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SELECTION OF WATER-SUPPLY PROJECTS UNDER DROUGHT*

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ABSTRACT

Proposed water-supply projects may be evaluated with respect to one or more objectives and in the context of one or more operating environments. Such evaluation is commonly considered a technical exercise and reserved for technical specialists. However, since preferences and judgment are required to identify and weigh relevant objectives and to assess the characteristics and likelihoods of different possible environments, project evaluation is unavoidably value-laden and thus should not be considered an exclusively technical enterprise. This article presents an approach to incorporating such values and judgments in the evaluation and selection of water-supply projects under drought conditions. The approach has two main parts. First, a multi-attribute value model is used to measure the attractiveness of candidate projects with respect to different objectives and scenarios regarding drought and water demand. The second part employs these measures in an optimization model to identify the correspondingly best set of projects. An example, using the Analytic Hierarchy Process and integer programming for the two tasks, illustrates the procedure and demonstrates the dependence of the projects selected on the values and judgments used.

Projects to improve water-supply systems may be designed or selected to meet any of several possible needs. Their aim may be to augment average or maximum daily water-delivery capacity, or the purpose may be to expand the service area. Since demand for water commonly does not coincide with its natural availability, another common goal is that of increasing the reliability of supply. And, as with some porkbarrel developments in the American West, projects may be conceived of largely in terms of their political payoffs. Clearly, projects need not be confined

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to only one of these goals, but may address several simultaneously. To one degree or another, water-supply projects clearly contribute to multiple objectives.

This article treats the consideration of such multiple objectives when evaluating and selecting among a set of water-supply projects, focussing on the explicit representation of the likely effects of drought upon project performance. It will be shown that how drought is defined and one's attitude toward risk influence the weights given the different objectives to which a project contributes. These weights, in turn, determine the priorities accorded the projects under consideration. By extension, decisions on project selection, far from being purely technical in basis, will be seen to encompass values and hence to be ultimately political. Methods that can take account of these aspects of water-project selection problem should be preferred over those that cannot.

GUIDELINES FOR A PROJECT-SELECTION PROCEDURE

Three sets of questions need to be answered to evaluate proposed projects with respect to a set of water-supply objectives. First, how important is each of the objectives? This in turn may depend on how well the existing water-supply system presently meets such goals, as well as on how the system's wider environment might change in the future. Two obvious elements of that environment are the demand for water and its available supply. Second, to what degree does each project by itself contribute to the achievement of each objective? Third, considering resource constraints and project interaction, how should one evaluate the worth of subsets of the entire group of candidate projects?

Answers to these questions help one to decide which projects should be implemented, although they do not themselves determine that selection. For example the selection philosophy may aim to *optimize* the water-supply system in accord with criteria pertaining to system performance. Projects might then be selected so as to maximize the total contribution of all projects together, taking into account limits on budget and other resources required for project development. This is the case discussed here. On the other hand, policy may be more concerned with the system's capacity to meet the challenges of a highly uncertain environment, in which instance adequate performance under a wide range of conditions and ease of modification might take precedence over optimization as conventionally understood [1-3].

In the context of the optimization approach, one can identify several desirable characteristics of any procedure designed to aid in the selection of water-supply projects. One should be able to use results from statistical and other empirical studies of hydrological systems to help predict future changes in water demand and availability. However, where there are inadequate data on such systems, or a lack of confidence in or misunderstanding of statistical analyses, there is a need to be able to complement such studies with personal judgment based on experience or other subjective factors. (Indeed, some (e.g., [4]) argue that the preferred way to represent all uncertainties is as probabilities based on personal judgments of likelihoods of the corresponding real-world events.) Furthermore, since any prediction will be uncertain, and the relative importance accorded any particular water-supply goal will be subjective, one should be able to examine the sensitivity of the projects' priorities to changes in such factors. Finally, to allow the allocation of project-development resources, the procedure should be able to incorporate constraints on such resources, and priorities should be determined on a ratio scale.

