7-1999

Water Supply Planning under Interdependence of Actions: Theory and Application

D. Marc Kilgour
Wilfrid Laurier University, mkilgour@wlu.ca

Keith W. Hipel
University of Waterloo

Siamak Rajabi
University of Waterloo

WATER RESOURCES RESEARCH, VOL. 35, NO. 7, PAGES 2225–2235, JULY 1999

Water supply planning under interdependence of actions: Theory and application

S. Rajabi, K. W. Hipel,[1] and D. M. Kilgour[2]

Department of Systems Design Engineering, University of Waterloo, Waterloo, Ontario, Canada

Abstract. An ongoing water supply planning problem in the Regional Municipality of Waterloo, Ontario, Canada, is studied to select the best water supply combination, within a multiple-objective framework, when actions are interdependent. The interdependencies in the problem are described and shown to be essential features. The problem is formulated as a multiple-criteria integer program with interdependent actions. Because of the large number of potential actions and the nonconvexity of the decision space, it is quite difficult to find nondominated subsets of actions. Instead, a modified goal programming technique is suggested to identify promising subsets. The appropriateness of this technique is explained, and the lessons learned in applying it to the Waterloo water supply planning problem are described.

1. Introduction

Decisions about water resources have been widely recognized as being multiple objective in nature. In fact, many theories and concepts of multiple-criteria decision making (MCDM) have been inspired by water resources planning problems [*Stewart and Scott*, 1995]. Usually, water supply planning problems have diverse economic, social, environmental, and political objectives. During the past two decades, many MCDM techniques have been developed for use in water resources planning problems [e.g., *Cohon and Marks*, 1973, 1975; *Loucks et al.*, 1981; *Goicoechea et al.*, 1982; *Roy et al.*, 1992; *Hipel*, 1992; *Rajabi et al.*, 1996; *Netto et al.*, 1996].

The main objective of this paper is to propose models and associated analytical techniques to select, within a multiple objective framework and under interdependence of actions, the best combination of long-term water supply strategies for the Regional Municipality of Waterloo, Ontario, Canada. This study is the first attempt to apply analytical multiple objective methods to the Waterloo water supply planning problem (WWSPP). Additionally, to the best of our knowledge, this is the first water supply planning study in which the interdependence of actions has been explicitly considered in the modeling process. Section 2 briefly describes the background and characteristics of the WWSPP. Section 3 defines the concept of interdependence of actions and explains various interdependencies that exist in the WWSPP. The general mathematical model of WWSPP is presented in section 4. Subsequently, section 5 proposes a solution methodology for the model, while section 6 discusses the input data. Then section 7 presents a brief discussion of the solutions. Finally, conclusions are drawn in section 8.

[1]Also at Department of Statistics and Actuarial Science, University of Waterloo, Waterloo, Ontario, Canada.

[2]Also at Department of Mathematics, Wilfrid Laurier University, Waterloo, Ontario, Canada.

Paper number 1999WR900001.
0043-1397/99/1999WR900001$09.00

2. Waterloo Water Supply Planning Problem

2.1. Background

The Regional Municipality of Waterloo is located in the southwestern part of Ontario, Canada, and comprises the three cities of Kitchener, Waterloo, and Cambridge, as well as several rural areas. The Waterloo region has an area of almost 1350 km^2 and is one of the most prosperous industrialized areas in Canada, with population of almost 0.5 million. At present, the Waterloo region is one of the largest communities in North America to rely almost entirely on groundwater. More than 90% of Waterloo's potable water is provided by some 126 wells; the remainder is drawn from the Grand River, which flows through the region. Because of increases in residential, industrial, and commercial demand and decreases in the reliability of groundwater sources, the Regional Government is currently developing a long-term water strategy to the year 2041 [*Associated Engineering*, 1994].

Like many other long-term water policy problems, there are several sources of uncertainty in the WWSPP. For example, actual water demand may not be as forecast, the capacities and reliability of some actions may not be accurately estimated, and implementation costs are not known precisely. In this study we do not explicitly include uncertainty for these parameters. Nevertheless, one can use any sensitivity analysis method on uncertain parameters to assess the effects of uncertainty on solutions.

In WWSPP the three competing strategies are referred to as tradition, security, and displacement. Each strategy is based on a specific philosophy. Tradition means to delay expansion of sources of water until demand exceeds supply. This strategy runs a high risk of shortages because of unexpected events. The Waterloo region has occasionally experienced contamination of some wells, leading to short-term water shortages. For example, in the early 1990s the wells supplying the town of Elmira were closed because of pollution of the underground aquifer; Elmira now receives its water via a pipeline from the city of Waterloo.

According to the security strategy, additional capacity should be developed to secure the region from any potential loss of water resources. This strategy increases confidence that future water demand will be met but also increases investment and operating costs.

The displacement strategy emphasizes the replacement of current sources of water, which would have several advantages. For instance, water from an alternative source, such as one of the Great Lakes, would not require domestic softening, and supplies would be more reliable and secure. It is noteworthy that the best subset of water supply actions may be different for each strategy because the strategies correspond to different water supply principles.

2.2. Criterion Identification

The overall purpose of WWSPP is to design and implement the best water resources plan to satisfy long-term demand. In light of this purpose, more specific objectives such as low cost, good water quality, low infrastructure impacts, minimum environmental impacts, low risk, and sufficient supply capability have been proposed for measuring the effectiveness of possible actions. Below is a brief description of each criterion.

2.2.1. Cost. This criterion measures the cost of water to the year 2041, covering investment, operations and maintenance, purchase of water from other regions as required, and water treatment.

2.2.2. Water quality. The Ontario Water Resources Act, implemented in 1972, is the main legislative instrument of the Ministry of Environment and Energy (MOEE) for regulating water quality in the province. The Ontario Clean Water Agency (OCWA), created by the Ontario Water Resources Act, is part of the MOEE, and its mission is to oversee the development of municipal water and wastewater infrastructure. All water sources must meet Ontario standards, both now and in the future. The level of treatment depends on the water supply action. This criterion also reflects public opinion on the aesthetic aspects of water quality. Judging and predicting water quality can be difficult; for instance, the physical, chemical, and bacteriological characteristics of groundwater from different fields may vary considerably.

2.2.3. Infrastructure impacts. Each action requires certain modifications to the existing water supply system, such as expansion of water mains and construction of reservoirs and pumping stations.

2.2.4. Environmental impacts. This criterion refers to long-term and short-term environmental impacts. The effects of actions on agriculture, agricultural water supplies, fisheries, wetlands, recreation, and surface water bodies are included in this criterion. These impacts are more significant for actions involving new construction, such as pipelines.

2.2.5. Risk. Maximizing the security and reliability of water is a major concern. Selecting actions that increase the flexibility of water supply reduces this risk. A project is flexible if it is multipurpose, quick to implement, easy to expand, and easy to modify in case of unexpected changes. Note that in some studies, one element of the risk criterion is the possibility of water shortage. However, we include this consideration in the supply capability criterion.

2.2.6. Supply capability. Most water resources planning research considers supply capability to be a set of constraints to be satisfied. However, in the WWSPP different strategies (i.e., traditional, security, and displacement) may lead to various policies for satisfying water demand. Therefore supply capability is included as an objective that should be maximized in the model. According to this objective, actions that provide large supply capability in the future are preferred. Clearly, larger supply capability imposes more cost. Note that the requirement to meet the minimum demand on the basis of the traditional strategy in each subregion is considered as a constraint in the analysis.

2.3. Available Actions

The definition and generation of actions is an important step in the process of multiobjective water resources planning but one to which little research effort has been devoted. Characteristically, water resources planning problems present a wide variety of possible actions. Most often, actions are not predefined clearly; in some cases, it is hard to determine when actions are feasible [*Keeney et al.*, 1997]. Figure 1 categorizes the set of main actions and their subactions for the WWSPP. (Capacities are measured in millions of imperial gallons per day, or MIGD; 1 imperial gallon equals 4.546 L). In the following, each main action is briefly described.

