 million cubic meters and is located upstream of Daechong Dam, and was completed in 2001. Water stored in Daechong Dam serves approximately 3 million people, including residents of Daejon and Chongju. Yongdam Dam will initially serve approximately 1.5 million people, including residents of Jonju City. Both dams are multipurpose.

Yongdam Dam's construction was very controversial. The dam remained unfilled after its construction because of concerns over its impact on Daechong Dam. In many aspects, this setting reflects a classic "upstream *vs.* downstream" conflict. Daechong Dam and the area it serves have a previously established water need, but Yongdam Dam and the area it serves present a new water demand that will likely increase. The rate of growth in the regions is also under debate. Both regions have demanded increases in their water allocations. Much of this debate revolves around the future population and water demand projections for Jonju City, the major beneficiary of Yongdam Dam. This conflict was exacerbated by an extreme meteorological event in the fall of 2001 that left Daechong Dam at its lowest storage level since its initial filling.

In addition to water quantity concerns, there are water quality concerns. A minimum instream flow target between the two dams has been suggested by downstream users as 12 $m^3/s$, but upstream users have suggested 5.4 $m^3/s$. An environmental flow target of 21 $m^3/s$ has been suggested below Daechong Dam. Daechong Dam and its tributaries provide water for many uses, including agricultural, municipal, industrial, domestic, recreational, and as habitat for fish and wildlife. However, local environmentalists, in particular, insist that the fish flow below the dam should be maintained at 21 $m^3/s$ to meet water quality standards. A failure to reliably meet fish flows in recent drought years (1994 and 1995) and conflicts between water use sectors have created severe taste and odor problems (e.g., eutrophication) caused by excessive nutrient loading to bodies of water and associated algal blooms.

### *Parties Involved in the Conflict*

Two local government departments and a group of nongovernmental organizations are involved in this regional conflict. The parties in this dispute include the Department of Water of Daejon City (DOD) and the Department of Water of Jonju City (DOJ), and a coalition of local environmental groups (LEGs). These departments focus on planning, designing, and managing water-related projects and are responsible for water supply planning and water distribution systems. Their respective estimates of the cities' population growth by 2020 vary by more than 1 million residents. The LEGs have insisted that the instream flow below the Daechong Dam should be maintained at 21 $m^3/s$ to meet the needs of navigation, recreation, and aquatic habitat. Table 1 summarizes major water conflicts in the Geum River Basin.

### *Conflict Resolution Process and Simulation Exercise*

Researchers (Palmer *et al.*, 2002; Ryu *et al.*, 2003) have begun to apply the shared vision planning approach to the Geum River Basin in Korea. This section summarizes the use of a shared vision planning model. The model will be used to assess the existing plans, develop management options for all water resources in the region, and create a negotiation environment to aid in the understanding and resolution of water resource conflicts.

Several simulated decision-making exercises in a shared vision modeling framework have been conducted for the Geum River Basin since April 2003 to evaluate the current system's outlook for 2003 and beyond. It was concluded that major new supply facilities were unlikely to be constructed in the near future. Simulation exercises were also devised to aid in evaluating alternative operating policies as a function of the ongoing water conflicts. There are two primary operational issues: (1) the appropriate value for instream flow targets downstream of Daechong Dam and between reservoirs, and (2) the

TABLE 1. Major Water Conflicts in the Geum River Basin.

| | **Downstream Users** | **Upstream Users** |
|---|---|---|
| Instream flow between dams (DOD *vs.* DOJ) | 12.4 $m^3/s$ | 5.4 $m^3/s$ |
| Instream flow downstream of Daechong Dam (LEGs) | 21 $m^3/s$ | Less than 21 $m^3/s$ (needs to be reconsidered) |
| Population forecast for city of Jonju (DOD *vs.* DOJ) | 2.5 million | 3.5 million |
| Upstream dam (Yongdam) operation (DOD *vs.* DOJ) | Upstream dam should be operated for downstream users | Upstream dam should be operated for upstream users |

Notes: DOD, Department of Water of Daejon City; DOJ, Department of Water of Jonju City; LEG, local environmental group.

allocation of water to meet regional growth, particularly during droughts. The two fundamental issues are addressed in the water conflict context by exploring four specific questions: (1) what was the safe yield of Daechong Dam before Yongdam Dam was constructed; (2) what is the safe yield of both dams, if they are operated for a single downstream user and no environmental flow is required; (3) how much of this yield is lost if environmental flows are required between the two dams; and (4) how much yield is lost when environmental flows are required downstream of Daechong Dam. Answers to these questions can help determine the best water allocation between regions and evaluate the effectiveness of drought management plans. The system's safe yield is the quantity of water that can be taken from the reservoir system over the 39 years (1963-2001) of historic inflows records with failures (denoted as a failure to meet a predetermined level) in only one year (a 97% annual reliability was used for this research).

To answer the questions listed above, a new simulation model of the system in a shared vision planning framework was developed; it is the WACOR$^2$ Model (Water Conflict Resolution-Relief Model). The model operates at a weekly time step and represents the major projects and operational features of the Geum River Basin (Palmer *et al.*, 2002; Ryu *et al.*, 2003).

WACOR$^2$ simulates the movement and storage of water within the basin given current operational policies. The analysis begins with the selection of model parameters (e.g., instream flow between dams and demand forecast for Jonju City) associated with water conflicts and analysis of the appropriate hydrologic record. The primary hydrologic input to WACOR$^2$ is weekly, naturalized streamflows. The model also incorporates conjunctive reservoir management and operating rules and multiobjective programming concepts to illustrate the tradeoffs between system reliability, operating strategy, environmental flows, and drought triggers. Operational parameters under consideration were also incorporated into the shared vision model. WACOR$^2$ explores system performance and reliability given various operating policies and alternative water conflicts and operating scenarios (described later). The model's outputs are reservoir levels and releases, from which system performance is evaluated relative to hydropower production, flood control, municipal and industrial diversions, and instream flow requirements for fish was calculated.