THE PROJECT SELECTION MODEL

The procedure described below meets the foregoing desiderata and is comprised of two main parts. First a multi-attribute value model is used to evaluate the overall worth of each project in terms of four principal criteria. Although the "Analytic Hierarchy Process" (AHP) is employed in the example which follows, other multi-attribute value methods are also available [4]. Constrained optimization using integer programming is then used to select the subset of projects which maximizes overall value subject to available budget and project interdependencies. The procedure is illustrated in an example adapted from a water-supply plan for part of the Hawaiian island of Maui [5]. Since there is a large and growing literature on the theory and applications of the AHP [6-11] only a brief qualitative description of the method is presented here.

The Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process is a general methodology for developing cardinal measures of the relative dominance of the elements of a system. In a decision problem, elements usually represent goals, criteria, actors, scenarios, or alternatives. In the AHP, the dominance of an element is usually referred to as its priority and is stated in terms of importance, preference, or likelihood. Although the AHP may be applied to feedback systems (networks) as well as to hierarchies [12, 13], as in the present case it is usually applied to the latter.

The AHP begins by decomposing the problem into a value tree, termed an analytic hierarchy, with levels representing relevant decision elements. Although the number of levels and what each represents vary with the application, the apex always represents the overall goal and the bottom-level elements represent alternatives. The procedure then consists of two main parts, that of determining each element's priority and that of aggregating those individual priorities into a composite priority for each alternative.

At the heart of the AHP is the eigenvector method for determining the priority of each element below the apex in the hierarchy. For each ("parent") element at level k, one constructs a square matrix whose cell entries are pairwise comparisons of the elements at level k-1 which are directly under it in the hierarchy (i.e., its "children"). Comparisons are typically made using a 1-to-9 integer scale and reflect the degree of dominance of the matrix's row element over its column element with respect to the parent element. If the column element is dominant, the reciprocal of the integer is used. The result is a positive reciprocal matrix with ones on the principal diagonal. Although in the absence of absolute measurement the dominance measures will be inconsistent (cardinally intransitive), Saaty [14] has show that the best estimates of these measures are given by the components of the normalized eigenvector corresponding to the maximum eigenvalue of the comparison matrix. Furthermore, these priorities belong to a new ratio scale derived from the set of comparisons themselves. Once priorities are determined for each element, they are multiplied upwards through the hierarchy, child by parent, beginning with the alternatives at the bottom. The overall priority of each alternative is the sum of its corresponding subproducts. Aggregation is thus by a weighted linear value function.

Valuing Projects with the AHP

Consider an existing water-supply system, such as that shown in Figure 1, and a set of projects, as listed in Table 1, representing additions which water managers wish to make to the system within a single planning period. If the total cost of all projects together is within the allotted budget, then all projects are implemented. If total cost exceeds the budget, then the task is to design the best portfolio of projects that does not violate budget limits, where the "best" one is that which maximizes the incremental value of the system. Two observations should be noted. First, in principle one should determine the incremental value of all subsets of the set of projects and then select the affordable subset whose value is highest. However, as in this case the number of subsets can be prohibitively large, and in practice one usually evaluates projects individually [15]. Second, even when project investment has already been scheduled over multiple periods, there still arises the need to choose among the projects earmarked for a given period. Since in an uncertain future both the nature and magnitude of water demand and the functioning of water-supply system will probably change, as may the available budget, new projects may come under consideration and priority of an old project may change. Projects not selected for implementation in the current period may thus be postponed and considered for the following one.

Figure 2 shows a hierarchy of scenarios, criteria, and candidate projects which may be used with the AHP to determine the relative value of each project. The overall goal, placed at the apex of the hierarchy, is to rate the individual projects according to their potential improvement to the water-supply system. The first level below the apex—referred to as Level 1, or L1—displays three different drought scenarios, and under each of those are three different scenarios of growth in water demand. At L3 are four criteria by which a project's worth may be evaluated. The L4 subcriteria represent the different water-supply functions which