Groundwater (GW): Currently, almost all water of the region is provided by groundwater from wells in different fields. This main action is the further development of groundwater supplies.

Aquifer recharge (AQ): This set of actions is based on the storage of treated drinking water in a suitable aquifer during periods of water surplus for use in seasonal peaks, emergencies, or as short-term and long-term water supply in subsequent years.

Grand River (GR): Currently, a small portion of the region's water is provided by the Grand River. Low water quality, especially in dry seasons, is a major concern for using Grand River. This action refers to higher extraction directly from this source.

Grand River low-flow augmentation (LF): To provide the opportunity for additional summer extraction, one set of proposed actions is augmentation of the Grand River in low-flow periods, using reservoirs or a pipeline from one of the Great Lakes.

Great Lakes pipeline (PL): This set of actions includes constructing pipelines from one of the Great Lakes along one of several possible routes.

In addition to the above actions, certain managerial, pricing, and regulatory policies could be implemented in conjunction with any solution to the problem. These policies may be especially important as an alternative to expensive water supply actions [e.g., *Bulkley*, 1995; *Ballweber*, 1995]. Even though the particular set of policies selected may affect the best subset of actions, we do not include these policies in the subset selection problem for several reasons. First, we do not at present have enough information on the measurable impacts of the available water policies on water actions across different criteria. As well, including water policies in the base model would increase the size and complexity beyond what is required for a demonstration of this methodology. Nevertheless, we emphasize that the structure of our model allows inclusion of all possible managerial, policy, and regulatory options. Moreover, the effects of some demand management policies can be examined by considering different scenarios in a sensitivity analysis. For example, different pricing policies may change the scenario for water demand.

3. Interdependence of Actions

Most systematic approaches to water resources planning assume independence of actions, even though actions are clearly

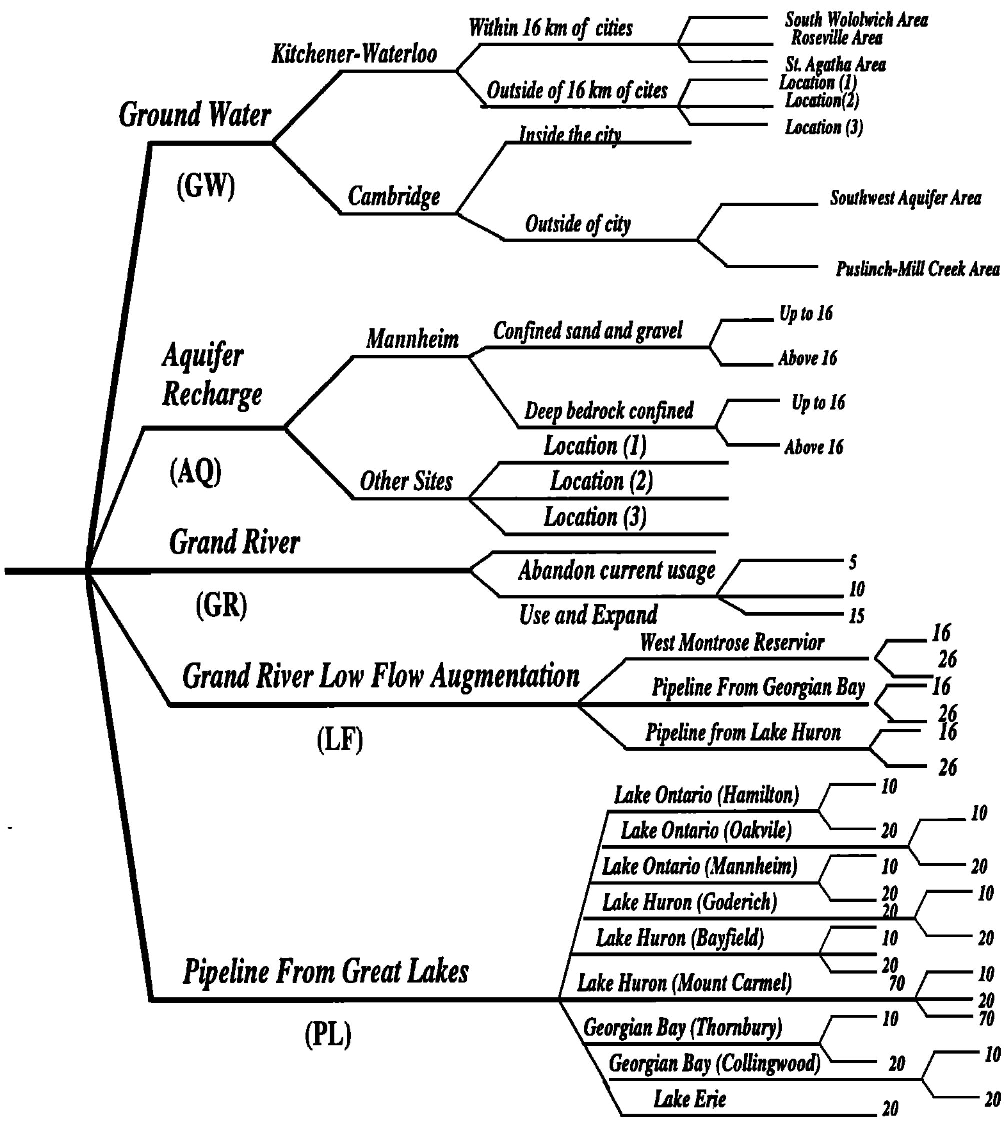

Figure 1. Main actions and subactions for the Waterloo Water Supply Planning Problem and their supply capacities [*Rajabi et al.*, 1996]. Capacities are given in millions of imperial gallons per day; 1 imperial gallon equals 4.546 L.

interdependent in many real-world water resources problems. Interdependence of actions is more common in the multiple-objective context since combinations of actions may be interdependent according to different objectives. There has been little research exploring the concepts and characteristics of interdependence of actions in the water resources planning problems.

Rajabi et al. [1997, 1998] present a general theoretical framework for examining, evaluating, and formulating interdependence of actions in multiple-criteria decision making. They examine the effects of interdependence on the modeling and resolution of subset choice. *Fishburn and LaValle* [1996] give a thorough discussion of the evaluation of subsets of actions when interdependence is binary. They identify necessary conditions on preferences in order that the value of any subset equals the sum of individual action values plus binary interaction terms.

Following original definitions put forward by *Rajabi et al.* [1998], let $\mathbf{A}$ be the set of all possible actions and let $\mathbf{A}_1, \mathbf{A}_2 \subseteq \mathbf{A}$, $\mathbf{A}_1 \cap \mathbf{A}_2 = \emptyset$, $\mathbf{A}_1 \neq \emptyset$, $\mathbf{A}_2 \neq \emptyset$, and let $\mathbf{A}^0 \subseteq \mathbf{A} \backslash (\mathbf{A}_1 \cup \mathbf{A}_2)$. Then the amount of interdependence of $\mathbf{A}_1$ on $\mathbf{A}_2$, given $\mathbf{A}^0$, on criterion $p \in \mathbf{P}$ is defined as

$$\phi_p(\mathbf{A}_1, \mathbf{A}_2|\mathbf{A}^0) = c_p(\mathbf{A}_1 \cup \mathbf{A}_2 \cup \mathbf{A}^0) - c_p(\mathbf{A}_1 \cup \mathbf{A}^0) - c_p(\mathbf{A}_2 \cup \mathbf{A}^0) + c_p(\mathbf{A}^0) \quad (1)$$

where $c_p(\mathbf{B})$ is the evaluation of $(\mathbf{B} \subseteq \mathbf{A})$ on criterion p. Without loss of generality, set $c_p(\emptyset) = 0$. Now the independence of two sets of actions is defined as follows:

Let $\mathbf{A}_1, \mathbf{A}_2 \subseteq \mathbf{A}$, $\mathbf{A}_1 \cap \mathbf{A}_2 = \emptyset$, $\mathbf{A}_1 \neq \emptyset$, $\mathbf{A}_2 \neq \emptyset$, and let $\mathbf{A}^0 \subseteq \mathbf{A} \backslash (\mathbf{A}_1 \cup \mathbf{A}_2)$. Then $\mathbf{A}_1$ and $\mathbf{A}_2$ are independent given $\mathbf{A}^0$, according to criterion $p \in \mathbf{P}$, written $\mathbf{A}_1(\mathbf{I}_p|\mathbf{A}^0)\mathbf{A}_2$, iff $\phi_p(\mathbf{A}_1, \mathbf{A}_2|\mathbf{A}^0) = 0$.