The model is designed specifically as a conflict resolution tool for its value to the ongoing debate surrounding regional goals and objectives of water management in this basin. All stakeholders participate as players to determine system parameters used in a shared vision model, and evaluate the system's performance responding to their interest (Ryu, 2006). If a negotiated agreement that allows all parties to decrease their harm equally is not identified, additional simulation runs are conducted until the most accepted alternatives are available among those stakeholders.

### *Analysis Output*

This analysis illustrates the range of potential benefits possible from the construction of the Yongdam Dam during drought years similar to 1981-1982 and 1994-1995. It appears that the construction of Yongdam Dam provides benefits to both upstream and downstream users of the Geum River. For instance, conjunctive dam operation increases system yield by approximately 11 $m^3/s$. The users of the upstream dam (Yongdam) should not expect more than 11 $m^3/s$ of yield from the system, because taking more than this would decrease the yield of the more senior user of the river. If less than 11 $m^3/s$ is taken from Yongdam Dam, however, the construction of the new dam is a regional benefit, with some of the benefits going to the upstream users and some to the downstream users. The additional storage provided by this dam could be used for many purposes, including providing water to upstream users and ensuring that environmental flows can be maintained between the two reservoirs. Yongdam Dam could also provide additional water during drought periods to downstream users, water that would not have been available without the dam.

However, there are clear conflicts between the environmental flows established downstream of Daechong Dam and the amount of water that can be diverted for municipal, industrial, and agricultural water supply from that dam. There are also conflicts between the environmental flows established between the two dams and the ability of the Yongdam Dam to supply water. The results imply that more severe water conflicts could occur because of future droughts or an incomplete management plan. Local governmental agencies agree that the existing water supplies in this relatively small basin are inadequate to satisfy the projected demand with current patterns of water use. The region desires to create a sustainable water resource plan that can address future growth, environmental concerns, and droughts that may occur in the future when the population has increased. More details about analysis output are available in the literature (Palmer *et al.*, 2002; Ryu, 2006).

## SUSTAINABLE WATER RESOURCES PLANNING

The concept of sustainable development was defined by the World Commission on Environment and Development as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987; Jaffe and Al-Jayyousi, 2002). Sustainable water resource development has received increased attention because of concerns about system reliability, water quality, economic efficiency, and financial security (Cai *et al.*, 2002; Jaffe and Al-Jayyousi, 2002). A variety of techniques can be incorporated into a general planning approach used to evaluate sustainable water resources planning and management. These approaches attempt to calculate the sustainability of a system that must address real world challenges (WCED, 1987). As with most of today's planning approaches, these techniques are typically implemented with computer models.

To investigate the sustainability of the Geum River water supply system, a series of constraints were first identified and explored. Planning alternatives were identified and then evaluated. This process is explained in detail below.

A series of water management constraints are proposed as a means of addressing the sustainability of the Geum River system over the next few decades. Two possible instream flows (5.4 and 12.4 $m^3/s$) between dams were tested as potential constraints. Obviously, a larger instream flow significantly lowers the system reliability of the upstream dam, while a lower flow target provides the reverse effect.

Another conflict variable is the population forecast for Jonju City in 2020. Two population options (2.5 and 3.5 million) were considered, based on the projections of two groups. The population projection, however, has been translated into demand forecast as a system constraint and incorporated into the decision-support system. Finally, the instream flow target (21 $m^3/s$) below Daechong Dam suggested by LEGs was incorporated into the analysis. Major releases for the instream flow target below Daechong Dam are directly related to the amount of water for hydropower generation. Because of this, two hydropower release (HDR) options (average rule and minimum rule based on historic reservoir operations) were also tested as a constraint (Table 2). Obviously, a high HDR lowers the system reliability of the upstream dam, while a lower hydro target provides the reverse effect.

Sixteen possible management scenarios were investigated to meet the suggested system reliability of 97%. Each scenario includes a set of system constraints associated with water conflicts, such as the inclusion of two different values for the HDR rule of Daechong Dam. Note that these scenarios are used for water conflict resolution; alternatives (a set of management options) discussed later will be used for sustainable water planning and management. The individual constraints associated with water conflicts were implemented at five-year intervals for a 20-year planning horizon (from 2000, the year of investigation). For instance, Scenarios 1 and 10 include different HDR strategies (such as an average rule or a minimum release rule) as well as different population forecast values for Jonju City in 2020 (Table 2).

TABLE 2. Sixteen Scenarios With System Constraints Associated With Water Conflicts.

| Scenarios | Hydro Release Rule of Daechong Dam | Instream Flow Below Daechong Dam ($m^3/s$) | Instream Flow Between Daechong and Yongdam ($m^3/s$) | Population of City of Jonju in 2020 (million) |
|---|---|---|---|---|
| 1 | AVG | 21 | 5.4 | 2.5 |
| 2 | AVG | 21 | 5.4 | 3.5 |
| 3 | AVG | 21 | 12.4 | 2.5 |
| 4 | AVG | 21 | 12.4 | 3.5 |
| 5 | AVG | × | 5.4 | 2.5 |
| 6 | AVG | × | 5.4 | 3.5 |
| 7 | AVG | × | 12.4 | 2.5 |
| 8 | AVG | × | 12.4 | 3.5 |
| 9 | MIN | 21 | 5.4 | 2.5 |
| 10 | MIN | 21 | 5.4 | 3.5 |
| 11 | MIN | 21 | 12.4 | 2.5 |
| 12 | MIN | 21 | 12.4 | 3.5 |
| 13 | MIN | × | 5.4 | 2.5 |
| 14 | MIN | × | 5.4 | 3.5 |
| 15 | MIN | × | 12.4 | 2.5 |
| 16 | MIN | × | 12.4 | 3.5 |

Notes: AVG, average rule of hydro release; MIN, minimum rule of hydro release; ×, release below Daechong based on hydropower targets.

