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MULTIOBJECTIVE WATER-RESOURCES PLANNING

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10-1 INTRODUCTION

Planning occurs at many levels in any social organization. Even though the scope of the plans will differ, the process of planning at each level is generally the same. Goals are considered, information is gathered and processed, alternative choices are defined and evaluated, and after a number of iterations that may modify the goals, information needs, and alternatives, eventually a decision is made, and a particular choice or plan is implemented. Often the process of planning continues, and plans may be modified after they have been implemented. Hence planning encompasses all activities leading up to a decision among choices and continues during the post-choice stage of implementation and control.[1]

This discussion shall be focused primarily on the "decision-among-choices" part of the planning process. While such decisions are made in public and private organizations, the emphasis in this chapter will be on decision-making in the *public* planning process, i.e., the process in which the final selection of an alternative rests with elected or appointed decision makers or policy makers who in some sense represent the public.

The alternatives formulated by water-resource planners generally attempt, explicitly or implicitly, to achieve various objectives. For the planner, it would be ideal if the choice of one policy over another—or the choice of one investment as compared to another—could be evaluated in terms of a single, well-established objective or goal. In fact, there are always numerous possible goals or objectives that are relevant—many of which are often conflicting—and the importance of each goal is rarely well articulated in advance of the time decisions are made. Public-policy decisions are often made from plans conceived and developed on the basis of a mostly qualitative integration of numerous economic, political, social, and technological objectives. The explicit trade-offs between each of these partially complementary and conflicting objectives are not always clear, and, therefore, the selection and implementation of plans often fail to meet many of the objectives to the extent originally envisioned.

From the start, we should specify several assumptions that are made in this review. The first assumption is that public policy is rarely implemented to satisfy only a single economic objective. The type and scale of public investments in water-resource development and management are usually based on a range of economic, social, and political factors, only some of which can be quantified. Often many important objectives defy quantification, and these, together with the quantifiable objectives, must be considered in the planning and decision-making processes. Thus, like most methods developed to define and evaluate alternative policies, the information obtained from the quantitative techniques discussed in this review can only assist the policy makers and planners; it cannot replace them.

The second assumption is that, among the objectives that can be quantified, the parameters or criteria used to describe them need not be directly comparable. No one has yet suggested a generally acceptable way of assigning a monetary value to environmental quality, for example, that is directly comparable to the monetary value of consumption or regional income and its distribution. Such assignments require the analyst to define the decision maker's welfare or utility function. The assumptions that the analyst or planner must make to derive such a function are unlikely to be those of the decision makers who are ultimately responsible for the establishment of policy. Hence analysts or planners must fall back to what they can do, namely, defining the alternatives available to the decision maker and evaluating each alternative based on each objective, thereby delineating the possible trade-offs between various objectives. These trade-offs among various noncommensurable objectives can be made clear to the decision makers only if each objective is expressed in terms that are meaningful to them.

The third major assumption of this discussion is that the ultimate specification of the relative importance of each objective, or, more accurately, the selection of a policy that in turn *implies* the relative importance of each objective, must take place in the political process. It is a fact that the relative weight given to each objective is ultimately based on political rather than solely economic, social, or technical criteria. These weights are always conditional, depending in part on the decision maker's perception of (1) his policy alternatives, (2) how each alternative would be implemented if selected, and (3) the likely outcomes. The distinguishing feature of public-policy making is that the power to accept, reject, and implement plans rests with public officials called *policy makers* or *decision makers*. The degree to which each alternative plan is acceptable to, or conforms to the preferences of, those policy makers who have the power of decision is a measure of the plan's political feasibility. Clearly, the policy makers themselves should be involved in this ranking process. The primary motivation behind the development of each of the quantitative methods to be discussed in this review has been to assist economists, engineers, and planners in effectively participating in a responsible political decision-making process.

10-1.1 Water-Resources Planning

Although it has sometimes seemed that in the United States the federal water-resources planning effort has been dedicated to the single goal of national economic development as typified by benefit-cost ratios, this has hardly been the case. More typical, perhaps, have been the attempts to manipulate the ratios of plans serving other objectives.[2] Previous and current federal policy for water-resources planning have recognized more than one national objective,[3,4] and even the rigorous proponents of benefit-cost analysis have indicated that intangible (nonmonetary) benefits, if significant, would compromise a strict benefit-cost criterion for project selection.[5,6]

To a considerable extent, any debate about the virtue of multiobjective water-resources planning has been rendered obsolete, at least in the United States. The National Environmental Policy Act of 1969, with its requirements for environmental impact statements, inserts de facto environmental objectives into planning. The recently enacted "Principles and Standards" of the Water Resources Council specify national economic development and environmental quality as federal water-resources planning objectives.[4]

It seems clear that water-resources planners will give increasing attention to the multiobjective nature of planning. The explicit analysis of varied and often conflicting objectives will be necessary, and alternatives that give varying weights to the various objectives will be required.[7] It is by no means clear, however, how this can be done. While economics has been added to the earlier engineering aspects of water planning, it would appear that ecology, sociology, and political science must be added to the planning effort. Somehow the various objectives and the techniques for plan formulation must be combined into a manageable interdisciplinary enterprise.

The formulation and selection of alternatives are further complicated by uncertainty in the outcome of any public policy due to factors outside the control of the planner or decision maker, and by the limited ability to consider simultaneously all relevant information pertinent to the policy even if there were no uncertainty. Even when supplemented with computers, the capacity of an individual planner or group of planners is limited.

10-1.2 The Role of Modeling

In order to deal with the complexities of multiobjective planning, planners are usually forced to construct simplified representations of their problems to enable them to process more efficiently what information they have in order to predict and evaluate the possible outcomes. These simplified representations or models can range from those that are solely conceptual, and wholly contained within the mind of a planner or decision maker, to those that are specified by many sets of algebraic equations, and contained within a program to be solved on high-speed digital computers. These latter models are usually grouped into what are called *mathematical models*.

Mathematical models can provide a useful means of bringing the diverse elements of the planning process together in a conceptual framework that ideally facilitates better understanding of alternatives by both the planner and the decision maker. While most mathematical models are restricted to only those aspects of the evaluation process that are quantifiable, the information derived from them may significantly assist the decision-making process in its selection of a final choice. This is especially true where multiple objectives have been identified. In these situations, usually some alternatives are preferable when particular objectives are considered, while other alternatives are preferable when different objectives are examined. As the number of relevant objectives and alternatives increases, the ability of the planner to manage the problem rapidly decreases. It is here where quantitative modeling techniques and those who know how to use them can be of considerable value as aids to, but not as substitutes for, the responsible political decision-making process.

10-2 DESCRIPTIVE MODELS OF THE PLANNING PROCESS

A reasonable model of the water-resources planning process assigns to the planner the function of formulating a set of alternatives. General goals are proposed directly or indirectly by special interests, public decision makers, and the planner. The planner must determine which of these goals are relevant and translate them into operational objectives or design criteria. Specific planning alternatives are generated which accomplish these objectives to varying degrees. One or more of the alternatives is submitted to a policy maker, or policy-making group, that either selects a plan for implementation or rejects the submitted alternative(s). Since policy makers hold elective or appointed roles in a political system, it follows that plan selection is inherently a political decision.[7,8,9,10] Hence in addition to questions of technical and financial feasibility, the problem of *political* feasibility is of critical importance in the public planning process. To be successful, water-resources planning must, to an extent, conform to the realities of political decision-making, and an understanding of the policy-making process is a requisite to effective multiobjective planning.

10-2.1 The Policy-making Process

Following the example of Strickland et al.,[11] a discussion of politics can start with some basic assumptions concerning human behavior. First, all individuals have goals. Such goals differ from person to person both in direction and in intensity. The same person may have many goals, some of which conflict with others. Similarly, the goals of one individual may conflict with or be similar to those of others. The relative value or worth of people's goals can be indicated by what they are willing to give up to achieve them. These assumptions imply that conflict has a central role in any social system. Furthermore, individuals are willing to exert some effort to prevent their goals from being frustrated. These implications lead directly to the need for a *political system*. When individuals seek to achieve their objectives through government actions, personal goals become *political goals*, and a *political decision* determines which political goals will be achieved.

Strickland et al.[11] introduce two concepts which clarify the mechanism of political decisions. The first of these is *agency*. Public decision makers are agents of the members of a political system and are authorized to make choices among political goals. Attention focuses on these agents or policy makers, and individuals try to influence them to support various goals. The principal mechanism of influence is through *association*, or more specifically, a political association. A political association attempts to get other people in a political system to accept the political goals of the association's members. One of the principal means of accomplishing this end is to influence the choices of the policy makers.

To summarize, a political system attempts to resolve the conflicting objectives of members of a society. Policy makers are agents of the society and decide which political goals are to be achieved. Supporters of the various political goals try to influence their agents' choices, and association is an important mechanism for such influence.

Inasmuch as political goals exist, then "interests" will exist which support these goals. Whether such interests are represented in a policy maker's decision depends largely on their influence and on his estimate of their potential influence. Organized groups will certainly have their effect, but it is not unreasonable to suppose that the goals of large unorganized segments of society will also be considered. The policy maker's choice will be influenced by interest groups, potential groups, his personal values, and the opinions of friends and political leaders.[12]

A policy maker's decision process can be ideally envisioned as a logical, well-defined process in which he surveys as many possible alternatives as time permits, predicts the consequences of each, and selects the alternative which most closely corresponds to his perception of the best. This synoptic ideal ignores some of the realities of political decision-making. The first of these is the uncertainty that is present in policy-making. "Uncertainty as to the facts and difficulty in arriving at correct factual judgments are among the most familiar elements in the life of a political decision maker."[13] Furthermore, the essential bargaining aspects of policy making are not included in the above description. If decisions are "by mutual adjustment among partisan advocates, each possessing different, or at least differently weighted, ends and values,"[14] the decision maker must trade off some goals for others. His choice is more compromise than evaluation. Social cooperation among interests and among policy makers who represent these interests is thus a distinctive feature of the policy-making process.[12,13,15]

10-2.2 Planning Strategies

Numerous strategies have been used by planners to deal with realities of policy-making. These strategies are usually modifications and combinations of three basic planning philosophies: target, optimization, and compromise planning.

The target planning philosophy involves the definition of a variety of feasible plans from which one is selected that best meets a predetermined set of objective values or targets that have been articulated by the political leadership. Target planning seeks to find those policies and instruments that will achieve the targets of the decision maker. As such, this method of planning is rational and defensible if the resulting plans are internally consistent, if the data on which the plans are based are reasonably accurate and complete, if the implicit and explicit assumptions in the plans are correct, and if the targets adequately reflect the social needs or goals of the decision makers.

Optimization planning is a refinement of target planning. Both require an a priori knowledge of the decision maker's preferences and desires. This planning philosophy assumes that these desires or preferences are expressed as objectives rather than targets and as such, planners seek to obtain optimal solutions given the available resources, rather than just to satisfy targets. The optimal solution is that plan which satisfies all feasibility constraints and is preferred to all other feasible plans.

Compromise planning is imperfect, but it is also more realistic. It does not assume that the targets or the relative weights given to each possible objective are known in advance of planning. Hence, the emphasis in this type of planning is on the generation of feasible plans and on the active involvement of the responsible decision maker in the selection of the best feasible plan or compromise. This planning philosophy recognizes that, once alternative plans have been defined, it is the responsibility of the political decision maker to analyze and evaluate all the quantitative and qualitative factors that should be analyzed and evaluated in the process of selecting the best plan.

10-3 WATER-RESOURCES PLANNING OBJECTIVES

Although it is generally recognized that objectives other than national efficiency have always been a part of water-resources planning, the Flood Control Act of 1936 saw the beginning of the benefit-cost ratio's role as the primary criterion for selection of federal projects in the United States. In this respect, a distinction is often drawn between planning for multiple *purposes* and multiple *objectives*. A basin plan for navigation and flood control which is evaluated on the basis of a benefit-cost ratio would have two purposes but only one objective—national economic development. Navigation and flood-control benefits and costs are considered as contributory to this single objective. Such distinctions are necessary to obtain benefit-cost ratios.

The new emphasis in multiobjective water-resources planning signals a shift in methods of evaluating plans and comparing objectives. New objectives, particularly those relating to environmental quality, are to be considered and objectives will not be compared solely on the basis of monetary benefits and costs.

10-3.1 Principles and Standards for Planning Water and Related Land Resources

Presidential approval of the U.S. Water Resources Council's "Principles and Standards"[4] culminated a period of debate, agency review, and testing of proposed water-resources planning methods which lasted for many years. The "Principles and Standards" apply to most federally related water-resources planning activities and replace previous federal policy.[3] Agencies are currently developing procedures and guidelines for implementation of the "Principles and Standards."

Two national water-resources planning objectives are established by the "Principles and Standards:"[4]

1 *National Economic Development* (NED): "Enhance national economic development by increasing the value of the Nation's output of goods and services and improving national economic efficiency."
2 *Environmental Quality* (EQ): "Enhance the quality of the environment by the management, conservation, preservation, creation, restoration, or improvement of the quality of certain natural and cultural resources and ecological systems."

