Environmental Decision Making: A Multidisciplinary Perspective

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Resource Allocation

Richard M. Vogel

1 INTRODUCTION

Should a dam that saves human lives and reduces flood-damage costs by millions of dollars each year be built if it eliminates a fish species? Should the EPA introduce legislation to reduce stack emissions from industrial plants if the legislation will cause those same plants to lay off workers due to increased costs? Should a city in an arid environment limit growth when growth means pumping so much groundwater that the ground surface begins to depress? These are typical dilemmas that stem from our need to use environmental resources. They are social dilemmas (see discussion in Chapter 2) but—at the same time—they are resource-allocation problems, problems whose solutions require the balancing of competing and interacting resources.

Presumably, at some additional cost, the flood-control dam that puts at risk a fish species could provide an appropriate fish ladder (see the Fish Ladder Case in Chapter 4). The problem, then, reduces to balancing the benefits of flood control against the costs of protecting (or not protecting) a fish species. Similarly, when deriving an environmental policy to reduce stack emissions from industrial plants, the EPA needs to balance the benefits of improved air quality against the costs of achieving improved emissions. Finally, the benefits of increased growth of the city in the arid environment due to the pumping of groundwater should be balanced against the costs associated with measures to reduce depression of the land surface caused by groundwater pumping.

Environmental decision problems are usually fraught with such political, economic, social, and technological complexities that they often appear to defy rational analysis. The environment is a complex system comprised of a set of resources: air, water, land, energy, plants, and animals. Usually these resources are not independent; rather, as in the need of animals for land and water, they interact. In many cases, some or all of these resources are in scarce supply; they may even be in competition with one another. As a result, most environmental decisions involve calculating the efficient allocation of these resources. Human resources such as labor, equipment, time, and money are often required for the sustainable development or preservation of the environmental resources; these, too, are often in scarce supply and subject to competing demands.

This chapter focuses on the presentation of a rational and systematic framework for structuring complex environmental decision problems. This framework, termed "systems analysis," was developed during World War II. The aim was to muster all available human and natural resources for the purpose of winning the war. Since World War II, the field of systems analysis has grown quickly, particularly after the advent of digital computers led to thousands of applications to complex business, political, economic, environmental, and other problems. Numerous texts now exist that formalize the systems approach to environmental decision problems (De Neufville & Stafford, 1974; Pantell, 1976; Loucks, Stedinger, & Haith, 1981; Haith, 1982; Ossenbruggen, 1984; De Neufville, 1990). Those texts include applications of systems analysis to resource-allocation problems having to do with water, land, air, and energy.

As an introduction to the use of the systems approach in structuring a complex environmental decision problem, consider the simplified but realistic example shown in Figure 7–1. The industrial city depicted is situated near a reservoir. The

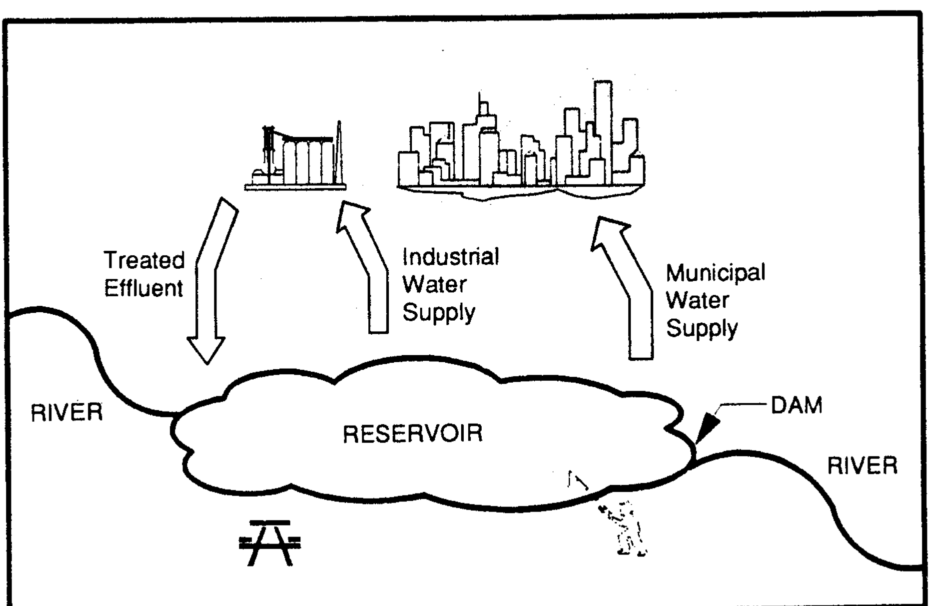

FIGURE 7–1. Description of water resource-allocation problem.

city presently draws water from the reservoir for both its municipal drinking-water supply and its industrial-process–water supply. The water is then treated and returned to the reservoir as treated effluent. The reservoir serves as the only potential source of water, limiting the city's growth. Simultaneously, the reservoir serves as a recreational area, is host to an abundant fish and wildlife population, and protects the town against catastrophic flooding.

