# Developing Inventory and Monitoring Programs Based on Multiple Objectives

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ABSTRACT / Resource inventory and monitoring (l&M) programs in national parks combine multiple objectives in order to create a plan of action over a finite time horizon. Because all program activities are constrained by time and money, it is critical to plan l&M activities that make the best use of available agency resources, However, multiple objectives complicate a relatively straightforward allocation process. The analytic hierarchy process (AHP) offers a structure for multiobjective decision making so that decision-makers' preferences can be formally incorporated in seeking potential solutions, Within the AHP, inventory and monitoring program objectives and decision criteria are organized into a hierarchy. Pairwise comparisons among decision elements at any level of the hierarchy provide a ratio scale ranking of those elements, The resulting priority values for all projects are used as each project's contribution to the value of an overall l&M program. These priorities, along with budget and personnel constraints, are formulated as a zero/one integer programming problem that can be solved to select those projects that produce the best program. An extensive example illustrates how this approach is being applied to l&M projects in national parks in the Pacific Northwest region of the United States, The proposed planning process provides an analytical framework for multicriteria decisionmaking that is rational, consistent, explicit, and defensible.

Managers for the National Park Service (NPS) and other agencies are charged with managing a wide array of natural resources, including measurable commodities, esthetic values, and ecosystem processes. However, there is often no calculable standard (such as economic value) by which to compare the importance of these resources. In addition, there are often so many different planning objectives and individual projects that it is difficult to keep track of all of them, let alone develop a program that emphasizes each one appropriately, A variety of economic, political, and personnel constraints make optimal resource management difficult to attempt, much less achieve. Yet it is essential that certain resource management activities receive priority over others due to limited time and money.

Planning under multiple objectives is inherently complex. Models that address multiple resource planning, such as Timber RAM (Navon 197 1), MUSYC (Johnson and Jones 1979), and FORPLAN Versions 1 and 2 (Johnson 1986, Johnson and others 1986), have evolved from timber management models (Alston and Iverson 1987). These models rely on linear programming (LP) to select one of several management options for any specific tract of land (Barber and Rodman 1990, Hof and others 1992). Trade-offs among uses for any particular area are determined by assigning dollar values to resource costs and benefits and computing optimal financial solutions.

In national parks, however, economic measures may be less important than legal, social, political, and biological concerns. The selection of resource management activities in national parks is largely driven by how well any activity satisfies park management objectives. Projects are combined into a cohesive program to meet large-scale objectives, such as inventory and monitoring (I&M) of park resources. In contrast to the timber/economic models above, resource management activities in national parks generally are not mutually exclusive and do not necessarily focus on particular tracts of land.

Aside from LP, several other mathematical pro-

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gramming methods have been used to deal with natural resource planning and allocation problems. In the 1970s, goal programming (e.g., Field 1973) was introduced to satisfy some of the inflexibility problems associated with LP. Despite relaxation of constraints in goal programming, many other limitations remained (Cohon 1978). Multiple objective programming (MOP) (e.g., Steur and Schuler 1978) brought an entirely new focus to these problems. Rather than finding an optimal solution, the MOP approach finds all feasible solutions that are not logically included in other feasible solutions. This set of candidate solutions is then examined to select those that have the best trade-offs among the desired objectives. At some point the MOP process includes decision-makers' preferences, either in the evaluation of candidate solutions or in the weighting of the objective functions prior to finding solutions (Bare and Mendoza 1988).

In both situations, however, decision-makers' preferences are not treated in a rigorous manner. Sorting the set of nondominated solutions may be prohibitively time-consuming and provides no explicit record or rationale for the decision process. Iterative MOP methods that use some initial decision-maker preferences to generate a solution and then revise those preference based on feedback have considerable appeal. Nevertheless, decision-maker preferences are just as important in selecting a final solution as are the mathematical relationships; consequently, they should be made explicit and should be open to analysis separately from the search for feasible and desirable solutions. Moreover, incorporating preferences by weighting objective functions may not accurately reflect the relationships among the objectives or between the objectives and the decision variables. For these reasons, existing MOP methods [with the exception of that of Mendoza and Sprouse (1989)] do not examine decision-maker preferences in a straightforward and analytic fashion.

In this paper, we address I&M activities as one aspect of resource management that can benefit from systematic planning. First, our approach contains an explicit method for eliciting and quantifying decision-maker preferences. Second, these "priorities" are used as coefficients in a mathematical optimization solution that selects projects based on their importance and subject to budget and time constraints. By disassociating the steps of preference specification and resource allocation subject to constraints, the planning exercise becomes more explicit and easier to understand and modify. This methodology, described below, can be generally applied to any similar planning activity in national parks or in other jurisdictions.