According to the above definition, independence of $\mathbf{A}_1$ and $\mathbf{A}_2$ implies that the amount by which the selection of set $\mathbf{A}_1$ increases the value on criterion p does not depend on whether $\mathbf{A}_2$ is also selected. The definition also implies that two sets $\mathbf{A}_1$ and $\mathbf{A}_2$ are interdependent given $\mathbf{A}^0$ if

Table 1. Examples of Interdependence of Actions in the Waterloo Water Supply Planning Problem

Groups of Actions	Criterion	Type	Description
Different groundwater fields	supply capability	unconditional (−)	water extraction from one field decreases the water extraction from other fields
Wells in one subregion	supply capability	unconditional and conditional (−)	water extraction from one well affects other wells
Aquifer recharge and Grand River low-flow augmentation	cost	unconditional (+)	aquifer recharge and low-flow augmentation could not be accomplished without a new treatment facility and/or a reservoir
Groundwater	water quality	unconditional and conditional (−)	cost of monitoring each well decreases when more wells are selected
Groundwater	environmental impacts	unconditional (+)	additional wells aggravate the effects on agriculture, farm wells, and wetlands
Grand River and groundwater	risk	unconditional (+)	risk increases with the selection of these actions
Grand River and low-flow augmentation	risk	unconditional (+)	risk increases with the selection of these actions
Pipeline and groundwater	infrastructure	unconditional (+)	infrastructure increases because of the major differences between these two actions
Pipeline and groundwater	risk	unconditional (−)	because they rely on two completely different water sources

$$\phi_p(\mathbf{A}_1, \mathbf{A}_2|\mathbf{A}^0) \neq 0$$

When two sets are interdependent there exists a synergistic relation between them. Define the synergy of $\mathbf{A}_1$ and $\mathbf{A}_2$, given $\mathbf{A}^0$, on criterion p as

$$\gamma_p(\mathbf{A}_1, \mathbf{A}_2|\mathbf{A}^0) = \frac{[c_p(\mathbf{A}^0 \cup \mathbf{A}_1 \cup \mathbf{A}_2) - c_p(\mathbf{A}^0)] - [c_p(\mathbf{A}^0 \cup \mathbf{A}_1) + c_p(\mathbf{A}^0 \cup \mathbf{A}_2) - 2c_p(\mathbf{A}^0)]}{[c_p(\mathbf{A}^0 \cup \mathbf{A}_1) + c_p(\mathbf{A}^0 \cup \mathbf{A}_2) - 2c_p(\mathbf{A}^0)]}$$
$$= \frac{\phi_p(\mathbf{A}_1, \mathbf{A}_2|\mathbf{A}^0)}{c_p(\mathbf{A}^0 \cup \mathbf{A}_1) + c_p(\mathbf{A}^0 \cup \mathbf{A}_2) - 2c_p(\mathbf{A}^0)} \quad (2)$$

Note that

$$\gamma_p(\mathbf{A}_1, \mathbf{A}_2|\mathbf{A}^0) = \frac{\text{actual increase in value} - \text{independent increase in value}}{\text{independent increase in value}} \quad (3)$$

Substituting (2) into (1) shows that the consequence of the combination of $\mathbf{A}_1$ and $\mathbf{A}_2$ given $\mathbf{A}^0$ equals

$$c_p(\mathbf{A}_1 \cup \mathbf{A}_2 \cup \mathbf{A}^0) = [c_p(\mathbf{A}_1 \cup \mathbf{A}^0) + c_p(\mathbf{A}_2 \cup \mathbf{A}^0)] \cdot [1 + \gamma_p(\mathbf{A}_1, \mathbf{A}_2|\mathbf{A}^0)] - c_p(\mathbf{A}^0)[1 + 2\gamma_p(\mathbf{A}_1, \mathbf{A}_2|\mathbf{A}^0)] \quad (4)$$

Expression (4) shows how synergy, γ_p, can be interpreted as an increase or a decrease in the consequence of joint selection of two actions.

Note that in most situations, evaluation according to a criterion may be readily available for individual actions but not for sets of actions, because these values are typically obtained from experts in different fields who prefer to evaluate each individual action on its own. In reality, time considerations, diversity of expertise, and lack of established procedures for eliciting information about interdependence mean that knowledge about interdependence is often sketchy. As a result, a great deal of subjectivity may be involved in aggregating values of actions into values of subsets of actions. Therefore in most real-world applications, especially when the number of actions is large, it is preferable to tackle a multiple-criteria subset selection problem directly through the underlying individual actions. In some water policy studies, interactions are taken into account by considering a combination of actions that explicitly involves the relationships among actions. Such approaches demand extra effort, especially for models with large numbers of actions [*Randall et al.*, 1990, 1997].

More description of the theory and practice of interdependence of actions is given by *Rajabi et al.* [1998, 1997b]. In the WWSPP there are several kinds of interdependence among actions that cannot be overlooked. Table 1 describes some groups of interdependent actions and the criteria under which they are interdependent, categorizes the interdependencies, and indicates whether the interdependence is positive or negative. Also, Table 2 shows the amount of synergy between actions on different criteria. For the sake of simplicity, only binary interdependencies are considered here. Furthermore, since interdependence is a symmetric relation, only one side of the interdependence between two actions is shown in this table. Note that in addition to those given in Table 1, there are some other interdependencies that affect the implementation of actions. For example, two options of aquifer recharge cannot be implemented simultaneously. These kinds of interdependencies have been included in the formulation of the model as hard constraints.

As shown in Table 1, actions can be interdependent either conditionally or unconditionally. When two actions affect each other (on a criterion) no matter what other actions are selected, they are unconditionally interdependent (i.e., $\phi_p(\mathbf{A}_1, \mathbf{A}_2|\mathbf{A}^0) \neq 0 \ \forall \ \mathbf{A}^0$), but if the connection holds only when an-

Table 2. Interdependent Actions and Estimated Synergies in WWSPP

Actions	Groundwater	Low Flow	Grand River	Aquifer Recharge
Groundwater	...	...	...	...
Low flow	...	...	...	...
Grand River	risk (+0.2), water quality (−0.1)	risk (+0.2), infrastructure (−0.1)	...	...
Aquifer recharge	risk (−0.1), infrastructure (+0.15)	cost (+0.2), risk (+0.15)	risk (−0.1), infrastructure (+0.2)	...
Pipeline	risk (−0.1), infrastructure (+0.2)	risk (+0.1), environment (+0.1)	risk (−0.1), infrastructure (+0.2)	environment (+0.1), risk (+0.2)

other specific action(s) is selected, they are conditionally interdependent. As an example of conditional interdependence, suppose that a_1 and a_3 are wells that are far enough from each other to be independent. However, if well a_2 is close to both a_1 and a_3, then when a_2 is selected the amount of water extraction from either a_1 or a_3 may affect the amount that can be extracted from the other. In this case, a_1 and a_3 are conditionally interdependent.

