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Experiences in multiobjective planning and management of water resources systems

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ABSTRACT The purpose of this paper is three-fold. First, multiobjective decision making is viewed as a philosophy and a process, rather than merely a set of procedures and algorithms; while methodologies are obviously important, the framework within which they are applied, and the communication between analysts and decision makers are the crucial determinants of the success in their application. The second part of the paper is devoted to a brief outline of some methodologies which have been found useful in multiobjective planning and management of water resources systems. Finally, the main thrust of the paper lies in presentation of experience gained in several studies.

Expériences dans le domaine de la planification et de l'aménagement à buts multiples de systèmes de ressources en eau
RESUME L'objet de cet article est triple. En premier lieu la prise de décision dans un projet à buts multiples est considérée comme une philosophie et un processus plutôt que le simple emploi d'une série de procédés et d'algorithmes; alors que les méthodologies gardent évidemment une grande importance, le cadre dans lequel on les applique et les liaisons entre analystes et responsables de décisions sont les éléments déterminants du succés de l'application de ces méthodologies. La seconde partie de cet article est consacrée à un bref résumé de certaines méthodologies qui sont avérées utiles dans la planification et l'aménagement à buts multiples de systéme de ressources en eau. Enfin le but principal de cet exposé est la présentation d'expériences acquises au cours de plusieures études.

PRINCIPLES AND ATTITUDES

Optimization can be used only when there is a single objective. The feasible solutions can then be ranked unambiguously according to this objective and the optimal one identified. When there is more than one objective, and the objectives are non-commensurate, which means they cannot be transformed into a single objective, the "optimal" no longer has the same "objective" sense as before. A compromise solution must now be selected on the basis of the decision maker's attitude to achievement of the various objectives: the levels of each and the trade-offs between them.

Two cases must be defined: (a) selection among a number of distinct alternatives, and (b) an infinite number of feasible solutions is defined by a set of constraints. In the first it is possible to start out with a full specification of all alternatives and to proceed to the final selection through weighting of the criteria and evaluation of the degree to which each alternative achieves each of the criteria. In the latter case the range of feasible solutions is not present at the outset, and for practical reasons it is possible to generate only a modest number of alternatives in the analysis.

Multiobjective decision making is a process, more than a collection of mathematical procedures and algorithms. It is a process in which decision makers and analysts interact in learning the range of outcomes in decision space (the values of the decision variables) and in objective space (the values of the objective functions). Practical methods for multiobjective decision making must be *interactive* and *iterative*. They should provide results at each step of the iterative analysis in a form which enables the decision makers to formulate their responses to these outcomes, and to incorporate their instructions into the next phase of the analysis.

MEANS AND METHODS

In their now classic paper Cohon & Marks (1975) provide a review of multiobjective programming techniques and evaluate their efficiency in water resources planning. This evaluation - itself formulated as a multiobjective problem - is based on three criteria: (1) the method must be computationally feasible, (2) it must foster explicit quantification of trade-off among objectives, and (3) it must provide sufficient information so that an informed decision can be made. Cohon & Marks concentrate on programming problems, in which an infinite number of feasible solutions is defined by a set of constraints, and conclude in recommending the surrogate trade-off (SWT) method (Haimes & Hall, 1974) and the constraint method (or, equivalently, the weighting method). Among the methods for selecting from a number of discrete alternatives they consider only Electre (Roy, 1971), and dismiss it as "... not applicable to water resources problems, since it is not computationally attractive and because trade-offs are obscured by the analysis".

Keeney & Raiffa (1976) devote much of their book to selection among a finite number of alternatives in view of more than one objective. They develop the theory of multiattribute utility and demonstrate its application. Keeney (1979) gives an interesting example of a water resources problem, wherein one out of ten sites is to be selected for developing a pumped storage facility of 600 MW, with three objectives: (1) minimum costs, (2) minimum detrimental transmission line impacts, and (3) minimum detrimental environmental impacts at the site. Four attributes are selected to measure these objectives: (1) first year costs, (2) transmission line distance, (3) acres of forest affected and (4) length of store-line affected at one particular site where a rare species resides. The paper details how the preference structure was established through elicitation of responses from the decision makers. A utility function is then constructed, and used in ranking the sites.

While the method is conceptually attractive, it seems impractical to obtain from the decision makers the responses needed for its implementation.