Similarly, other scenarios can be defined as one of these combinations considering the rest of the constraints, such as instream flow between dams and below Daechong Dam (Ryu, 2006).

The reliability of Daechong Dam and Yongdam Dam was calculated for each of the possible scenarios associated with ongoing water conflicts at five-year intervals (Table 3). Water demand associated with population was projected at five-year intervals based on time-dependent linearly increasing historic water use. This was projected so that water demand per capita in 2020 was sufficient to meet municipal demand for 2.5 million people in Jonju City. Water demand was adjusted per capita when the population forecast became 3.5 million people, because this population forecast is considered a special case for water conflicts. As a result, the model presents how the system will respond to a major conflict associated with a population forecast. All these system constraints associated with water conflicts can be adjusted and applied to the model through the control panel used by stakeholders. The shaded areas shown in Table 3 indicate system reliabilities that are higher than 97%, which has been defined as an acceptable level; 100% reliability implies that no failure was identified during a simulation period. Note that 100% reliability is unrealistic in a statistical sense, but we assumed that no failure can be obtained in deterministic inflows and demand forecasts. As shown in Table 3, a majority of the scenarios meet the reliability standard until the year 2010. Unlike other scenarios, Scenario 3 with the same system configuration with different instream flows shows that system reliability decreases gradually until the year 2010 and beyond. Scenario 3 suggests that in this case, the reliability of supplies to both cities decreases at approximately the same rate, possibly making the sacrifice acceptable to both sides (Ryu, 2006).

TABLE 3. The System Reliability of Sixteen Management Scenarios Over Next 20 Years.

| Year Scenario | System Reliability | 2000 | 2005 | 2010 | 2015 | 2020 |
|---|---|---|---|---|---|---|
| 1 | Yongdam | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | Daechong | 0.98 | 0.96 | 0.94 | 0.92 | 0.89 |
| 2 | Yongdam | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 |
| | Daechong | 0.98 | 0.96 | 0.94 | 0.92 | 0.88 |
| 3 | Yongdam | 0.99 | 0.98 | 0.97 | 0.96 | 0.93 |
| | Daechong | 0.99 | 0.98 | 0.97 | 0.95 | 0.93 |
| 4 | Yongdam | 0.99 | 0.98 | 0.97 | 0.96 | 0.86 |
| | Daechong | 0.99 | 1.00 | 0.97 | 0.95 | 0.90 |
| 5 | Yongdam | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | Daechong | 1.00 | 1.00 | 0.99 | 0.98 | 0.96 |
| 6 | Yongdam | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 |
| | Daechong | 1.00 | 1.00 | 0.99 | 0.98 | 0.94 |
| 7 | Yongdam | 0.99 | 0.98 | 0.97 | 0.96 | 0.93 |
| | Daechong | 1.00 | 1.00 | 0.99 | 0.98 | 0.97 |
| 8 | Yongdam | 0.99 | 0.98 | 0.97 | 0.96 | 0.86 |
| | Daechong | 1.00 | 1.00 | 0.99 | 0.98 | 0.95 |
| 9 | Yongdam | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | Daechong | 0.99 | 0.98 | 0.97 | 0.96 | 0.95 |
| 10 | Yongdam | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 |
| | Daechong | 0.99 | 0.98 | 0.97 | 0.96 | 0.94 |
| 11 | Yongdam | 0.99 | 0.98 | 0.97 | 0.96 | 0.93 |
| | Daechong | 0.99 | 0.99 | 0.98 | 0.97 | 0.96 |
| 12 | Yongdam | 0.99 | 0.98 | 0.97 | 0.96 | 0.86 |
| | Daechong | 0.99 | 0.99 | 0.98 | 0.97 | 0.94 |
| 13 | Yongdam | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| | Daechong | 1.00 | 1.00 | 0.99 | 0.99 | 0.98 |
| 14 | Yongdam | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 |
| | Daechong | 1.00 | 1.00 | 0.99 | 0.99 | 0.97 |
| 15 | Yongdam | 0.99 | 0.98 | 0.97 | 0.96 | 0.93 |
| | Daechong | 1.00 | 1.00 | 1.00 | 0.99 | 0.98 |
| 16 | Yongdam | 0.99 | 0.98 | 0.97 | 0.96 | 0.86 |
| | Daechong | 1.00 | 1.00 | 1.00 | 0.99 | 0.96 |

### *Alternatives*

Although Scenario 3 is an acceptable and feasible solution for water conflict resolution until 2010, it is necessary to develop sustainable water resource planning and management alternatives beyond 2010 with considering a population projection of 3.5 million. A series of water management alternatives are proposed as a means of addressing the water conflicts in the Geum River Basin. Five alternatives were analyzed with the shared vision model. This analysis identifies combinations of management options that could be feasible solutions. From a sustainability perspective, the individual alternatives were also evaluated after the year 2010 as a function of the population forecast of Jonju City. If an alternative cannot meet the system reliability of 97% at any time, additional management options must be added to increase reliability to meet the system target. Thus, all five alternatives should satisfy the system reliability goal of 97% at the simulated time in the future.

The first step in the creation of alternatives is to define management options that would be preferred by at least one participant. This step implicitly suggests that the participant is a key player in the decision process. Next, each alternative is evaluated to investigate whether it meets the planning criteria and system reliability and is feasible when it is applied individually or in conjunction with other management options. A total of six management options are considered, including adjustment of the HDR below Daechong Dam (denoted as HDR hereafter), adaptation of the water price scheme in case of water shortage during drought periods, a conservation plan for reservoirs and water uses (CON), restrictions on water uses (RES), expansion of the existing reservoirs (EOR), and the use of alternate water resources (AWR) such as ground-water or waste-water reuse. For instance, hydropower production is a result of releases made for other purposes, such as meeting instream flow requirements, irrigation and other water demands for downstream users. If storage in the reservoir is above the rule curve, then the target HDR is made. Otherwise, no additional release is made. A water pricing scheme that increases the price of water during droughts is utilized. We assumed that the price elasticity would result in a 15% reduction in demand (USACE, 1996) during a typical drought. A broad conservation program, including the requirement of restricted flow devices for showers and faucets, replacement of leaking or damaged pipelines, and some reuse of gray water, is estimated to reduce demand by 5-10%. Water-use restrictions, both voluntary (outdoor) and mandatory restrictions (outdoor and indoor) is estimated to decrease demands 5-15% and 10-30%, respectively (AWWA, 2005). The expansion of the Daechong Reservoir is also examined. Two reservoir expansion options (30 million cubic meters and 60 million cubic meters) are considered. Aquifer storage and recharge, in-town water storage, and the integration of regional water supply systems, if necessary, could also be considered as AWR. However, all of the alternate resources in the model are represented as single value of ground water, which is assumed to have a minimum and maximum pumping rate of 5 and 15 $m^3/s$, respectively. Each management option has been previously described in detail in the literature (Ryu, 2006).