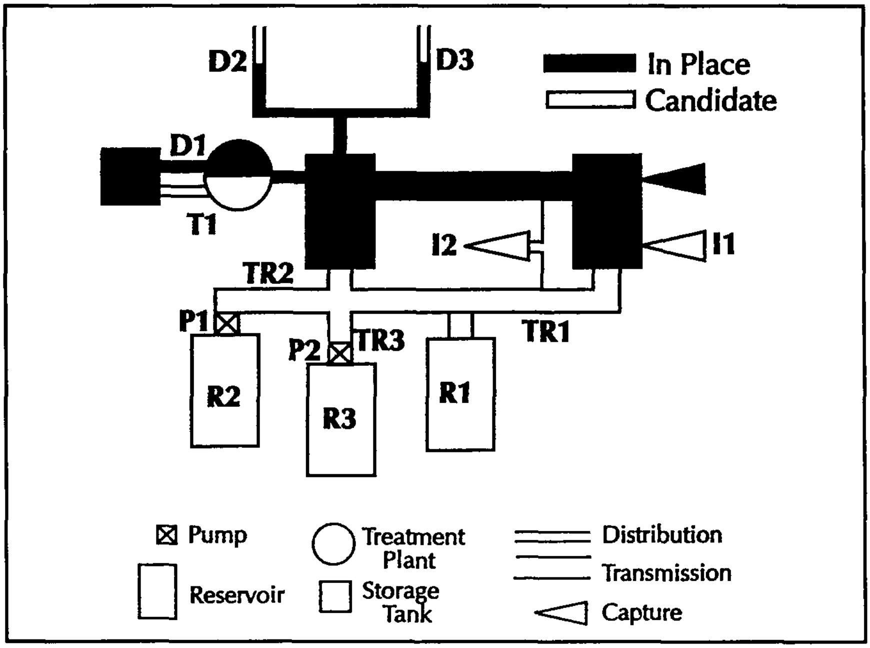

Figure 1. Schematic diagram of an existing water-supply system and the projects proposed to expand and improve it.

Table 1. Candidate Projects

Project ID	Description	Cost ($1000)
D1	11,500 ft 16" transmission line	1000
D2	2000 ft 6" distribution line	127
D3	4800 ft 6" distribution line	301
I1	Repair intakes	80
I2	Fix intakes and 2,115 ft 24" transmission line	420
R1	100 million gallon (MG) reservoir	13000
R2	50 MG resesrvoir	5400
R3	75 MG reservoir	12000
T1	Expand treatment plant to 2.5 mgd	315
TR1	17,000 ft 36" transmission line	4300
TR2	6000 ft 24" pipeline	1000
TR3	3000 ft 24" transmission line	700
P1	Pump from reservoir R2 to treatment plant	50
P2	Pump from reservoir R3 to treatment plant	50