## Inventory and Monitoring

The NPS is charged with protecting and preserving national park lands. To carry out this mandate, NPS managers need to know what they are protecting and when it is threatened. Inventories provides information on the current condition of park resources, and monitoring provides the ongoing assessment needed to track the condition of resources and identify threats to their integrity (Silsbee and Peterson 1991, 1993). National parks have been inventoried and monitored for many years. Examples of individual projects include species checklists, visitor counts, academic research, and weather records. Only recently, however, has any effort been made to bring these activities together in an integrated program throughout the national park system.

This heightened interest in I&M has led to a national emphasis on tracking the condition of the vast array of resources under NPS stewardship. Some programs outside of the NPS intensively monitor a wide variety of ecological parameters to identify resource trends and conditions of small areas, such as the Hubbard Brook, New Hampshire, and H. J. Andrews, Oregon, experimental forests (Likens and others 1977, McKee 1984). Other programs involve large areas or many sites networked across the United States, including the: (1) National Atmospheric Deposition Program, National Trends Network (NADP/NTN 1989), (2) Forest Service Continuous Forest Inventory Program (Knight 1987), (3) Forest Service Forest Health Monitoring Program (Radloff and others 199 1), and (4) US Environmental Monitoring and Assessment Program (Messer and others 1989). Some of these programs focus on a narrow set of variables (e.g., precipitation chemistry) addressing specific data needs; others measure a broad spectrum of variables over large and diverse geographic areas.

The first step in designing I&M programs is to define objectives carefully (e.g., Garton 1984, Hinds 1984, Hirst 1983, Johnson and Bratton 1978, Jones 1986). Authors who do not emphasize defining objectives as a first step nevertheless state specific objectives in their discussions (e.g., Davis 1989, Halvorson 1984). Clearly, not all objectives can be accomplished in a completely satisfactory manner. Limitations in budget and personnel force managers, consciously or unconsciously, to prioritize objectives.

Once the basic objectives of a program are defined, the next step is to determine specific ecosystem attributes that should be inventoried or monitored (Davis 1989, Hinds 1984). Choice of attributes depends to a large extent on the objectives (Table 1).

Table 1. Summary of monitoring objectives, strategies for selecting ecosystems and attributes for monitoring, and intended audience for resulting information (from Silsbee and Peterson 1991)

| | Strategies | | |
|---|---|---|---|
| Objectives | Ecosystem selection | Attributes | Audience |
| Inform internal decision makers | Ecosystems involved in specific management decisions | Attributes involved in specific management decisions | NPS managers |
| Influence external decision makers | Ecosystems most threatened by outside activities | Attributes most likely to show effects of outside activities | External decision makers |
| Satisfy legal mandates | Determined by legal requirements | Determined by legal requirements | Variable |
| Maintain familiarity with resources | Broad spectrum, but mainly areas of suspected change | Attributes most sensitive to change | NPS personnel |
| Provide better understanding of resources | Broad spectrum of ecosystems | Broad spectrum of attributes | Scientists and NPS personnel |
| Provide background information | Broad spectrum of ecosystems | Attributes of day-to-day interest to visitors and others | Scientists, NPS personnel, visitors |
| Provide early warning of global or regional problems | Ecosystems most likely to be sensitive to change | Attributes most likely to show detectable change | External decision making |
| Provide background data for exploited areas | Ecosystems comparable to large areas outside park | Attributes of interest in managing outside areas | External decision makers |

Attributes (or specific I&M projects) that satisfy the most important objectives should ultimately receive greatest emphasis in an I&M plan. Subsequent development of monitoring protocols for selected ecosystem attributes is a relatively straightforward process, dictated by project cost limitations and the intensity of sampling needed to give useful and meaningful results (Hinds 1984, Hoffman 1988). For example, MacDonald and others (199 1) provide guidelines, in the form of an expert system, to select monitoring parameters for streams in the Pacific Northwest.

Although there is a conceptual framework for I&M programs (National Park Service 1992), there is no analytical approach available for I&M planning. A standardized planning procedure is needed to help NPS managers develop individual park I&M programs. This procedure should be generic enough to encompass any type of objective. It should assist managers in decision making under complex situations with a large number of alternatives. The program should provide insight into the rationale for decisions, improve the quantification of those decisions, incorporate multiple opinions in a group setting, and assist with efficient allocation of I&M program resources. Finally, it should be sufficiently flexible to be easily modified and updated.