These management options for promoting a sustainable water supply over the next 20 years in the Geum River Basin were combined to create five alternatives to meet the 97% system reliability goal for the years beyond 2010. Each alternative contains at least two management options, such as adjustment of HDR or restrictions. The results indicate that no single management option guarantees a system reliability of 97% through 2020 and that a suite of additional management options is needed.

Table 4 compares the management options. Alternative 1 includes adjustments of the HDR option, voluntary restrictions, a water conservation program, a pricing scheme, and development of AWR. The combination of adjusting the HDR option, voluntary restrictions, and a water conservation program results in meeting system reliability of 97% until 2020, when the first price scheme would be introduced. If the population of Jonju City is estimated as 3.5 million rather than 2.5 million in 2020, additional ground water (e.g., 15 $m^3/s$ of ground water) must be pumped as an alternate source of water to meet the targets (Table 4). Note that bold and italic characters represent more rigorous management options applied when Jonju's population is forecasted to grow to 3.5 million people. For instance, AWR, HDR, and RES represent, respectively, maximum 15 $m^3/s$ of ground-water pumping, minimum HDR, and mandatory restriction options applied to meet system targets; no management options in the year columns (e.g., 2015) imply that the management options made before that year still meet the system reliability of 97% so that no additional action is required.

TABLE 4. Sustainable Alternatives for Geum River Basin for Next Few Decades.

| | **Years of Investigation** | | | | |
|---|---|---|---|---|---|
| **Alternatives** | **2010** | **2015** | **2020** | **2025** | **2030** |
| 1 | CON, HDR, RES | | WPS, ***AWR*** | | |
| 2 | CON, HDR, RES | | AWR | ***AWR*** | |
| 3 | WPS | | RES | ***HDR*** | ***RES*** |
| 4 | CON | | EOR, RES | ***RES*** | |
| 5 | CON, HDR, RES | | ***HDR***, WPS | ***RES*** | ***AWR*** |

Notes: AWR, development of alternate water resources; CON, conservation program; EOR, reservoir expansion; HDR, adjustment of hydropower release; RES, water restriction; WPS, water price-scheme.

Bold and italic characters represent more rigorous management options applied when Jonju's population is expected to be 3.5 million people.

## EVALUATION OF ALTERNATIVES

To identify the Pareto-optimal solutions, all aspects of the problem must be considered. A common approach is to include a cost-benefit analysis of each alternative (Blowers, 1993). Although cost effectiveness is a very important measure for the project evaluation, a decision made solely on an economic evaluation would not be acceptable to stakeholders in this basin. Furthermore, a series of modifications to incorporate more subtle political variables into the analysis is ongoing. Alternatively, an MCDM approach was utilized to evaluate the complex water resource allocation and management tradeoffs between stakeholders and system objectives using subjective scales. In using this approach, selecting a "preferred" solution from potential alternatives depends on the evaluation procedure that integrates the model and the stakeholders.

The MCDM approach applied to this problem requires consideration of multiple participants with different preferences. Such a model is applied to help multiple stakeholders integrate multiple dimension viewpoints and address individual or group concerns and opinions through interaction (Cai *et al.*, 2004; Watabe *et al.*, 1992).

### *Mathematical Justification*

The MCDM utilized incorporates the water resource decision makers' long-term planning goals. The weighted benefit obtained by each stakeholder is calculated as:

$$\begin{aligned}\mathrm{DV}\,(i,m,k) &= E\,[\alpha(i,m,k)\cdot\beta(i,m,k)]\\ &= E[\alpha(i,m,k)]\cdot E[\beta(i,m,k)],\end{aligned} \tag{1}$$

where DV is the decision vector of benefits; $i$ is the 1, 2,…, $I$ is the alternative index; $m$ is the 1, 2,…, $M$ is the evaluation criterion index; $k$ is the 1, 2,…, $K$ is the stakeholder index; and $E$ is the weighted benefit matrix, equivalently mathematical expectation; $\alpha$ and $\beta$ are the weighted value of individual stakeholder and differentiated interest on group stakeholders at a given alternative associated with evaluation criterion, respectively.

$E\,[\alpha(i,m,k)]\cdot E\,[\beta(i,m,k)]$ is defined as:

$$\begin{aligned}E[\alpha(i,m,k)] &= A_{i,j}\cdot B_{j,m}\cdot\left[\sum_{m=1}^{M}\sum_{j=1}^{J} w_{m,j}\cdot P(j,k)\right]\\ E[\beta(i,m,k)] &= A_{i,j}\cdot B_{j,m}\cdot\left[\sum_{m=1}^{M}\sum_{j=1}^{J} w_{m,j}\cdot Q(j,k)\right],\end{aligned} \tag{2}$$

where $E[\alpha(i,m,k)\cdot\beta(i,m,k)]$ is the value of joint weighted benefit matrix between stakeholders ($k$) at given alternative ($i$) associated with evaluation criteria ($m$); $E\,[\alpha(i,m,k)]$ is the weighted benefit matrix of individual stakeholder ($k$) at given alternative ($i$) associated with evaluation criteria ($m$); $E\,[\beta(i,m,k)]$ is the weighted benefit matrix of differentiated interest on group stakeholders ($k$) at given alternative ($i$) associated with evaluation criteria ($m$); $A$ and $B$ is the binary variables; $j$ is the 1, 2,…, $J$, is the management options; $P$ and $Q$ are the benefit matrices of individual and group stakeholders for the management options, respectively; and $w$ is the weight of the management option on the criterion.