Saaty (1977, 1980) has developed a method for setting priorities among a number of alternatives according to more than one criterion. De Graan (1980) modified some of the method's features, and applied it to several problems of water resources. The method works as follows. L alternatives are to be ranked according to N criteria. The criteria are ranked by filling a matrix:

$$
\begin{array}{c|cccc}
i \diagdown j & 1 & 2 & \dots & N \\
\hline
1 & a_{11} & a_{12} & \dots & a_{1N} \\
2 & a_{21} & a_{22} & \dots & a_{2N} \\
\vdots & \vdots & \vdots & & \vdots \\
N & a_{N1} & a_{N2} & \dots & a_{NN}
\end{array}
\tag{1}
$$

where a_{ij} is the relative importance - as seen by the decision maker - of criterion i relative to criterion j, using the following scale:

a_{ij}	*Meaning*
1	Equal importance
3	Weak preference of i over j
5	Considerable preference of i over j
7	Strong " " " " "
9	Absolute " " " " "
2,4,6,8	Intermediate values

Obviously $a_{ii} = 1$. Also, once a_{ij} is selected, then $a_{ji} = 1/a_{ij}$. A total of $N(N - 1)/2$ values are required. This provides a redundancy of data, since consistency of preferences would mean $a_{ik} = a_{ij}a_{jk}$. This redundancy is used to compute measures of consistency.

The eigenvalues of the matrix are the relative weights of the criteria w_n, $n = 1,\dots, N$, which are [0,1]. A good approximation of these values can be computed by the following simple procedures:

$$b_{ij} = \ln a_{ij} \tag{2}$$

$$x_n = \Sigma_{j=1}^{N} b_{ij}/N \tag{3}$$

$$w_n = \exp(x_n)/\Sigma_{i=1}^{N} \exp(x_i) \tag{4}$$

The coefficient of regression, which is a measure of consistency, is given by

$$R = [N\Sigma_{i=1}^{N} x_i^2/\Sigma_{i<j} b_{ij}^2]^{\frac{1}{2}} \tag{5}$$

Values ($R > 0.9$) indicate acceptable consistency. Other measures of consistency can also be computed.

Now the L alternatives are ranked with respect to each of the criteria separately, using the same method. An (LxL) matrix is filled with a_{ij} values on the same scale of 1 to 9. The entries now denote the relative contribution of the alternatives to the criterion. For example, $a_{ij} = 3$ would mean here that alternative i contributes a little more than alternative j to attainment of the objective measured by the criterion presently under consideration, $a_{ij} = 7$ much more, and so on.

A set of relative weights, which sum to 1.0, of the alternatives for each criterion are computed as above. Denoting by $w_\ell(n)$ the relative weight of alternative ℓ with respect to criterion n, then ranking of the alternatives with respect to all criteria is by the priorities P_ℓ, $\ell = 1,\ldots,L$, which are also [0,1] and sum to 1.0:

$$\begin{bmatrix} P_1 \\ P_2 \\ \cdot \\ \cdot \\ \cdot \\ P_L \end{bmatrix} = \begin{bmatrix} w_1(1) & w_1(2) & \ldots & w_1(N) \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ \cdot & & & \cdot \\ w_L(1) & w_L(2) & \ldots & w_L(N) \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ w_N \end{bmatrix} \tag{6}$$

The method is useful in dealing with hierarchies of objectives and means for attaining them. Final selection of the preferred alternative can be aided by a coefficient of concordance, which *measures the degree of consistent achievement of an alternative* with respect to all criteria:

$$C_\ell = \frac{(P_\ell - 1/N)}{[\Sigma_{i=1}^{N} w_i(w_\ell(i) - 1/N)^2]^{\frac{1}{2}}} \tag{7}$$

Multiobjective programming methods have been classified by Cohon & Marks (1975) into three categories:

(a) generating techniques, in particular the weighting method and the constraint method;

(b) techniques which rely on prior articulation of preferences, among them goal programming, the surrogate worth trade-off (SWT) method, and the assessment of utility functions;

(c) techniques which rely on progressive articulation of preferences, among them the step method (STEM) and the iterative weighting method.

In methods of the first category trade-off curves (between two objectives) or surfaces (for three objectives) are generated. Points on the trade-off curve are *efficient*: the value of one objective cannot be improved from an efficient point without degradation in the value of another. In the weighting method a weighted sum of the objectives is used as the objective function. The trade-off curve is generated by changing parametrically the weights. In the constraint method one objective is used as the objective function for optimization while another is constrained parametrically within its range of possible values. The two methods are equivalent, since they both generate trade-offs.

Trade-off curves show how much has to be given up in one objective to gain a unit improvement in the other. This rate changes from point to point along the curve, and is used to locate a "best compromise" solution.

In methods which depend on progressive articulation of preferences the procedure is different. For example, the step method (called STEM, Benayoun *et al.*, 1971) starts with a "payoff table". Each row contains the values of all objectives at a solution point where one of the objectives attains its optimum. The ranges of values of all objectives, over all the single objective optima, are examined by the decision makers, who are then asked to narrow the range of admissible solutions by imposing additional constraints on the values of the objectives. These are added to the constraint set and the process of generating a "payoff table" repeated. The process is repeated until the range of feasible solution is narrowed to an accepted solution.

The methods outlined briefly here have been found by the author to be practical and useful in real applications. They have been used in the case studies described in the following sections.