The ambitious nature of the NPS I&M program, coupled with limited park budgets, make careful design of I&M programs critical. Effort must be strategically directed toward areas that give the most return of valuable park resource information for time and money expended. A systematic approach is needed to prioritize projects and allocate resources to the most important I&M projects. The remainder of this paper will: ( 1 ) introduce an analytical process for prioritizing projects using the analytic hierarchy process (AHP) (Saaty 1980), (2) use integer programming to allocate I&M resources to maximize total priority of selected projects, and (3) illustrate these ideas with an I&M program example.

## A Systematic Approach to Planning and Decision Making

Humans constantly choose activities to undertake and times and ways to conduct them. Businesses make decisions on whom to hire, how to evaluate employees, how to develop marketing plans, and which equipment to purchase. Personal decisions may include choices about various career opportunities or which car to buy or which city to live in. Problems of choice are often so complex that we are not capable of considering all the necessary factors simultaneously to arrive at a logical and rational decision. Problems rarely have a single decision criterion and a natural measurement scale applicable to all possible alternatives. As a result, managers often base decisions on intuition and limited knowledge without considering a more rational or integrated plan. While this approach may result in acceptable decisions, it is not sufficiently rigorous where rational structure, quantification, justification, and documentation are necessary.

The development of' I&M programs for national parks is a complex process that involves a wide range of issues and may include hundreds of individual decisions and judgments. Development of an I&M program requires technical information as well as the personal knowledge and judgments of resource managers. A planning approach is needed for viewing I&M in an organized framework while still incorporating valuable personal knowledge.

Our approach to I&M program development has three separate steps:

- Identify I&M projects
- Prioritize projects
- Maximize I&M program value over all projects

First, decision makers must identify potential I&M projects that would fulfill program objectives. This is an important first step, but we defer discussion of selecting potential projects until later in the paper. Second, these projects are prioritized based on their total contribution to the goals of the I&M program. These priorities, then, represent the relative value that each project contributes to the total program. We use the analytic hierarchy process to estimate those priorities systematically. Third, budget and personnel constraints are incorporated into program planning so the total program value over all implemented projects is maximized. This last step lends itself to an integer programming solution, where the decision variables are the projects (each with the value “1” implemented, or “0” not implemented), the coefficients are the priority values for each project, and the minimal list of constraints includes budget and personnel time. The last two steps of this process are discussed in further detail below.

## The Analytic Hierarchy Process

The AHP has proven value for planning and decision making (Saaty 1980). It has been used for planning, resource allocation, and priority setting in business (Ramanujam and Saaty 1981), energy (Gholomnezhad 1981, Saaty and Mariano 1979), health (Dougherty and Saaty 1982), marketing (Arbel 1987, Bahmani and Blumberg 1987, Dyer and Forman 1991), and transportation (Saaty 1977). A survey of many AHP applications can be found in Zahedi (1986).

The AHP can support decision making for many types of complex processes and is appropriate for I&M planning. Its advantage is that it allows decision makers to organize a large number of decision criteria and judgments, weigh the relative contributions of each, and arrive at a final assessment that is both consistent and defensible. AHP's two key concepts are: (1) the use of hierarchies to structure decision making, and (2) the application of judgment measures and formal mathematics to express and quantify individual preferences.

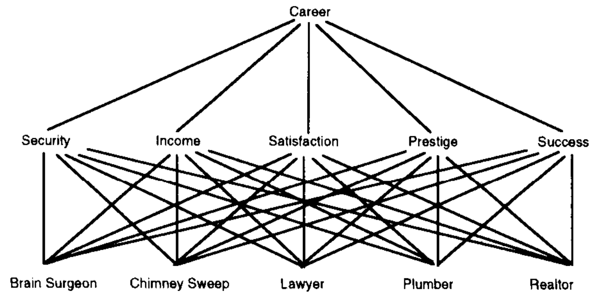



**Figure 1.** A hierarchy for selecting a career depicts the selection criteria and the alternative careers being evaluated.

### Hierarchies

To construct a hierarchy, a primary goal (or focus) is placed at the top. The goal in Figure 1 is to select a possible career out of the list: brain surgeon, chimney sweep, lawyer, plumber, and realtor. The criteria that are used to make this decision are: job security, income, job satisfaction, prestige, and likely success in reaching the career goal. Subordinate criteria could be considered in a more detailed analysis, but this single level of criteria is sufficient for the sake of example. The alternative careers being compared are placed below these criteria in the hierarchy. In general, the elements at each level are relatively independent, and one level influences the elements of the next higher level only. In a mathematical theory of hierarchies, Saaty (1990b) describes a method for evaluating the relative contributions (priorities) of elements at one level of the hierarchy to elements at the next higher level.