To what extent should future municipal and industrial growth of this city be limited by the environmental constraints posed by the reservoir and river? Which is more important—providing the city with an adequate supply of water for both municipal and industrial uses, preserving the fish and wildlife populations, maintaining recreational facilities, or controlling floods? Both the city and reservoir are artificial, yet both must act in harmony with the natural environment to assure the maintenance of fish and wildlife populations. Drawing too much water from the reservoir could result in water levels that are too low for swimming and boating, and too low to maintain fish and wildlife. The city also runs the risk of running out of drinking water and industrial-process water if the reservoir is drawn down too low. Water purveyors are reluctant to draw water from the bottom of a reservoir due to its typically poor quality. Yet if the reservoir is expected to prevent floods, then the water level must be kept relatively low, particularly during the flood season, to accommodate the storage of flood waters. In addition, adequate water must be released from the reservoir to satisfy the demand for water in downstream communities.

Further potential conflicts of interest exist between the use of the reservoir for boating, swimming, supplying water, and maintaining fish and wildlife populations. Ideally, the treated effluent that is returned to the reservoir after being used for industrial and municipal water-supply purposes must be of adequate quality so as not to prevent recreational uses of the reservoir, damage the fish and wildlife populations, or impact public health. This can be achieved only at a cost. The interactions and potential conflicts among the various uses and users of the single resource—water—are so complex that there exists a vast literature devoted solely to such water resource-allocation problems [see Burges (1979), Loucks, Stedinger, & Haith (1981), Yeh (1985), and Rogers & Fiering (1986) for a review of the literature].

Moreover, a complete systems analysis would include the trade-offs among all environmental resources; we focus on just water to simplify the discussion of the method. The potential conflicts that arise in the allocation of other environmental resources contain features that are very similar to those in the example described here. In all such problems, the environment may be viewed as a system of resources that can be managed to improve overall social welfare. Resource-allocation problems occur worldwide, and the associated conflicts affect both developed and developing countries. Reaching consensus on the solution of such problems can be particularly challenging when the resources are in scarce supply or are in competition with one another. In addition, resource-allocation problems tend to require the consideration of multiple, incommensurate, and often conflicting planning objectives.

Resource-allocation problems viewed in a systems-analysis framework generally contain two important features:

- The formulation of appropriate and relevant system objectives is a necessary prerequisite to the efficient management/allocation/exploitation of environmental resources (air, land, water, and energy).
- All pertinent environmental, economic, legal, political, ethical, technological, and other constraints must be evaluated together, as a system, in order to meet the desired system objectives.

For the example described in Figure 7–1, these two features may be summarized as follows:

- It is impossible to evaluate the trade-offs inherent in the allocation of water for the purposes of municipal drinking-water supply, industrial-water supply, flood control, boating, swimming, and the maintenance of fish and wildlife populations, without defining an objective or set of relevant objectives for the persons or sectors of society affected by the resulting environmental decisions.
- Once a suitable objective or set of objectives is formulated, all relevant conflicts and/or constraints regarding the allocation of the resource must be evaluated together, as a system, to meet the desired objectives.

The systems-analysis approach requires quantifying the system objectives in the form of an expression termed the "objective function." The systems approach then requires the optimization of that objective function in a fashion consistent with the constraints resulting from the finite availability of the various resources. An objective function is a measure of the effectiveness of a particular solution to the decision problem. In our example, one appropriate objective function measures the net social welfare of the neighboring region as well as of the town because the recreational and environmental benefits of the sound management of the reservoir extend beyond the boundaries of the town.

Net social welfare is difficult, at best, to estimate. Surrogate measures such as minimizing system cost to satisfy required demands, achieving equity among all system users, and enhancing overall environmental quality could be employed. The first of these measures is easily quantified, whereas the latter two are much more difficult. Many measures and objectives that first appear difficult to quantify are, in fact, amenable to quantification. At first, one may wonder how to quantify the utility or value associated with a scenic view. As shown in Chapter 4, Section 4.2, multiattribute utility can include dimensions of aesthetics. In addition, methods are available for quantification of some factors such as the land inundated by a lake, lake recreation, scenic vistas, or the loss of a wild and scenic river (James & Lee, 1971). Most system analysts attempt to satisfy what they perceive to be the dominant objective(s) and temper the analysis with subjective inclusion of other measures. Maknoon and Burges (1978) argue that this may not be the best way to proceed, but many environmental decisions have been implemented successfully, and many engineering projects have been constructed and maintained successfully, using such an approach.

In addition to a precise definition of the system objective(s), the constraints imposed upon the allocation of each resource must be quantified. "Feasible" solutions to a resource-allocation problem must satisfy all relevant constraints. For example, we might wish to maximize net social welfare, subject to the following constaints:

1. Town must have an ample quantity of high-quality drinking water.
2. Town must have ample industrial-water supply.
3. Reservoir must remain clean enough to support fish and wildlife populations.
4. Reservoir must remain low enough during flood season to accommodate flood waters.
5. Reservoir must remain high enough to supply ample municipal drinking water and industrial-water supply during periods of drought.
6. Reservoir levels must be stable enough to accommodate recreational functions.
7. Water release from the reservoir must be adequate for use by downstream communities.

Here a feasible solution would be one that satisfies all seven constraints. In most decision problems such as this one, there are an infinite number of feasible solutions. The optimal decision is to choose the feasible solution that best meets the desired objective(s).

Environmental decision problems such as this one usually contain features that are difficult to quantify. Hence, mathematical decision models are, at best, an approximation of actual systems. Nevertheless, systems analysis can lead to an increased understanding of a complex decision problem. When it does, it provides reliable input to the environmental decision-making process.