The beneficial and adverse effects of any project or plan are to be displayed in four accounts:

1 NED account
2 EQ account
3 Regional Development (RD) account
4 Social Well-Being (SWB) account

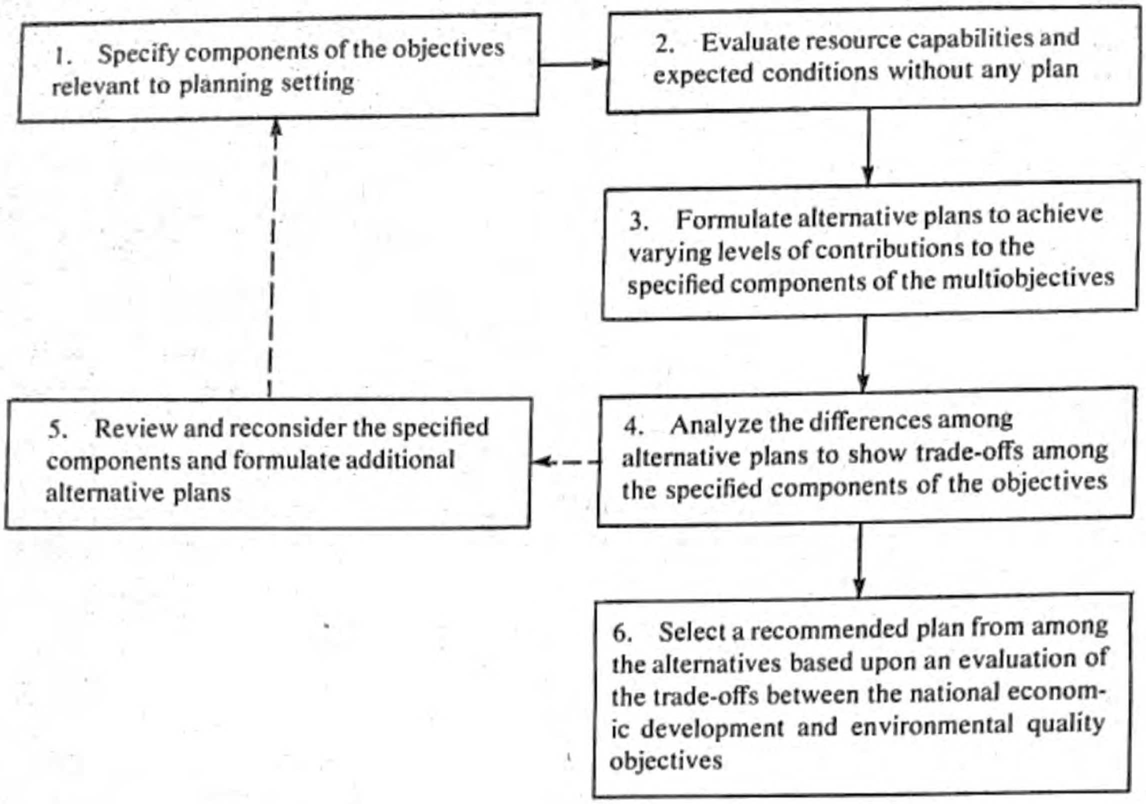

FIGURE 10-1
Plan formulation procedures specified by the *Principles and Standards*.[4]

Impacts are to be quantified in monetary terms for NED, but nonmonetary quantification and "qualitative dimensions" are permissible for the other accounts.

The essence of the planning process envisioned by the "Principles and Standards" is the formulation of at least two plans, one of which emphasizes NED and the other EQ. The procedures for plan formulation are indicated in Fig. 10-1. Regardless of emphasis, the effects of each alternative are to be displayed in the four accounts mentioned earlier. This detailed accounting is to facilitate the identification of trade-offs among objectives. For example, the sacrifice in NED benefits associated with the EQ plan would be seen, or the loss of certain EQ benefits entailed in the NED plan could be identified. The accounting procedure is exceptionally detailed. An illustrative example provided in the "Principles and Standards" indicates 16 pages of accounts for just one plan. Additional plans would require comparable presentation and a final set of comparative tables is required to evaluate trade-offs among alternative plans.

As will be seen shortly, it is useful to consider the formulation and selection aspects of the planning process separately. The "Principles and Standards" are directed primarily toward formulation and can perhaps be considered an example of the compromise planning strategy discussed earlier. The provision for specific alternatives and the four accounts provide decision makers not only with a range of choice but also with the information necessary for evaluating trade-offs between objectives. Since we have seen that policy makers function by trading off the objectives of some groups for those of others, there is every reason to believe that the planning effort suggested by the "Principles and Standards" should provide useful input to the policy-making process.

The future of the "Principles and Standards" is not certain. Section 80 of the Water Resources Development Act of 1974 (PL93–251) requires a reevaluation of the "Principles and Standards," and there is little question that agencies are having difficulty in implementing all provisions of the new planning requirements.[16,17] One problem, in particular, involves the detailed presentation of plan impacts, which may, paradoxically, constrain effective decision-making. Considering environmental effects, the account for any plan may include dozens or even hundreds of physical and subjective parameters. It thus can become very difficult to evaluate trade-offs among EQ and NED objectives. In addition, there is considerable uncertainty concerning what constitutes a suitable EQ plan. All components of the EQ objective can seldom be emphasized simultaneously, and without quantitative indices for overall evaluation of environmental impacts, any EQ plan will be open to serious challenge. Certainly the formulation of an EQ plan which results in sharply reduced NED benefits compared to the NED plan may cause a bias against the EQ alternatives.

Finally, the "Principles and Standards" can be faulted for their overly normative view of water-resources planning. In particular, there seems to be little recognition of the political aspects of planning. One exception is the test of *acceptability* which refers to "the workability and viability of the plan in the sense of acceptance of the public and compatibility within known institutional constraints."[4] The earlier discussions of political feasibility indicate that such a test may prove to be more critical to the planning process than many of the other factors which are emphasized in the "Principles and Standards."

10-4 QUANTIFICATION OF WATER-RESOURCES PLANNING OBJECTIVES

Although a degree of ambiguity is not without its charms, particularly within a political system, the success of multiobjective water-resources planning rests to a considerable extent on the planner's ability to ascribe operationally meaningful, quantitative parameters to objectives. The systematic evaluation of trade-offs certainly is much more difficult when objectives are intangible or nonquantitative. Obviously the use of mathematical modeling is limited to situations involving quantifiable objectives.

Planning objectives are quantified on either monetary or nonmonetary scales. The measurement of monetary costs and benefits has reached a high level of refinement, even with objectives for which market prices do not reflect true social benefits and costs or do not exist at all. An example is found in the methods developed for inputting recreation demands and hence monetary benefits associated with recreation use of water-resources projects.[18]

Several attempts have been made to devise single parameters to describe a broad range of environmental quality objectives. The intent is to develop meaningful indicators which include broad ranges of quality aspects. Two examples can be given for air quality and water quality.

The Third Annual Report of the Council on Environmental Quality[19] measures progress in attaining air-quality objectives in terms of several indices. One of these is the Mitre Air-Quality Index (MAQI), which is given by

$$\mathrm{MAQI} = (I_c^2 + I_s^2 + I_p^2 + I_n^2 + I_o^2)^{1/2} \tag{10-1}$$

where I_c is a carbon monoxide index
I_s is a sulfur dioxide index
I_p is a particulate matter index
I_n is a nitrogen dioxide index
I_o is a photochemical oxidant index

The indices for individual pollutants are defined in such a fashion as to be greater than unity if EPA secondary air-quality standards are exceeded. The MAQI is essentially an objective criterion which could be applied uniformly on a national or regional scale.

Dinius[20] has proposed a very different general indicator for water quality. The Dinius water-quality parameter is highly subjective, in that the judgment of the planner or of water-quality specialists working with the planner is essential in its formulation. Thus, values of the index for different localities or regions are not likely to be comparable. Water quality Q, measured in percent, is given by

$$Q = \frac{w_1 Q_1 + w_2 Q_2 + \cdots + w_n Q_n}{w_1 + w_2 + \cdots + w_n} \tag{10-2}$$

where Q_i is the ith quality constituent (dissolved oxygen, chlorides, etc.) measured in a scale of 0 to 100
w_i is the weight or relative importance of the ith quality constituent

In a given planning venture, the scales for the Q_i and the weights w_i will be selected by the planner in consultation with water-quality "experts." The water-quality objective for any plan is measured by the levels of Q achieved at various points of interest.

The identification of uniformly acceptable quantitative indicators for the nonmonetary objectives of water-resources planning which are meaningful to the planner, the decision makers, and the public is not likely to be achieved in the near future, if at all. The planner does not have to be unduly restricted by this prognosis, however. There is no shortage of possible parameters or methods for quantification. Moreover, attention to, and understanding of, objectives of most concern to the public as reflected in the policy-making process

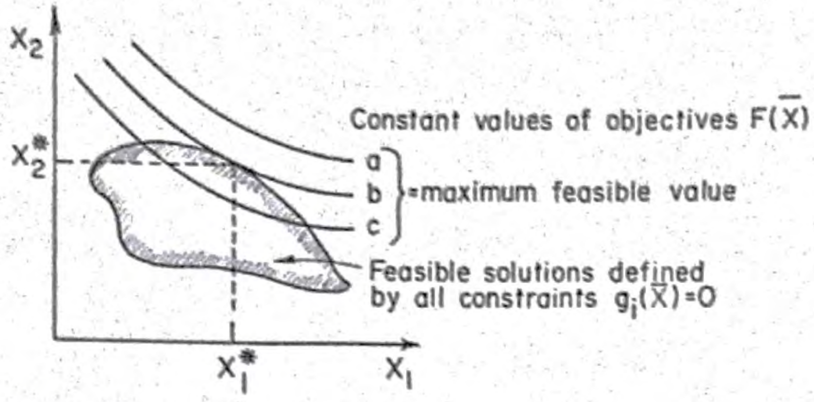

FIGURE 10-2
A two-variable policy program whose optimal solution is X_1^*, X_2^*.

provide a means of selecting numerical indicators appropriate to these objectives. Failure to make this effort will defeat much of the value of multiobjective planning and result in an unjustifiable bias toward the more readily quantifiable objective of economic efficiency.

10-5 MATHEMATICAL MODELS FOR MULTIOBJECTIVE PLANNING

The general multiobjective planning problem is the selection of a vector of decision variables, $\mathbf{X} = (x_1, x_2, \ldots, x_L)$, which may represent project or plan outputs, the allocations of scarce resources as inputs, and policies for project or plan operation. Certain technical relationships among variables, $g_i(\mathbf{X}) = 0$, $i = 1, 2, \ldots, m$, constrain planning alternatives or define the limits of technical feasibility. Single-objective models built for the purpose of helping in the selection of the best solution assume that the decision makers' preferences are known and can be expressed as a single-objective function $F(\mathbf{X})$ whose value for a particular solution vector $\mathbf{X}$ expresses the utility of $\mathbf{X}$ for the decision maker. In these situations it is simply a computational problem to find the vector $\mathbf{X}^*$ which optimizes $F(\mathbf{X})$ subject to all constraints $g_i(\mathbf{X}) = 0$. Assuming only two policy variables X_1 and X_2 and an objective $F(\mathbf{X})$ that is to be maximized, this problem is illustrated in Fig. 10-2.

Most regional development or public investment analyses require a comparison of various solution vectors $\mathbf{X}$ based on numerous objectives or goals. Of the objectives that are quantifiable, each can be described by a function $F_j(\mathbf{X})$ that should be either maximized or minimized.† The task now becomes one of appropriately or optimally trading off the value of one objective for another, if by increasing one objective value, one or more other objective values decrease.

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† In this discussion each $F_j(\mathbf{X})$ will be assumed a superior objective; i.e., it is to be maximized. Obviously any inferior objective can be changed to a superior one by multiplying by minus one.

Planning thus consists of the selection of a plan

$$\mathbf{X} = (x_1, x_2, \ldots, x_L)$$

which is technically feasibile, i.e., satisfies all the constraints

$$g_i(\mathbf{X}) = 0 \qquad i = 1, 2, \ldots, m$$

and best accomplishes certain objectives whose values are

$$F_j(\mathbf{X}) \qquad j = 1, 2, \ldots, n$$

The fundamental characteristic of multiobjective water-resources planning is that the various objectives $F_j(\mathbf{X})$ are frequently both incommensurable and conflicting. Thus if two plans

$$\mathbf{X}_1 = (x_{11}, x_{12}, \ldots, x_{1L})$$
$$\mathbf{X}_2 = (x_{21}, x_{22}, \ldots, x_{2L})$$

are compared, it may be found that the first plan achieves higher levels of certain objectives and lower levels of other objectives when compared to the second plan. In general, unless $F_j(\mathbf{X}_1) \geq F_j(\mathbf{X}_2)$ or $F_j(\mathbf{X}_2) \geq F_j(\mathbf{X}_1)$ for all objectives j, selection of either plan implies a reduction of some objective values for a gain in others.

10-5.1 Trade-Offs and Political Feasibility

Political feasibility can be discussed in the context of the basic planning philosophies discussed in previous sections of this chapter. The use of targets presumes that minimum objective levels T_j have been articulated by, or can be inferred from, the actions of decision makers. Thus, technically feasible plans that achieve targets are assumed to be politically feasible. Such plans are defined by those values of $\mathbf{X}$ such that

$$F_j(\mathbf{X}) \geq T_j \qquad \forall j \tag{10-3}$$

$$g_i(\mathbf{X}) = 0 \qquad \forall i \tag{10-4}$$

Apart from questions of how the targets T_j are to be determined, the target strategy contains some interesting implications. Considering a two-objective planning example, if objective targets T_1 and T_2 are specified, and any plan with, say, $F_1(\mathbf{X}) < T_1$ is rejected, the implication is that no level of $F_2(\mathbf{X})$ can compensate for the loss $T_1 - F_1(\mathbf{X})$. Below certain minimum levels, no trade-offs of objectives are possible. The political inference is that decision makers wish to provide certain minimum levels of satisfaction to all groups whose objectives are reflected in plans under consideration. While this may or may not be realistic, it provides no clear guideline for comparison of several plans, each of which *exceeds* target levels. The maximization of a single objective, say, $F_1(\mathbf{X})$, subject to constraint equations (10-3) and (10-4), provides this guideline but implies that no increase in targeted objectives over the target levels T_j will compensate for decreases in the primary objective $F_1(\mathbf{X})$.

Optimization planning, as indicated by

$$\text{Maximize} \qquad F(\mathbf{X}) \tag{10-5}$$

$$\text{Subject to} \qquad g_i(\mathbf{X}) = 0 \quad \forall i \tag{10-6}$$

requires that questions of political feasibility and preference be completely described by the objective function $F(\mathbf{X})$. Again, apart from the reasonableness of this assumption, the inference is that trade-offs between objectives are known at all levels of the objectives. For example, again consider two plans for a two-objective planning situation, which have decision vectors $\mathbf{X}_1$ and $\mathbf{X}_2$, respectively. Even though $F_1(\mathbf{X}_1)$ may be greater than $F_1(\mathbf{X}_2)$, and $F_2(\mathbf{X}_1)$ less than $F_2(\mathbf{X}_2)$, political preference could be determined by evaluating $F(\mathbf{X}_1)$ and $F(\mathbf{X}_2)$. If, say, $F(\mathbf{X}_1) > F(\mathbf{X}_2)$, then the trade-off of $F_2(\mathbf{X}_2) - F_2(\mathbf{X}_1)$ for $F_1(\mathbf{X}_1) - F_1(\mathbf{X}_2)$ represents the net increase in political preference, $F(\mathbf{X}_1) - F(\mathbf{X}_2)$.