### Priority Measures

Events, places, and things can be classed as desirable, important, or likely based on prior experiences with those entities. Therefore, they can be placed in relation to one another on a measurement scale, even if the measurement scale cannot be explicitly specified. By making pairwise comparisons of the influence of one element relative to another, a ratio scale emerges that captures the priorities of those elements with respect to the comparison criterion. In the hierarchy of Figure 1, the weight of influence that any element of level i has for a property at level $i-1$ (i.e., the next higher level) can be determined by performing pairwise comparisons of all elements in level i with respect to the property of interest at level $i-1$. Elements with a greater influence for the property possess a higher priority value with respect to that property. These comparisons can be performed for all elements of all intermediate levels of the hierarchy. The alternatives present at the bottom level (e.g., the career choices in the lowest level of Figure 1) can then be compared in a pairwise fashion with respect to their standing for each criterion at the next higher level. A matrix $\mathbf{A} = (a_{ij})$ $(i,j = 1, \ldots, n)$ can be constructed consisting of all pairwise comparisons made at any level with respect to some property or criterion in the level above.

Each of the elements $a_{ij}$ can be thought of as a ratio $w_i/w_j$ that indicates how much more important (or preferred or likely) element *i is* relative to element *j*. The vector $\mathbf{w} = [w_1 w_2, \ldots, w_n]$ contains the true priority values (or weights) for each of the *n* elements that are compared. We estimate the weight vector **w** based on judgments $a_{ij}$ regarding these ratios. Ratio judgments are taken from the scale (1,3,5,7,9), where intermediate values (2,4,6,8) can also be used. This scale is justified based on the work of Fechner (1966) on "just noticeable differences" and on the simultaneous comparison limit of 7 ± 2 by Miller (1956). The ratio 1 indicates that the two elements are equal in that comparison, and of course $a_{ii} = 1$. If element j is more important than element *i*, then $a_{ij} = 1/a_{ji}$ It can then be shown (Saaty 1980, 1990b) that equation 1 holds and states that **w** is an eigenvector of **A** with eigenvalue *n*.

$$\mathbf{A}\mathbf{w} = n\mathbf{w} \tag{1}$$

Equation 1 holds, however, only in the case where $a_{ij} = w_i/w_j$, i.e., all judgments are absolutely consistent. This condition is usually satisfied only when we use some instrument to produce absolute judgments, e.g., a ruler to measure length. Because consistency is not the case in general, there are multiple eigenvalues $\lambda_i$ and multiple eigenvectors $\mathbf{x}_i$ where equation 2 holds.

$$\sum_{i=1}^{n} \lambda_i = n \tag{2}$$

The nature of the matrix **A** ensures, however, that small variations in the $a_{ij}$ from $w_i/w_j$ do not create a large difference between the largest eigenvalue $\lambda_{max}$ and *n*, and that the remaining eigenvalues stay near 0 (Saaty 1990b). Therefore, by replacing *n* with $\lambda_{max}$ in equation 1, we can solve for **w.** The resulting vector **w** of priorities is normalized, so that

$$\sum_{i=1}^{n} w_i = 1 \tag{3}$$

Because $\lambda_{max}$ differs from *n* due to inconsistency in **A,** the deviation of $\lambda_{max}$ from *n* can be used as a measure of inconsistency for the subjective judgments. Because $\lambda_{max} \geq n$ and the sum of all eigenvalues equals *n*, the remaining eigenvalues must be negative and $\lambda_{max} - n$ equals the absolute value of the sum of the remaining eigenvalues. Saaty (1987) derives a consistency index (CI) as the average of the absolute values of the remaining eigenvalues.

$$\frac{\lambda_{max} - n}{n-1} \tag{4}$$

To determine if this measure of inconsistency deviates significantly from zero, a consistency ratio (CR) is defined for **A** as the CI of **A** divided by the average CI for a set of randomly generated positive reciprocal matrices of the same size as **A** (Saaty 1990b). Consistency ratios above 0.1 indicate that the judgments should be reexamined to identify where inconsistency arises. The target value of 0.1 is proposed by Saaty (1980) based on empirical studies. Vargas (1982) used a more analytical argument to show that the value of 0.1 is a conservative one that satisfies a statistical test at $\alpha = 0.05$ for 3 x 3 matrices. For matrices of size $n \geq 4$, the upper bound for the CR value tends to increase up to 0.2, therefore, selecting CR $\leq 0.1$ works for all *n*.