2 THE SYSTEMS APPROACH TO RESOURCE ALLOCATION

2.1 Optimal Resource Allocation Using Mathematical Programming

The field of systems analysis has come to mean different things to different people. Yet in the fields of engineering, applied mathematics, science, and even business, systems analysis is a well-defined and unified field that is synonymous with operations research or management science. Rogers and Fiering (1986) provide a description of the techniques of systems analysis. Hillier and Lieberman (1990a, 1990b) provide an excellent introduction to a variety of systems-analysis techniques for both stochastic and deterministic systems. The emphasis in this chapter—as was true in Ounjian (1979), Loucks, Stedinger, & Haith (1981), and Haith (1982)—will be on one of the most powerful of all systems-analysis techniques: mathematical programming.

Mathematical programming as a means of solving resource-allocation problems requires a set of precise statements regarding the overall objectives and constraints associated with an environmental decision problem. These statements must be precise enough to allow an analyst to convert each objective and constraint into mathematical terms.

For the moment, consider an abstract resource-allocation decision problem in which two resources x and y exist. Each of these resources is in scarce supply. In addition, there are certain physical, economic, political, legal, and ethical constraints or limitations associated with the separate and joint use of these two resources. Figure 7–2(A) depicts the feasible combinations of resources x and y given the physical, economic, political, legal, and ethical constraints associated

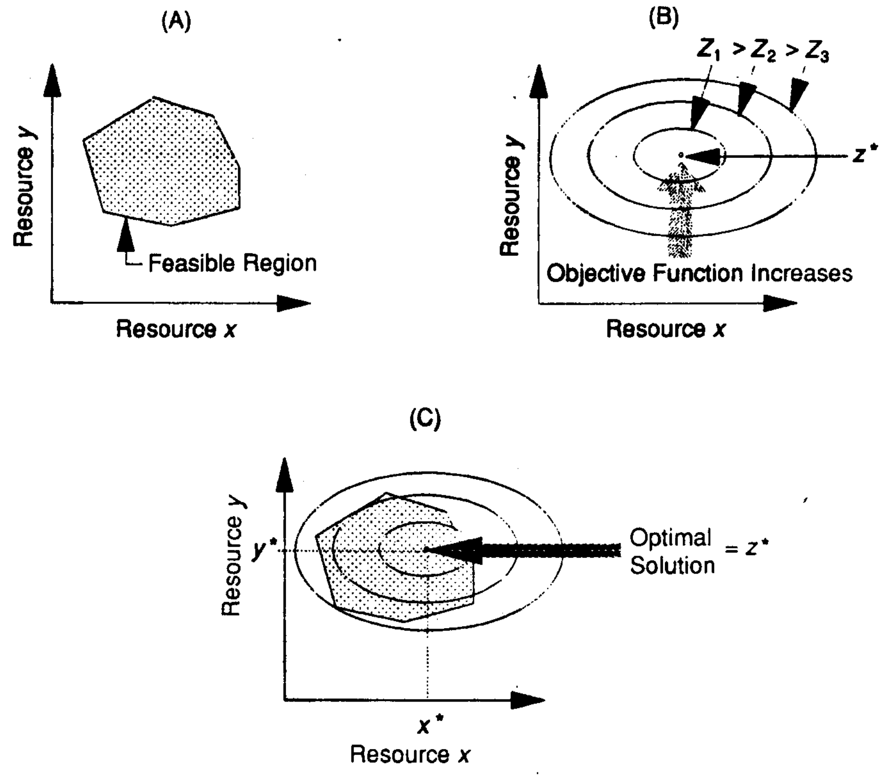

FIGURE 7–2. A resource-allocation decision problem.

with their separate and joint uses. This region, known as the feasible region, corresponds to the shaded region in Figure 7–2(A). Essentially, the feasible region results from the simultaneous solution of the complete system of equations that describe the constraints or limitations associated with the separate and joint use of the resources. The feasible region contains an infinite number of possible combinations of resource x and resource y, all of which are potential solutions to this resource-allocation decision problem because they satisfy all the constraints. The decision problem reduces to determining which of these infinite possible feasible combinations of resource x and resource y is optimal in terms of the stated objective(s).

Suppose we define a set of objectives regarding the allocation of these two resources. Reaching consensus on objectives is often the most challenging task connected with the implementation of a mathematical program or any other systems-analysis method. Computer-aided exercises in negotiation are increasingly being used to help reach consensus regarding the complex economic, legal, political, and institutional issues that surround the allocation of scarce environmental resources, especially in times of crises (Sheer, Baeck, & Wright, 1989). For the moment, assume consensus is reached on the objectives having to do with the allocation of resources x and y. Suppose further that the objective is quantified in terms of a function

$$Z = f(x, y), \tag{7–1}$$

where Z is an agreed upon measure of utility or value of allocating an amount x and y of resources x and y, respectively. Essentially, x and y are decision variables whose optimal values we seek. For example, Z might be the net benefits, in economic terms, associated with the allocation of resource x and resource y. Figure 7–2(B) depicts values of the objective function Z as a function of the amount of resource x and y allocated. Here each ellipse represents a constant value of the objective function, and the objective-function value increases as we head toward the center of those ellipses. Figure 7–2(B) is like a mountain: As we climb to the peak (denoted by Z^*), the value of Z increases. If the objective function describes net benefits, then we seek a maximum; however, if the objective function describes net costs, then we seek a minimum. Figure 7–2(C) combines the feasible region with the objective function contours and shows that the solution Z^* is both feasible *and* optimal. Therefore, the optimal allocation of resources in this instance is to allocate x^* of resource x and y^* of resource y.