4. Model Building

This section explains the main elements of the mathematical model developed to select the best combination of actions for the WWSPP. The problem is formulated as a multiple-objective mixed-integer programming problem with some nonlinear terms that arise because of the interdependence of actions. The notation used for formulating a model for the WWSPP is given in the notation section.

The solutions to be presented below address the following questions: (1) Which actions should be implemented? (2) What level or capacity for each action should be selected? (3) During which period should these actions be implemented? (4) What percentage of each selected action should be assigned to each subregion?

4.1. Objective Functions

For each criterion p, $p = 1, \cdots, |\mathbf{P}|$, the function to be maximized or minimized is

$$\max(\min)\ Z_p = \sum_{i=1}^{|\mathbf{A}|} (FS)_{pi}^t \delta_i + \sum_{i=1}^{|\mathbf{A}|} \sum_{t=1}^{T} (VS)_{pi}^t \sum_{r=1}^{|\mathbf{R}|} x_{ir}^t + \sum_{j=1}^{|\mathbf{A}^0|} \sum_{t=1}^{T} (VS)_{pj}^t \sum_{r=1}^{|\mathbf{R}|} y_{jr}^t + \sum_{k=2}^{|\mathbf{A}|} \sum_{\mathbf{S}\in \mathbf{L}_p^k} \phi_p(\mathbf{S}) \cdot \left(\prod_{a_i \in \mathbf{S}} \delta_i \right)$$

In these objective functions, the first term on the right-hand side represents the sum of the fixed scores of all selected actions. For instance, when $p = 1$, the term equals the investment cost of the selected actions. The second term is the (discounted) sum of variable scores of the selected actions on each criterion over the entire planning horizon. The third term represents the sum of the variable scores of the actions currently in use. The last term of the objective function represents the amount of interdependence of actions. For instance, when actions a_i and a_j are interdependent on criterion p, the quadratic term ($\phi_p(i, j)\delta_i\delta_j$) appears in the objective function for criterion p. The binary variable, δ_i, in the objective functions is defined as follows:

$$\sum_{t=1}^{T} Z_i^t - M_1\delta_i \le 0 \qquad a_i \in \mathbf{A} \tag{5}$$

$$\sum_{t=1}^{T} Z_i^t \ge \delta_i \qquad a_i \in \mathbf{A} \tag{6}$$

where M_1 is a sufficiently large number. Expressions (5) and (6) ensure that δ_i takes the value 1 if and only if action a_i is used at least once during the time horizon. Introducing the variables δ_i significantly decreases the number of nonlinear terms arising from interdependent actions.

4.2. Constraints

4.2.1. Demand. In accordance with the traditional supply strategy, one must satisfy the average demand for each subregion in each period. This set of constraints ensures that for all regions and all periods, a minimally adequate water supply is assigned.

$$\sum_{i=1}^{|\mathbf{A}|} C_i x_{ir}^t + \sum_{j=1}^{|\mathbf{A}^0|} C_{jr}^t y_{jr}^t \ge D_r^t, \tag{7}$$

$$t = 1, 2, \cdots, T \quad r = 1, \cdots, |\mathbf{R}|$$

4.2.2. Budget. The set of constraints in (8) specifies that the total investment, maintenance, and operating costs (first criterion) should not exceed available funds for each period.

$$\sum_{i=1}^{|\mathbf{A}|} (FS)_{1i}^t \delta_i + \sum_{i=1}^{|\mathbf{A}|} (VS)_{1i}^t \sum_{r=1}^{|\mathbf{R}|} x_{ir}^t + \sum_{j=1}^{|\mathbf{A}^0|} (VS)_{1j}^t \sum_{r=1}^{|\mathbf{R}|} y_{jr}^t + \sum_{k=2}^{|\mathbf{A}|} \sum_{\mathbf{S}\in \mathbf{L}_1^k} \phi_1(\mathbf{S}) \cdot \left(\prod_{a_i \in \mathbf{S}} \delta_i \right) \le B_t, \tag{8}$$

$$t = 1, \cdots, T$$

4.2.3. Technology. Constraints (9) and (10) force variable Z_i^t to take the value 1 if and only if action a_i is used at least once in a subregion. Also, (11) and (12) ensure that the total usage of each action does not exceed its capacity.

$$\sum_{r=1}^{|\mathbf{R}|} x_{ir}^t \le M_2 Z_i^t \qquad i = 1, \cdots, |\mathbf{A}|, t = 1, \cdots, T \tag{9}$$

$$M_3 \sum_{r=1}^{|\mathbf{R}|} x_{ir}^t \ge Z_i^t \qquad i = 1, \cdots, |\mathbf{A}|, t = 1, \cdots, T \tag{10}$$

$$\sum_{r=1}^{|\mathbf{R}|} x_{ir}^t \leq 1 \qquad i = 1, \cdots, |\mathbf{A}|, t = 1, \cdots, T \qquad (11)$$

$$\sum_{r=1}^{|\mathbf{R}|} y_{jr}^t \leq 1 \qquad j = 1, \cdots, |\mathbf{A}^0|, t = 1, \cdots, T \qquad (12)$$

where M_2 and M_3 are sufficiently large numbers. For some main actions, only one subaction can be selected. For example,

$$\sum_{a_i \in \mathbf{A}_{lf}} Z_i^t \leq 1 \qquad t = 1, \cdots, T \qquad (13)$$

$$\sum_{a_i \in \mathbf{A}_{pl}} Z_i^t \leq 1 \qquad t = 1, \cdots, T \qquad (14)$$

The constraints in (13) and (14) ensure that at most one action can be selected from each of the two main actions, low-flow augmentation and pipeline.

4.2.4. Variable type. The variable types are

$$x_{ir}^t \geq 0; y_{jr}^t \geq 0 \qquad a_i \in \mathbf{A}, a_j \in \mathbf{A}^0\ r = 1 \cdots, |R|, t = 1, \cdots T$$

$$Z_i^t, \delta_i \in \{0, 1\} \qquad a_i \in \mathbf{A}, t = 1, \cdots T \qquad (15)$$

4.2.5. Linearization. The above formulated problem is a nonlinear multiple-criteria mixed-integer program. Since most theories of integer programming have been developed in a linear framework, it is more convenient to convert this program to a linear one. For each k and p, and $\mathbf{S} = \{i_1, i_2, \cdots, i_k\} \in \mathbf{L}_p^k$, define $Q_\mathbf{S} = \delta_{i_1} \cdot \delta_{i_2} \cdots \delta_{i_k}$ and add the following two constraints:

$$\delta_{i1} + \delta_{i2} + \cdots + \delta_{ik} - Q_\mathbf{S} \leq k - 1 \qquad (16)$$

$$-\delta_{i1} - \delta_{i2} - \cdots - \delta_{ik} + kQ_\mathbf{S} \leq 0 \qquad (17)$$

In this way a multiple-objective subset selection problem under interdependence of actions is expressed as a linear multiple-objective mixed-integer problem. One can also change each cross-product variable ($Q_\mathbf{S}$) to a continuous variable by replacing (17) with the set of inequalities

$$\delta_{i_j} \geq Q_\mathbf{S} \qquad \forall j \in \mathbf{S} \qquad (18)$$

5. Solution Methodology

There are three general approaches to tackling the WWSPP problems formulated above: (1) Assess the utility function of the decision maker (DM) to aggregate all objectives into one; then solve the single objective problem. (2) Solve a vector optimization problem to find the set of efficient solutions. (3) Decide on a reasonable goal on each criterion and use goal programming (GP) to find a combination as close as possible to this goal.