Saaty ( 1990b) demonstrates that the priority vector **w** is relatively unaffected by small changes from consistency in the judgments $a_{ij}$ as long as none of the $w_i$'s becomes very small. Consequently, to assure the stability of an underlying ratio scale from pairwise comparisons: (1) judgments must deal with a "small" number of items in order for the judgments to be consistent and (2) items should be relatively "comparable" so that none of the final weights is very small. "Small" is consistent with the social scientists' observation of 7 ± 2 (Miller 1956), and "comparable" suggests that a scale with less than 10 values (one order of magnitude) should be used. Consequently, the AHP restricts the comparison matrix to seven items and uses a nine-point judgment scale.

The AHP provides a way to estimate and measure judgments about several alternatives with respect to particular criteria. However, we still must be able to combine judgments about several criteria, each criterion possessing its own influence (or priority). The example in Figure 1 shows how this works. Table 2 contains the pairwise judgments about the criteria at level 1 of Figure 1 with respect to the goal, "select a

Table 2. Pairwise judgments compare job criteria with respect to their importance for selecting a career

| | Security | Income | Satisfaction | Prestige | Success |
|---|---|---|---|---|---|
| Security | 1 | 3 | 2 | 3 | 1 |
| Income | 1/3 | 1 | 1/4 | 2 | 1/2 |
| Satisfaction | 1/2 | 4 | 1 | 3 | 1 |
| Prestige | 1/3 | 1/2 | 1/3 | 1 | 1/3 |
| Success | 1 | 2 | 1 | 3 | 1 |

Table 3. Pairwise judgments compare alternative careers with respect to security[a]

| | Surgeon | Sweep | Lawyer | Plumber | Realtor |
|---|---|---|---|---|---|
| Surgeon | | 3 | 1 | ½ | 5 |
| Sweep | | | 1/2 | 1/3 | 3 |
| Lawyer | | | | 2 | 5 |
| Plumber | | | | | 5 |
| Realtor | | | | | |

[a] $\mathbf{w}_1$ = [0.250, 0.116, 0.305, 0.273, 0.056]; CR = 0.064

career" at level 0. If $a_{ij} > 1$ for element $a_{ij}$ of the table, then the row heading is $a_{ij}$ times more important than the column heading for selecting a career. The influence of the headings is reversed where $a_{ij} < 1$, i.e., the column heading is then $1/a_{ij}$ times more important than the row heading. This matrix results in a priority vector (transposed) $\mathbf{w}_c'$ = [0.315, 0.107, 0.256, 0.078, 0.244] with a CR of 0.038.

We then create similar tables comparing all of the career alternatives with respect to each of the criteria. This process produces five other tables, one for each of the criteria. For reasons of space, only one of those tables is included here. Table 3 contains pairwise comparisons of the alternative careers with respect to "security." Only the upper diagonal elements are given; the lower diagonal elements are reciprocals. From Table 3, the local score for the career "brain surgeon" with respect to "security" is 0.25. The omitted tables would result in priority vectors $\mathbf{w}_2, \ldots, \mathbf{w}_5$ that are similar to $\mathbf{w}_1$. To calculate the partial global score of "brain surgeon" with respect to "security" we multiply the priority of "security" with respect to "career" by the score for "brain surgeon" with respect to "security." The partial global scores for "brain surgeon" with respect to "income, " "satisfaction," etc., can be calculated in a similar fashion. The total global score for "brain surgeon" as a career goal is then the sum of each partial global score with respect to each criterion. The final weight vector **w** contains the normalized priority values for the alternative careers. A shorthand description for the calculation of **w** is derived by forming a matrix from the column vectors $\mathbf{w}_1$, $[\mathbf{w}_1 \mathbf{w}_2 \mathbf{w}_3 \mathbf{w}_4 \mathbf{w}_5]$, and multiplying it on the right by the column vector $\mathbf{w}_c$:

$$\mathbf{w} = [\mathbf{w}_1 \mathbf{w}_2 \mathbf{w}_3 \mathbf{w}_4 \mathbf{w}_5]\ \mathbf{w}_c \quad (5)$$

The final weight vector w of priorities for this example, thus calculated and transposed, is [0.298, 0.215, 0.161, 0.221, 0.104]. Based on the structure of the hierarchy in this example and on the judgments specified, **w** represents the preferences for pursuing those five careers. A final consistency ratio can be calculated by determining a consistency index for the hierarchy as a whole and then dividing that value by the random index for a similarly structured hierarchy. To calculate a CI for the entire hierarchy, the CI for each judgment matrix is multiplied by the priority weight for the property for which the matrices comparisons are made; these are then summed for the entire hierarchy. Similar calculations are used to determine the random index. Consequently, for situations where individual judgment matrices are somewhat inconsistent, but have a low priority, those inconsistent judgments do not substantially affect the consistency of the entire hierarchy.