Other outcomes are possible. Often the largest (or smallest) value of an objective function is infeasible, in which case an inferior solution becomes optimal. In general, the optimal solution is the feasible solution that maximizes (or minimizes) the objective function. It is also possible, however, that the resource constraints are so conflicting that no feasible solution exists. Such cases may represent conflicts of interest among the participants in the decision-making process. In other instances, a poorly defined problem may lead to an unbounded solution in which it appears that the optimal solution is to allocate an infinite amount of one or more resources. While such situations are mathematically possible, they represent physically unrealizable cases.

When either the constraints on a problem or the objective function is nonlinear, the problem is termed a nonlinear programming problem. Figure 7–2 is a representation of one such programming problem because the objective function is nonlinear (i.e., it is elliptical). In this instance, the feasible region is a convex polygon formed by the intersection of seven lines. Each of those lines represents a unique (linear, in this instance) constraint on resources x and y. In actual resource-allocation problems, there are often hundreds or even thousands of constraints and decision variables, in which case the feasible region becomes an n-dimensional polygon.

When both the objective function and constraints are linear, then the problem reduces to a linear program: Powerful algorithms have been developed to solve either class of problems [see Hillier & Lieberman (1990a) for an introduction]. Such algorithms are now available in the form of computer software for use on both mainframe and personal computers (Schrage, 1989).

2.2 A Linear Programming Example for Resource Allocation

In this section, a simple example of resource allocation is presented using a graphical approach to clarify the systems framework for formulating and solving an environmental resource-allocation problem. When several sources of water—such as groundwater aquifers and surface waters, each with different characteristics—are available, it is often possible to exploit their differences to improve the overall environmental quality of the water delivered to consumers. Use of surface water and groundwater supplies together in some systematic fashion is termed *conjunctive use* (Buras, 1963; Maknoon & Burges, 1978; Coe, 1990). The conjunctive operation of surface-water and groundwater resources can lead to increases in yield and reliability of the overall system. The idea is to manage and coordinate the resources in such a way that the total system-yield exceeds the sum of the yields of the separate components of the system when their operation is not coordinated.

Surface waters are available seasonally, yet often significant uncertainty exists as to when and how much water will be available in a particular year. Surface-water impoundments (storage reservoirs) can be constructed to store and regulate surface waters to reduce that uncertainty. Reservoirs are subject to evaporation and seepage losses in addition to all the potential conflicts of interest discussed in the problem in Section 1. For example, storing water for use during times of drought is in conflict with the need to keep surface-water storage reservoirs empty for flood protection.

Unlike the supply of surface waters, groundwater supply is much less variable over time and is already stored in large aquifers that are not subject to evaporation and seepage losses. Both surface and underground sources of water are subject to contamination from a variety of sources (landfills, dust and dirt accumulation on streets, agricultural wastes, industrial wastes, etc.), which in any given circumstance will cause either the ground- or surface-water reserves to be the cleaner source.

Figure 7–3 depicts a simple two-dimensional conjunctive-use problem in which a city seeks to allocate its groundwater *(G)* and surface water *(S)* supplies in an optimal fashion. Here we define S and G as the volumes of surface-water and groundwater resources to be delivered to the city on an annual basis. As in the example shown in Figure 7–2, each resource is subject to constraints or limitations. The hydrologic characteristics of each supply source dictate that only a finite amount of groundwater and surface water is available, hence $G \leq G_{\max}$ and $S \leq S_{\max}$, where $G_{\max}$ and $S_{\max}$ are the maximum sustainable groundwater and surface-water yields from each source. Estimates of these values would be obtained from detailed hydrologic investigations of the groundwater and surface-water supplies. The maximum sustainable yields correspond to the maximum

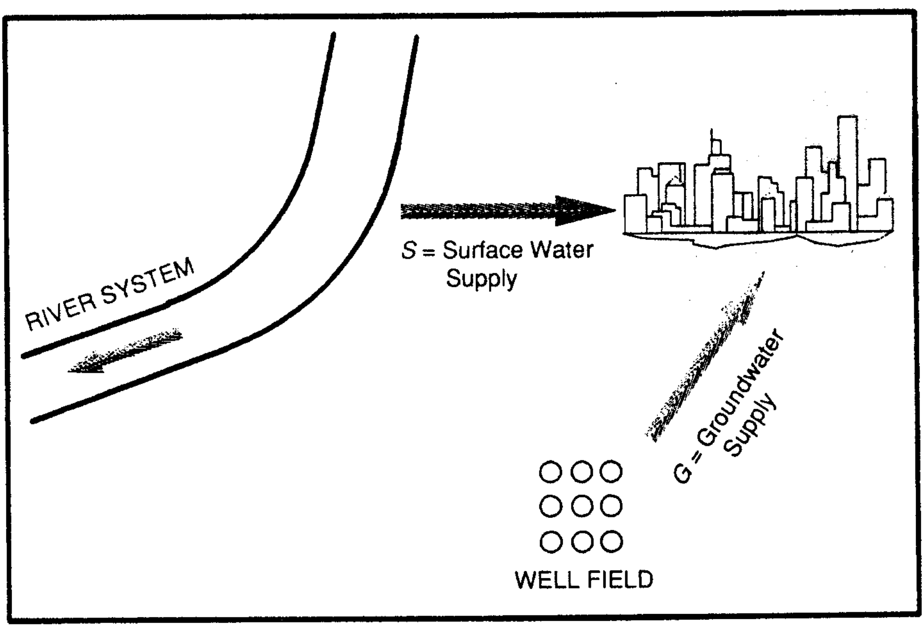

FIGURE 7–3. Conjunctive-use example: problem description.