It is clear that both target and optimization planning, or any mixture thereof, all require detailed a priori knowledge of policy makers' preferences, and each has inherent assumptions concerning the nature of trade-offs that are possible in the policy-making process. Compromise planning, on the other hand, does not necessarily require either a priori preference data or restrictions on possible trade-offs. In its most basic form, political questions may be avoided entirely, and planning may consist of the technical formulation of a small or large number of alternatives that are submitted to policy makers. The planner's task is considered complete if the plans cover a range of alternatives and if the objectives achieved by each plan are adequately described.

A more sophisticated view of compromise planning, however, incorporates political preferences into the planner's activities. Without making assumptions concerning the exact nature of objective trade-offs, attempts are made to look at a range of possible trade-offs and to screen alternatives for their political feasibility. Modeling techniques appropriate to this approach often require the systematic involvement of responsible decision makers in the planning process and/or the inclusion of the planner in policy-making.

The above form of compromise planning will be emphasized in the remainder of the discussion. Since no preference, value, or utility functions are assumed, this pragmatic approach may be less appealing to those accustomed to well-formulated problems. Nevertheless, for many public-policy decisions, these techniques compare favorably to those previously discussed for assisting in the selection of politically feasible and efficient multiobjective water-resource plans.

It is convenient to view compromise planning as two related processes: the first is plan formulation, or the identification of efficient trade-offs among objectives; the second is plan selection, or the identification of optimal trade-offs.

There are a number of approaches that can be used to examine the trade-offs between separate and noncomparable objectives. If there are only two or three objective functions $F_j(\mathbf{X})$ and a relatively few decision variables in the

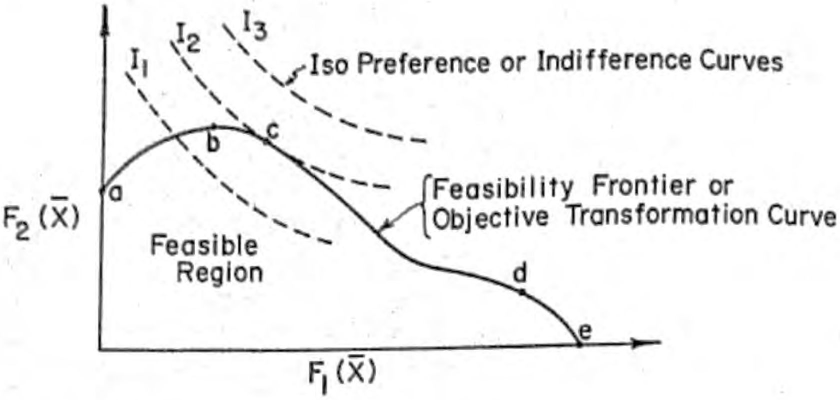

FIGURE 10-3
Feasible solutions for a two-objective problem.

vector **X**, then it might be possible to simulate all feasible combinations of decision variables in order to plot or graph the values of each of the objective functions associated with each vector **X**. The envelope of these values would define the efficient vectors **X** and the trade-offs that are possible among these efficient combinations of **X**. These concepts are illustrated for a two-objective problem in Fig. 10-3.

Each point within the feasible region in Fig. 10-3 represents a particular set of values for the decision variables in the vector **X** that satisfy a set of constraints $g_i(\mathbf{X}) = 0$, $i = 1, 2, \ldots, m$. The decision vectors that lie on the feasibility frontier, curve *abcde*, are those that define the maximum value of objective $F_2(\mathbf{X})$ given a particular value of objective $F_1(\mathbf{X})$. Of interest to the planner and policy maker are the trade-offs defined by certain combinations of feasible and efficient decision vectors. Each decision vector on the *bcde* portion of the feasibility frontier is efficient, in that there can be no increase in one objective value without a decrease in the other objective value. Solutions on the *ab* portion of the frontier are inferior solutions in the sense that they are dominated by other solutions having higher values for each objective. Inferior-solution vectors are of interest only if some of the objectives are inferior, i.e., if they are to be minimized.† If all objectives are superior, then only the efficient superior solutions need be considered.

Clearly the use of simulation models as a means of defining the feasibility frontier and the corresponding trade-offs between each efficient decision vector becomes less attractive as the number of variables and objectives increases. A simple graphical presentation of the trade-offs between objectives $F_j(\mathbf{X})$ becomes impossible as their number increase beyond three. For these reasons optimization techniques are usually suggested as a means of estimating feasible and efficient decison vectors **X**.

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†Such a situation would be indicated by a negative-sloped decision maker's indifference curve.

It is appropriate here to mention that different models of the same decision problem could result in different feasibility frontiers. Simplifying assumptions, often dictated because of algorithmic, computer, data, or budget limitations, are the primary reason why there is some uncertainty associated with the resulting feasibility frontier. This uncertainty might lead many to argue that the frontier is really a range of points, perhaps best represented by a probability distribution. In addition, politicians whose expectations or aspirations exceed what appears to be feasible might also suggest that one or more restrictions specified in the constraint set are really not constraints, or that they are willing to give up what is required to enlarge the feasible region (as illustrated in Fig. 10-2) to where it includes an otherwise infeasible aspiration or target.† It is also possible that what appears feasible *ex ante* is infeasible *ex post*, or vice versa, regardless of the model used to define feasibility. While all these arguments can be valid in certain situations, we will assume throughout the remainder of the discussion that the planning process can derive a reasonably well-defined and accurate feasibility frontier and, hence, a finite set of efficient alternatives from which a choice can be made.

The goal of plan formulation is the generation of plans that lie on the transformation curve. This can also be interpreted as the identification of efficient trade-offs. Any point on the transformation curve corresponds to a specific trade-off or marginal rate of substitution between the objectives, as indicated by the slope of the curve. Thus, plans *b*, *c*, and *d* in Fig. 10-3 correspond to three different marginal rates of substitution between objectives $F_1(\mathbf{X})$ and $F_2(\mathbf{X})$.

Plan selection is the identification of one of the efficient plans corresponding most closely with policy-making preferences. The indifference curves I_1, I_2, and I_3 are considered as curves of equal political preference. Of course, different individuals or groups may have different sets of indifference curves. The optimal plan for any particular policy maker is the plan on the objective transformation curve that achieves the highest level of political preference, e.g., plan *c* in Fig. 10-3. The optimal trade-off or marginal rate of substitution for the policy maker is indicated by the slope of the transformation curve at that same point *c*.

The remaining sections will discuss modeling techniques that have been proposed for identifying efficient trade-offs as indicated by plans on an objective transformation surface (for *n*-dimensional planning problems) and for estimating optimal trade-offs or plans, i.e., those that attempt to maximize political preferences. Since data generally do not exist to define completely either transformation or isopreference surfaces, the modeling techniques will attempt to approximate the surfaces by considering a relatively small number of efficient planning alternatives. Conceptually, the approaches correspond to the procedure illustrated in Fig. 10-3. However, in practice, the complete mapping of feasible and efficient alternatives is seldom possible or even necessary.

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†This argument is essentially over the proper scope of the problem being analyzed.

Any method that is used to define the possible trade-offs between multiple objectives can result in a relatively large number of efficient alternative solutions. As the number of objectives increases, so do the number of alternative solutions usually required to define the possible trade-offs among these objectives. This in turn requires more computer time and expense. Perhaps more importantly, it also requires more of the decision maker's time to examine the numerous solution vectors that define the efficient trade-offs. Decision makers are not always willing to take the time to do this.

Considerable evidence suggests that, contrary to what would appear to be rational behavior, decision makers have typically not yearned for the opportunity of selecting what they judge to be the best from among a large number of alternative efficient solutions to a particular problem. They are more inclined to request from their staff or from an appropriate agency their opinion of the single best solution, and then either accept or reject it. This shifts the burden of trading off the values of conflicting objectives to those technicians proposing the single policy solution. If their trade-offs are considered appropriate by the decision makers, their proposed policy will likely be accepted; otherwise it will probably be rejected. The iterative process of proposing a solution and having it accepted or rejected by the decision makers is one means of focusing in on the trade-offs that are considered acceptable, but not necessarily optimal, by the decision makers.

The selection of the optimal trade-offs between multiple public-policy objectives must, by definition, require the participation of responsible political decison makers. They are required to specify these optimal trade-offs among objectives in a political environment that is dynamic and changing and very demanding of their time. The remainder of this chapter will review some techniques that have been proposed for helping responsible planners and decision makers to estimate efficient alternative solutions and the trade-offs that may be required to obtain a politically acceptable solution.

10-6 FORMULATION OF PLANNING ALTERNATIVES

A variety of modeling techniques are appropriate to the generation of efficient water-resource plans. In general, the approaches may be categorized as optimization or simulation models. Optimization models can be applied to problems in which the technical feasibility restrictions $g_i(\mathbf{X}) = 0$ and the objective functions $F_j(\mathbf{X})$ are both explicit and mathematically well defined. Constraints which can be approximated by linear functions are particularly desirable since they facilitate the use of linear and separable programming methods. Recent examples[21,22,23] of the use of optimization models for multiobjective planning should be referred to.

Simulation methods are used extensively in water-resources planning.[24] In its most basic form, simulation modeling consists of finding solutions to the feasibility conditions $g_i(\mathbf{X}) = 0$, $i = 1, 2, \ldots, m$, and evaluating objectives

$F_j(\mathbf{X})$, $j = 1, 2, \ldots, n$, in either a deterministic or probabilistic form. The varied nature of simulation models defies simple categorization. An illustration of the flexibility of such models is found in the work of Kane et al.[25,26] Since simulation methods will not, in general, produce Pareto efficient plans, optimization and simulation are sometimes used conjunctively.[27,28] The planning problem is first described by simplified models which are amenable to optimization. The generated plans are then studied using more realistic (and complex) simulation models. The optimization stage is considered as a screening method for identifying promising (Pareto efficient) alternatives, and the simulation stage provides a realistic evaluation of plan feasibility and performance.

Optimization models generally require a number of simplifying assumptions, and as such are seldom exact models of real-world planning situations. As opposed to simulation methods, however, optimization can be used to approximate the feasibility frontier or objective transformation surface. Of course the accuracy of the plans generated will depend on the modeling assumptions, and as previously mentioned, different optimization models of the same problem may not produce identical transformation surfaces.

Perhaps the most common optimization model is the modified target planning model discussed in the previous section. A feasibility frontier is generated by maximizing a single objective $F_1(\mathbf{X})$ while varying the target levels T_j of other objectives $F_j(\mathbf{X})$:

$$\text{Maximize} \qquad F_1(\mathbf{X}) \tag{10-7}$$

$$\text{Subject to} \qquad F_j(\mathbf{X}) \geq T_j \qquad \forall_j \neq 1 \tag{10-8}$$

$$g_i(\mathbf{X}) = 0 \qquad \forall_i \tag{10-9}$$

By selecting different target values T_j, a set of plans could be generated, each of which achieves a maximum level of $F_1(\mathbf{X})$ for a specified set of targets T_j's. See, for example, the work of Miller and Byers.[22]

Numerous variations on target modeling have been prepared and used. A number of studies (e.g., Charnes et al.,[29] Holt et al.,[30] and Theil,[31] to mention only a few) have, in essence, proposed models that minimize the loss, if any, of not meeting targets. Relative loss functions L_j are specified in such a way that any deviation D_j from a target $[D_j = T_j - F_j(\mathbf{X})]$ reflects a penalty for not achieving the target. The problem then is to find a plan $\mathbf{X}$ that minimizes the maximum loss:

$$\text{Minimize} \qquad \max_j L_j(D_j) \tag{10-10}$$

An alternative approach, called *goal-programming*,[32] replaces that objective function (10-10) that minimizes the maximum loss by one that minimizes the absolute sum of losses:

$$\text{Minimize} \qquad \sum_j |L_j(D_j)| \tag{10-11}$$

The optimization planning model, Eqs. (10-5) and (10-6), can also be used to formulate alternatives. If the units of each objective $F_j(\mathbf{X})$ are the same, say, dollars, then it is relatively easy to combine separate objectives into a single function. For example, Dorfman and Jacoby[33,34] identify in monetary units the net benefits of a regional environmental quality management program for each of a variety of interest groups within a region. These separate net benefit functions are then weighted relative to one another. Assuming additive values, the tradeoffs between objectives are obtained by varying the relative weights in an objective function that maximizes the sum of the weighted individual objectives. Denoting the relative weight of objective $F_j(\mathbf{X})$ by $W_j \geq 0$, the objective function can be written

$$\text{Maximize} \qquad \sum_j W_j F_j(\mathbf{X}) \tag{10-12}$$

where the relative weights sum to 1 and the units of each objective $F_j(\mathbf{X})$ are the same. By varying the assumed relative weights, the convex portion of the feasibility frontier can be defined.

The success of any approach used to define the feasibility frontier critically depends on the assumptions of the convexity of the alternative combinations of the different objectives. A convex set of feasible alternatives has the property that a straight-line segment between any two points in the set lies wholly within the interior of the set. For example, the portions *abc* and *de* of the feasibility frontier illustrated in Fig. 10-3 are convex. If parts of the feasibility frontier are not convex (e.g., curve *cd*), or if it is convex but contains inferior points (e.g., curve *ab*), the maximization of various weighted sums of individual objectives will not define all points on the frontier. In these situations, the feasibility frontier can be defined by constraining the values of some of the objectives while maximizing weighted combinations of the others. More efficient adaptive search techniques have also been proposed in the recent operations research literature.

The multiobjective problem becomes more complex when the objectives $F_j(\mathbf{X})$ are not all expressed in the same units. In these cases it is useful to define a scaling function $S_j(F_j(\mathbf{X}))$ to ensure that each objective $F_j(\mathbf{X})$ ranges over the same set of numbers, for example, between 0 and 1 as illustrated in Fig. 10-4. The objective $F_j(\mathbf{X})$ in Fig. 10-4 is assumed to range between a minimum value m_j and a maximum value M_j. The maximum value M_j of objective $F_j(\mathbf{X})$ can be obtained from Eq. (10-12) by setting $W_j = 1$ and all other weights to 0. The minimum value m_j can be obtained by setting $W_j = 0$ and selecting the minimum of all solutions $F_j(\mathbf{X})$ generated by various combinations of relative weights associated with the other objectives. In this case the objective function (10-12) is modified to become

$$\text{Maximize} \qquad \sum_j W_j S_j(F_j(\mathbf{X})) \tag{10-13}$$

where again the relative weights W_j range between 0 and 1 and sum to 1, and

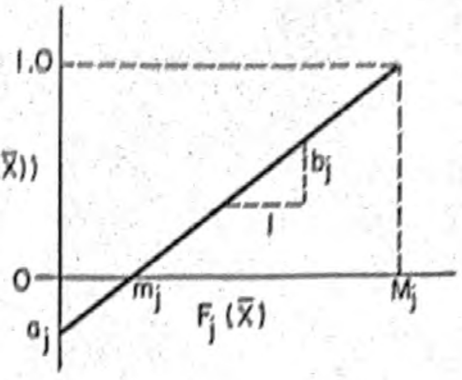

FIGURE 10-4
Scaling objective values.

each scaling function $S_j(\cdot)$ transforms the value of the objective $F_j(\mathbf{X})$ to be within an interval, say, from 0 to 1.