Equivalently, DV is the decision vector that reduces the evaluation of an alternative to a single number for each criterion, whose element $P(i,m,k)$ indicates the weighted performance value of alternative ($i$) associated with the weight to evaluation criterion ($m$) to stakeholder ($k$). $w_{\mathrm{mj}}$ is a matrix that contains the weight of each management option ($j$) on each criterion ($m$). For example, the element $w_{mj}$ ($m = 1,\ldots, M$, $j = 1,\ldots, J$) of $w$ is the evaluation of the m^th^ criterion with respect to the j^th^ management option.

The elements of $w_{mj}$ are defined by the stakeholders, perhaps with the guidance of the analysts. The elements of $w_{mj}$ can be represented by numeric values (e.g., ordinal scale from 0 to 10) or category values (e.g., bad, fair, good, and excellent), depending upon which are the most appropriate (Cordeiro Netto *et al.*, 1996; Raju *et al.*, 2000). However, for computability purposes, $w_{mj}$ is considered to be composed of nonnegative numbers. $A$ and $B$ are binary variables that are activated by management options and evaluation criteria, respectively. For instance, if $A_{i,j} = 1$, then management option $A_{i,j}$ is activated. If management is not activated, $A_{i,j}$ is equal to 0. Similarly, $B_{j,m}$ is also defined as a binary variable (Ryu, 2006). $P(j,k)$ and $Q(j,k)$ represent individual and group benefit matrices for the management options, respectively. Stakeholders evaluate management options differently depending on their value system. $P(j,k)$ denotes the priority of the management options by an individual stakeholder, while $Q(j,k)$ denotes the relative priority of the stakeholders in the overall decision process. Now the relative ranking of a management option by an individual stakeholder relative to all stakeholders can be defined as $Q(j,k)$:

$$Q(j,k) = \frac{P(j,k)}{\sum_{k=1}^{K} P(j,k)}, \tag{3}$$

where

$$\sum_{j=1}^{J} P(j,1) = \sum_{j=1}^{J} P(j,2) = \cdots \sum_{j=1}^{J} P(j,k) = 1$$

Therefore,

$$\sum_{j=1}^{J}\sum_{k=1}^{K} P(j,k) = K \tag{4}$$

Equivalently,

$$\sum_{k=1}^{K} Q(1,k) = \sum_{k=1}^{K} Q(2,k) = \cdots \sum_{k=1}^{K} Q(I,k) = 1 \tag{5}$$

The elements of $P(j,k)$ are an indication of the relative importance of criterion ($j$) to participant ($k$).

However, the sum of values should be unity. Similarly, the elements of $Q(j,k)$ are an indication of each management option's priority between stakeholders obtained with $P(j,k)$, formulated above.

### Numerical Application to the Geum River Basin

Possible evaluation criteria integrated into the evaluation procedure in this study include financial feasibility, public involvement, environmentally friendly functionality, water quality improvement, educational benefit, and energy conservation (Simonovic, 1996; Cai *et al.*, 2004). Each component can be weighted in order of importance based on the perspective of each stakeholder (Palmer and Lund, 1985; ReVelle *et al.*, 2004).

Simulation exercises were devised to evaluate alternative operating policies as a function of the ongoing water conflicts. Table 5 shows the performance of management options relative to six criteria identified in the conflict resolution process ($w_{mj}$). The values contained in Table 5 were estimated on the basis of a meeting with individual stakeholders in the Geum River Basin during 2003-2004. Note that the relationship in between management options and evaluation metrics is presented using an ordinal scale.

This evaluation procedure requires selecting the best compromise solution. The stakeholders' priority matrices $P(j,k)$ are calculated using Equation (4), and the management option priority matrix is denoted as $Q(j,k)$ in Equation (3) (Table 6). For instance, DOD ranked adjustment of hydro release as the most favorable management option with the weight of 0.3 in $P(j,k)$ matrix. However, in a negotiation, DOD also has to compete with other stakeholders, such as DOJ and LEGs, to take this option in favor of 0.38 (see

TABLE 5. The Performance Matrix of Evaluation Criteria Corresponding to Management Options.

| | **Criteria** | | | | | |
|---|---|---|---|---|---|---|
| **Management Options** | **Financial Feasibility** | **Public Involvement (Sacrifice)** | **Environmental Functionality** | **Water Quality Improvement** | **Educational Benefit** | **Energy Conservation** |
| Adjustment of hydro release | 1 | 0 | 3 | 3 | 0 | 1 |
| Price scheme | 0 | 2,3 | 1 | 1 | 1 | 1,2 |
| Water conservation program | 1 | 2 | 3 | 3 | 3 | 3 |
| Voluntary restriction | 0 | 2 | 1 | 1 | 3 | 3 |
| Mandatory restriction | 1 | 3 | 1 | 1 | 1 | 2 |
| Reservoir expansion | 3 | 1 | 0 | 2 | 0 | 0 |
| Ground water (development of alternative water source) | 2 | 1 | 0 | 1 | 0 | 0 |

Notes: 3, performs well for criteria; 2, performs moderately for criteria; 1, performs fair for criteria; 0, performs poorly for criteria.