amount of groundwater and surface water that is available in a given year. Since groundwater reserves and surface-water reserves are physically connected at the stream-aquifer boundary, the determination of maximum sustainable yield poses a complex hydrological problem. In the case of surface water, delivery of an amount S may entail the construction of a reservoir. In the case of groundwater, delivery of an amount G will entail the construction of a well field. In both cases, a distribution system (possibly even a treatment plant) is required to assure adequate quality of the delivered water resource. In fact, the water supply will likely be contaminated by use; hence, a sewer system and associated wastewater treatment facility will be required. Furthermore, the yield of each system is subject to natural and artificially induced variability.

In planning for the growth of the city, it is necessary to provide an adequate conjunctive supply of both surface water and groundwater to meet the demand for water in the coming decades. Typically, water-use projections are obtained by predicting the increase (or decrease) in the demand for water on the basis of projections of population growth, industrial growth, and other demographic, economic, and political factors. For example, water-pricing strategies affect the demand for water [see Chapter 6, and Howe & Linaweaver (1967)] and hence should be included in water-use projections. Similarly, legislation that favors industrial growth can affect future demand for water. In addition, conservation programs that reduce per-capita water use will have an effect on the future demand for water. In short, all pertinent factors that influence future water use can be analyzed together to obtain a single water-use projection for planning purposes. Here we assume that such a comprehensive water-use projection leads to the conclusion that $G + S \geqslant K$, where $G + S$ represents the total conjunctive supply delivered, and K is the projected annual demand for water for the city at some future date.

In most situations, both the quality and the quantity of available groundwater and surface-water supplies will differ. Environmental legislation often dictates the allowable surface-water and groundwater withdrawals from a river basin on the basis of their impact on fish and wildlife populations, land subsidence due to drops in the groundwater level, or total basin yield. In this example, we assume that such considerations lead to the constraint that the groundwater allocation cannot be greater than the surface-water allocation or, mathematically, $G \leq S$. This constraint is mathematically simple—deceptively so. Arriving at such constraints in practice may involve very detailed engineering studies of the environmental consequences of various combinations of conjunctive use.

We have now summarized the environmental, legal, and hydrologic constraints on the allocation of ground and surface waters in this example. The optimal utilization of this natural resource is assumed to be essential for the establishment of a stable economic and social structure for the city in coming decades. The term "optimal" should always raise a number of important questions. Optimal for whom, to what end, and under what conditions? These questions amount to a quest to define objectives for the allocation of these two resources. In this example, we first assume that our objective is to maximize the net benefits corresponding to the allocation of groundwater and surface water. We define an objective function $Z = b_g G + b_s S$, where b_g and b_s denote the net benefits of one unit of groundwater and surface-water supplies, respectively. Then Z denotes the total net benefits that result from the decision to supply the amounts G and S. The total net benefits are defined as the total project benefits minus the total project costs corresponding to the allocation of resources G and S.

The project costs will include the construction costs (for the well field, reservoir, treatment plant, and distribution network associated with the conjunctive-use system) and operating and maintenance costs, all discounted over the life of the project to account for the time value of money [see Loucks, Stedinger, & Haith (1981, Chapter 2)].

The project benefits may include revenues from the sale of water, in addition to intangible and tangible benefits of the additional growth the city can now afford. For example, a portion of the benefits of increased growth can be measured in increased tax revenues that come with such expansions. It is likely that costs will accrue as well. For example, fish populations may suffer from lower instream-flows during the summer months. The coefficients b_g and b_s represent the aggregate net benefits associated with both resources. Note that it is entirely possible for b_g and/or b_s to be negative, denoting net costs from the allocation of these resources.

Most projects exhibit economies of scale, that is, the marginal cost of allocating an extra unit of each resource tends to decrease as the size of the project increases. Projects that exhibit economies of scale in their marginal or average costs do not necessarily also exhibit economies of scale in net project benefits. Nevertheless, when economy-of-scale effects are present, the objective function Z becomes a nonlinear function of the decision variables instead of the linear function assumed here.

This resource-allocation decision problem reduces to the mathematical problem of maximizing Z, where

$$Z = b_g G + b_s S, \tag{7-2}$$

subject to the following constraints:

$$G \le G_{\max}, \tag{7-3}$$

$$S \le S_{\max}, \tag{7-4}$$

$$G + S \ge K, \tag{7-5}$$

$$G - S \le 0. \tag{7-6}$$

In addition, the constraints $G \geq 0$ and $S \geq 0$ are implied. This problem is a linear-programming problem because the objective function Z, and all constraints, are linear functions of the decision variables G and S. Figure 7–4 depicts the constraint Equations (7–3) through (7–6), using arrows to denote graphically the direction of each inequality. The shaded region satisfies all four constraints; hence, any combination of G and S that falls in that region is a feasible solution to the problem. Here feasibility is defined in terms of the issues that were considered in the development of each constraint equation.