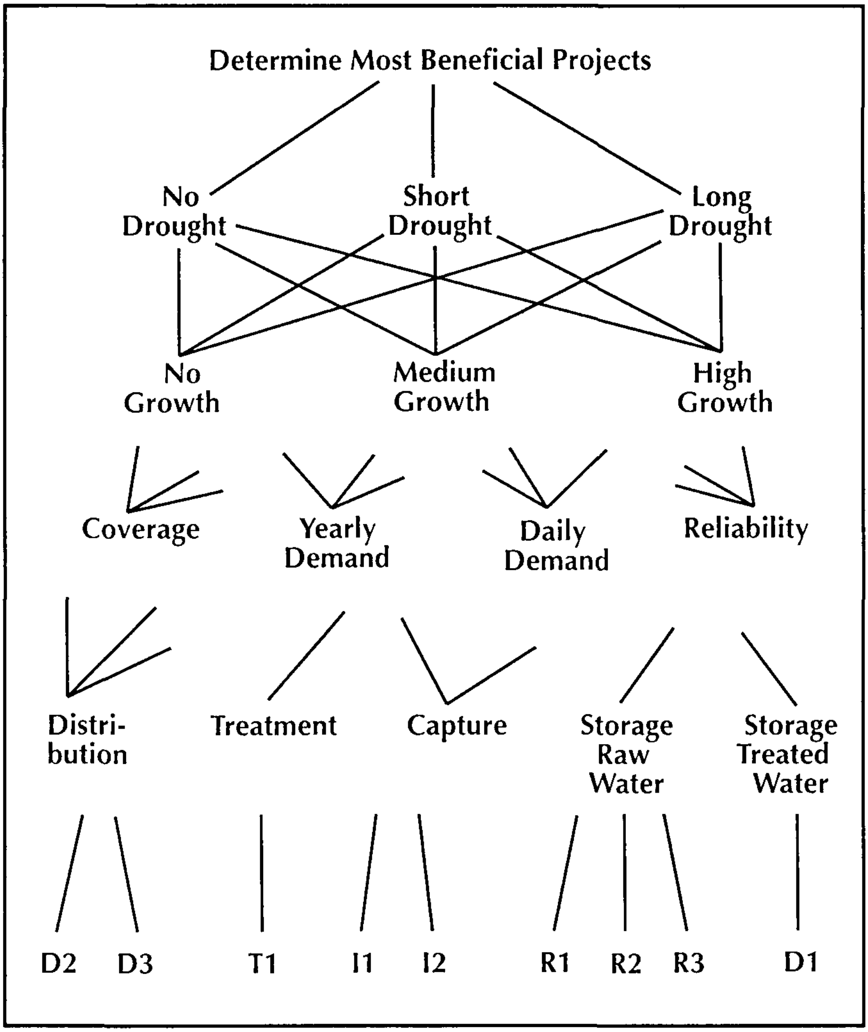

Figure 2.

projects may perform and which contribute to the achievement of the four goals at L3. Below these functions are the candidate projects themselves.

Sets of comparisons are required with respect to every element—the "parent" nodes—at levels 0 through 4. Pairwise comparisons of drought scenarios at L1 with respect to the overall goal at L0 are made in terms of likelihood: how much more likely is drought scenario 1 than drought scenario 2? Scenarios may be defined in any way relevant to the problem at hand. For this example, they were identified in terms of the length of regional drought events as defined according to the Bhalme and Mooley Drought Index and described in detail elsewhere [16]. With the duration of the minimum drought lasting two months, a "SHORT DROUGHT" is defined here as one of two to five months' duration, and a "LONG DROUGHT" as one lasting six months or more. All other conditions are termed "NO DROUGHT."

Three different scenarios are considered for growth in water demand, expressed by the elements at L2. "NO GROWTH" refers to an annual growth rate not exceeding the average during the previous five years, MEDIUM GROWTH to a rate falling between one and two times that average, and HIGH GROWTH to a rate greater than these.

The four goals of the water-supply system at L3 are defined thus:

1. DAILY DEMAND—to meet the peak hourly demand, measured in average flow during that hour, on all days of the year;
2. YEARLY DEMAND—to meet total demand over the entire year, measured in total volume;
3. COVERAGE—to extend service to all potential customers in the region; and
4. RELIABILITY—to eliminate supply unreliability, measured as the sum of daily demand-over-supply differences throughout the year.

The elements at level 4 are conventional terms for the principal functions of the different components of a water-supply system, functions which in turn contribute directly to the criteria above. DISTRIBUTION refers to the conveyance of treated water to the ultimate consumers. Aside from its obvious contribution to the COVERAGE objective, it will also affect YEARLY DEMAND and DAILY DEMAND in two ways: first, by meeting the portion of these demands exerted by the consumers that the new lines will serve, and, ultimately, through the limitations posed by the finite flow capacity of those lines. TREATMENT and TREATED-WATER STORAGE facilities help meet DAILY DEMAND since maximum hourly throughput depends on the flows emanating from these two types of source. CAPTURE facilities, such as intakes and their associated pumps, not only add to the total amount of water made available during the year, contributing to YEARLY DEMAND; they also support the RELIABILITY goal, since under drought additional intakes can extract water from new sources and help to relieve a deficit without adding to the total yearly supply. Finally, a major purpose of RAW-WATER STORAGE facilities, such as reservoirs, is to enhance the reliability of supply.

"Transmission," referring to the conveyance of water from point of capture to a raw-water storage facility or directly to the treatment plant, does not appear at level 4 since by itself it contributes nothing to any of the L3 objectives. That it may be required for other components to function is undeniable, and such requirements are taken care of in the optimization model.

Policies and Assessments

Pairwise comparisons required by the AHP were made with respect to all parent nodes, beginning at the bottom of the hierarchy and working up level by level. The assessments of projects relative to L4 functions, and of those functions with respect to the L3 criteria, constitute "effects," or "impact" matrices. The "scores" in these matrices are not merely the ratios of impact scores in terms of natural units, but rather ratios of the value, or worth, of such consequences. Although such valuation makes it clear that these assessments are not objective, they are more easily agreed-upon than the preference and likelihood assessments, which are more overtly value-laden, needed higher up.