## An Integer Programming Model

Using the AHP as above, each I&M project can be given a value score indicating its contribution to the goals of an I&M program. Each project also requires some expenditure of I&M program money and personnel. Therefore, implementing projects only on the basis of their value does not necessarily make the most effective use of program resources. It is sometimes possible to use benefit-cost ratios as the selection criterion for such resource allocation problems (Saaty 1980, 1990a, Saaty and Vargas 1982). By using benefit-cost ratios, projects with the best economic payoff are the most desirable. The goal of I&M program planning, however, is to do the most I&M work for the given budget and personnel limitations, where "most" is defined as the greatest total program value. In addition, the benefit-cost approach does not apply when other program resource constraints such as personnel time are considered.

We used AHP-derived priority values as objective function coefficient estimates in an LP model. Linear programming then maximizes total program value, subject to constraints. Although the combination of AHP and linear programming has been used previously (Saaty 1986, Saaty and Kearns 1985), we formulated our approach independently. Mendoza and Sprouse ( 1989) used the AHP in combination with MOP, where the AHP was used to prioritize feasible solutions obtained from the LP model.

In programming, we used a zero/one integer approach. Each project $x_i$ is either implemented (1) or not implemented (0) in an I&M program. This 0/1 stipulation is relaxed in an Olympic National Park case study report (Peterson and others 1994) in which budget dollars and personnel time are allocated in units with nondiscrete, i.e., real number, values. For simplicity, we used the 0/1 integer formulation in this description. A solution for the integer programming problem, which describes an I&M program, consists of a vector $\mathbf{x} = [x_1, x_2, \ldots, x_n]$ where each $x_i$ is either 0 or 1. The value $w_i$ of each project for the total I&M program is taken from the weight vectors that are estimated using the AHP. Each project also has a budget requirement $c_i$ and a requirement for a certain number of full-time employee (FTE) years $t_i$. The resulting formulation is:

$$\begin{aligned} &\text{maximize } Z = \sum_{i=1}^{n} w_i x_i \\ &\text{subject to: } \sum_{i=1}^{n} c_i x_i \leq \text{total budget} \qquad (6) \\ &\qquad\qquad\quad \sum_{i=1}^{n} t_i x_i \leq \text{total FTEs} \end{aligned}$$

This is the minimum set of constraints that are important. It is also possible to include other constraints, such as restrictions on the timing of projects. For example, if a particular project to analyze snow chemistry (project 30) should not be performed until a geographic survey of snow accumulation has been completed (project 42), then the constraint $x_{42} \geq x_{30}$ would be added to the formulation above.

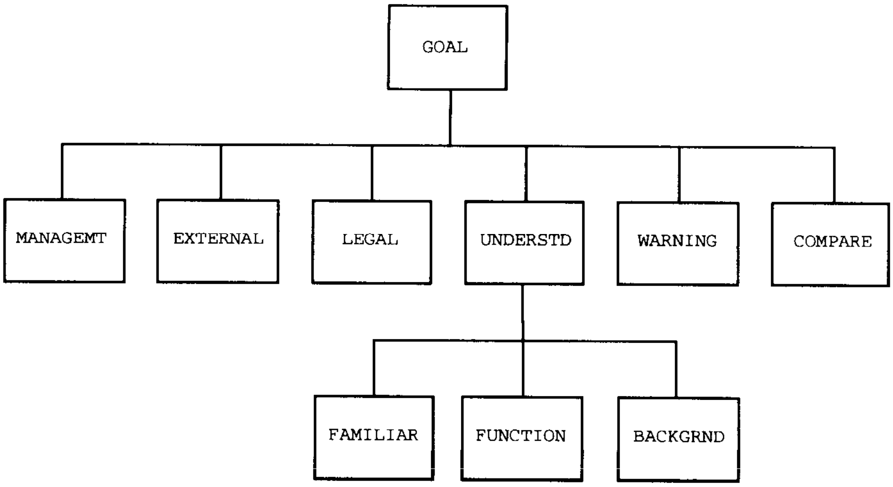
It should be emphasized that, as in any optimization problem, the result is only as realistic as the parameter values used in the calculations. More accurate budget or personnel estimates, or revised value judgments, may change the resulting I&M program. Iterative use of this planning process will ensure that the results are stable and acceptable. The following discussion illustrates how this I&M program planning process incorporates the AHP and constrained optimization.