WATER POLICY FOR ISRAEL

In a study of policy alternatives for Israel's water sector (Shamir *et al.*, 1981) the Saaty method is being used to evaluate policy options in more than a dozen areas, including: development and utilization of the sources, development and operation of the conveyance and distribution systems, water quality, desalination, pricing, allocations, R&D, the legal basis and the institutional structure of the water sector. Some 20 criteria are used to measure the effect of each possible policy on achieving the objectives of the water sector.

Saaty's method is effective as a means for focusing the discussions and for explicit formulation and evaluation of alternatives and criteria, and for eliciting points of view and preference trade-off. The process is conducted with groups of experts, interest groups and decision makers.

REGIONAL WATER RESOURCES PLANNING

Har-Ha'Negev region, Israel

A water resources plan for a 4000 km^2 region in the arid south of Israel was evolved by Alkan & Shamir (1980) with six objectives. The water system is made of two parallel pipeline networks, the one carrying potable water and the other sub-potable water, as shown in Fig.1.

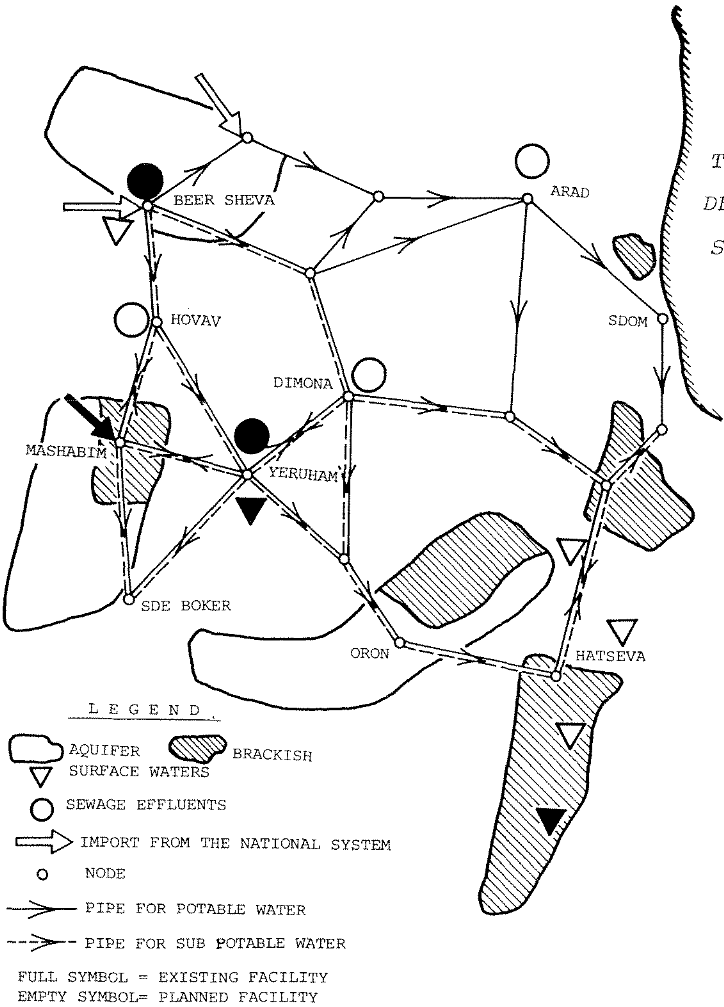

Fig. 1 Har-Ha'Negev water supply system.

Structure of the model There are local water sources and imports from outside the region. They are divided into potable and sub-potable, and include fresh and brackish groundwater, flood water and reclaimed sewage. The consumers are domestic, industrial and agricultural. Each consumer can tolerate up to a certain percentage of sub-potable water in his supply. A linear programming model was developed, with the following components.

Decision variables Capacity added to each source and each pipeline, beyond the existing capacities, and the seasonal quantities to be produced at each source, transferred through each pipeline and delivered to each consumer. The year is divided into two seasons: a three month summer, during which the peak agricultural demand occurs, and the nine remaining months.

Constraints The following constraints are imposed on the system: continuity at nodes, maximum potential of the sources, bounds on seasonal extraction from the sources, minimum seasonal allocation to the consumers, ratio of sub-potable to potable water to each consumer.

Objectives The six objectives are: (a) minimum total cost, (b) minimum operating cost, (c) maximum net benefit from supply of water to agriculture, (d) maximum employment in the region in water based industry and agriculture, (e) minimum water import from external sources, and (f) maximum utilization of reclaimed sewage effluents in the region.