The scaling function can easily be made linear for use in linear programming models. As illustrated in Fig. 10-4, the scaling function can be defined as $a_j + b_j F_j(\mathbf{X})$, where

$$a_j = \frac{-m_j}{M_j - m_j} = \frac{-M_j}{M_j - m_j} + 1 \tag{10-14}$$

$$b_j = \frac{1}{M_j - m_j} \tag{10-15}$$

Using these linear scaling functions, objective function (10-13) is simply

$$\text{Maximize} \qquad \sum_j W_j[a_j + b_j F_j(\mathbf{X})] \tag{10-16}$$

where, of course, $\Sigma_j W_j \cdot a_j$ is a constant that can be ignored for the purpose of estimating the trade-offs between separate objectives F_j. Scaling functions may also be used to scale losses in the target optimization models.

The scaling term can be combined with the relative weights so that together they sum to 1. The advantage of this is that different solutions resulting from different weighting strategies can easily be compared. As before, let the value of M_j and m_j represent the maximum and minimum value of the objective $F_j(\mathbf{X})$, respectively. The nonnegative weights $\hat{W}_j$ that sum to 1 and include the previously defined relative weights W_j and the scaling or normalizing constants S_j are defined as

$$\hat{W}_j = \frac{W_j/(M_j - m_j)}{\sum_j [W_j/(M_j - m_j)]} \tag{10-17}$$

The objective function, Eq. (10-13), is then

$$\text{Maximize} \qquad \sum_j \hat{W}_j F_j(\mathbf{X}) \tag{10-18}$$

Again, by varying the relative weights $\hat{W}_j$ between 0 and 1 such that $\Sigma_j \ \hat{W}_j = 1$, the trade-offs between each separate objective $F_j(\mathbf{X})$ can be defined.

10-7 PLAN SELECTION: THE IDENTIFICATION OF POLITICALLY FEASIBLE ALTERNATIVES

In the plan formulation stage of the planning process, numerous, hopefully efficient, alternatives $\mathbf{X}_k$ are produced. Each plan $\mathbf{X}_k$ is a vector of decision variables and accomplishes objective levels $F_j(\mathbf{X}_k), j = 1, 2, \ldots, n$. The generated plans should satisfy technological feasibility $g_i(\mathbf{X}) = 0, i = 1, 2, \ldots, m$, and ideally be Pareto optimal or efficient; that is, any increase in one objective value is possible only by decreasing one or more other objective values. If the planner has included objectives which are of concern to policy makers (or the groups which influence the policy-making process), and a broad spectrum of alternatives has been formulated, it is not unreasonable to argue that the planner has performed his function well. He can present these alternatives to decision makers and, after a selection has been made, proceed with plan implementation. The planner could thus avoid more than marginal involvement with questions of political feasibility.

The viability of this approach rests on two assumptions. First, the planner must be capable of formulating Pareto efficient plans that may include a large number of objectives. Second, decision makers must be willing to examine a rather large set of complex alternatives. We have just indicated that there is little reason to believe that either assumption is valid. The formulation of a multiobjective water-resource plan is an expensive, time-consuming process, and even in planning situations that are amenable to mathematical modeling, we have seen that formulated plans may only approach a feasibility frontier. Planning budgets are finite, and policy makers' time is a scarce resource. Thus policy makers may not wish to see a large number of planning alternatives. Efficient use of policy makers' time would dictate the screening of plans so that they may select from a small set of promising alternatives. Hence, it is difficult to eliminate politics from planning. The challenge, perhaps, is to make considerations of political feasibility explicit rather than implicit in the planning process.

The systematic identification of politically feasible water-resource plans can be approached in several ways. If decision makers can be involved in plan formulation, methods are available for estimating their preferences for the various objectives and plans. In this fashion, optimal trade-offs among objectives can be determined with relative certainty, and one or more plans can be identified as being closely aligned with the decision makers' preferences. If policy makers have neither the time nor the inclination for such involvement, optimal trade-offs will be uncertain, and planners must utilize some means of estimating or predicting these trade-offs. Models appropriate to both situations will now be outlined.

10-7.1 Certain Preferences

In Sec. 10-5, plan selection was described as the identification of a plan on an objective transformation curve which achieves the highest level of political feasibility as indicated by a decision maker's isopreference curve (Fig. 10-3). This selection can be effected using indifference analysis as indicated by Raiffa[35] and applied by Haith.[36,37] The procedure is illustrated in an example.

Consider a planning situation in which there are three objectives of concern to a decision maker, described by objective functions $F_1(\mathbf{X}_k)$, $F_2(\mathbf{X}_k)$, and $F_3(\mathbf{X}_k)$. Let the level of objective j achieved by plan $\mathbf{X}_k$, $F_j(\mathbf{X}_k)$ be indicated by F_{jk}. Any plan can thus be specified by the vector (F_{1k}, F_{2k}, F_{3k}). An arbitrary reference level, F_3^* is chosen for objective 3, and the decision maker is asked to specify a level of objective 1, $\tilde{f}_k$ such that he is indifferent between $(\tilde{f}_k, F_{2k}, F_3^*)$ and (F_{1k}, F_{2k}, F_{3k}). In other words, a trade-off is made between the first and third objectives. This is denoted

$$(\tilde{f}_k, F_{2k}, F_3^*) \simeq (F_{1k}, F_{2k}, F_{3k})$$

In an analogous fashion, trade-offs between objectives 1 and 2 are made by selecting a reference level F_2^* and specifying f_k such that

$$(f_k, F_2^*, F_3^*) \simeq (\tilde{f}_k, F_{2k}, F_3^*)$$

Assuming transitive indifferences, we infer that

$$(f_k, F_2^*, F_3^*) \simeq (F_{1k}, F_{2k}, F_{3k})$$

All plans can be evaluated in a similar fashion, using the same reference levels F_2^* and F_3^*. The result is a new set of plans which differ only in the levels of the first objective function $f_1, f_2, f_3, \ldots$. These plans can be ranked according to these values, and the original plans can thus be ordered in terms of the decision maker's priorities. The questions that must be answered to identify trade-offs using indifference analysis are similar to those required by the surrogate worth trade-off method currently being advocated by Haimes and his associates.[38]

In addition to indifference analysis, several other simpler techniques are available for ranking alternatives based on interactions between the planner and the decision maker. These are called *dominance*, *satisficing*, and *lexicography*. They involve the comparison of alternative decision vectors $\mathbf{X}_k$ based on the values of $F_j(\mathbf{X})$ of each separate objective j. Unlike indifference analysis, they do not require the decision maker to specify how much more of one objective value he must have in order to get less of another.

Dominance exists if one alternative results in an equal or higher value for all objectives than do all other alternatives, and if for at least one objective, its value is strictly higher than those of the other alternatives. In other words, for a particular alternative k^* to dominate, $F_j(\mathbf{X}_k^*) \geq F_j(\mathbf{X}_k)$ for all objectives j and alternatives k, and for at least one objective, $F_j(\mathbf{X}_k^*) > F_j(\mathbf{X}_k)$ for all alternatives $k \neq k^*$. Perhaps more important, if one alternative results in all objective values being equal to or less than the corresponding objective values of all other alternatives, then clearly it is dominated by those alternatives and can be dropped from further consideration. Note that this procedure does not require any specification of the degree of preference for any particular objective values, nor does it require any assessment of the relative importance of each objective value. In fact, the objective values do not even have to be expressed in numerical terms.

While dominance can be a useful method for reducing the size of some decision problems, it is not a very effective method for making the final decision when a number of alternatives remain. For example, all alternatives $\mathbf{X}_k$ that are on the noninferior portion *bcde* of the feasibility frontier in Fig. 10-3 are not dominated; i.e., there exist no other alternatives that have equal or higher values for each of the objectives. Since the formal studies of dominance by Pareto, these nondominated alternatives are often called *Pareto optimal* or Pareto admissible. As implied in Fig. 10-3 there are usually many Pareto optimal or efficient alternatives and each has an objective value that is higher than that of all other alternatives. Although dominance has reduced the number of alternatives from all those that are feasible to those that define the feasibility frontier, the problem of choice among these efficient alternatives remains.

One method of further reducing the number of alternatives is called *satisficing*. As described by Simon,[39] the decision maker supplies the minimal objective values he will accept for each objective. Those alternatives that do not meet these targets are dropped from further consideration. Those that remain are again screened after increasing the minimal acceptable values of one or more objectives. When used in an iterative fashion, the number of alternatives can be reduced down to a single choice. Like dominance, satisficing requires no numerical values for each objective. Nor is any special credit given to alternatives having relatively high values of one or more objectives.

Lexicography involves the ranking of alternatives based on a comparison of objective values for each objective, one at a time, and in order of their importance to the decision maker. Thus the decision maker must specify which objective is most important and then compare the values of this objective for all alternatives. If for this most important objective one alternative has a higher objective value than any of the other alternatives, then it is chosen and the decision process ends. If there is more than one alternative having the highest value of that most important objective, then these and only these alternatives are considered in the next comparison based on the second-most-important objective. The process continues in this lexicographic fashion until either a single alternative emerges or all objectives have been considered.

Each of these techniques, while simple and requiring relatively little information, has a number of limitations. To overcome some of these, other, more complex evaluation techniques have been proposed, necessarily requiring more information and assumptions.

10-7.2 STEM, An Iterative Procedure

Within a mathematical programming framework, Benayoun et al.[40] have proposed a sequential iteration and exploration technique that involves the decision maker. The process "teaches" the decision maker to recognize what he considers as good solutions and important objectives. The final solution selected by the decision maker represents a best compromise among conflicting objectives. Assuming that preferences do not change during the decision-making process, the best compromise is achieved in a relatively small number of iterations. The authors have labeled their approach STEM (step method).

STEM assumes that the decision maker is initially unable to define the relative importance of the separate objectives $F_j(\mathbf{X})$. To teach the decision maker, a number of calculation and decision-making iterations are required, involving essentially a conversation between the analyst and the decision maker. During the decision-making phase of each iteration, the decision maker examines the results of the calculation phase and develops new insights and information about his objectives. This information in turn is used in the calculation phase of the next iteration, thereby providing a guide for the search of the best compromise.

The STEM procedure begins with n alternatives, each of which maximizes one of the n objectives. The first iteration minimizes the maximum weighted difference D between objectives $F_j(\mathbf{X})$ and their respective maximum values M_j:

$$\text{Minimize} \qquad D \tag{10-19}$$

$$\text{Subject to} \qquad D \geq W_j\,[M_j - F_j(\mathbf{X})] \qquad \forall_j \tag{10-20}$$

$$g_i(\mathbf{X}) = 0 \qquad \forall_i \tag{10-21}$$

Constraints (10-20) simply ensure that D is no less than each weighted difference between the maximum and the actual value of each objective, and, as before, constraints (10-21) are all the other constraints specific to the problem being solved. The weights W_j indicate the relative magnitude of the deviations from the optimum. These weights include scale or normalizing terms. The weights W_j can be defined as a quotient of a sensitivity parameter γ_j and a scaling parameter α_j:

$$W_j = \frac{\gamma_j}{\alpha_j} \tag{10-22}$$

Recalling that M_j is the maximum value of $F_j(\mathbf{X})$ and denoting m_j as the minimum value assumed by $F_j(\mathbf{X})$, the numerator of Eq. (10-22)

$$\gamma_j = \begin{cases} \dfrac{M_j - m_j}{M_j} & \text{if } M_j > 0 \\[2ex] \dfrac{m_j - M_j}{m_j} & \text{if } M_j \leq 0 \end{cases} \tag{10-23}$$

indicates the relative range of the values assumed by objective $F_j(\mathbf{X})$. If, for various solution vectors $\mathbf{X}$, the value of $F_j(\mathbf{X})$ does not vary much from the optimum solution M_j, the objective is not sensitive to a variation in the weighting values W_j, and therefore a relatively small weight can be assigned to this objective. As the variation in $F_j(\mathbf{X})$ becomes larger with changes in the decision vector $\mathbf{X}$, the weight W_j will become correspondingly greater. (Note that this relative weight has nothing to do with the relative political importance of the corresponding objective.)

The denominator or α_j term of Eq. (10-22) is used to scale each objective and ensure that the sum of the relative weights W_j equals 1. Initially this constant equals

$$\alpha_j = (M_j + K) \sum_l \frac{\gamma_l}{M_l + K} \tag{10-24}$$

where if any $M_j \leq 0$, $K = 1 - \min_j M_j$; otherwise $K = 0$. On succeeding iterations the relative weights of the objectives whose values are satisfactory are set to 0, and thus α_j is changed accordingly by summing only over those objectives whose values are unsatisfactory. By normalizing the values of each objective, and ensuring that the relative weights sum to 1, different solutions obtained from different sets of relative weights can easily be compared.

The solution to the first iteration is a plan $\mathbf{X}_o$, which yields a vector of objective values, $\mathbf{Z}_o = [F_1(\mathbf{X}_o), F_2(\mathbf{X}_o), \ldots, F_n(\mathbf{X}_o)]$. The decision maker compares these results with the ideal objective vector $\mathbf{Z} = [M_1, M_2, \ldots, M_n]$. If the values of some components of $\mathbf{Z}_o$ are satisfactory and others are not, the decision maker must accept a certain reduction in the value of one or more satisfactory objectives in order to improve the unsatisfactory ones in the next iteration. Hence, the decision maker must identify the satisfactory objective values $F_j^*(\mathbf{X}_o)$ that can be reduced and the permissible amount of the reduction, ΔF_j^*. Prior to the next iteration the relative weights W_j^* of the satisfactory objectives are set equal to 0, the feasible region is modified by the additional constraints

$$F_j^*(\mathbf{X}) \geq F_j^*(\mathbf{X}_0) - \Delta F_j^* \qquad \forall j^* \tag{10-25}$$

$$F_j(\mathbf{X}) \geq F_j(\mathbf{X}_0) \qquad \forall j \neq j^* \tag{10-26}$$

and the α_j terms used in Eq. (10-24) are increased to ensure that the relative weights of the nonsatisfactory objectives sum to 1.