## An I&M Planning Example

The AHP allows one to define criteria for establishing priorities in a straightforward yet powerful way. For example, priorities may be set for some aspect of an I&M plan based on economic and biological factors. The biological factors may be subdivided into several subfactors, such as endangered species status, susceptibility to air pollution, and geographic distribution. Each of these subfactors can be divided into subfactors at a finer resolution. The hierarchical process can continue for many levels to include all possibilities that should be considered. Rankings are assigned within each level of the process. The structure of the hierarchy may differ depending on the I&M topic in question. The linkages can obviously become quite complex after only a few levels and cannot be tracked efficiently with pencil and paper. Because such tedious calculations would distract an I&M program planner from the important task of providing judgments and would make the entire procedure inefficient, the AHP has been incorporated into the software package Expert Choice [Expert Choice, Inc., Pittsburgh, Pennsylvania (tradenames are used for informational purposes only; no endorsement by the US Department of Agriculture or the US Department of the Interior is implied)].

The AHP/EC (in the form of Expert Choice) allows one to apply hundreds of qualitative and quantitative assessments simultaneously to establish linkages and calculate final rankings quickly and accurately, a task that cannot be done with pencil and paper (or calculator). It allows a resource manager to explore the nature of decisions used to establish priorities in I&M planning. The planning–knowledge data base created in this way can be changed and updated at any time, so it is a flexible tool for planning and decision making.

A number of difficulties arise, however, when a decision includes more than a few alternatives. First, all alternatives must be compared in a pairwise fashion in the bottom level of the hierarchy. For $n$ alternatives, $n^2/2 - n/2$ comparisons must be made at each node in the bottom level. Second, computational complexity increases rapidly with matrices of increasing size. Third, it is difficult to consider more than seven alternatives simultaneously and still obtain consistent judgments. To deal with these problems within the AHP framework, AHP/EC enables one to create an intensity scale for each of the lowest-level criteria in the hierarchy. Then each of the decision alternatives is rated using those scales. AHP/EC provides a spreadsheet-like environment for rating each alternative with respect to each lowest-level criterion, using the




GOAL --- OVERALL RANKING OF PROJECTS
MANAGENT --- SUPPORT MANAGEMENT DECISION-MAKING
EXTERNAL --- INFLUENCE OUTSIDE DECISION-MAKERS
LEGAL --- SATISFY LEGAL MANDATES
UNDERSTD --- BETTER UNDERSTAND RESOURCES
FAMILIAR --- MAINTAIN FAMILIARITY WITH RESOURCES
FUNCTION --- UNDERSTAND ECOSYSTEM FUNCTION
BACKGRND --- PROVIDE BACKGROUND INFORMATION
WARNING --- EARLY WARNING OF GLOBAL OR REGIONAL PROBLEMS
COMPARE --- PROVIDE COMPARISON WITH UNEXPLOITED AREAS

**Figure 2.** The top level of the I&M hierarchy contains eight objectives, three of which can be organized as part of a more general objective. Abbreviated terms in the figure are explained in the legend.

intensity scale developed for that criterion. These intensity scales abandon the relative worth concept of paired comparisons in favor of absolute measures. Therefore, rank reversals (the substitution effect) that might occur when a new alternative is introduced to the analyses are no longer possible (Forman 1987). The rating scale implementation was used in this exercise because realistic I&M planning situations often include 30 or more different projects.

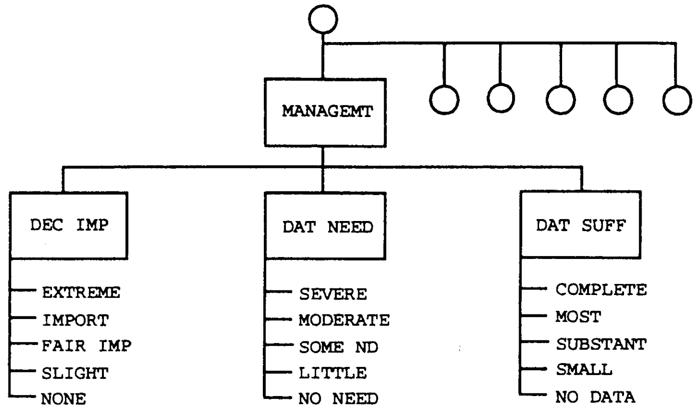
The model does not provide a wholly objective approach to assigning ratings to projects. Different users may get entirely different results, depending on the priorities given to different objectives and criteria, and the ratings assigned to each criterion for the individual projects. However, the model does compel the user to recognize and quantify decisions about the importance of different objectives when one project is chosen over another. The model helps to clarify the trade-offs and sort through the different alternatives, making the ranking process more explicit.