Next, we consider which of the infinite number of feasible solutions is optimal with respect to our objective. Equation (7–2) can be rewritten as

$$G = (Z/b_g) - (b_s/b_g)\,S. \tag{7–7}$$

Equation (7–7) is a straight line that intercepts the G axis at $G = Z/b_g$ and has a slope equal to $-b_s/b_g$. A variety of possible optimal solutions exist, depending on the magnitudes of the net benefits associated with one unit each of groundwater and surface water, b_g and b_s.

Below, two of these solutions are considered. Figure 7–5 plots the objective function [Equation (7–7)] by superimposing dashed lines over the feasible region. Figure 7–5 depicts the optimal solution to be $S^* = S_{max}$ and $G^* = K - S_{max}$ when the net unit benefits of surface water are positive ($b_s > 0$) and the

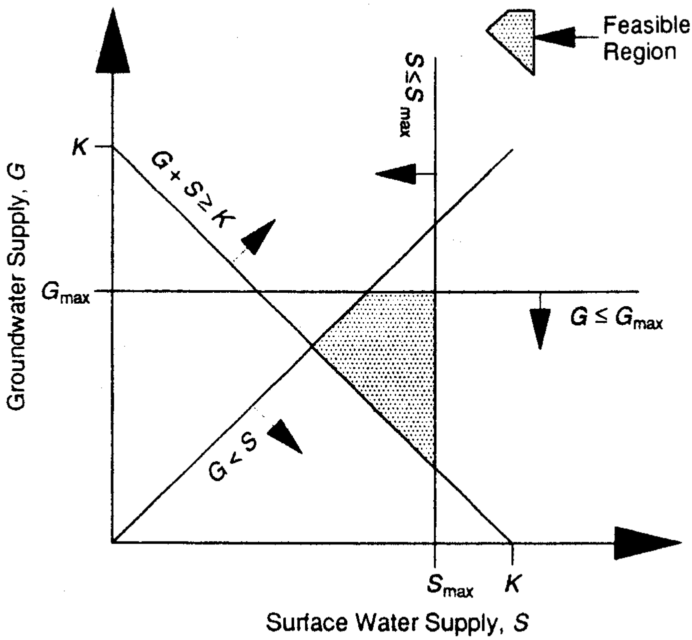

FIGURE 7–4. Conjunctive-use example: feasible region.

net unit benefits of groundwater are negative ($b_g < 0$). This implies that the legal, economic, and environmental costs of construction and operation of the groundwater supply system are greater than their corresponding benefits, whereas the opposite is true for the surface-water supply system. The optimal solution is to provide as much surface water as is feasible—S_{max}—while limiting groundwater to its minimum feasible amount—which turns out to be $K - S_{max}$. In this instance, there is no incentive to increase groundwater supply to the point where the legal and environmental constraint ($G \leq S$) becomes limiting. Hence the only constraints that have an effect on the problem are the demand-projection constraint $G + S \geq K$, and the hydrologic constraint on surface water $S \leq S_{max}$.

Figure 7–6 plots the objective function again by superimposing dashed lines over the feasible region. In this instance, the net unit benefits of surface water are negative ($b_s < 0$) and the net benefits of groundwater are positive ($b_g > 0$). Now the optimal solution depends on the ratio b_s/b_g. As Figure 7–6 shows, the optimal solution is $S^* = K/2$ and $G^* = K/2$ when $|b_s| > b_g$. However, if $|b_s| < b_g$, then the optimal solution is $S^* = G_{max}$ and $G^* = G_{max}$. The solution to any linear programming problem is going to be one of the corners of the space associated with the region of feasible solutions. If the slope of the objective function is less than 45°, then the corner $S^* = K/2$ and $G^* = K/2$ is the optimal solution. If, however, the slope is greater than 45°, then the corner $G^* = G_{max}$ and $S^* = G_{max}$ is the optimal solution.

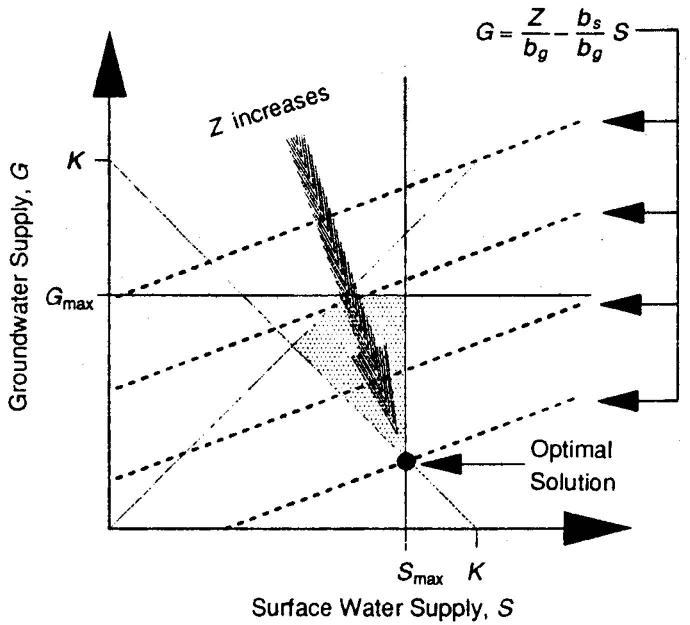

FIGURE 7–5. Conjunctive-use example: optimal solution when $b_g < 0$ and $b_s > 0$.