The next iteration begins with the solution of the modified programming problem [Eqs. (10-19), (10-20), (10-21), (10-25), and (10-26)] and ends with a further adjustment in the relative weights and constraint set. This sequence of iterations continues until either all or none of the components of the objective vector $\mathbf{Z}$ are satisfactory. If all the components are satisfactory, the decision vector $\mathbf{X}$ represents the best compromise. If none of the components is satisfactory, there is no solution to the problem. For an n-objective problem the total number of iterations required to obtain either a best compromise solution, or no solution, is no more than n, providing the decision maker does not change his preferences during the iterative process. The latter assumption, of course, is rather heroic, but its violation would not detract significantly from the potential usefulness that an iterative procedure similar to STEM might have in the decision-making process.

The analyst using STEM can further assist the decision maker by presenting the results of a sensitivity analysis on the different objective functions in the neighborhood of the solution **X** for each iteration. Also, during each calculation phase several discrete reductions between 0 and the maximum acceptable reduction ΔF_j^* of each satisfactory objective can be evaluated. When the best compromise solution has been obtained, the relative weights that would yield this solution can be calculated a posteriori if desired, by the simultaneous solution of Eqs. (10-27) and (10-28):

$$\text{Constant} = W_j(M_j - F_j(\mathbf{X})) \qquad \forall j \tag{10-27}$$

$$\sum_j W_j = 1 \tag{10-28}$$

The iterative STEM procedure can be illustrated by a simple numerical example. In this example the STEM procedure will be modified to examine inferior objectives, i.e., ones that are minimized. Suppose there are two municipal waste-water treatment facilities that must be built in a small river basin in order to improve stream quality. The treatment efficiency of each facility, X_1 and X_2, must be determined.

For planning purposes three objectives are identified. Each of the two municipalities wishes to minimize its treatment costs, or equivalently, its required treatment efficiency. Since the federal government is subsidizing a specified (and equal) fraction of the cost of each facility, it is interested in minimizing the total cost. Assuming that the cost of X_1 is half that of X_2 for each value of X_1 and X_2, the three objectives are

$$\text{Minimize} \qquad X_1 \tag{F-1}$$

$$\text{Minimize} \qquad X_2 \tag{F-2}$$

$$\text{Minimize} \qquad X_1 + 2X_2 \tag{F-3}$$

These objectives are subject to a variety of constraints $g_i(X_1, X_2) = 0$ that define all feasible combinations of X_1 and X_2. Included among these constraints are the effluent or stream-quality standards applicable to the basin. These feasible combinations are illustrated by the shaded region in Fig. 10-5a. Also illustrated are the minimum values of each of the three objectives. Clearly, not all objectives can be minimized simultaneously, and it is up to the local river basin commission to achieve an acceptable compromise among the three interested parties, if possible. An analyst on the river basin commission staff begins the STEM procedure by calculating a payoff matrix of the values of the jth objective when the kth objective is minimized. In this case these values

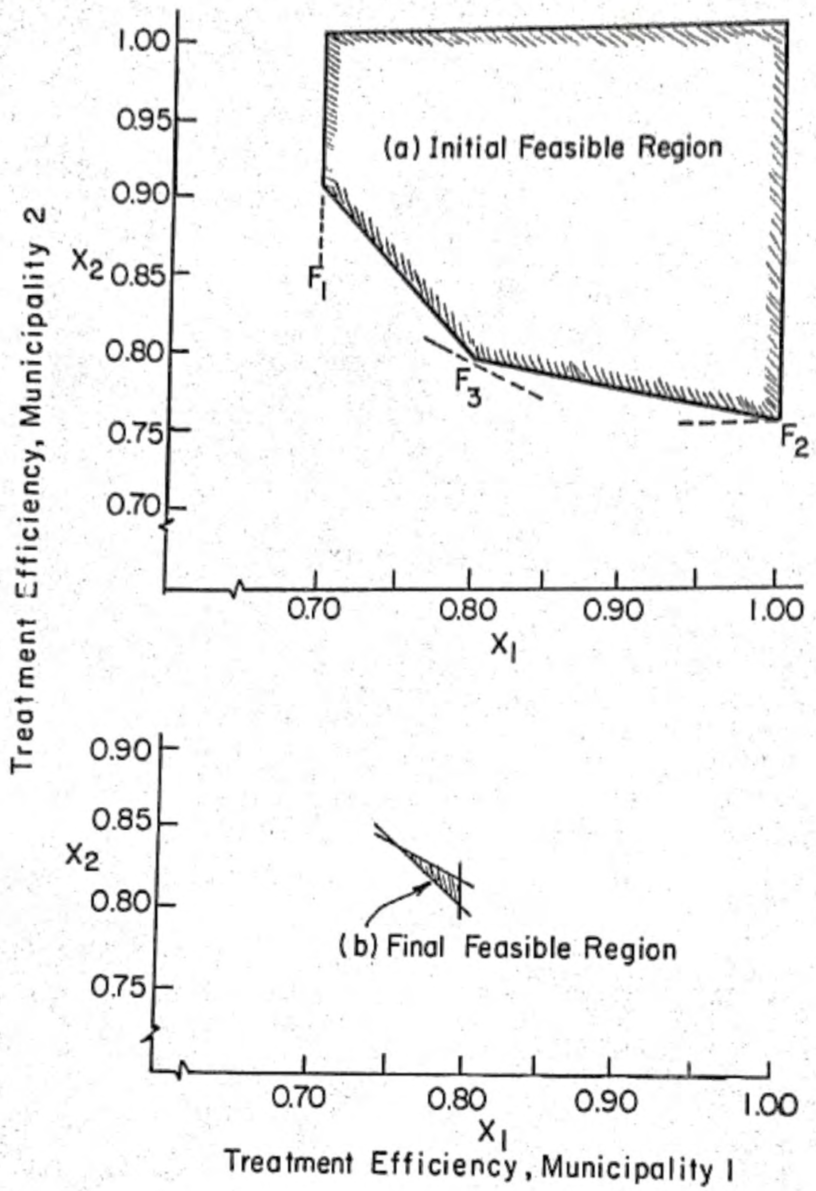

FIGURE 10-5
Feasible combinations of treatment efficiencies.

can be observed from Fig. 10-5*a*:

		Objective F_k		
	k / j	1	2	3
Objective F_j	1	0.70	1.00	0.80
	2	0.90	0.75	0.80
	3	2.50	2.50	2.40

Using the values in the payoff matrix, the weights W_j defined by Eqs. (10-22), (10-23), and (10-24) for each of the three objectives j are 0.60, 0.37, and 0.03, respectively. Using these weights in constraints (10-20), the values of X_1 and X_2 that minimize the maximum weighted difference between the objective $F_j(\mathbf{X})$ and its minimum value m_j are 76 and 84, respectively. Hence the values of the three objectives are 0.76, 0.84, and 2.44, respectively. This efficient solution is then presented to the representatives of the two municipalities and the federal government.

Suppose that the representative from municipality 2 (which would have to treat at a higher efficiency than municipality 1) is not satisifed with this solution because of the difference in required treatment efficiencies between the two municipalities. The representative from municipality 1 must then state how much, if any, he is willing to increase treatment efficiency in order to achieve a more equitable solution. Assuming that he is willing to increase treatment efficiency by 4 percent, the next iteration of STEM begins by considering only those combinations of X_1 and X_2 defined by all constraints $g_i(X_1, X_2) = 0$ and the additional constraints (10-25) and (10-26), modified, of course, for inferior objectives:

$$\begin{aligned} X_1 &\leq 0.76 + 0.04 \\ X_2 &\leq 0.84 \\ X_1 + 2X_2 &\leq 2.44 \end{aligned}$$

These feasible combinations are illustrated in Fig. 10-5*b*.

The relative weight of the first objective (F-1) whose value has been increased and is satisfactory is now set equal to 0. The weights W_2 and W_3 of the remaining objectives equal 0.92 and 0.08, respectively. These weights are then used to recalculate an efficient solution. In this case the solution that minimizes the maximum difference between the objective values and their minimum feasible values is also the solution that minimizes the total cost, namely, $X_1 = X_2 = 0.80$. Clearly all three interested parties are satisfied with this objective, unless, of course, the representative from municipality 1 changes his mind.

The STEM algorithm just discussed corresponds to an educational process that leads to a best compromise. As was illustrated, the process involves the reduction of some superior objective values (or an increase in some inferior objectives) in order to achieve more acceptable values of other objectives.

10-7.3 Uncertain Preferences

If policy makers cannot or will not become involved in the iterative processes described above, the planner is placed in the difficult position of attempting to estimate or infer the policy makers' preferences. These preferences must be considered as uncertain quantities, and the planner is forced to rely to a considerable extent on his judgment for their determination. Personal judgment has always played a role in planning, of course, and estimates of political feasibility have often been made implicitly by planners. The two approaches that have been proposed for analyzing situations in which the preferences are uncertain go somewhat beyond such implied determinations. Each attempts to model the policy-making process, and the planner is forced to be quite explicit in providing the (judgmental) data that is required. The methods are experimental and are subjective in nature. Users of mathematical models frequently attribute undue accuracy and objectivity to the results of their efforts. Such optimism should obviously be avoided when dealing with models of the political process.

One of the two approaches is a probabilistic form of indifference analysis that assumes the trade-offs can be described by subjective probabilities that are determined by the planner's judgment. Techniques for assigning such probabilities are available,[35,36] and in general, they provide a means for explicit and consistent quantifications of personal judgment. The procedure is applicable also to decision-making problems involving small or large policy-making groups.

The other approach can be termed *policy simulation*. Buckley and McLaughlin[41] have developed such a simulation procedure for estimating political feasibility. They have focused on the agencies which influence the policy-making process rather than on the policy makers themselves. By simulating the agencies' reactions to a proposed multiobjective water-resource plan, conflicts among groups are identified, probable coalitions in support of and in opposition to the plan are formed, and the plan is either accepted or rejected according to the levels of political power possessed by both coalitions.

Buckley and McLaughlin utilized this simulation procedure to compare the political feasibility of alternative water-development plans for the Maule River Basin, Chile. This method was also adopted by Burke et al.[42] to analyze the hypothetical water-quality problem proposed by Dorfman and Jacoby.[33]

SUMMARY

The National Water Commission has noted that multiobjective water-resources planning has "yet to be successfully fashioned and implemented in the field."[43] There are two main reasons why implementation has been difficult. Quantification of nonmonetary planning objectives has not been easy, and thus far there have been few methods and established precedents or guidelines for planners to follow. Yet guidelines and methods are beginning to appear in the literature. The primary purpose of writing these notes has been to provide planners with a review of some of these methods and guidelines.

The methodologies that have been reviewed in this chapter represent only a few of a relatively large class of procedures designed to assist the planner in the definition and evaluation of multiple-objective policies. Each of these methodologies, to a greater or lesser extent, provides a mechanism for estimating the trade-offs between conflicting objectives. Some go beyond this to predict what the politically optimal trade-offs may be. Most would agree that, for a multiple-objective solution to be optimal, the choices between conflicting objectives must reflect the best interests of society. Those who are responsible for expressing and articulating these interests are the political decision makers.

Thus it is inescapable that responsible politicians must become involved in the process of selecting the optimal trade-offs between multiple objectives. In the planning process, the relative weights that define these trade-offs are considered to be unknown variables. The precise values of these relative weights will be known only after the political process has selected its final solution. The relative weights of different objectives, as well as the instruments that contribute to meeting these objectives, should reflect conscious political decisions with respect to these political questions at the time those decisions are made. They involve political preferences concerning the future and therefore must be revised as frequently as new policies or new investments are made. To permit project formulators or evaluators to select the final values of these relative weights is to turn over political decisions to technicians.

On the other hand, the political decision-making process often encourages technicians to assign values to the relative weights. One reason for this is the politician's reluctance to learn the methodology of policy analysis and evaluation or to spend the time answering seemingly "academic" questions that would eventually lead to a set of well-defined relative weights. Another reason is that political leaders rely on the support of distinct interest groups that are often in conflict with one another. In such situations it is obviously to the advantage of political leaders not to be too explicit in quantifying political value judgments regarding trade-offs between conflicting objectives. Technicians, of course, all too often encourage politicians not to intervene in making value judgments in areas in which they consider themselves competent. But it is precisely in these areas that they themselves have bias or special interests.

It is clear that what is needed is a methodology that does not require explicit intervention by the political decision makers, yet does make use of value judgments that must be defined by the political decision-making process. The only way that this can be done is to have policy makers recognize that the assignment of values to the relative weights of various objectives is their responsibility, and that they must devote more time to acquiring the skills necessary to articulate those values in advance of specific decision-making.† If the decision makers could indicate even a reasonable range of appropriate values for the relative weights of each objective, planners could present to the decision makers policy alternatives and their trade-offs that reflect only these ranges of politically determined weights.

In the meantime, perhaps the best procedure for planners to follow is to consider the relative weights as unknown, to identify the values of the weights that make significant differences in the values of the objectives, and to define the policies that are efficient for different ranges of weights. These alternative policies, together with their policy implications, can then be submitted to the

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†Compared to the static assignment of values for relative weights, policy makers can be expected to have even more difficulties in articulating the future changes in the values of the relative weights. These too have to be determined. To the planner, the horizon of each objective is unknown, as well as its relative weight.

responsible decision makers. Such a planning procedure, it is hoped, would ensure that the political leadership is aware of the relevant alternatives and the efficient trade-offs among multiple goals. At the same time it would stress the importance of the politician's role in the assignment of relative priorities and in the definition of the best compromise solution. Finally, such a procedure would form the basis for a systematic determination of the relative priorities among various goals by the political process, leading, it is hoped, to a time when they will be at least approximately specified in advance of particular policy formulation and evaluation. If estimates of the values of relative weights are ever to be known in advance of policy planning, it will be necessary for technicians to take the initiative and force responsible decision makers to reveal their value judgments. Rather than presenting to them a single project plan or policy that represents a best compromise between conflicting objectives, planners should put political choice in the hands of those responsible for making those choices—the politicians who are accountable to the people affected by those choices. Through the further development and use of analytical planning techniques similar to those reviewed in this discussion, technicians can begin to enlighten those who would suggest that public-policy evaluation and analyses should not be political.