Comparisons of elements at L1, L2, and L3 were made for all combinations of three different policies; with two variants for each policy, eight different cases were modeled. In general, the greater the expected rise in water demand, the greater the importance given the two DEMAND criteria. Likewise, expected increases in drought probability and/or length were accompanied by increased importance given to RELIABILITY. Otherwise, assessments depended on the combination of policies in effect. Policies pertain to criterion (goal) preferences, drought-scenario likelihoods, and the relationship between drought scenario and water-demand management. The distinctions in each area can be summarized as follows.

Criterion Preferences:

(C1). Growth Policy: Emphasis is on meeting growth in water demand. DEMAND and RELIABILITY are preferred over COVERAGE. RELIABILITY is slightly preferred over DEMAND in SHORT DROUGHT/MEDIUM GROWTH and LONG DROUGHT/HIGH GROWTH scenarios.

(C2). Current Demand Policy: Emphasis is on providing good service to existing customers and to serve potential customers (e.g., households, commercial establishments) already resident in the service area but currently lacking service. COVERAGE is heavily emphasized over DEMAND and at least as preferred as RELIABILITY. RELIABILITY is at least as preferred as DEMAND.

Drought Likelihood:

(D1). Frequency-Based: Drought is defined as "climatic" drought—i.e., characterized entirely by climatic attributes—and is measured with respect to relative frequencies of drought events. The probabilities used are: NO DROUGHT, 75 percent; SHORT DROUGHT, 20 percent; LONG DROUGHT, 5 percent.

(D2). Judgmentally-Based: Drought probabilities reflect personal appraisals of recurrence likelihood. "Drought" is an amalgam of climatic attributes and the effects of these on economic, social, and agricultural systems. Events in the far past are heavily discounted relative to more recent ones. Recent attention to possible global warming results in equal probability being assigned to each scenario.

Drought & Demand Management:

(M1). No Relation: Drought likelihood is expected to have no influence on demand-management policies. MEDIUM GROWTH and HIGH GROWTH scenarios are considered of equal likelihood and are significantly more likely than the NO GROWTH case.
(M2). Direct Influence: The higher the expected likelihood and length of drought, the stronger will be policies that attempt to inhibit growth in water demand.

Thus, comparisons at level 3 (with reference to L2 elements) were made under four different circumstances of drought and demand management (D1-M1, D1-M2, D2-M1, D2-M2), and those comparisons were made in two different ways (C1, C2). The comparisons were in terms of preference, responding to questions of the type: "Given a long drought and a medium growth rate in water demand, is it more important to meet peak daily demand or to expand coverage?" These assessments can be seen as implicit reflections of one's attitude toward risk. For example, two people may assign different levels of importance to "reliability" even though they entirely agree on the drought probabilities.

Table 2 shows the priorities resulting from the comparisons for each of the eight cases, as calculated by the eigenvector method for the analytic hierarchy of Figure 1. Inspection of the table reveals changes not only in cardinal priorities but also in the rankings of the projects, although in many cases the changes are so small as to seem insignificant. For example, under cases of relatively infrequent drought (D1) and constant criterion preferences—i.e., comparing C1-M1-D1 with C1-M2-D1, and C2-M1-D1 with C2-M2-D1—changes in demand-management policy result in only one change in project rankings, and that difference is cardinally marginal. Neither does demand management have any effect on project rankings when drought likelihood is high (D2) and the satisfaction of current demand is emphasized (C2). Considerable differences do result, however, when management policies or criterion preferences change in conjunction with changes in drought-likelihood assessment, e.g., the difference between C2-M2-D1 and C2-M1-D2, and between C1-M2-D1 and C2-M2-D2. Thus, one's views about the likelihood of drought (and by extension what constitutes it), the relative importance of each of the water-supply goals, and the type of demand-management policy to invoke, all value-laden questions, clearly have the potential to affect project selection.

In addition to their use in ranking the projects, the AHP-derived priorities (weights) also measure the benefit (assuming the goals used are sufficient in this regard) to be derived from each project. Dividing a priority by the corresponding

Table 2. Project Rankings and Priority Weights as Derived by the AHP Value Model for Each Composite Scenario (Circled projects are tied, and lines indicate changes in rank.)