TABLE 6. Priority Matrix $P$ and $Q$.

| | | **Stakeholders** | | |
|---|---|---|---|---|
| **Cases** | **Management Options** | **DOD** | **DOJ** | **LEGs** |
| Individual stakeholder's priority matrix $P$ | Adjustment of hydro release | 0.3 | 0.2 | 0.3 |
| | Price scheme | 0.1 | 0.1 | 0.1 |
| | Water conservation program | 0.2 | 0.2 | 0.3 |
| | Voluntary restriction | 0.2 | 0.2 | 0.1 |
| | Mandatory restriction | 0.05 | 0.05 | 0.1 |
| | Reservoir expansion | 0.05 | 0.15 | 0.0 |
| | Ground water | 0.1 | 0.1 | 0.1 |
| Stakeholder management option priority matrix $Q$ | Adjustment of hydro release | 0.38 | 0.25 | 0.38 |
| | Price scheme | 0.33 | 0.33 | 0.33 |
| | Water conservation program | 0.29 | 0.29 | 0.43 |
| | Voluntary restriction | 0.40 | 0.40 | 0.20 |
| | Mandatory restriction | 0.25 | 0.25 | 0.50 |
| | Reservoir expansion | 0.25 | 0.75 | 0.00 |
| | Ground water | 0.33 | 0.33 | 0.33 |

Notes: DOD, Department of Water of Daejon City; DOJ, Department of Water of Jonju City; LEG, local environmental group.

*Q*(*j,k*) in Table 6) during the give-and-take negotiation setting.

Table 7 shows the DV generated by Equation (1) used to evaluate alternatives. The majority of DVs in both Alternatives 1 and 5 are larger than that of any other alternatives, thus all stakeholders prefer these two alternatives. For instance, LEGs will not need to change their individual preference to accept Alternative 5 because they have the largest preference already, but the other two DOD and DOJ may need to adjust their preference on "financial feasibility" by moving some preference from either "educational benefit" or "energy conservation." If this is a case, however, the role of LEGs will be critical in this negotiation setting in the sense that only LEGs are able to allow DOD and DOJ to adjust (e.g., increase or decrease) preference on a particular interest by adjusting LEGs' largest preference on any other criteria. This implies that LEGs' cooperation and their preference adjustment are required to reach the final group agreement. Figure 2 illustrates the weighted benefits provided to the individual stakeholders and group stakeholders for each alternative. The figure shows that all stakeholders prefer Alternatives 1 and 5. Alternatives on the unit circle represent the range of acceptable weighted benefits. Maheswaran and Basar (2003) note that a system is unstable if the eigenvalues of quasi-linear utility functions lie inside the unit circle. This concept is interpreted in MCDM perspective and adopted to determine an acceptable range of management options along with total benefit by individual stakeholders. For instance, the upper portion of the unit circle (above a 45° linear line) represents a condition in which the weighted benefits for individual stakeholders are more favorable than the weighted benefits for group stakeholders in an alternative. In other words, no individual can improve without harming someone else.

Consequently, Alternatives 1 and 5 are considered the most favorable plans (Figure 2) because the weighted benefits are greater than those in other alternatives in Table 7. This analysis also shows the benefits associated with management options by a stakeholder, as well as a group of stakeholders. Alternative 5, in particular, is the preferred alternative because "environmental functionality," "educational benefit," and "energy conservation" dominate the evaluation process, as shown in Table 7. The major difference between Alternatives 1 and 5 is the feasibility of the individual management options in the alternative. This may be the result of the environmental impacts associated with the individual projects (such as ground-water contamination that may occur because of pumping or the negative impacts associated with construction of in-city storage).

A different perspective is provided in Figure 3, which presents the tradeoff associated with each alternative between an individual's total benefits and those of all other stakeholders. It appears that Alternatives 5 and 1 always dominate the other alternatives. The priorities held by the LEGs and by DOD make Alternatives 3 and 4 inappropriate because of the emphasis on constructed solutions. Alternative 2 requires the development of additional water resources to address potential shortages by continuously pumping ground-water resources after 2020. The major difference between Alternatives 1 and 5 is the availability of ground water during the next 25 years. Alternative 1 requires substantially more ground-water pumping to meet the reliability targets than does Alternative 5 after 2020. This feature makes Alternative 1 less attractive to the DOD and DOJ, because of their concerns over the increased cost of water. Figures 2 and 3 indicate that Alternative 5 is the best compromising alternative given the current management options and decision criteria in the MCDM process. Alternative 1 is also clearly next best.

Alternatives in this figure can be also compared by a "Northeast corner rule" that implies that an alternative that lies both to the "north" and "east" of

TABLE 7. Decision Vector of Weighted Benefit.

| | Alternative 1 | | | Alternative 2 | | | Alternative 3 | | | Alternative 4 | | | Alternative 5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Alternative Criteria** | **DOD** | **DOJ** | **LEGs** | **DOD** | **DOJ** | **LEGs** | **DOD** | **DOJ** | **LEGs** | **DOD** | **DOJ** | **LEGs** | **DOD** | **DOJ** | **LEGs** |
| Financial feasibility | 0.44 | 0.18 | 0.66 | 0.44 | 0.18 | 0.66 | 0.56 | 0.66 | 0.29 | 0.44 | 0.58 | 0.27 | 0.56 | 0.23 | 1.00 |
| Public sacrifice | 0.60 | 0.48 | 0.47 | 0.35 | 0.28 | 0.27 | 0.35 | 0.40 | 0.13 | 0.08 | 0.13 | 0.10 | 0.90 | 0.74 | 1.00 |
| Environmental functionality | 0.89 | 0.87 | 0.81 | 0.74 | 0.70 | 0.69 | 0.41 | 0.33 | 0.25 | 0.54 | 0.48 | 0.60 | 1.00 | 1.00 | 1.00 |
| Water quality improvement | 0.74 | 0.50 | 0.83 | 0.63 | 0.41 | 0.71 | 0.48 | 0.50 | 0.29 | 0.51 | 0.54 | 0.52 | 0.83 | 0.56 | 1.00 |
| Educational benefit | 0.87 | 0.87 | 0.76 | 0.69 | 0.69 | 0.59 | 0.30 | 0.30 | 0.10 | 0.14 | 0.14 | 0.30 | 1.00 | 1.00 | 1.00 |
| Energy conservation | 0.80 | 0.79 | 0.64 | 0.66 | 0.64 | 0.52 | 0.34 | 0.32 | 0.14 | 0.20 | 0.18 | 0.31 | 1.00 | 1.00 | 1.00 |
| Sum | 4.34 | 3.69 | 4.18 | 3.51 | 2.90 | 3.45 | 2.44 | 2.51 | 1.21 | 1.92 | 2.06 | 2.10 | 5.29 | 4.53 | 6.00 |

Notes: DOD, Department of Water of Daejon City; DOJ, Department of Water of Jonju City; LEGs, local environmental groups.