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REFERENCES

1. SIMON, H. A., "Models of Man," John Wiley & Sons, Inc., New York, 1957.
2. WHITE, G. F., "Strategies of American Water Management," The University of Michigan Press, Ann Arbor, 1969.
3. *Policies, Standards, and Procedures in the Formulation, Evaluation, and Review of Plans for Use and Development of Water and Related Land Resources*, Senate Document No. 97, 87th Cong., May 1962.

4. "Principles and Standards for Planning Water and Related Land Resources," Water Resources Council, *Fed. Regis.*, vol. 38, no. 174, pt III, September 10, 1973
5. CICCHETTI, C. J., R. K. DAVIS, S. H. HANKE, and R. H. HAVEMAN, Evaluating Federal Water Projects: A Critique of Proposed Standards, *Science*, p. 723, 24 August 1973.
6. ECKSTEIN, O., "Water-Resource Development," Harvard University Press, Cambridge, Mass., 1958.
7. BURBY, R. J., III, "Politics and Planning," doctoral dissertation, University of North Carolina, Chapel Hill, 1968.
8. MAASS, A., Benefit-Cost Analysis: Its Relevancy to Public Investment Decisions, *Q. J. Econ.*, vol. LXXIX, pp. 208–226, May 1966.
9. RABINOVITZ, F. F., "City Politics and Planning," Atherton Press, Inc., New York, 1969.
10. RANNEY, D. C., "Planning and Politics in the Metropolis," Charles E. Merrill Books, Inc., Columbus, Ohio, 1969.
11. STRICKLAND, D. A., L. L. WADE, and R. E. JOHNSTON, "A Primer of Political Analysis," Markham Publishing Company, Chicago, 1968.
12. LINDBLOM, C. E., "The Policy-Making Process," Prentice-Hall, Inc., Englewood Cliffs, N.J., 1968.
13. DAHL, R. A., "Modern Political Analysis," 2d ed., Prentice-Hall, Inc., Englewood Cliffs, N.J., 1970.
14. SCHULTZE, C. L., "The Politics and Economics of Public Spending," The Brookings Institution, Washington, D.C., 1968.
15. BUCHANAN, J. M., and G. TULLOCK, "The Calculus of Consent," The University of Michigan Press, Ann Arbor, 1962.
16. DONOVAN, W. J., and J. J. JORDAN, Emerging Corps of Engineers Guidelines Implementing the Planning Requirements of WRC's Principles and Standards and Related Policies, Universities Council on Water Resources Workshop on Multiple Objective Planning and Decision-Making, Las Vegas, July 16–18, 1974.
17. O'NEAL, W. G., The Tennessee Valley Authority and Multiple Objective Planning, Universities Council on Water Resources Workshop on Multiple Objective Planning and Decision-Making, Las Vegas, July 16–18, 1974.
18. HOWE, C. W., "Benefit-Cost Analysis for Water System Planning," American Geophysical Union, Washington, D.C., 1971.
19. "Environmental Quality—The Third Annual Report of the Council on Environmental Quality," Washington, August 1972.
20. DINIUS, S. H., Social Accounting System for Evaluating Water Resources, *Water Resour. Res.*, vol. 8, no. 5, pp. 1159–1177, 1972.
21. COHEN, J. L., and D. H. MARKS, Multiobjective Screening Models and Water Resource Investment, *Water Resour. Res.*, vol. 9, no. 4, August 1973.
22. MILLER, W. L., and D. M. BYERS, Development and Display of Multiple-Objective Project Impacts, *Water Resour. Res.*, vol. 9, no. 1, pp. 11–20, 1973.
23. MONARCHI, E. D., C. C. KISIEL, and L. DUCKSTEIN, Interactive Multiobjective Programming in Water Resources: A Case Study, *Water Resour. Res.*, vol. 9, no. 4, August 1973.

24. JOHNSON, W. K., Use of Systems Analysis in Water Resource Planning, *J. Hydraul. Div., Am. Soc. Civ. Eng.*, vol. 98, no. HY9, pp. 1543–1556, 1972.
25. KANE, J., W. THOMPSON, and I. VERTINSKY, Environmental Simulation and Policy Formulation: Methodology and Example (Water Policy for British Columbia), vol. 1, pp. 39–55, Proceedings of the International Symposium on Modelling Techniques in Water Resources Systems, Ottawa, May 1972.
26. KANE, J., I. VERTINSKY, and W. THOMPSON, KSIM: A Methodology for Interactive Resource Policy Simulation, *Water Resour. Res.*, vol. 9, no. 1, pp. 65–80, 1973.
27. JACOBY, H. D., and D. P. LOUCKS, Combined Use of Optimization and Simulation Models in River Basin Planning, *Water Resour. Res.*, vol. 8, no. 6, pp. 1401–1414, 1972.
28. SIGVALDASON, O. T., et al., The Saint John Study: An Example of Complementary Usage of Optimization and Simulation Modelling in Water Resources Planning, vol. 3, pp. 576–602, Proceedings of the International Symposium on Modelling Techniques in Water Resources Systems, Ottawa, May 1972.
29. CHARNES, A., and W. COOPER, "Management Models and Industrial Applications of Linear Programming," vol. 1, John Wiley & Sons, Inc., New York, 1961.
30. HOLT, C. C., Quantitative Decision Analysis and National Policy: How Can We Bridge the Gap? in Bert G. Hickman (ed.), "Quantitative Planning of Economic Policy," The Brookings Institute, Washington, D.C., 1965.
31. THEIL, H., Linear Decision Rules for Macrodynamic Policy Problems, in Bert G. Hickman (ed.), "Quantitative Planning of Economic Policy," The Brookings Institute, Washington, D.C., 1965.
32. CHARNES, A., W. COOPER, M. A. KEANE, E. F. SNOW, and A. S. WALTERS, A Mixed Goal Programming Model for PPBS in a Consumer Protection Regulatory Agency, 7th Mathematical Programming Symposium, The Hague, September 1970.
33. DORFMAN, R., and H. D. JACOBY, An Illustrative Model of River Basin Pollution Control, in R. Dorfman et al., "Models for Managing Regional Water Quality," chap. 3, Harvard University Press, Cambridge, Mass., 1972.
34. LOUCKS, D. P., and H. D. JACOBY, Flow Regulation for Water Quality Management, in R. Dorfman et al., "Models for Managing Regional Water Quality," chap. 9, Harvard University Press, Cambridge, Mass., 1972.
35. RAIFFA, H., "Decision Analysis," Addison-Wesley Publishing Company, Inc., Reading, Mass., 1968.
36. HAITH, D. A., The Political Evaluation of Alternative Metropolitan Water-Resource Plans, Tech. Rep. No. 31, Cornell University Water Resources and Marine Sciences Center, July 1971.
37. HAITH, D. A., and D. P. LOUCKS, Estimating the Political Feasibility of Alternative Water-Resource Plans, vol. 2, pp. 309–318, Proceedings of the International Symposium on Modelling Techniques in Water Resources Systems, Ottawa, May 1972.
38. HAIMES, Y. Y., W. A. HALL, and H. T. FREEDMAN, "Multiobjective Optimization in Water Resources Systems," Elsevier Scientific Publishing Company, New York, 1975.

39. SIMON, H. A., A Behavioral Method of Rational Choice, *Q. J. Econ.*, vol. 69, pp. 99–118, 1955.
40. BENAYOUN, R., J. DE MONTGOLFIER, J. TERGNY, and O. LARITCHEV, Linear Programming with Multiple Objective Functions: Step Method (STEM), *Math. Programm.*, vol. 1, no. 3, December 1971.
41. BUCKLEY, J. W., and R. T. MCLAUGHLIN, Simulation of Political Interaction in Multiple-Purpose River-Basin Development, Report No. 100, Massachusetts Institute of Technology, Hydrodynamics Laboratory, October 1966.
42. BURKE, R., J. HEANEY, and E. E. PYATT, Political Interactions and Water Resources Management: A Quantitative Approach, National Symposium on Watersheds in Transition, Fort Collins, Colo., June 1972.
43. "Water Policies for the Future," Final Report of the National Water Commission, Government Printing Office, Washington, D.C., June 1973.

11

MATHEMATICAL MODELING AND WATER-RESOURCES DECISION-MAKING

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11-1 INTRODUCTION

It was possible for a brilliant person to know nearly all there was to know about what we can loosely define as science until about the end of the sixteenth century.[1] Versatile geniuses like Aristotle, Theophrastus, Vitruvius, Isidore of Seville, or Leonardo da Vinci could discuss most subjects authoritatively. Man's knowledge of the natural and social systems was at a stage where it was still possible, albeit difficult, for a really gifted man to master all the information available.

The situation started to change around the seventeenth century, and by the early eighteenth century, tremendous advances in natural sciences had made it impossible for anyone to be a universal encyclopedist. This realization was gradually reflected in the development of a new area of knowledge, which initially became known as *natural philosophy* and began to be distinguished increasingly from traditional philosophy. The nineteenth century witnessed not only an explosion of human population but also an exponential increase in human knowledge and, with it, technological developments. It was no longer possible for any one person to master natural philosophy completely, and hence it had to be subdivided further—initially into physics and chemistry, and later to other areas like life sciences and biological sciences.

The information explosion of the twentieth century ensured that it was almost humanly impossible for anyone to know as much as there is to know on even one individual subject—for example, water. Even if this were possible, it is now virtually impossible for anyone to read, understand, and assess the latest developments in the field of water and thus remain current with the state-of-the-art.

These developments clearly indicate that decision-making in the water-resources area, or in other areas of natural resources management, has become progressively complex over the decades and is bound to become more complex in the future.

11-2 DECISION-MAKING

One of the fundamental facts not often recognized is that planners make recommendations, management scientists make models, and managers make decisions. A certain amount of overlap in such a structure is not only necessary but essential. However, the problem arises when this simple fact is overlooked and modelers try to usurp the decision-making process or decision makers abdicate their responsibilities to modelers. Drake[2] suggests that recognition of this simple principle is the single most important element that differentiates between successful and unsuccessful projects.

The primary role of a decision maker is to make right decisions, which may be defined as decisions made on the basis of perfect knowledge.[3,4] Perfect knowledge in this context means that the decision maker knows exactly the probabilities of each of the outcomes, as well as their values to him. Since no decision maker can ever have perfect knowledge, one has to accept the fact that some of the decisions made will be imperfect (i.e., not the best). The best that one can aim for is to make the right decisions on the basis of available information within the time constraint under which the decisions have to be made. Ideally, under our existing democratic framework, the decision maker chooses a specific course of action over a series of available alternatives sent to him for consideration by his advisors, and the decision made stems from the logical consequence of his assessment of possible outcomes and his personal evaluation of the outcomes in the sense that the assessment and the valuation determine the ultimate action. By valuation, we mean the body of views which an individual decision maker holds that enables him to choose one alternative over another.

Basically, there are two different types of models for decision-making: *technocratic* and *incremental*. In the technocratic approach, one starts from the recognition and analysis of the problem, and then, proceeding through a series of sequential and progressive steps and through analysis of all feasible alternatives and the possible consequences of these alternatives, the "optimal" solution is eventually chosen. It requires specialized inputs from different disciplines and generally tends to favor quantitative techniques over qualitative ones. It often disregards irrationalities of political processes, idiosyncrasies of human behavior and the vagaries of ideas and preferences of individual decision makers. Consequently, solutions are often unacceptable to the policy makers and, if accepted, sometimes difficult to implement for sociopolitical reasons.

The second model is incremental decision-making and is the traditional bureaucratic approach. The advances are made in small steps, and there is rarely any drastic change or reorientation of policies. It assumes that there is no one right decision or solution but a continuous stream of minor decisions on a subject whenever it confronts the decision maker. It eschews absolute solutions and is in a sense a type of trial-and-error approach, or it can be described as a process of "muddling through." It is invariably a short-term approach, and rarely are the short-term objectives linked to the long-term goals or the eventual master plan. The attraction of incremental decision-making to our present democratic framework is obvious. Very few politicians really have an opportunity to be interested in the long-term objectives of the society: in fact, very few countries, if any, have made any decision as to the type of society they would like to develop by the year 2000 or 2020. National dialogues in this area have hardly even begun. Most politicians are pragmatic, and, consequently, their major objectives are to get elected in the next election and to retain power for their party. Thus, they have to be more interested in the short-term results that would satisfy a maximum number of people, or at least alienate the least number, so that their election is not in jeopardy. Hence, incremental decision-making appeals to them because it is a process of "satisficing"—in contrast to the process of optimizing.

There are other "advantages" to the incremental decision-making. It allows compromises, trade-offs, and revision of views; in fact it encourages such processes because they invariably "dilute" the actions initially suggested and thus eschews absolute solutions. It tolerates ambiguity, and implicitly considers bureaucratic interests, power struggles, and the rigidity and inefficiency of the institutions that might be involved in making decisions or implementing the results of such decisions. It also considers the power and effectiveness of external pressure groups and prefers traditional and customary approaches rather than experimenting with radically different procedures and solutions.

The appeal of incrementalism will be further clarified if we consider the decision-making process in a real world. Some of its common traits are the following:

1 A decision maker can devote only a limited amount of time to any one individual subject under consideration. This is primarily because a significant portion of the available time is devoted to the discussion and solution of trivial problems or minor crises rather than detailed consideration of major policy issues and problems. Thus, it is not unusual to see the entire top management of an organization spend a half day arguing on insignificant problems such as the location of bulletin boards in a building instead of considering major policy decisions.

2 Nearly all decision makers are involved in more activities than they can consider carefully and simultaneously. (Whether they should be involved in all these activities is another question.) Consequently, they can consider only a part of their major responsibilities while the remainder either do not get the necessary attention or remain latent.

3 A decision maker has only a limited span of attention; that is, because of physical and mental constraints, he can handle only a limited amount of information at any one time.

4 Only a limited number of policy alternatives are considered for any one decision.

5 The alternatives considered are generally those that differ incrementally from existing policies.

6 For the limited number of alternatives considered, even fewer possible consequent scenarios are constructed and evaluated.

7 The extent of relevant information available to a decision maker on the policy under consideration is only a small fraction of potential information available on the subject. More information can be made available, but it would necessitate expenditure of more time and money. In addition, some decision makers suffer from the "don't confuse me with facts" syndrome.

8 Decisions eventually made are rarely nontraditional and controversial. This does not mean that decisions made do not provoke controversies—only that reasons for such controversies were not foreseen. In other words, decision makers tend to prefer safe and traditional solutions that do not make any waves.