Multiobjective programming A variant of the STEM method was used to converge to a "best compromise" solution. At each iteration constraints on the range of the objectives are added, as depicted schematically in Fig.2 for the case of two objectives, both of which are to be maximized. f_1 and f_2 are the two objectives. When f_1 is maximized separately, disregarding f_2, point A_o is obtained, at which f_1 attains its best possible value, M_1. At that point $f_2 = m_2$, which is the worst value for f_2. Similarly, C_o is obtained by maximizing f_2, disregarding f_1. The values there are $f_2 = M_2$ and $f_1 = m_1$. The range of possible values for each objective - between m and M - are used to determine (through some form of "negotiation" between the proponents of the various

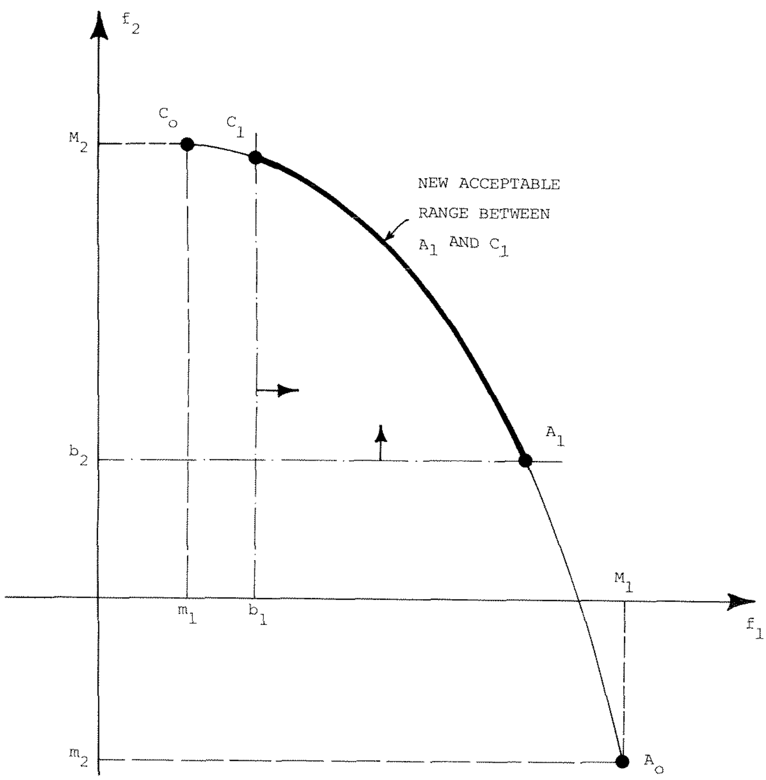

Fig. 2 Narrowing the acceptable range.

objectives) lower bounds, b_1 and b_2, on the values of the objectives. The result is a narrowed range of acceptable solutions. Points A_1 and C_1 are obtained by single objective optimization, as were A_o and C_o, with the added constraints $f_1 \geq b_1$ and $f_2 \geq b_2$. The details of the method specify how these lower bounds are determined. The procedure continues iteratively until the acceptable range of solutions is so narrow as to actually define a specific solution. The method works for any number of objectives.

The information generated at each iteration helps the decision makers to understand the consequences of the progressive compromises and constraints between the objectives. The "efficiency frontier", curve A_oC_o in Fig.2, is not generated (as in the generating methods), and is "revealed" progressively through generation of the extreme points at each iteration (first A_o and C_o, then A_1 and C_1, etc). Through observation of how these points locate within the full range of possible values, between m and M for each objective, the decision makers formulate their instructions for the next iteration.

Water supply for the Province of South Holland

A similar approach was used to develop a water supply plan for a 3300 km^2 area in Holland, with 3 million people in 150 municipalities. (Bresser & Pluijm, 1981; RID, 1981). Again, potable and sub-potable water systems are considered, as shown in Figs 3 and 4. An optimization model and a simulation model were developed to aid the multiobjective decision making process. The first, a multiobjective linear programming model, is based on approximate representations of the system and is used as a screening tool for identifying preferred solutions. The simulation model is more detailed and accurate, and is employed to examine suggested solutions more fully. The multiobjective linear program has the following components.

Decision variables Development of the sources, of the pipelines and of the water treatment plants, and the amounts to be transported through all links of the system.

Constraints Demands are to be met, at all consumer nodes, maximum potential of each source, water balances at all nodes, maximum capacity of links.

Objectives The selection and formulation of objectives was one of the major features of this work. They are:

(a) costs: minimization of the sum of fixed and variable costs, over all elements of the system;

(b) water quality: 12 quality parameters were selected, a weighted sum of their values defines a water quality index, which is then weighted by the quantities of water and summed over all demand points in the system;

(c) public health: defined similar to the water quality index, for public health parameters relating to water;

(d) reliability of supply: for each route connecting sources to consumers the mean time between failures (MTBF) and mean time to repair (MTTR) of all links in this route are used to compute an availability factor, which is multiplied by the quantity delivered