Each of the above approaches has strengths and weaknesses. Assessing the DM's value function is quite difficult and may involve a great deal of subjectivity. This is especially critical when the number of criteria is large. Vector optimization may produce a very large set of efficient alternatives; after using this method the DM must still select a specific solution. For example, *Ruhe* [1988] shows that for a particular class of bicriteria transshipment problems, there are 2^n supported efficient solutions, where n is the number of nodes. As well, using vector optimization to obtain the set of unsupported efficient solutions in this multiple-criteria zero-one problem may be quite difficult because of the nonconvexity of the decision space. In fact, most multiple-criteria zero-one procedures are applicable only to small problems. Moreover, when the purpose is to select a combination of actions, the individually dominated actions should not be removed first, since there is a possibility that under some value functions, a combination including one or more dominated actions may be the best alternative [*Rajabi et al.*, 1996]. This occurrence becomes more likely in the presence of interdependence, making large numbers of decision variables inevitable in the multiple-criteria zero-one problem.

Goal programming (GP), one of the most popular methods in MCDM because of its combination of validity, acceptability, and ease of use, has been applied in many different areas. *White*'s [1990] survey of multiple-objective optimization publications found that 280 out of 400 applications involved variations on GP techniques. The popularity of GP is partly due to the fact that GP problems can be solved with most standard mathematical programming procedures and software.

Even though GP seems to be suitable for the WWSPP, there are some difficulties. To use GP, one must specify the level of goals for all criteria and define the distance metric used to measure the distance of feasible solutions from the target. In many practical cases, both of these steps are difficult to implement. The DM and analyst must have enough knowledge of the problem to be able to set reasonable goals and select an appropriate metric. Moreover, except for the Chebyshev type, GP requires the same assumptions as multiattribute value theory, including additive independence of attributes, ratio-scaled weights, and interval-scaled attribute value functions. Additionally, if the goals are assigned at or above the ideal point, the Archimedean GP chooses the same solution as a linear additive value function.

Despite their many advantages and their popularity, the Chebyshev and Archimedean formulations have been criticized by some researchers, sometimes on the basis of thorough experiments [*Hobbs et al.*, 1990; *Stewart*, 1992]. Archimedean GP may generate solutions that are far from some criterion goals. In other words, even though the weighted sum of the deviations from goals is minimized, the solution may be far from the goal on one or more criteria. Moreover, in most practical MCDM problems, large deviations from a specified goal are likely to be of disproportionate importance compared to small deviations. But Archimedean GP does not take this issue into account because in this method the unit cost for the deviations of any size is constant. *Stewart* [1992] suggests using the L_2 norm instead of Archimedean GP to alleviate this difficulty. However, using L_2 makes the problem more difficult to solve. Moreover, there is no reason to believe that this norm reflects the DM's behavior better than others.

Chebyshev GP does not have these weaknesses. In Chebyshev GP the most critical criterion always receives the most attention, and aggregation of deviations is avoided. However, Chebyshev GP can result in a solution with a large weighted sum of deviations. It has also been shown that Chebyshev GP solutions may reject some reasonable solutions in favor of others that are more balanced [*Ignizio and Cavalier*, 1994]. Note that both Archimedean and Chebyshev GP are often used to find a promising solution according to the aspiration levels and the priority of objectives specified by the DM. However, in many situations the DM might prefer to have several good solutions to choose from, possibly by including qualitative criteria.

In what follows, we propose a new GP approach which

Table 3. Water Demand in Three Main Areas to the Year 2041

	Year									
Region	1996	2001	2006	2011	2016	2021	2026	2031	2036	2041
Kitchener-Waterloo	30.1	31.8	33.9	36	38.2	40	41.6	43.3	44.7	46
Cambridge	15.1	16	17	18.1	19.2	20	20.8	21.6	22.3	23
Rural area	4	4.7	5.3	6.1	6.9	7.4	8.1	8.5	8.9	9.3

Demand given in millions of imperial gallons per day; 1 imperial gallon equals 4.546 L.

overcomes the above mentioned shortcomings of Chebyshev and Archimedean GP techniques, while maintaining the original GP structure. Let d_p^+ and d_p^- denote positive and negative deviations from the goal on criterion p. Construct the following two-objective mathematical programming problem:

Problem Q_1

$$\min \sum_{p=1}^{|\mathbf{P}|} w_p(d_p^- + d_p^+)$$

$$\min \left(\max_p w_p(d_p^- + d_p^+) \right)$$

subject to

$$\sum_{\iota=1}^{|\mathbf{A}|} (FS)_{p\iota}^t \delta_\iota + \sum_{\iota=1}^{|\mathbf{A}|} \sum_{t=1}^{T} (VS)_{p\iota}^t \sum_{r=1}^{|\mathbf{R}|} x_{\iota r}^t + \sum_{j=1}^{|\mathbf{A}^0|} \sum_{t=1}^{T} (VS)_{pj}^t \sum_{r=1}^{|\mathbf{R}|} y_{jr}^t$$

$$+ \sum_{k=2}^{|\mathbf{A}|} (-1)^{k+1} \sum_{\mathbf{S} \in \mathbf{S}_p^k} \phi_p^{\mathbf{S}} \cdot \left(\prod_{a_\iota \in \mathbf{S}} \delta_\iota \right) + d_p^- - d_p^+ = G_p$$

$$p = 1, \cdots, |\mathbf{P}|, \text{ constraints (5)–(15)},$$

where G_p is the goal assigned for criterion p and w_p is the penalty per unit deviation of objective function p from the specified goal. We call program Q1 a multiple-objective GP problem in which both the weighted sum of the deviations and the maximum deviations from goals are simultaneously minimized.

One can use any multicriteria integer approach to solve problem Q1. However, given the difficulty of finding unsupported efficient solutions in multicriteria integer problems and the fact that only some representative GP-efficient solutions are needed, we adopted a weighted approach to find a portion of the efficient solutions of (Q1). Hence our solution involves a convex combination of the first and the second criteria.

The WWSPP model can be reformulated using a hybrid $L_{1,\infty}$ norm as follows:

Problem Q_2

$$\min \left\{ (1-\lambda) \left[\sum_p w_p(d_p^+ + d_p^-) \right] + \lambda \max_p (w_p(d_p^+ + d_p^-)) \right\}$$

subject to the same set of constraints as problem Q1. In the above formulation, term *e* is the Archimedean part of the goal programming problem and term *f* is the Chebyshev part. Moreover, $0 \le \lambda \le 1$ is the coefficient of tendency toward the Chebyshev or Archimedean norm. This objective function can be viewed as a hybrid of L_1 and L_∞ norms, denoted $L_{1,\infty}$.

Since the objective function of problem Q2 is not smooth, we change it to the following program:

Problem Q_3

$$\min \left[(1-\lambda) \left(\sum_p w_p(d_p^+ + d_p^-) \right) + \lambda \beta \right]$$

subject to

$$w_p(d_p^+ + d_p^-) \le \beta \qquad \forall p$$

with the rest of the constraints as in problem Q1. Solving problem Q3 for different values of λ gives different solutions that the DM can choose among.

Note that when there are only two criteria and all constraints are linear, the combined Chebyshev-Archimedean GP is similar to the compromise set [*Zeleny*, 1982]. In fact, in this case, when the solutions of L_1 and L_∞ lie on the same edge of decision space, the set of solutions in the combined Chebyshev-Archimedean GP is identical to the compromise set. The next section provides some numerical information for the WWSPP.

6. Input Data

Population growth is the main cause of increase in water demand in the Waterloo region. Table 3 shows the predicted water demand for each subregion, in terms of MIGD to the year 2041. Table 4 provides actual evaluations for the water supply actions according to the main criteria. The scores for water quality, environmental impacts, and risk criteria are estimated according to the preliminary evaluations obtained by *Associated Engineering* [1994], which were based on expert judgment. Arrows show the direction of preference for each criterion. It is assumed that the preference of the DM is monotonically increasing or decreasing on each criterion.