	D1 (Frequency-Based Drought)				D2 (Judgment-Based Drought)			
Rank	C1-M1	C1-M2	C2-M1	C2-M2	C1-M1	C1-M2	C2-M1	C2-M2
1	D2 (.238)	D2 (.262)	D2 (.379)	D2 (.498)	I2 (.171)	R1 (.177)	D2 (.389)	D2 (.422)
2	D3 (.229)	D3 (.189)	D3 (.228)	D3 (.232)	R1 (.171)	D2 (.171)	D3 (.185)	D3 (.220)
3	I2 (.141)	T1 (.142)	I2 (.143)	I2 (.090)	D3 (.156)	I2 (.167)	R1 (.118)	R1 (.105)
4	T1 (.134)	I2 (.140)	I1 (.073)	I1 (.045)	D2 (.153)	D3 (.143)	I2 (.117)	I2 (.093)
5	D1 (.079)	D1 (.079)	T1 (.057)	T1 (.042)	D1 (.097)	T1 (.085)	R3 (.048)	R3 (.045)
6	I1 (.074)	I1 (.076)	R1 (.046)	R1 (.036)	T1 (.090)	D1 (.077)	I1 (.045)	I1 (.033)
7	R1 (.059)	R1 (.061)	D1 (.031)	D1 (.025)	R3 (.069)	R3 (.077)	D1 (.038)	D1 (.030)
8	R3 (.030)	R3 (.032)	R3 (.026)	R3 (.020)	I1 (.058)	I1 (.060)	T1 (.037)	T1 (.028)
9	R2 (.017)	R2 (.019)	R2 (.016)	R2 (.012)	R2 (.034)	R2 (.042)	R2 (.023)	R2 (.024)

Policy on Water Demand
C1: Growth-Oriented
C2: Current-Demand Oriented

Drought and Demand Management
M1: No Relation
M2: Direct Influence

project's cost is a measure of efficiency analogous to a benefit-cost ratio. If there were no resource (e.g., budget) constraints, benefits would be maximized by ordering the projects according to this ratio and simply selecting the top one on the stack when conditions warranted a new project. With resource constraints, however, such a procedure does not guarantee maximum benefits, and optimization is required.

Project Selection

Integer programming was used to determine the set of projects to implement so as to derive maximum total benefits. The potential benefits of each project were represented by the project's priority, and constraints were of two main types: those pertaining to resource availability and those corresponding to interdependence conditions among the projects themselves. Considering budget limits as the only resource constraint, the following model will identify the optimal set of projects for any budget level.

$$\text{Maximize Benefits } B = \sum_j P_j X_j \tag{1}$$

subject to

$$\begin{aligned}&4300\ TR1 + 80\ I1 + 420\ I2 + 1000\ D1 + 13000\ R1 +\\&127\ D2 + 315\ T1 + 5400\ R2 + 1000\ TR2 + 50\ P1 +\\&301\ D3 + 12000\ R3 + 700\ TR3 + 50\ P2 \le \text{budget}\end{aligned} \tag{2}$$

$$TR1 \le R1 + R2 + R3 \tag{3}$$

$$R1 \le I1 + I2 \tag{4}$$

$$R2 \le I1 + I2 \tag{5}$$

$$R3 \le I1 + I2 \tag{6}$$

$$D1 \le T1 \tag{7}$$

$$R1 + R2 \le I1 + I2 \tag{8}$$

$$R1 + R3 \le I1 + I2 \tag{9}$$

$$R2 + R3 \le I1 + I2 \tag{10}$$

$$I1 + I2 - TR1 \le 1 \tag{11}$$

$$I1 + I2 - R1 - R2 - R3 \le 1 \tag{12}$$

$$TR2 = R2 \quad (13)$$

$$P1 = R2 \quad (14)$$

$$TR3 = R3 \quad (15)$$

$$P2 = R3 \quad (16)$$

$$X_j = 1, \text{ if project } j \text{ is selected,} \quad (17)$$

$$= 0, \text{ otherwise}$$

The X_j in Expression (1) represent the variables in Exp (2)-(16) and refer to the projects listed in Table 1. The P_j in Exp (1) represent their AHP-derived priorities. Notice that P_j is nonzero only for the projects appearing in the analytic hierarchy, i.e., those in Table 2. The coefficients in the left-hand side of Exp (2) are the costs of the corresponding projects, and their sum cannot exceed the budget available.