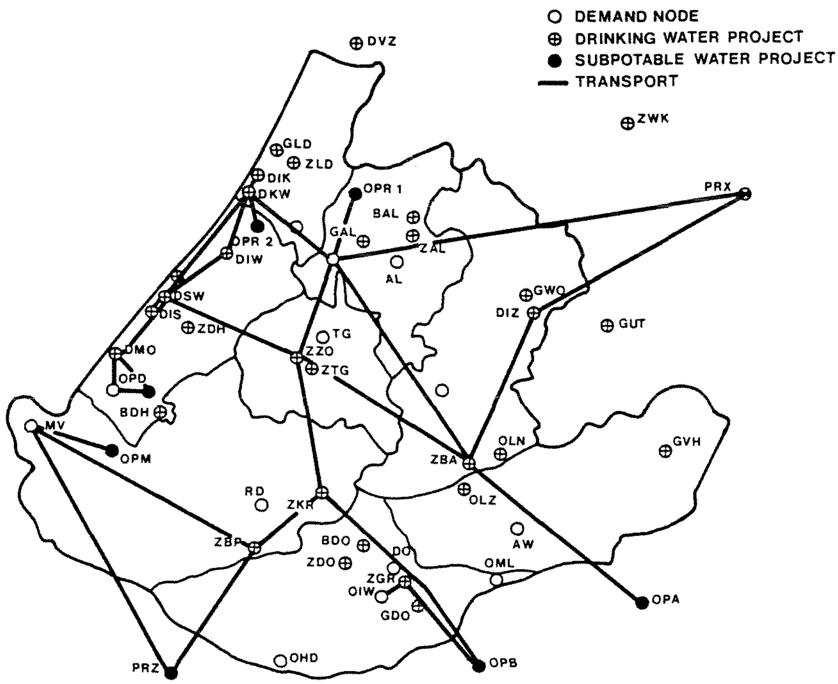

Fig. 3 Province of South Holland: sub-potable water system.

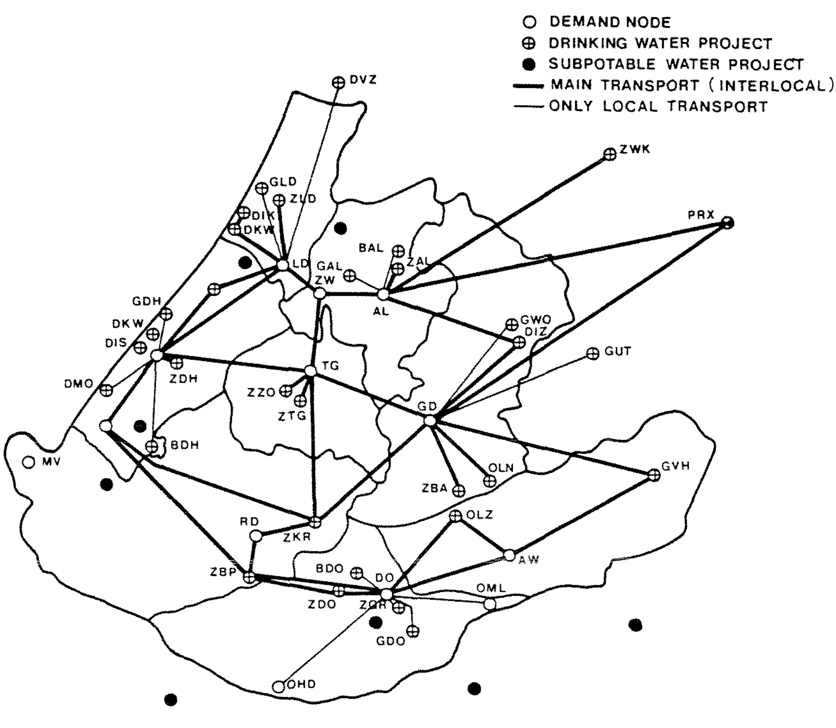

Fig. 4 Province of South Holland: drinking water system.

in the link, and summed over all links in the system;

(e) damage to nature: the area damaged is related to the capacity of each water project, is then multiplied by an "influence index" and by the "unit value" of the area derived from a nation wide survey and summed over all water projects;

(f) energy consumption: minimization of the overall energy consumption, by all water projects in the system.

Multiobjective programming The weighting method was used to generate trade-off curves between pairs of objectives, as shown for costs *vs.* damage to nature in Fig.5. In the top part of this figure, 13 solution points are indicated in the two-objective space. The ranges of values of the two objectives are: -584 ha, i.e. a reduction