Since there is no explicit information on the DM's goal for each criterion, the ideal point of the problem is used as the initial target of the problem. Recall that the ideal point is a solution which is best according to all criteria. Solving the overall goal programming problem with the ideal point as the goal provides some initial solutions to the DM. If the DM is not satisfied with this set of solutions, or if he or she wants to examine the robustness of the solutions, the second step is started.

In the second step the DM specifies the percentage of the ideal point on each criterion that can be downgraded without penalty. Then the model is solved for this new target. The decision process is terminated when the DM is satisfied with the solution. The model is built such that the DM can easily enter these percentages.

The importance of each criterion is reflected as the rate of

Table 4. Scores of Actions According to Criteria

Actions	Investment ↓ Cost, 10^6 Dollars	Operation ↓ Cost, 10^6 Dollars	Water Quality ↑	Infrastructure Impact ↓	Environmental Impact ↓	Risk ↓	Supply Capability ↑, MIGD
GW1	100	4	50	30	60	80	29
GW2	61	2.4	50	30	60	80	20
AQ1	8.6	5.9	70	40	45	50	40
AQ2	17	8.8	70	50	45	50	40
GR	5	2	30	30	40	80	5
LF1	112	6.2	60	60	50	60	50
LF2	123.6	6.6	60	60	40	70	unlimited
LF3	111.25	6.7	60	60	90	70	unlimited
PL1	120.4	4.2	70	60	80	30	unlimited
PL2	126	3.4	70	65	80	30	unlimited
PL3	181	2.3	80	60	80	30	unlimited
PL4	222	2.5	70	60	80	30	unlimited

MIGD, millions of imperial gallons per day; 1 imperial gallon equals 4.546 L.

penalty for unit deviation from the goal of each criterion in the model. These rates, estimated according to the preliminary study by *Associated Engineering* [1994] and interviews with personnel in the Regional Municipality of Waterloo, are as follows:

$$w_{\text{cost}} = 0.3,\ w_{\text{water quality}} = 0.1,\ w_{\text{infrast. impacts}} = 0.1$$

$$w_{\text{environ. impacts}} = 0.1,\ w_{\text{risk}} = 0.2,\ w_{\text{supply capability}} = 0.2$$

To examine the effects of changes in criterion weights on the selected subsets, a sensitivity analysis was carried out. On the basis of the DM's judgment, weights were restricted according to the following relations:

$$w_{\text{cost}} > w_{\text{risk}} \geq w_{\text{supply capability}} > w_{\text{other criteria}}$$

7. Discussion of Results

The WWSPP was modeled using GAMS (general algebraic modeling system) and solved with LAMPS (linear and mixed-integer programming system). Different logical constraints and special ordered sets were added to the set of constraints to reduce computational time. Also, the planning horizon was divided into 5, rather than 10, periods to reduce the number of integer variables. The combined Chebyshev-Archimedean procedure was then employed to solve the model.

In this section it is demonstrated that interdependence of actions should not be ignored. In other words, solutions of the model with and without interdependence are quite different. Moreover, the study shows that the convex combination of weighted and Chebyshev GP produces different GP solutions with balanced deviations from goals. Hence the DM has the opportunity to compare these different solutions, perhaps by considering criteria that could not be stated formally.

Even though the model presented in this paper is inspired by a real-world water resources problem, the following simplifications are made:

No explicit uncertainty: As explained in section 2.1, this study does not explicitly include the values of estimated parameters.

Longer time periods: To reduce the number of discrete variables and hence to decrease the computational requirement, we divided the planning horizon into five periods, each 10 years long. Clearly, shorter time periods would provide more accurate solutions.

To achieve the above mentioned objectives, WWSPP was solved for different values of $0 \leq \lambda \leq 1$, with and without interdependence. Solving the model for different values of λ provides some combined-GP nondominated solutions to the problem. All these solutions are potentially good decisions; the DM can confidently choose among them according to his or her preference.

Table 5 shows the subset of actions selected as a function of λ, as well as deviations of the solutions from goals for two different cases; when interdependence of actions is taken into account; and when it is not. The third and fifth columns of this table show the deviations of the solutions from goals for cost, water quality, infrastructure impacts, environmental impacts, risk, and supply capability criteria. Figure 2 depicts the information in Table 5 in a schematic form.

As Table 5 and Figure 2 show, the subset of actions selected is different depending on whether interdependence of actions is included or ignored. When $0.4 \leq \lambda < 0.8$, the best solution for the case of interdependence is AQ2 and GW1, while for no interdependence, it is AQ2 and PL2. The reason for this discrepancy is that the desirable synergistic effects of AQ2 and GW1 exceed any desirable synergies between AQ2 and PL2 because of interdependencies on different criteria. As Table 4

Table 5. WWSPP: Sets of Actions Selected and Deviations from Goal

	With Interdependence		Without Interdependence	
λ	Actions	Deviations From Goal	Actions	Deviations From Goal
$0.0 \leq \lambda < 0.4$	AQ2, PL2	(248, 33, 111, 110, 60, 5)	AQ2, PL2	(241, 33, 100, 120, 50, 5)
$0.4 \leq \lambda < 0.8$	AQ2, GW1	(236, 47, 75, 70, 65, 60)	AQ2, PL2	(241, 33, 100, 120, 50, 5)
$0.8 \leq \lambda < 0.95$	AQ2, GW1	(236, 47, 75, 70, 65, 60)	AQ2, GW1	(236, 47, 65, 70, 65, 60)
1	GW1, AQ1, GR1	(234, 96, 105, 130, 101, 170)	GW1, AQ1, GR1	(234, 87, 105, 140, 90, 170)

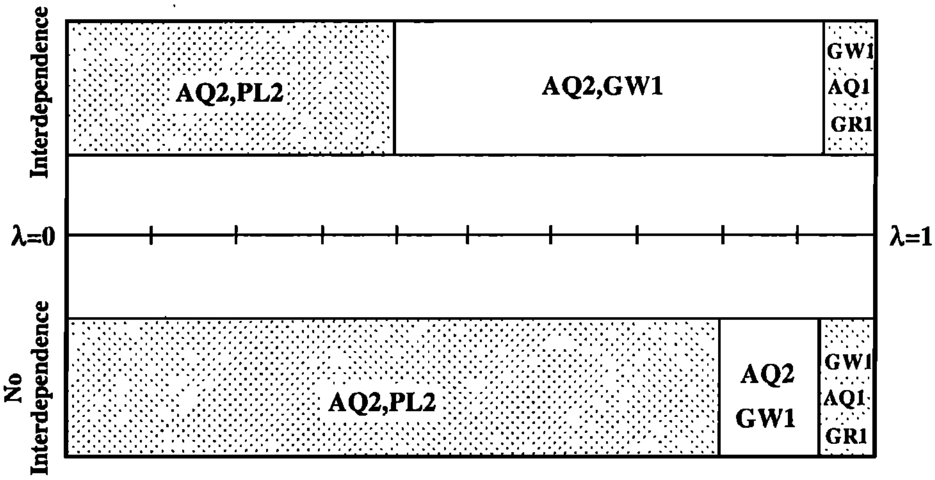

Figure 2. Set of selected actions as function of λ.

indicates, AQ2 and GW1 exhibit a desirable synergy on the risk criterion. But PL2 and AQ2 have an undesirable synergy on both the environmental impacts and risk criteria. Hence, when interdependence of actions is taken into account, the combination of AQ2 and GW1 is better than combination of AQ2 and PL2. Note that ignoring the interdependence of actions and selecting actions (AQ2, PL2) instead of (AQ2, GW1) leads to an increase in the risk criterion of 25%.