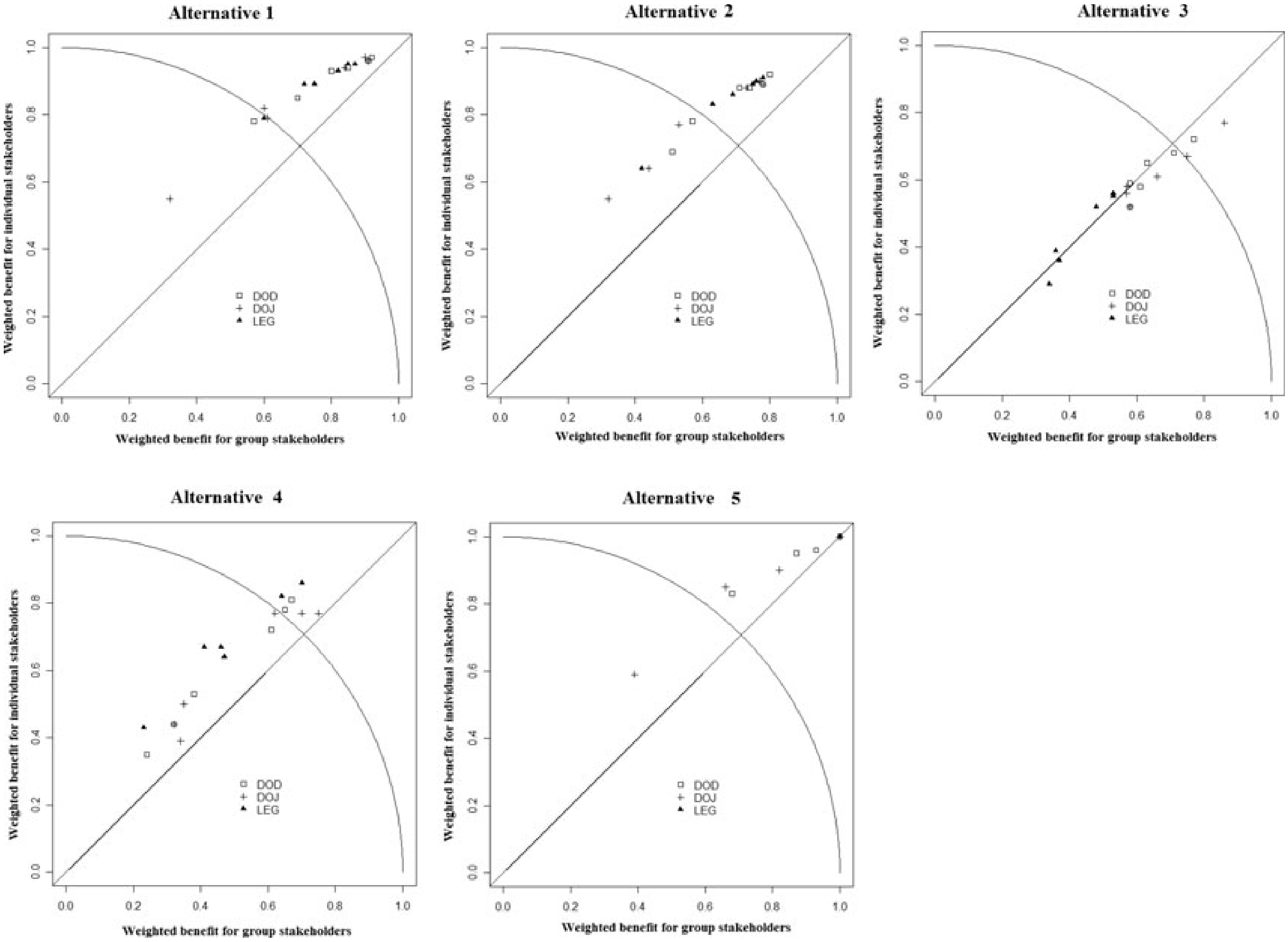

FIGURE 2. Intercomparison of Alternatives Considering Weighted Benefit Between Individual and Group Stakeholders.

another alternative provides more benefits to both the group stakeholders and the individual stakeholders. The results of this evaluation were somewhat unexpected. Regardless of which of the individual stakeholders' points of view were selected, Alternatives 5 and 1 were consistently the preferred choices, and Alternatives 4 and 3 were poorly ranked. The results did not exhibit the typical tradeoffs that exist between stakeholders, with certain stakeholders supporting an alternative that is not preferred by other stakeholders. This could occur for two primary reasons. First, Alternatives 5 and 1 may simply be excellent alternatives, which meet the needs of a wide range of stakeholders well. This seems likely since they are similar, with only one major option in each portfolio of options that is different. Second, the rankings of alternatives may be consistent between stakeholders because alternatives that did not reflect the preferences of stakeholders were removed from consideration earlier in the process. This could occur because of the desire not to include alternatives that were particularly unacceptable to any of the stakeholders.

## CONCLUSION AND FUTURE WORK

A modeling framework was developed to apply a multi-criteria decision-making process to evaluate alternatives with multiple stakeholders in the Geum River Basin.