9 The general tendency is to solve minor kinks in a major problem, and in this way buy some time until the next kink appears. In other words, there is a general reluctance to tackle the disease: there is a marked preference for curing individual symptoms as they surface.

10 Consequently, most of the time is devoted to the solution of minor crises as they surface. Thus, the entire decision-making process often becomes one of "crises management," rather than development and pursuance of future long-range policies and goals. Current decisions are rarely linked to the long-range plans, and the future is often discounted. In fact, often times a viable long-range plan does not even exist!

11 Most managers, by the time they reach the real decision-making role, are fairly close to retirement. They have very little inclination for radical innovative solutions and the resulting problems of implementation. Thus, they would prefer to "coast" rather than innovate. For others that reach the decision-making role at a relatively younger age, they plan to stay in one position for a definite span of time before moving on to "greener pastures." Thus, very often their motto is "don't rock the boat."

Decision-making in North America and probably in other regions as well, is innately incremental. This does not mean that a decision maker who follows incremental decision-making processes is automatically irrational. The inherent complexities and interconnectedness of the present-day resource management problems make the attainment of rationality in decision-making a difficult task because rationality, in most circumstances, is neither clearcut nor can it be automatically determined. When the multidimensionality of the problems is considered, in terms of social, economic, technical, legal, and political rationalities, it soon becomes evident that multidimensional optimization is no simple task. The solution that is technically and economically optimal may be socially unimplementable or politically unacceptable. Our present state of knowledge for obtaining multidimensional optimal solutions in such diverse sectors leaves much to be desired.

This, however, does not mean that the present mode of decision-making cannot be improved. Even assuming the fact that incremental decision-making is a fact of life and is here to stay for a considerable period of time, the process can be improved substantially. There is absolutely no reason why such a process should remain predominantly remedial, where ambiguity and lack of hard decisions is tolerated or the future effects of present decisions are discounted. In a democratic, diverse, and pluralistic society, incremental decision-making has much to offer. What is necessary is to change or modify the existing process. Decisions within such a framework can still be made on the basis of thorough systematic analysis and thought. Most decision makers, if they wish, have access to adequate expertise that can successfully use systems analysis and other logical techniques to analyze the most complex problems. There is no reason why a model cannot be developed so that the current decisions can be linked to the long-range objectives. What is necessary is a change of style and a reordering or restructuring of priorities. We need to think a little more of the future and a little less of the present.

11-3 SYSTEMS ANALYSIS AND DECISION-MAKING

In the context of the present discussion, we shall define management as the process of converting information into action, as shown in Fig. 11-1. Management success depends not only on the quality and extent of the information available but also on what information is selected for use and ultimately channeled into the decision-making process.

The complexity and bewildering variety of questions and problems faced by a present-day resources manager make him singularly hard pressed to develop rational and efficient policies and strategies within rather limited time and budgetary constraints. The intensity and diversity of demands on our limited water resources have increased to such an extent within a rather limited period of time that the management policies must be increasingly finely tuned to resource availabilities in terms of space, time, and cost. The recognition and

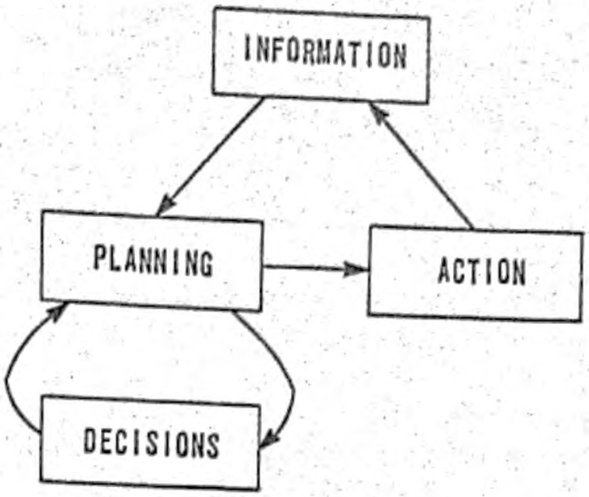

FIGURE 11-1
Flow chart of the management process, illustrating the basic components and sequence of events.

acceptance of the concept of multipurpose water planning, increasing societal awareness of environmental conservation and quality of life, emergence of articulate and powerful special-interest groups, and rapidly changing public perceptions of and attitudes toward the fundamental principles on which water management is based need flexibility and dexterity that is becoming increasingly difficult for decision makers and administrators to maintain. The problem is further compounded by the fact that the appropriate information required to make a decision often seems to be scarce and is invariably inadequate. Even if the required information is available, it is often not channeled into the decision-making process because it is either in a diffused or inappropriate form or could not be obtained and analyzed within the time frame by which decisions have to be made. In fact, one can argue that the unkown is like the universe—expanding constantly.

Thus, even though decision-making in the area of water-resources planning and management has become exceedingly complex at present, and will become more so in the future, it is becoming increasingly apparent that the average decision maker has been supplied with few, if any, new tools and concepts in the past several decades. The advent of electronic computers has provided some relief, but the computer cannot by itself solve any problem. The computer, however, can be used to analyze complex water-management problems by building models. Thus, it is essential that the right information be fed into a computer so that the analysis is logical and reasonably comprehensive for the policy under consideration. This will ensure that decision makers have better understanding and insight into the problems so as to significantly improve their performances.

Recent developments in the arena of systems analysis have made it possible to provide decision makers with a selected range of viable alternatives within which decisions may be made. Thus, systems analysis provides relevant facts and alternatives; the decision maker chooses the strategy. The problem, however, is that, in any comprehensive planning of water and other related resources, an infinite number of alternatives present themselves. Admittedly, one can explore more alternatives by mathematical modeling with the aid of current high-speed digital computers than would be otherwise possible, but it should be realized that even utilizing the most advanced techniques and the latest computers, one cannot examine *all* the alternatives. This is a point worth stressing, and an example will make it clear: If it is assumed that there are 50 major design parameters in a moderately sized river basin study, and if each of these parameters is assigned three values—say, the most expected, 15 percent higher, and 15 percent lower—one would have to analyze a total of 3^{50} designs, or approximately 6 million billion billion designs. Clearly such an analysis is not only impossible but also impractical. One has to be selective, and hence modeling necessitates sampling. Unfortunately, our present state of knowledge of sampling in 50 or more dimensions leaves much to be desired. Thus, the quality of decision-making within a modeling context will greatly depend on the analyst's experience and judgment in the sense that the viable alternatives presented to a decision maker, within which the final decision is to be made, is constrained by the analyst's abilities and limitations. Models cannot replace experience, but they can augment it.

If one accepts the fact that modeling adds one more dimension to the decision-making process and has the potential to improve it significantly, one can legitimately ask why it lacks credibility with the policy makers to such an extent that it is rarely used to develop or select ultimate policies. Modeling is used quite extensively in an operational sense but rarely within a decision-making framework. To the best of our knowledge, nowhere in North America or Western Europe does systems analysis and extensive mathematical modeling enter directly into policy-making. There is no built-in interactive capability between decision makers and systems-type tools and techniques. Modeling is carried out by technical experts and at best is used as an input to the technical recommendations requested by decision makers. Nowhere do the decision makers get their hands on the model itself.

One question that may be asked at this point is, if models lack credibility in general, why has the Club of Rome's study on "The Limits to Growth"[5] enjoyed such popularity and credibility? Perhaps an analysis of this question would provide some insight into the reluctance of the decision makers and, at times, of the public to accept the results of formal methods of complex analyses. Clearly, "The Limits to Growth," a highly condensed but well-written report on a computerized global model, provided a bandwagon for parties who were already convinced that the world is headed straight for disaster. Whatever the merits or demerits of the contention, the report was the first comprehensive attempt to analyze the global resource management problems and the future of mankind through a systematic framework. The interesting point is that the results of this computer analysis were generally accepted by the public, but it is not yet clear that the book has influenced decision makers to a significant extent. This particular incident is a simple but effective illustration to indicate that mathematics and abstract model formulation do not necessarily put people off.

11-4 THE CREDIBILITY PROBLEM

During the last decade or so, water-resources planners and managers have been deluged with an ever-increasing number of publications of the modeling of water-resources systems, and it is highly unlikely that there would be any abatement of this flood in the foreseeable future. Nearly all the models developed remain academic exercises and are seldom used. While the importance of the development of such models as a training exercise cannot be denied, far too high a percentage of models is being developed that is not being used or is of dubious practical value, often for some very good reasons. Considering the potential of systems analysis to improve the decision-making process, and the resources and efforts that go into the development of these models, it is important to analyze why models do not have credibility with the decision makers.

There are many reasons for the "credibility gap." The first and foremost one is probably of communication. The proponents of mathematical modeling and computer technology generally have done a very poor job of translating outputs into terms that are readily understandable to those not so intimately involved in the art. Aside from the inescapable fact that the systems analysts' fundamental language is mathematical and, therefore, not easily comprehensible to all, their oral and written communication is replete with jargon that serves only to "turn off" nonmodelers. In addition, the results of modeling exercises are generally reported in several bulky volumes that are full of differential equations and other complex mathematical algorithms. Very few people, except perhaps for the handful of systems analysts working in that area, have time to read the massive reports, and even if they had time, still fewer could understand it. Seldom are the results of modeling efforts presented in simple, straightforward, meaningful ways—not at all condescending, but nevertheless understandable to those for whom the results are intended. Admittedly, we cannot escape the fact that mathematics and the computer are essential ingredients of modeling, but in this case it is not the *means* to the end that count; *it is the end itself*. The results should be shown to other than fellow modelers in forms that all can understand, appreciate, and perhaps act upon.

It is becoming increasingly critical for modelers to take every possible opportunity to draw the users, including decision makers, into their circle of discussion. Modelers tend to communicate with themselves and often tend to form self-sufficient cells, perhaps because paradoxically it is easier not to reduce their language to nonmathematical terms.[6] One is reminded of Pooh Bah in *The Mikado*, who when asked to explain a piece of mendacity for which he was about to be tried, and when asked why he told the particular lie, replied: "Well, it was merely corroborative detail intended to add verisimilitude to an otherwise bald and unconvincing narrative."

We need better communication and understanding between decision makers and modelers so that the problems of the policy makers are brought more to the fore and the model is relegated to its proper status as an aid to the decision-making process. The effort to effect this communication should not be one-sided. Those who could or should use the results of modeling processes should make an equivalent determined effort to acquaint themselves with the new tool and what it can do for them.

Another major reason for the development of the credibility gap is the lack of user involvement in the development process. McKinsey & Company[7] carried out a study on the relative successes of 36 major corporations in using computers and concluded that user involvement is widely neglected, and the neglect invariably proves to be costly. The continuous user involvement ensures that the modeler has the full knowledge of the perception of the situation being modeled from the viewpoint of the users. Such interactions often prove to be mutually beneficial and educational. The model thus developed will tend to be more relevant for the purpose for which it was devised, and the user will have more trust in its validity and capabilities, since he had a hand in developing it. What generally happens is that the ultimate user has very little involvement with the development phase and consequently has to accept the final product on faith. Thus, not surprisingly, decision makers do not rely on the models for evaluating alternatives.

There is also need to dispel some myths about modeling; there are some mistaken impressions that have grown over the years through our failure to effect good communication. Among these is that modeling is mainly an intellectual exercise and that no practical examples can be shown where it has served the decision-making process. Even though there is some truth in this statement, it is not exactly correct. We have examples to prove the contrary and can prove the point, if given the opportunity.[8,9] Here again, the fault may lie more with the modeler for not presenting his results so that both their origin and their merits are clearly evident.

Another myth is that the approach is too costly and time consuming. Model developments take man-years and time, and computers are expensive to run. But then physical models have been used for years in many areas. Mathematical models are not any more expensive and are easy to interpret. Thus, this myth is largely nonsense, but one has to admit that systems analysts have not done a good job of convincing those who have to pay the bills that all the promised goods can be delivered on time and at reasonable budgets.

There are other reasons why the potential of models is not used as an aid to making decisions. Many major events are too complex for good mathematical modeling to have any predictive utility. Since the underlying hypotheses and assumptions and their predictions are untestable, the situation warrants theoretical excursions into the future. There is nothing basically wrong with such a situation, except that sometimes the analysts get carried away with the mathematical sophistications and then carry out careful simulation of the seventeenth-order situations when the zeroth-order situations are completely controlled by the noise and thus improperly understood. Frosch[10] provides some interesting examples of such pitfalls.

Among other reasons for the existing sad state of affairs are the following. Proponents of modeling have often been unrealistic about the costs of models developed or the time within which a product can be delivered. Computer programs take notoriously longer than planned, and data are often not accessible in the form wanted. Data requirements for some have been extensive and often unrealistic. This makes the initial cost and development-time estimates somewhat unrealistic and can seriously affect the sponsor's time schedule and reputation. In other cases models have been incapable of meeting the objectives for which they were contracted. Some did not represent the realities adequately, and consequently their use for decision-making would have been unrealistic. Many models have tended to be somewhat inflexible, and some are developed for one objective but used for another. Finally, it is not exactly unusual to find that it is a specific procedure that is being offered as a general solution to all problems rather than a direct attempt to start with a decision maker's perceived problem and then attempt to solve it. In general, the solution-in-search-of-problems approach has proved to be a failure.

11-5 BASIC RULES OF MODELING

There are no hard and fast rules on model developments or their use, but the following are offered as an initial guideline. It should be realized that, like other areas of research and development, there are always exceptions to the rules.

1 Start with a simple model and keep it simple. This is probably the most important rule of model building. In most cases of mathematical modeling, no attempt is made to include *all* the parameters and variables, since this would make the model unnecessarily large and unwieldy. The simplicity or complexity of any model should be dependent on the types of information desired from it and its intended end use. However, the limitations of the assumptions made to simplify a real-world situation so that it can be modeled and maneuvered relatively easily should be clearly spelled out and understood. In other words, individual models are operative over a specified range, and the user will do well to remember this shortcoming.

It is not surprising to find that managers and decision makers prefer simple models that they can understand—even though these models may have been based on a qualitative structure, broad assumptions, and limited data—to complex models whose assumptions may have been partially hidden and whose parameter interrelationships may be the result of obscure mathematical manipulations.[11]

2 In general it is worthwhile not to build generalized all-purpose models. These models are expensive to develop, difficult to control because they are unwieldy, and have huge data requirements. The sensitivities of results from such models at the micro level are inadequate for most purposes. They are difficult to understand, except perhaps by specialists, and therefore their acceptability to the decision makers is dangerously suspect.