Moreover, Table 5 shows that the combined Chebyshev-Archimedean model produces several different GP nondominated solutions with different properties. Aquifer recharge is the only action that is recommended in all cases. The main reason that aquifer recharge is always selected is that the investment cost of this action is quite low in comparison with other actions (see Table 4); implementing aquifer recharge and then using only a portion of its capacity is justifiable. An important practical observation is that if the planning horizon is extended, then other actions may be selected instead of aquifer recharge. Note that as the value of λ increases, and hence as the objective function of GP model approaches a Chebyshev norm, the maximum deviation from the goals over all criteria is minimized. However, at the same time the sum of weighted deviations is increased substantially. The cost criterion always has the maximum deviation.

Table 6 shows the percentages of water utilization of each selected action by each subregion, when $\lambda = 0.5$ and interdependence is taken into account. For this situation, new groundwater sources have to be implemented starting at an early stage. Only a small portion of the capacity of this resource is used (12.5%) at the beginning; gradually, usage is increased so

Table 6. Optimal Water Supply Assignment for Each Subregion for the Interdependence Case: $\lambda = 0.5$

	Selected Actions			
Regions	AQ2	GW1	OGW	OGR
		1996–2001		
KW	···	···	0.693	0.217
Cambridge	···	0.125	0.307	···
Rural	···	···	···	0.783
		2002–2011		
KW	···	0.51	0.586	···
Cambridge	···	···	0.411	···
Rural	···	···	0.002	1
		2012–2021		
KW	···	···	0.773	1
Cambridge	···	0.87	0.059	···
Rural	···	···	0.168	···
		2022–2031		
KW	···	···	0.848	1
Cambridge	···	1	0.036	···
Rural	0.17	···	0.116	···
		2031–2041		
KW	···	···	0.909	1
Cambridge	···	1	0.068	···
Rural	0.415	···	0.023	···

KW, Kitchener-Waterloo.

Table 7. Optimal Water Supply Assignment for Each Subregion for the No Interdependence Case: $\lambda = 0.5$

	Selected Actions			
Regions	AQ2	PL2	OGW	OGR
		1996–2001		
KW	···	···	0.693	0.127
Cambridge	···	0.125	0.307	···
Rural	···	···	···	0.783
		2002–2011		
KW	···	···	0.818	···
Cambridge	···	0.505	0.182	···
Rural	···	0.005	···	1
		2012–2021		
KW	···	0.87	0.377	1
Cambridge	···	···	0.455	···
Rural	···	···	0.168	···
		2022–2031		
KW	0.17	1	0.316	1
Cambridge	···	···	0.491	···
Rural	···	···	0.193	···
		2032–2041		
KW	0.415	···	0.726	1
Cambridge	···	1	0.068	···
Rural	···	···	0.211	···

KW, Kitchener-Waterloo.

Table 8. Optimal Water Supply Assignment for Each Subregion for the Interdependence Case: λ = 1

Regions	Selected Actions GW1	AQ1	GR1	OGW	OGR
		1996–2001			
KW	···	···	···	0.586	1
Cambridge	···	···	···	0.364	···
Rural	0.125	···	···	0.05	···
		2002–2011			
KW	0.51	···	···	0.586	···
Cambridge	···	···	···	0.275	1
Rural	···	···	···	0.139	···
		2012–2021			
KW	···	···	···	0.773	1
Cambridge	0.87	···	···	0.059	···
Rural	···	···	···	0.168	···
		2022–2031			
KW	···	···	···	0.848	1
Cambridge	1	···	···	0.036	···
Rural	···	···	0.68	0.139	···
		2032–2041			
KW	0.51	···	···	0.909	1
Cambridge	1	···	···	0.068	···
Rural	···	0.33	1	0.023	···

KW, Kitchener-Waterloo.

Table 9. Optimal Water Supply Assignment for Each Subregion for the No Interdependence Case: λ = 1

Regions	Selected Actions GW1	AQ1	GR1	OGW	OGR
		1996–2001			
KW	0.125	···	···	0.636	0.127
Cambridge	···	···	···	0.364	···
Rural	···	···	···	···	0.783
		2002–2011			
KW	···	···	···	0.818	···
Cambridge	0.505	···	···	0.182	···
Rural	0.0055	···	···	···	1
		2012–2021			
KW	···	···	···	0.773	1
Cambridge	0.5	···	···	0.227	···
Rural	0.37	···	···	···	···
		2022–2031			
KW	1	···	0.68	0.316	1
Cambridge	···	···	···	0.491	···
Rural	···	···	···	0.193	···
		2032–2041			
KW	1	0.33	1	0.266	1
Cambridge	···	···	···	0.523	···
Rural	···	···	···	0.211	···

KW, Kitchener-Waterloo.

that in the fourth and fifth periods this action is at full capacity (10 MIGD, or 4.6×10^6 L d^{-1}). On the other hand, another selected action, AQ2, is needed only in the last two periods, and only 41% of its capacity will be utilized at the end of the planning horizon. As pointed out earlier, AQ2 is selected because of its low investment cost, even though its operating cost is relatively high. Additionally, in this case the analysis recommends that the entire capacity of the existing groundwater sources and the Grand River should be utilized; replacing them with new water sources is not justified. This is mainly because the cost criterion has priority over all other criteria.

Table 7 shows information similar to that in Table 6, except that interdependence of actions is ignored. As shown in this table, the solution is quite different when interdependencies are not taken into account. Here a second pipeline option (PL2) is chosen instead of groundwater. In the first period, only 12% of its capacity is utilized; gradually, usage is increased. In the fourth period the entire capacity of action PL2 is used for Kitchener/Waterloo, while in the fifth period it is assigned to Cambridge. Again, AQ is used partially only for the last two periods. Additionally, current water supply actions (groundwater and Grand River) are used completely in all periods. Therefore, if the interdependence of actions is ignored, the solution changes dramatically.

Tables 8 and 9 show the solution of the WWSPP when the GP objective function is a pure Chebyshev norm (i.e., λ = 1) with and without interdependence of actions. In this case three new actions are selected: GW1, AQ1, and GR1. These new actions, along with OGW and OGR, provide a solution minimizing the maximum deviation from the target over all criteria, relative to all other feasible solutions, even though the deviations from the target for other criterion goals may be comparatively large. For this situation, GR1 is utilized only in the last two periods and AQ1 is needed, but only partially and only in the last period. Note that the presence of interdependence does not affect which actions are selected, but it alters substantially their distribution over the subregions.

8. Conclusions

In this paper a real-world water supply planning problem, the WWSPP, is modeled as a multiple-objective mixed-integer programming problem. The study clearly shows the importance of accounting for interdependence of actions, even when the amount of interdependence is moderate. Without considering interdependence of actions, subset evaluation and selection require less information assessment and fewer computations, so it is tempting to ignore interdependence of actions in the WWSPP. However, this case study vividly demonstrates that the additional work required to explicitly include interdependence will be rewarded by better choices of water supply actions. Moreover, it is shown that the combined Chebyshev-Archimedean GP is a useful tool to generate different attractive solutions, with or without interdependence of actions. Finally, these solutions provide valuable insights and guidance into how better decisions can be made.

Notation

- T number of planning periods; the planning horizon (1997–2041) has been divided into five periods.
- t index corresponding to the planning period; $t = 1, \cdots, T$.
- $\mathbf{R}$ the set of subregions; $\mathbf{R} = \{$Kitchener-Waterloo, Cambridge, Rural Areas$\}$.
- r index corresponding to subregion; $r = 1, 2, 3$.
- $\mathbf{A}$ the set of actions, $\mathbf{A} = \{a_1, a_2, \cdots, a_i, \cdots, a_{|\mathbf{A}|}\}$.
- $\mathbf{A}$ $\mathbf{A}_{GW} \cup \mathbf{A}_{AQ} \cup \mathbf{A}_{GR} \cup \mathbf{A}_{LF} \cup \mathbf{A}_{PL}$, the union of the subsets of actions in groundwater, aquifer

recharge, Grand River, low-flow augmentation, and pipeline, respectively.

i index corresponding to a specific action.

x_{ir}^t the fraction of water from action i assigned to subregion r in period t.