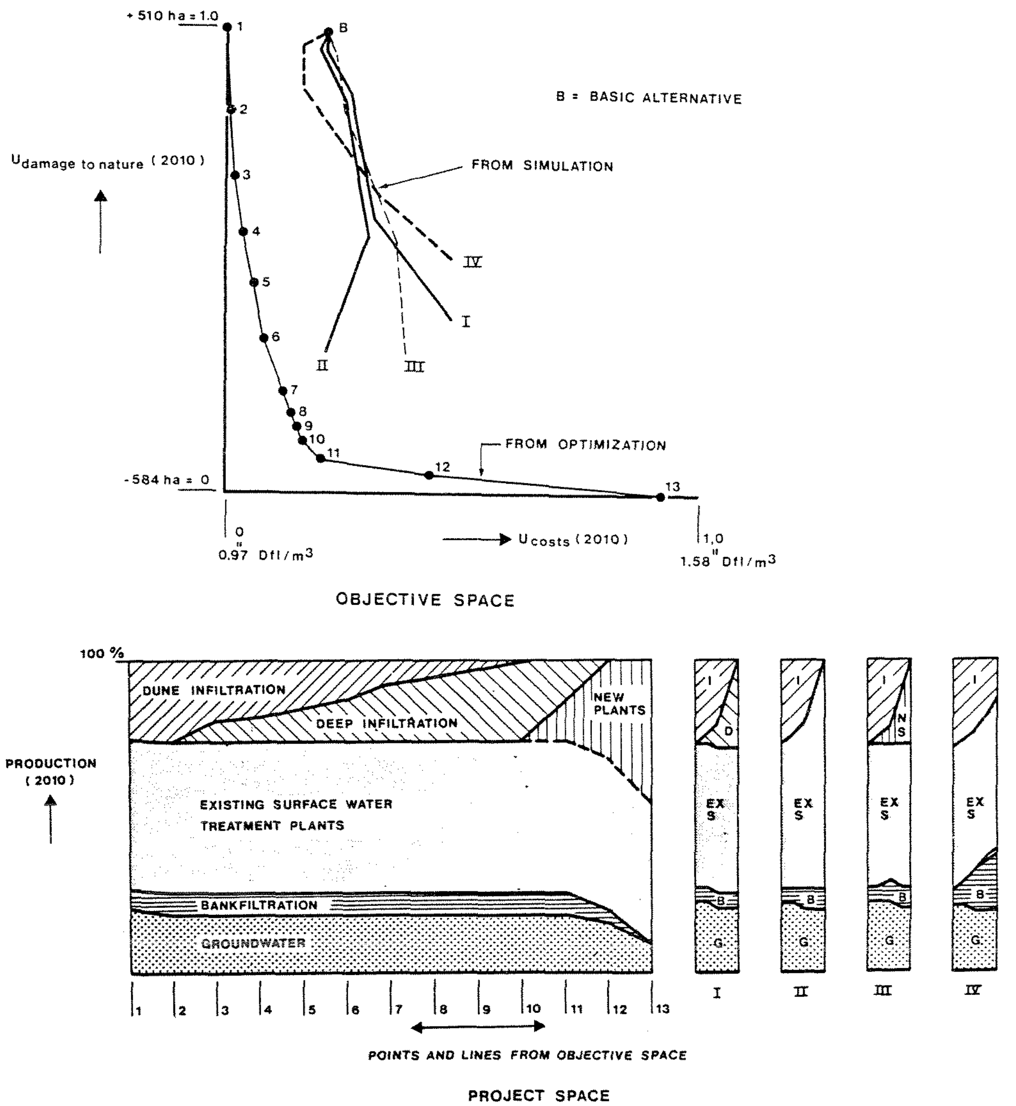

Fig. 5 Province of South Holland: trade-off between cost and damage to nature.

in the (weighted) damaged area by 584 ha, to +510 ha, with a concurrent cost range between 1.58 Dfl/m^3 and 0.97 Dfl/m^3. The relatively sharp corner around point 11 indicates a good compromise solution: relative to point 1 it incurs little extra cost for a substantial reduction in damage to nature, and relative to point 13 it has a little more damage to nature in return for a major reduction in cost. Point B represents a basic alternative around which simulation was used to search for improved solutions. All points on the simulation results are feasible but not efficient, while the 13 solutions from the optimization are efficient but may be inaccurate due to the approximate nature of the optimization model. The bottom of Fig.5 depicts the overall nature of the physical systems corresponding to the 13 solutions, showing the percentage of the total supply obtained from each of the source types.

REAL TIME OPERATION OF A RIVER BASIN

The city of Seattle, Washington, extracts a major portion of its water from the Cedar River, which also provides water for fish spawning and hydropower generation. A multiobjective linear programming model has been developed (Howard, 1975; Flatt & Howard, 1976) for real time operation of the river.

Figure 6 depicts the river basin, in which the Chester Morse Lake is the controlling reservoir. A closed form mathematical model has been developed to compute the number of spawning fish as a function of the flow regime in the river, and allows formulation of the fish production objective. The development of the fish growing model was essential in the management process. Without an acceptable model of this aspect it was impossible to proceed with the multiobjective management process.

Constraints of the linear programming model reflect both physical laws and operational considerations which represent navigation, flood control and downstream lockage requirements not explicitely included in the model as objectives. The decision variables are monthly water releases from Chester Morse Lake, and the model is run for a 12-month-ahead period, with an assumed deterministic hydrology.