3 There should be some initial commitment from the decision makers to use a model, and this support should come from the upper echelon of management. There are three basic considerations, before such commitments can be obtained: technical (is it possible?), economical (is it worthwhile?), and organizational (will it be accepted and used?).

4 If the success of a model is judged by its use, the user must play an important part in its development. The user involvement should start right from the fundamental problems of the determination of the objectives and continue throughout the process. The systems analysts should give special attention to the user's perception of the problem. Such an involvement will not only ensure that the user is familiar with the broad working principles of the model (thus requiring less education and training later) but also will substantially increase the probability of the model's acceptability, since the user had a hand in its development. This involvement process has to be planned carefully so that it does not consume too much of the user's time.

5 Modeling and the data-collection process should proceed in parallel. Modeling often gives a better insight to the type of data that should be collected. The mere existence of data is not enough; its accessibility, accuracy, and usability are important criteria. Raw data often require a great deal of massaging before it can be converted to a form where it can be used as input to a model.

6 The chances of a model being used are greatly enhanced if good documentations are available. This also ensures, that if the chief programmer leaves the organization, the model's use and further development are not unduly handicapped.

7 Very few models developed are one-shot affairs. They have to be continually updated as more information and data become available, as understanding of the process being modeled improves, or as the user becomes more sophisticated in their use. Without such improvements, models tend to become out of date, with the resulting loss of their usefulness and credibility.

8 The model should be so structured that current decisons can be linked to the long-term plans. It should be able to provide answers to questions such as what decisions should be made at present to realize the long-term plans, or how do the current decisions affect and how are they affected by future plans.

9 Modeling and managing are in a sense different types of arts: they require different types of knowledge and skill and tend to attract different types of people.[12,13] Thus, the modeler should know not only the environment for which the model is intended but should also have close working relations with the decision makers who will eventually use the model. Ideally the modeler should be an inside man, to facilitate better communication and understanding between the developers and users.

10 Some degree of user education is essential if a model is to gain acceptance. Since most of the senior management in existing water agencies were trained before the systems analysis era, they do not fully comprehend the strengths and weaknesses of such analyses, and, consequently often have little faith in the results. One approach is to lead the potential user through a sequence of models of increasing scope and complexity.

11-6 SOME FACTORS TO CONSIDER

Let us consider some of the major factors and developments that have substantial bearing on the possible use of mathematical modeling in water-resources decision-making.

11-6.1 Positive Factors

1 Developments in computer technology have been so rapid in recent years that hardware capability is seldom a limiting factor in solving even the most complex problems that may be encountered in water-resources management.

2 Commensurate advances have also taken place in our mathematical knowhow. As computer technology has advanced, it has given a great impetus to mathematicians to broaden their horizons by developing new methods and refining old techniques. Developments in one area have spurred developments in another, and this has turned out to be a constructive circle.

3 These advances have reduced the cost of solving problems. Costs of solving specific problems have declined by as much as 50 percent during the past 5 years, and hence, cost per se is less of a limitation today. In most practical studies in the areas of water-quality management or water-resources allocation, computer costs are in the range of 5 to 7 percent of the total study costs.

4 Expertise in mathematical modeling is no longer confined to universities: it is now available in many public organizations and private institutions. Young engineers, economists, and scientists, as well as graduates in business management and public administration, now entering the labor market are familiar with computers and modeling. They may need more training to handle real-life problems, but the basic technical expertise is already there.

5 Water-resources planning and management problems can be and have been solved by mathematical modeling techniques. Often it is the only practical and rational means to simulate future scenarios or to evaluate the consequences of alternative policy decisions.

11-6.2 Negative Factors

In spite ot the positive factors discussed above, all has not been sweetness and light with this relatively new technique. There are several negative factors to consider as well.

1 Mathematics is a language by itself, and it is not easily translated for those who are not "native" to it. Unfortunately, very little, if any, attention has been given to the means by which such a translation process can be achieved. There has been almost negligible investment in transforming model results into a commoner and more understandable media of communication. In contrast, hundreds of millions of dollars have been spent on model developments.

2 Data requirements for modeling activities often *appear* to be formidable, and at certain times there is a tendency to simplify data-collection programs without regard to the real need. In actual practice, requirements for *meaningful* information may be less with the modeling approach. In fact, with judicious efforts, models can be used to *reduce* wastes in collection, storage, and management of largely useless data.

3 There is not a clear distinction between the role of model as an instrument of research, a teaching tool, or an aid to decision-making. These roles are distinct, and there exists a need to correct the popular notion that models are only the product of academia and are as such ivory-tower exercises with very little validity in the real world of decision-making. There is nothing basically wrong with a systems analyst living in an ivory tower, provided it is not his only place of residence.

4 At certain times the user is given the erroneous impression that the model developed is his sole guide to decision-making rather than an additional, albeit important, source of insight to the problems.

5 Models sometimes become a substitute for hard thinking. Computer printouts often provide an unreal aura of accuracy, and the results thus may be accepted without any challenge. Models are only as good as the assumptions and the data on which they are based. The "garbage in, garbage out" concept is certainly very valid for modeling. From a decision-making viewpoint, it is more desirable to have a person who voices healthy skepticism about the results than a person who is gullible.

6 There seems to be some resemblance between models and motherhood—people tend to consider both desirable. Model developers often forget to ask the most important and relevant questions—For what? For whom?—until the model is almost completed.

7 Practical and successful cases of model use have not been well presented, documented, or publicized. In contrast, the notorious failures are well known and have received considerable publicity—to the general detriment of modeling. Many of these failures are largely due to the aerospace and defense-oriented industries that moved into the area of water-resources management due to cutbacks in their own industries. They championed modeling as the all-purpose solution and, not surprisingly, could not deliver the goods promised due to their failure to comprehend the social-economic-ecological complexities and uncertainties that are inherent in all water-management problems.

11-7 POSSIBLE REMEDIES

The present situation with regard to the use of mathematical modeling for decision-making has been discussed in the previous sections. It clearly indicates that there is no solid reason why the modeling approach should not be widely used in water-resources management, and yet, as systems analysts and modelers, we have done a miserable job of making our point with those who would benefit most by its use. If systems analysis is to take its proper place in decision-making, there must be a concerted attempt to improve the credibility of the technique with the users. We must show that this mode of analysis not only has tremendous potential for problem analysis but that it can actually be used today to make decisions rationally and effectively. Such an attempt would not require a revolution or a tremendous amount of resources, but it would need development of a new mentality among the proponents of the technique—a John Roebling type of mentality.

John Roebling had a dream—a great dream—but its effective culmination depended on his ability to spin wire. He never gave up. He designed and built the machines to spin wire and, through his son, successfully carried through the construction of the Brooklyn Bridge. He died figuratively looking out the window of his home in Brooklyn while his son was in the process of completing the construction of the bridge. The problem with modeling is that we have very few systems analysts who have the mentality and characteristics of a John Roebling, who are willing to get their hands and feet dirty so that the task is completed satisfactorily and usefully. As a result, there has been a proliferation of unvalidated, untested, and useless models, many of which can be classified somewhere between dilettantism and academic exercises.

The basic problem that has created this unfortunate state of affairs is the lack of proper communication between those who build the models and those who use them. Therefore, high priority should be given to immediate means of improving communication. There are at least four attractive ways to improve communication and the image of modeling in the eyes (and minds) of decision makers.

1 Define concisely the decision maker's problem and his information requirements. Modelers should know what information is required by water-resources managers, policy makers, and certain technologists at each hierarchical level of the decision-making process. The amount required and the form of useful information varies with each level, and we should devise the means to provide only what is required and can be successfully assimilated within the time frame available for making decisions.

It is suggested that we should initiate programs to define this scaling of information with the level of decision-making, starting with the highest level and working downward. Such a program would require the cooperation and the personal attention of key administrators and the active involvement of a few knowledgeable proponents of the art of modeling who can get to the heart of the communication problem. The job is not big, but it is certainly the most important one.

Equally necessary for the modelers is to keep a close watch on the changes in perception and understanding of the decision makers of the problems or set of problems being modeled. Model development takes time, and very often it takes more than a year from the time the decision to build a model is made to the time of its completion. Since the real world is seldom static, the world of the decision maker changes somewhat during the model-development phase. His perception of the problem being modeled, its priority in terms of other problems that must be solved, or other events that are beyond his control could significantly affect the direction of the modeling process. Thus, it is not enough to decide on the objective of the modeling at the beginning of the process with the user: the modeler must know the change in thinking of the user or the chain of events that could affect the direction of model development. Models developed in a vacuum would seldom be used.

2 Conduct "hands-on" workshops using simple but practical examples of how decision capability can be enhanced by considering a host of different alternatives within the modeling process. The management-gaming technique, with man-machine interaction to illustrate the power and fallibilities of modeling, is a good way to initiate the noninitiated. By carefully selecting a problem that has relevance to the user and displaying the results immediately on CRT displays, the subjective prowess of the decision maker–player can be tested. Many simple models of water-resources situations have been designed, or can be easily designed, for these types of workshops where the primary aim is education. This type of approach has already been tried in a few organizations (including the author's own), and the results so far have been quite promising and stimulating.

3 Illustrate some real cases in straightforward and understandable terms. Three or four case studies can be selected and addressed to problems that are of relevance to the organization. These can be graphically illustrated by slides, filmstrips, or movies to highlight the role of models in decision-making. The examples must be real, but need not be specifically identified, in the interest of conveying the general rather than the specific approach. Some examples in the area of water-resources management could be:

a Screening alternative strategies for pollution control in a river system or an estuary

b Determining the impact of effluent charges

c Siting of a thermal or nuclear power plant on a large lake or river
d Determining environmental and ecological effects due to the construction of a large dam
e Assessing ecological response to nutrient removal
f Evaluating alternative strategies to contain an oil spill

4 Develop improved methods for displaying model results or results of model applications. The capability currently exists to produce graphic displays directly from the computer. An animated film sequence of a simulation of a water-management problem would go far toward bridging the communication gap. To the best of the author's knowledge no such demonstration of results is yet available, or has yet been attempted.

Consider the possibility of showing in a few minutes on the screen the intrusion of salinity into an estuary, the blooming of algae in a lake, the effect of a pipeline or a canal on the migration patterns of wildlife, the routing of a flood through a river system, or the spreading of an oil spill from a tanker in the high sea. Results could be made available on video tapes produced from computer output or on film prepared from CRT displays or graphic plotters. Such media for communication could be employed directly in the process of screening alternatives by technical personnel or in presenting alternatives (after preliminary screening) to nontechnical decision makers.

It is evident that the development of economical means to "animate" model results is a must. Much of the knowledge and technology is already available; it needs only to be assembled and directed to the task. Costs to produce a "pilot" to demonstrate the approach would be only a fraction of the investment made to develop models. One could even visualize that the production of a "computer graphic package" could be a standard part of model development in the future, like calibration or sensitivity analysis. At modest cost, we could thereby achieve much improved understanding among all who are still in doubt about the practical future of mathematical modeling.

11-8 CONCLUSION

The world is becoming increasingly more complex, and the major problems of resources management are not only becoming even more so, but are also increasingly more interwoven. Therefore, it is essential to utilize all the techniques that are available so that the appropriate strategies and viable alternatives can be determined and the consequences of possible policy decisions can be evaluated. There is no doubt that systems analysis can significantly aid the policy makers to better carry out their functions, but whether systems analysis, in spite of its great promise, will actually be used for these purposes is another question.

Few models fail because technical expertise or state-of-the-art of computer technology is inadequate or because they are improperly implemented from a technical viewpoint; they fail more because too much concentration is placed on the technical issues and not enough on the managerial ones. There is no doubt that the present state-of-the-art of mathematical modeling has advanced sufficiently to be of decisive use in policy-planning and decision-making.[14,15] Admittedly, some of our current models in this field are rather crude and somewhat dependent on the experience and judgment of the analysts, but in the final analysis, *the issue is very definitely on the side of having a model, even a crude one, rather than having no model at all.*

REFERENCES

1. BISWAS, A. K., "History of Hydrology," North-Holland Publishing Company, Amsterdam, 1972.
2. DRAKE, J. W., "The Administration of Transportation Modelling Projects," D. C. Heath and Company, Boston, 1973.
3. BISWAS, A. K., Mathematical Models and Their Use in Water Resources Decision-Making, vol. 5, pp. 241–248, Proceedings of the 14th Congress, International Association for Hydraulic Research, Paris, France, 1971.
4. CHURCHMAN, C. W., "Prediction and Optimal Decision," Prentice-Hall, Inc., Englewood Cliffs, N.J., 1961.
5. MEADOWS, D. H., et al., "The Limits to Growth," Universe Books, New York, 1972.
6. BISWAS, A. K., et al., Water Quality Modelling: State-of-the-Art, in A. K. Biswas (ed.), "Modelling of Water Resources Systems," vol. 2, pp. 427–442, Harvest House Ltd., Montreal, 1974.
7. MCKINSEY & CO., "Unlocking the Computer's Potential," McKinsey & Co., Inc., New York, 1968.
8. BISWAS, A. K., Mathematics and Computers, in A. Utton and D. H. Henning (eds.), "Interdisciplinary Environmental Approaches," pp. 154–167, Educational Media Press, Costa Mesa, Calif., 1974.
9. BISWAS, A. K., Systems Approach to Water Management, *Bull. Int. Comm. Irrig. Drain., New Delhi*, pp. 12–19, January 1975.
10. FROSCH, R. A., The Sin of Simulation, in D. D. Sworder (ed.), "Systems and Simulation in the Service of Society," pp. 7–10, Simulation Councils, Inc., La Jolla, Calif., 1971.
11. LITTLE, J. D. C., Models and Managers: The Concept of a Decision Calculus, *Manage. Sci.*, vol. 16, no. 8, p. B–466, April 1970.
12. GRAYSON, C. J., Management Science and Business Practice, *Harvard Bus. Rev.*, pp. 41–48, July–August 1973.
13. HAMMOND, J., The Role of the Manager and Management Scientist in Successful Implementation, *Sloan Manage. Rev.*, Winter, 1974.
14. BISWAS, A. K., Introduction, in A. K. Biswas (ed.), "Modelling of Water Resources Systems," vol. 1, p. VI, Harvest House Ltd., Montreal, 1974.
15. BISWAS, A. K., Application of Mathematical Models to Water Resources Planning, in J. A. Taylor (ed.), "Climatic Resources and Economic Activity," pp. 159–172, David & Charles, Newton Abbot, U. K., 1974.

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