Z_i^t binary variable corresponding to action i in period t; equal to 1 if action i is used in period t and 0 otherwise.

C_i the total supply capability of action i; hence $C_t x_{ir}^t$ is the amount of water from action i assigned to region r in period t.

j index corresponding to the actions in use in 1996.

$\mathbf{A}^0$ the set of actions in use in 1996.

D_t^r the demand in period t for subregion r according to the traditional supply strategy.

y_{jr}^t the fraction of water from old action j to be used in subregion r in period t.

C_j' the supply capability of the jth action currently being used; hence $C_j' y_{ir}^t$ is amount of water from the jth old action assigned to region r in period t.

$\mathbf{P}$ the set of criteria {cost, infrastructure impacts, water quality, environmental impacts, risk, supply capability}.

p index corresponding to the set of criteria, $p = 1, \cdots, |\mathbf{P}|$.

$(FS)_{pi}$ the fixed score of the ith action according to criterion p.

$(VS)_{pi}^t$ the variable score of action i for period t according to criterion p.

$\mathbf{L}_p$ collection of all sets of interdependent actions according to criterion p.

$\mathbf{L}_p^k$ collection of interdependencies among k actions on criterion p; for example, $\mathbf{L}_p^2$ is the set of all pairs of interdependent actions on criterion p.

$\phi_p(\mathbf{S})$ the amount of interdependence within actions in set $\mathbf{S}$ on criterion p; for example, $\phi_p(i, j)$ is the amount of interdependence within actions a_i and a_j according to criterion p.

Acknowledgments. The authors greatly appreciate the thoughtful suggestions put forward by the two referees, Benjamin F. Hobbs and Norio Okada, which significantly improved the quality of the paper. The research contained in the paper was supported financially by the Natural Science and Engineering Research Council (NSERC) of Canada and the Iranian Ministry of Higher Education.

References

Abu-Taleb, M. F., and B. Mareschal, Water resources planning in the Middle East: Application of the PROMETHEE V multi-criterion method, *Eur. J. Oper. Res.*, *81*, 500–511, 1995.

Associated Engineering, *Regional Municipality of Waterloo, Long Term Water Strategy, Phase 1 Report*, Etobicoke, Ont., Canada, 1994.

Ballweber, J. A., Prospects for comprehensive, integrated watershed management under existing law, *Water Resour. Update*, *100*, 19–23, 1995.

Bulkley, J. W., Integrated watershed management: Past, present, and future, *Water Resour. Update*, *100*, 7–18, 1995.

Cohon, J. L., and D. H. Marks, Multi-objective screening models and water resources investment, *Water Resour. Res.*, *9*, 826–836, 1973.

Cohon, J. L., and D. H. Marks, A review and evaluation of multi-objective programming techniques, *Water Resour. Res.*, *11*, 208–220, 1975.

Fishburn, P. C., and I. H. LaValle, Binary interactions and subset choice, *Eur. J. Oper. Res.*, *92*, 182–192, 1996.

Glover, F., and E. Woolsey, Converting the 0-1 polynomial programming problem to a 0-1 linear program, *Oper. Res.*, *22*(1), 180–182, 1974.

Goicoechea, A., D. R. Hansen, and L. Duckstein, *Multi-objective Decision Analysis with Engineering and Business Applications*, John Wiley, New York, 1982.

Haimes, Y. Y., W. A. Hall, and H. T. Freedman, *Multi-objective Optimization in Water Resources Systems: The Surrogate Worth Trade-Off Method*, Elsevier, New York, 1975.

Hipel, K. W. (Ed.), *Multiple Objective Decision Making in Water Resources*, *Monogr. Ser.*, no. 18, Am. Water Resour. Assoc., Herndon, Va., 1992.

Hobbs, B. F., What can we learn from experiments in multi-objective decision analysis?, *IEEE Trans. Syst. Man Cybern.*, *16*(3), 384–394, 1986.

Hobbs, B. F., V. Chankong, and W. Hamadeh, Screening water resources plans under risk and multiple objectives: A comparison of methods, U.S. Army Corps of Eng., Washington, D.C., 1990.

Ignizio, J. P., and T. M. Cavalier, *Linear Programming*, Prentice-Hall, Englewood Cliffs, N. J., 1994.

Keeney, R. L., T. L. McDaniels, and V. L. Ridge-Cooney, Using values in planning wastewater facilities for metropolitan Seattle, *J. Am. Water Resour. Assoc.*, *32*(2), 293–303, 1997.

Loucks, D. P., J. R. Stedinger, and D. A. Haith, *Water Resource Systems Planning and Analysis*, Prentice-Hall, Englewood Cliffs, N. J., 1981.

Netto, O. C., E. Parent, and L. Duckstein, Multi-criterion design of long-term water supply in southern France, *J. Water Resour. Plann. Manage.*, *122*(6), 403–413, 1996.

Rajabi, S., K. W. Hipel, D. M. Kilgour, Multiple objective water supply planning, in *Proceedings of International Conference on Water Resources and Environmental Research: Towards the 21st Century*, vol. 2, pp. 167–174, Water Resour. Res. Cent., Disaster Prev. Res. Inst., Kyoto Univ., Kyoto, Japan, 1996.

Rajabi, S., D. M. Kilgour, and K. W. Hipel, Action-interdependence in multiple criteria subset selection, *Tech. Rep. 207-O-140797*, Dep. of Syst. Design Eng., Univ. of Waterloo, Waterloo, Canada, 1997.

Rajabi, S., D. M. Kilgour, K. W. Hipel, Modelling action-interdependence in multiple criteria decision making, *Eur. J. Oper. Res.*, *110*(3), 490–508, 1998.

Randall, D., M. H. Houck, and J. R. Wright, Drought management of existing water supply systems, *J. Water Resour. Plann. Manage.*, *116*(1), 1–20, 1990.

Randall, D., L. Cleland, C. S. Kuehne, G. W. Link, and D. P. Sheer, Water supply planning simulation model using a mixed-integer linear programming "engine," *J. Water Resour. Plann. Manage.*, *123*(2), 116–124, 1997.

Roy, B., R. Slowinski, and W. Treichel, Multi-criteria programming of water supply systems for rural areas, *Water Resour. Bull.*, *28*(1), 13–31, 1992.

Ruhe, G., Complexity result of multicriteria and parametric network flow using a pathological network of Zadeh, *Oper. Res.*, *32*, 9–27, 1988.

Stewart, T. J., A critical survey on the status of multiple criteria decision making theory and practice, *OMEGA*, *20*(5, 6), 569–586, 1992.

Stewart, T. J., and L. Scott, A scenario-based framework for multicriteria decision analysis in water resources planning, *Water Resour. Res.*, *31*(11), 2835–2843, 1995.

Szidarovszky, F., M. E. Gershon, and L. Duckstein, *Techniques for Multi-objective Decision Making in Systems Management*, Elsevier, New York, 1986.

White, D. J., A bibliography on the application of mathematical programming multiple-objective methods, *J. Oper. Res. Soc.*, *41*(8), 669–691, 1990.

Zeleny, M., *Multiple Criteria Decision Making*, McGraw-Hill, New York, 1982.

K. W. Hipel and S. Rajabi, Department of Systems Design Engineering, University of Waterloo, Waterloo, Ontario, N2L 3G1 Canada.

D. M. Kilgour, Department of Mathematics, Wilfrid Laurier University, Waterloo, Ontario, N2L 3C5 Canada. (mkilgour@ wlu.ca)

(Received November 3, 1997; revised December 28, 1998; accepted December 29, 1998.)