The deterministic LP analysis is submitted to a detailed simulation model, which generates the probable outcomes of operating under the selected policy. The LP model considers the three objectives: water supply, fish production and power generation. Trade-off curves of objective pairs are used to identify good compromise solutions. It is interesting to note that while the whole exercise of multiobjective analysis was generated by a perceived conflict between water supply and fish production, the results, shown in Fig.7, proved that a solution could be found which is near optimal for both objectives. What started out as a battle between interests ended in cooperation.

Note in Fig.7 that the fish spawning objective, expressed as a fraction of the theoretical maximum number of spawners accommodated by the river, does not reach 1.0. The reason is that the originally stated number of spawners could not be reached under any feasible operating policy; there is simply not enough water in the river.

WATER AND LAND MANAGEMENT IN A LAKE REGION

The Cooking Lake area, east of Edmonton, Canada, provides opportunities for suburban development, farming and many types of recreation. Precipitation and evaporation in the seven-lake region shown schematically in Fig.8, is closely balanced. Management of the land and lakes must be based on consideration of several objectives. A deterministic linear programming model (Howard & Shamir, 1976) was developed for this purpose. Several other models were also used to examine in more detail and accuracy by simulation the physical processes and the consequences of proposed management plans.

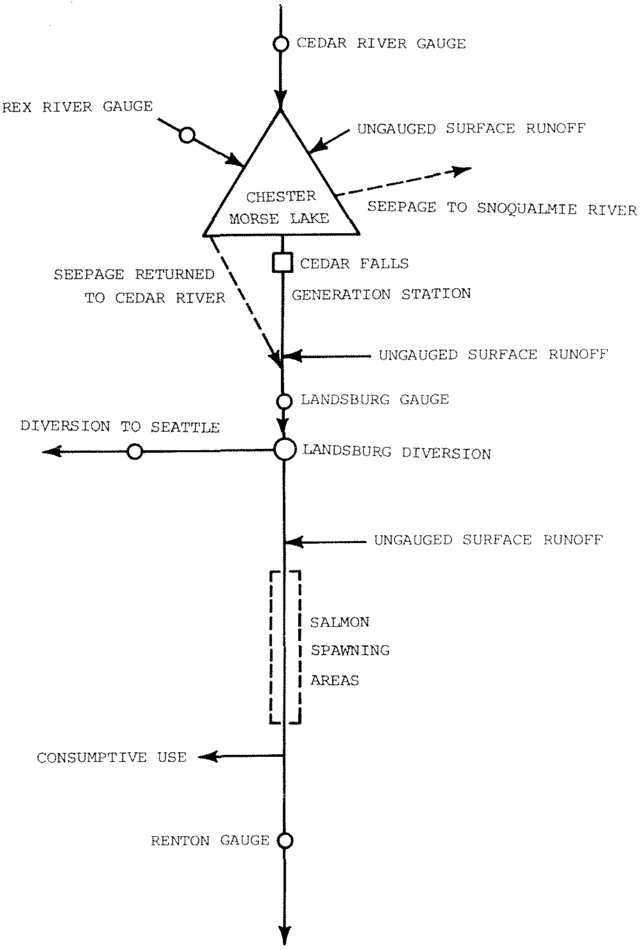

Fig. 6 Cedar River model.

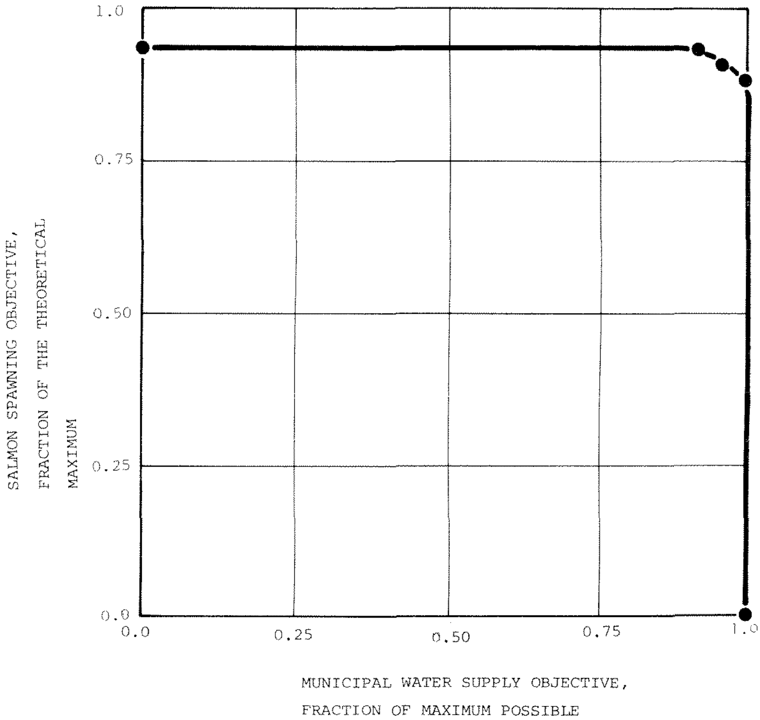

Fig. 7 Trade-off between municipal supply and fish.