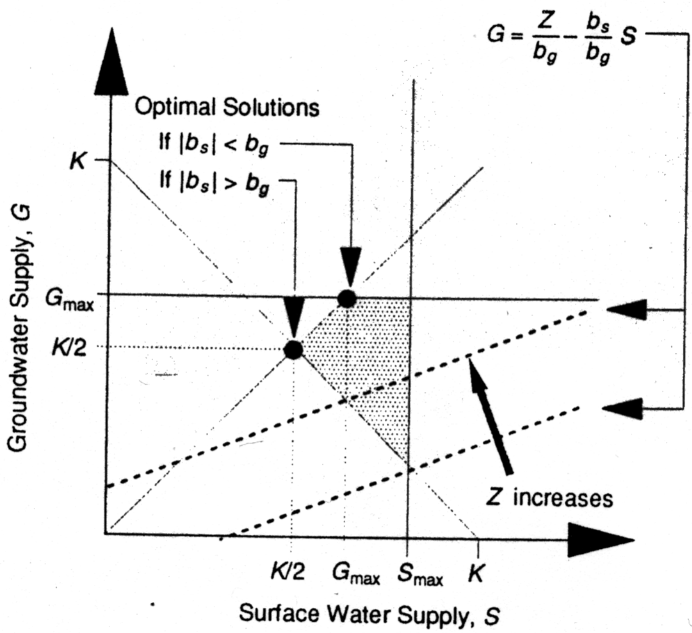

FIGURE 7–6. Conjunctive-use example: optimal solution when $b_g > 0$ and $b_s < 0$.

Realistic cases of resource allocation usually involve so many constraints and such complex objective functions that our graphical approach needs to be replaced by mathematical programming methods. The two-dimensional example that we have been discussing demonstrates the principles of systems-analysis approach for resource allocation. Furthermore, the example demonstrates one of the most promising uses of systems analysis in practice, that is, to identify a range of nearly optimal solutions to a decision problem. An improved understanding of the variety of solutions—not necessarily optimal, yet in the neighborhood of the optimal solution—can provide important insight into the overall decision process.

2.3 Alternate Objectives Produce Alternate Solutions

This conjunctive-use example documents the way the optimal solution depends on both the feasible region (defined by the constraints) and the character of the objective function. Alternate objectives often lead to alternate optimal solutions. Suppose, for example, that our objective was to *minimize* the total cost associated with the conjunctive allocation of surface water and groundwater. Then the optimization problem becomes one of minimizing Z, where

$$Z = c_g G + c_s S, \tag{7–8}$$

subject to the constraints set by Equations (7–3) through (7–6) and where c_g and c_s are the unit cost of supplying groundwater and surface water, respectively. In this instance, the optimal solution is $S^* = S_{\max}$ and $G^* = K - S_{\max}$ if $c_s < c_g$ and $S^* = K/2 = G^*$ if $c_s > c_g$. It would never be economically attractive under this objective to supply more than the required capacity K. Recall that previously, in Figure 7–6, one of the optimal solutions did lead to a total supply $G + S$ in excess of K.

This example is perhaps so oversimplified that the solutions may be obvious without the application of systems analysis. Once again, in actual environmental decision problems, when there are often hundreds of decision variables, hundreds of constraints and multiple objectives, systems-analysis techniques can provide insight into the trade-offs that are often far too complex for any one analyst or even group of decision makers to comprehend.

2.4 Obstacles to the Effective Use of Systems Analysis

In fields like industrial engineering, business, and project management, the application of systems-analysis methods such as mathematical programming is routine and highly effective. For example, most airline companies could not survive without using mathematical programming to allocate their manpower, airplanes, and customers in an optimal fashion. Flight schedules are routinely obtained from mathematical-optimization programs. Most texts in project management contain chapters that describe the standard use of systems analysis to solve resource-allocation problems [see for example, Meredith & Mantel (1989)], where the resources are manpower, money, time, and equipment.

In environmental resource allocation, mathematical-programming approaches are in their relative infancy. Some investigators argue that systems analysis has had little practical value in solving complex water-resource–allocation problems, describing a host of obstacles to the effective use of mathematical programming in allocating water resources (Rogers & Fiering, 1986). Others have argued that the most important recent advance made in the field of water-resource allocation is the development and adoption of systems-analysis techniques to plan, design, and manage complex water-resource systems (Yeh, 1985). As with most engineering approaches, there are gaps between the theory and the application of systems analysis.

Perhaps the most significant obstacle to the successful and effective use of systems analysis is in reaching consensus on the relevant objectives and constraints in a particular decision problem. Usually, there are many participants and factors in an environmental decision problem (e.g., citizens, engineers, politicians, regulatory authorities, the environment, etc.), and reaching consensus on any issue—particularly the objectives—is not simple. (See Chapter 9 for a strong argument against the prospect of achieving a consensus.) Participants tend to have different objectives, which means multiple, incommensurate, and often conflicting objectives must be considered.

In most realistic environmental problems, constraint equations and objective functions are either mathematically intractable or difficult to quantify. In many instances, data are sparse or unavailable for the necessary mathematical formulation. Even in the best of situations, when the mathematics is tractable and the data are available, managers, politicians, and possibly even engineers are reluctant to attach much credibility to a mathematical interpretation of a problem that is fraught with nontechnical (e.g., political, legal, and social) complexities. Decision makers, resource specialists, and citizen groups often argue that their knowledge and experience are not properly incorporated into the systems models. The recent surge in research related to knowledge-based engineering (expert systems) has emerged as a potential approach for integrating general human expertise and some degree of intelligent judgment into what is often referred to as "decision support systems" (Simonovic & Savic, 1989).