The procedure used in this study includes the development of a simulation model as a tool for water resource conflict management, and it makes use of an MCDM technique that takes into account financial feasibility, public involvement, environmental functionality, water quality improvement, educational benefit, and energy conservation. Two major procedures

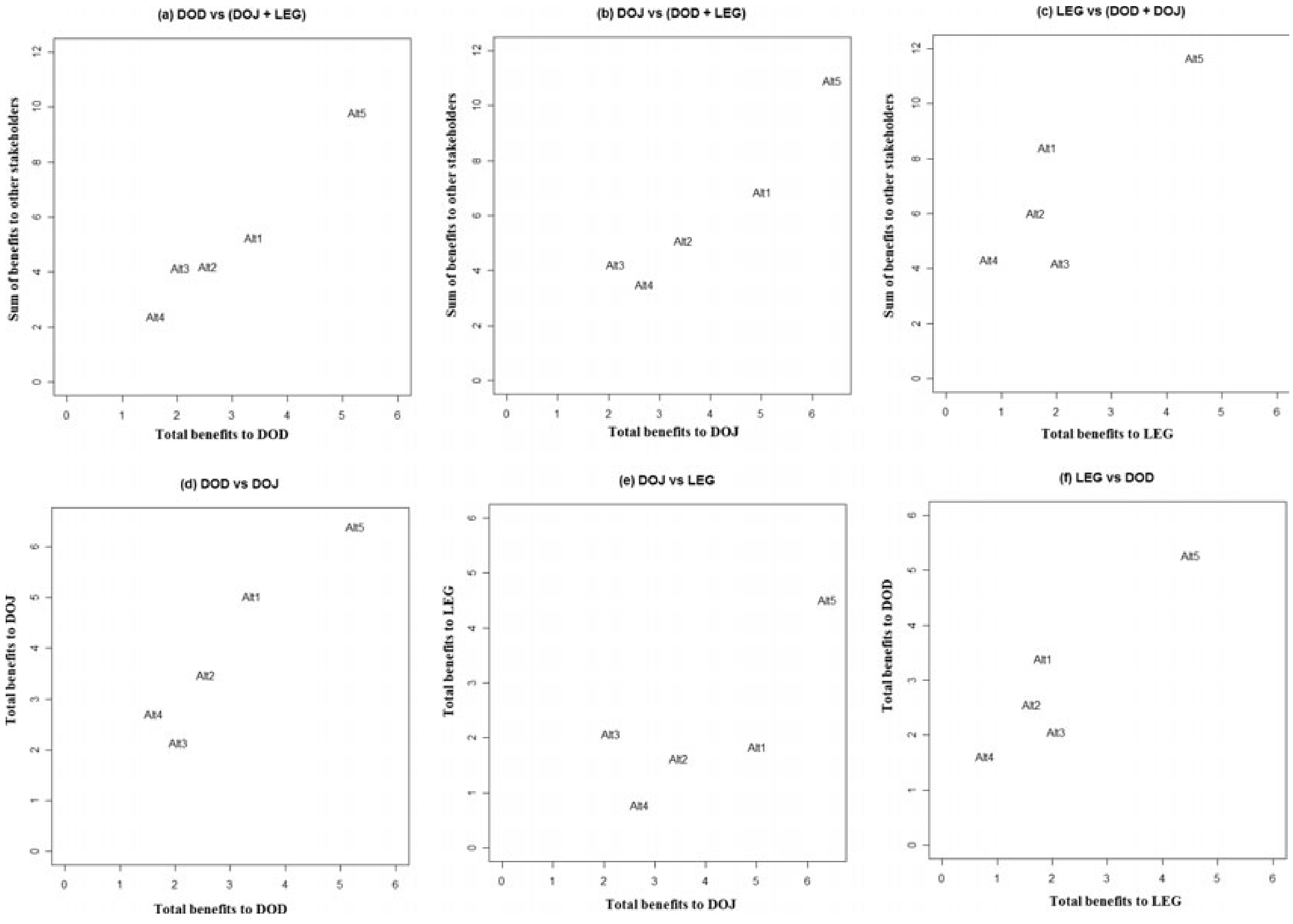

FIGURE 3. Intercomparison of Alternatives by Individual and Other Stakeholders.

are conducted in this research. The first one utilizes a simulation model of decision making in a shared vision modeling framework associated with water conflict constraints to reach consensus about which management options best address stakeholders' collective concerns. Ongoing conflicts further facilitate the development of sustainable water resources planning for droughts as well as uncertain water demand so that potential management alternatives are generated with a set of management options. Potential management alternatives are then evaluated by assessing total benefit associated with management options by individual and group stakeholders. The advantage of the MCDM framework is that it allows a wide range of flexibility during initial stages of the decision-making process. It is anticipated that efforts will continue in the evaluation of potential water management options in the basin and the opportunity to work with stakeholders to better incorporate regional considerations, constraints, and objectives will occur. Because the establishment of environmental flows will have impacts on the system yield and because the region continues to grow, the conflicts will increase unless cooperative solutions can be reached.

Future research should address the integration of appropriate science and engineering knowledge into the political process and techniques that will encourage decision makers to focus on the appropriate technical issues while they also consider the ubiquitous political concerns. Additionally, since the weighting factors in this study are selected subjectively according to stakeholders' related expertise, the variability of the level of satisfaction with model results by the stakeholders should also be analyzed with many different weighting schemes during the give-and-take of the negotiation setting to reach ultimate water conflict resolution. Specific future research should include: (1) evaluation of the role of uncertainty in stakeholders' acceptance or rejection of alternatives (2) development of a detailed drought management plan to support system operation and management during periods of low flow, (3) continued analysis of the impacts that instream flow requirements have on the system's safe yield and its ability to generate economic benefits, and (4) sensitivity analysis of weighting factors chosen by one group of stakeholders along with comparable counterparts selected by another group.

Finally, although the tool developed in this research is a methodological one that succeeds at shared vision planning, researchers still need to address gaps in engineering models and explore the social benefits of alternatives and subsequent results. Such human/social elements of the tool are also critical to the success of the tool, because they enhance our understanding of human-environment interaction and its role in achieving sustainable environmental systems and increase our understanding of human/social factors in water resources planning, management, and policy.

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