Decision variables Several land uses are possible in each of the lakes' basins, including farming, cottages, urban subdivisions, various nature preservation and recreational activities. The areas designated for each are the primary decision variables. The lakes themselves provide the basis for many of the recreational activities and also for natural species which are a main attraction of the area. Land uses depend on water resources, and in turn affect them, especially lake water quality. The model is designed to yield the land uses, water transfers between lakes, water treatment facilities, lake levels, lake water qualities and groundwater levels.

Constraints Constraints reflect the physical laws of the system, as well as limitations imposed by economic, legal and institutional considerations.

Objective function The weighting method was used to examine the trade-offs between objectives, thus a single objective function was formulated with the weights of the various components changed parametrically during the analysis. The components include: benefits from each type of land use (by assessed values for subdivisions, farming, etc., and by utilities assigned by decision makers to recreation, nature preservation, etc), value assigned to lake levels and water qualities (again, assessed values for economic uses and assigned values for others), capital and operation costs for water transfers and water treatment facilities.

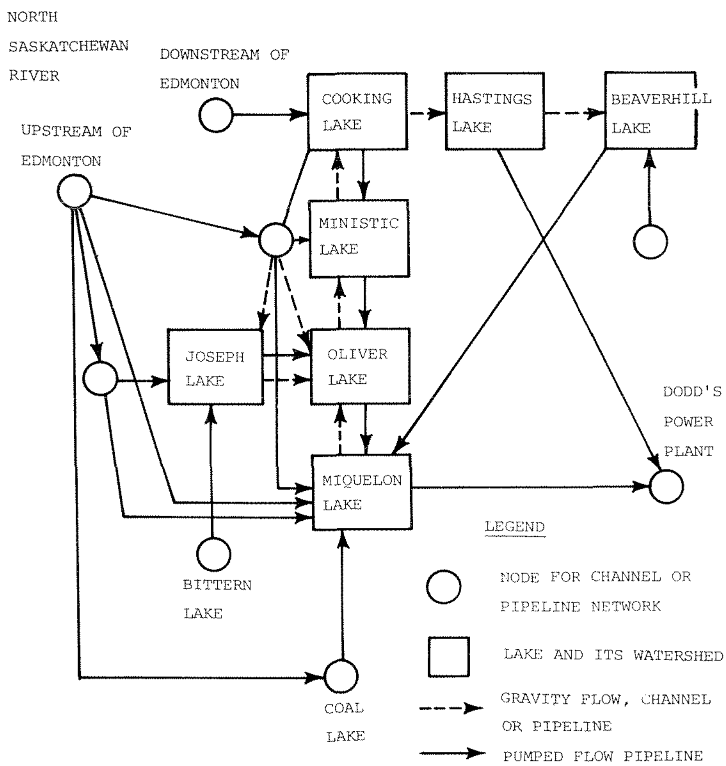

Fig. 8 Schematic map of the Cooking Lake area.

Interactive model The linear programming model was put in an interactive computer program, which was designed to solicit relative weights for the subjective components of the objective function, generate a detailed description of the resulting optimal solution and allow modifications for the next iteration.

Runs of the model with different weighting schemes provided the analysts with an appreciation of the range of outcomes to be expected. The main issue which brought about this investigation was the concern voiced by cottage owners and residents of Edmonton who seek recreation in the Cooking Lake area about lake levels and water qualities. These had been affected by the activities in the area and also by a sequence of dry years. By the time the study was completed the dry spell ended, lake levels rose and water quality was restored to acceptable levels, so that the recommendations of the study were put aside for possible future reference.

CONCLUSIONS

The examples described, in somewhat general terms, in the previous sections serve to demonstrate the types of situations where multi-objective decision making in water resources planning and management can be used. As emphasized in the introduction, the most important features of the methodologies employed are those which create a framework for joint work of the analysts with the decision makers, in a learning process which allows progressive articulation of positions and preferences on the basis of previous analyses. Most water resources planning and management problems are so complex as to preclude the possibility that any individual or group of decision makers and analysts can assess the implications of the decisions to be made, especially with multiple objectives. This is why models and multiobjective decision making methodologies are needed.

The experiences described above indicate that multiobjective planning and management of water resources systems is no less nor more successful in aiding real life decision making than attempts to use other operational research methodologies. It does, however, add an important dimension to the decision making process. Success depends on several factors: the skill of the analyst in capturing the essence of the decision problem, his ability to develop and solve an appropriate model, and, most important, to communicate the process and results of his work to those charged with making the actual decisions.

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