3 SUMMARY

The approach introduced here, *systems analysis,* provides a useful framework for structuring the trade-offs inherent in the allocation of scarce and competing resources. Despite the obstacles discussed in Section 2.4, systems analysis is a powerful prescriptive tool of rational decision making. When consensus can be reached on a precise description of the objectives of a particular resource-allocation problem, combined with a precise description of the legal, ethical, economic, social, political, and environmental constraints, then systems analysis is likely to be an important aid in implementing the often difficult decisions required in environmental resource allocation.

Mathematical programming may appear mechanical, rational, and objective. Its sound application, however, requires substantial expertise in all facets of the decision problem including its environmental, political, legal, social, and ethical dimensions, in addition to a healthy dose of common sense and good judgment. In short, the analyst building the systems model should be a polymath! If systems analysis is to be an effective ingredient in the environmental decision-making process, then its associated model structure will have to include all relevant aspects of the problem. An effort should be made to quantify all measures or objectives that appear unquantifiable or "fuzzy."

A few important themes emerge from recent literature on the application of systems analysis to environmental resource-allocation problems. The obstacles to the effective use of systems analysis in actual resource allocation are substantial. Poor and limited data, nonquantifiable or fuzzy objectives and constraints, intractable mathematics, and the gaps inherent between the theory and practice of systems analysis are just a few of the obstacles mentioned. Even given these stumbling blocks, systems analysis still holds promise for clarifying the trade-offs among competing and conflicting environmental resources. At the very least, systems analysis can be used to identify a range of acceptable decision options. By examining a variety of "near optimal" solutions to a decision problem, systems-analysis methods hold great promise for improving our insight into environmental resource-allocation decisions.

EXERCISES

1. A regional authority has the responsibility of managing the use of water for all river basins under its jurisdiction. Environmental legislation dictates that the regional authority must issue permits to any industry or town that plans to withdraw water from the river basin. For example, the authority must issue permits for the withdrawal of water from a river basin for domestic purposes such as drinking water, lawn sprinkling, and car washing, and for industrial purposes such as cooling, manufacturing, treatment, and other commercial processes. On the one hand, the regional authority wishes to assure that, after all the necessary permits are issued, ample water to support fish and wildlife populations is left in the rivers. On the other hand, the regional authority does not want to prevent economic growth and prosperity in the region by restricting economic growth because of limited water resources. Use your knowledge of the systems approach to structure and formulate this problem. One of the most difficult tasks here is to define the decision variables. Carefully define in words each of the decision variables, objectives, and constraints. Once you have structured the problem, describe the information that must be collected to solve the problem faced by the agency. Discuss which characteristics of the problem are the most difficult to quantify.

2. A city is attempting to find the least-cost solution to allocating its water resources. Presently, the city has two reservoirs, numbered 1 and 2, with maximum yields of 10 and 5 million gallons per day (mgd), respectively. The city needs *at least* 10 mgd. Water from Reservoir 1 costs $1000 per mgd and water from Reservoir 2 costs $2000 per mgd. The quality of water in Reservoir 2 is higher than that in Reservoir 1; thus, to assure adequate quality of the delivered water, the water provided from Reservoir 2 must amount to at least half the quantity of water delivered from Reservoir 1. Formulate this problem as a linear program, and use the graphical approach (as applied in the discussion of Figures 7–4 through 7–6) to obtain the optimal allocation of water from these two reservoirs. If the city seeks to minimize its costs, how much water should it draw from Reservoir 1 and Reservoir 2?

3. Select an environmental decision problem that interests you. Attempt to formulate the decision problem, using the systems framework, in a manner similar to that used with the water-resource example in this chapter. First, carefully define in words the decision variables, the objective function(s), and the constraints. In resource-allocation problems, the decision variables are *usually* the resources that need to be managed, but that may not always be the case. Next, describe your model formulation in mathematical terms, as was done for the example in the text. If your problem contains only two decision variables, use the graphical approach described in the text to obtain the optimal solution. If you do not have sufficient information available to develop the mathematical formulation, describe what information you need and how you might obtain it.

4. Based on your own interests, select a case study from the list of additional readings in the next section. Evaluate the use of systems-analysis techniques for the case study you have chosen. Comment on the strengths and weaknesses of systems analysis for the case study in question.

ADDITIONAL READINGS

For further general information about systems analysis see Miser and Quade (1985) and Hillier and Lieberman (1990a, 1990b). For interesting case studies on resource allocation using systems analysis, see Moore (1973), De Neufville and Marks (1974), and Von Lanzenauer (1986). For allocation of land resources, see Williams and Massa (1983), Diamond and Wright (1989), and Alonso (1964); for allocation of energy resources, see Bruckner, Fabrycky, and Shamblin (1969), Cootner and Lof (1974), and Haith (1982). For more on the allocation of water resources, read Loucks, Stedinger, and Haith (1981), Biswas (1976), and Hall and Dracup (1970). Finally, see Davis (1973) and Gustafson and Kortanek (1976) for more information concerning allocation of air resources.

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