Expressions (3)-(16) represent the dependencies among individual projects. Exp (3) states that transmission line TR1 may be added only if at least one reservoir is constructed. Exp (4)-(6) together require additional capture (right-hand side) before new reservoirs (left-hand side) can be added. Exp (7) requires expansion of the treatment plant (T1) before an additional conveyance line (D1) to the storage tank is built. Exp (8)-(10) together require both capture projects (right-hand side) to be selected before two or more reservoirs may be added. In Exp (11), transmission line TR1 must be added if both intake projects I1 and I2 are chosen. Exp (12) states that if both I1 and I2 are selected, then at least one of the three reservoirs must be built. Exp (13)-(16) require that the condition of the projects on the left-hand side (chosen/not chosen) be the same as that for those on the right-hand side.

Substituting for P_j the priorities corresponding to one of the eight cases, replacing the X_j in Exp (1) with the projects in Table 1, and selecting a budget level of interest for Exp (2), one may solve Exp (1)-(17) to identify the optimal project package corresponding to that situation. Surprisingly, of the higher budget levels examined, the optimal set is identical for all eight cases, varying only with the budget limit (Table 3). For the budget limits below $20 million that were examined, however, differences in optimal project packages do indeed surface. Table 4 shows the results for a budget of $19 million. For the budget levels examined, the optimal packages are identical for all cases characterized by infrequent drought (D1). When drought likelihood is considered higher (D2), it is the criterion preference (C1 vs C2) that effectively determines the optimal set of projects.

These results demonstrate clearly the effect that alternative estimates of drought likelihood and goal priorities can have on infrastructure evaluation. In addition to the probability estimation process itself, different estimates of

Table 3. The Optimal Set of Projects for All Cases

Budget	Projects													
($\$10^6$)	D1	D2	D3	I1	I2	R1	R2	R3	T1	TR1	TR2	TR3	P1	P2
20	x	x	x	x	x	x			x	x				
25	x	x	x	x	x	x			x	x				
30	x	x	x	x	x	x	x		x	x	x		x	
35	x	x	x	x	x	x		x	x	x		x		x

Note: x = project is selected.

Table 4. Optimal Sets of Projects for a Budget of $19 Million

	Projects													
Case	D1	D2	D3	I1	I2	R1	R2	R3	T1	TR1	TR2	TR3	P1	P2
C1-M1-D1	x	x	x	x	x		x		x	x	x		x	
C1-M2-D1	x	x	x	x	x		x		x	x	x		x	
C2-M1-D1	x	x	x	x	x		x		x	x	x		x	
C2-M2-D1	x	x	x	x	x		x		x	x	x		x	
C2-M1-D2		x	x	x	x	x			x	x				
C2-M2-D2		x	x	x	x	x			x	x				
C1-M1-D2	x	x	x		x	x			x					
C1-M2-D2	x	x	x		x	x			x					

Note: x = project is selected.

drought likelihood can arise from different conceptions of drought (e.g., agricultural versus climatic) as well as from the selection of different climatic attributes or the use of different thresholds for those selected. Differences in drought-scenario probabilities and goal priorities can result entirely from their being assessed by different people: a long-time resident may base his estimation of drought recurrence probabilities on his past experience, while an engineer might prefer a statistical analysis of rainfall records; an aquatic biologist may define drought according to streamflow but a climatologist might focus on rainfall; a land developer might give considerable weight to increasing the capacity of the water-supply system, whereas farmers might prefer efforts aimed at improving reliability. Variations in subjective judgments, underlain by different values, can thus lead to different appraisals of alternative water-supply system improvements.

CONCLUSION

The selection of water-supply projects should be made according to multiple criteria, and drought is apt to influence how well a project meets one or more of those criteria. The evaluation of the projects should thus take into account the likelihood of droughts of different magnitude and duration and the effect they have on overall system goals. Just as important, however, is the evaluation of goal importance, a process which is inherently value-laden and quite likely political. Neither drought-likelihood estimation nor goal appraisal should be regarded as purely technical enterprises. A general approach to project assessment that embodies these characteristics first builds a multi-attribute value model (e.g., via the AHP) to determine project priorities and then employs the priorities as weights in the objective function of a mathematical program. The model's output identifies the optimal set of projects to be selected.

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