## Model Structure

The model is structured as a hierarchical arrangement of: (1) I&M objectives (at the highest level of the model), (2) criteria useful for rating projects with respect to each objective, (3) an intensity scale for rating each project with respect to each criterion, and (4) actual ratings for each project across all criteria.

The objectives are those described by Silsbee and Peterson (1991) and are illustrated in Figure 2. They can be assigned relative rankings in whatever way the user desires. A complete spectrum of possible score assignments exists, including: (1) one objective with maximum importance and all others with an importance of zero, (2) all objectives of equal importance, or (3) any combination of unequal rankings for different objectives. Projects that meet only one objective well are rated highly when that objective is important relative to the others; they are not rated highly if that objective is less important. Three subobjectives are specified for the major objective “better understand resources” in Figure 2; these must be ranked relative to their contribution to this major objective. They are then treated in a similar way as the remaining objectives in the model.

For each objective in the model, three to four criteria describe how well a project meets the objective. The user must assign one of five rating scores to each project for each criterion (e.g., see Figure 3). The




MANAGEMT --- SUPPORT MANAGEMENT DECISION-MAKING

DEC IMP --- HOW IMPORTANT IS THE DECISION?
DAT NEED --- WHAT IS THE NEED FOR DATA TO SUPPORT A DECISION?
DAT SUFF --- ARE THE DATA SUFFICIENT TO ASSIST WITH A DECISION?

EXTREME --- EXTREMELY IMPORTANT
IMPORT --- MODERATELY IMPORTANT
FAIR IMP --- FAIRLY IMPORTANT
SLIGHT --- SLIGHTLY IMPORTANT
NONE --- NOT IMPORTANT

SEVERE --- SEVERE NEED FOR DATA
MODERATE --- MODERATE NEED
SOME ND --- SOME NEED
LITTLE --- LITTLE NEED
NO NEED --- NO NEED

COMPLETE --- COMPLETE -- NO FURTHER DATA NEEDED
MOST --- PROVIDES MOST NEEDED DATA
SUBSTANT --- PROVIDES A SUBSTANTIAL AMOUNT OF NEEDED DATA
SMALL --- PROVIDES ONLY A SMALL AMOUNT OF NEEDED DATA
NO DATA --- DOES NOT PROVIDE DATA TO SUPPORT DECISION

**FIgure 3.** The first objective in the I&M hierarchy contains three criteria, each with a correspending rating scale.

scores are given descriptive names (e.g., extremely important, moderately important, etc.), but they are really just numerical scores ranging from satisfying the criterion extremely well to not satisfying it at all. It is easier in many cases to apply judgments based on word descriptions rather than to assign numerical values, but either one can be used. In assigning scores, it is more important to judge how well the project meets the criterion than to make it fit the words used in the model. The following objectives and criteria are included in our model of an I&M program.

### Support Management Decision-Making (Objective 1)

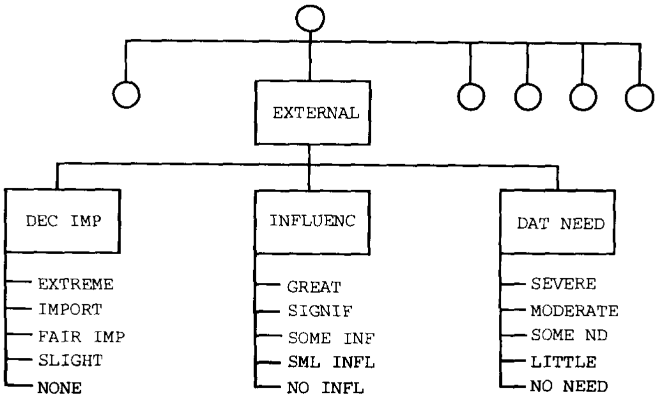
The three most important criteria for determining how well a project supports management decision making are (Figure 3):

1. How important the decision is for which supporting data are needed.
2. How badly the data are needed for an informed decision.
3. How well the project will provide the data needed for the decision.

### Influence External Decisions Affecting the Park (Objective 2)

The three most important criteria for determining how well a project provides data to support external decisions more favorable to the park are (Figure 4):

1. The importance to the park of the decision being made.
2. The potential for park managers to influence the decision.
3. The degree to which information from the project being considered will increase the influence of the NPS over the decision being made.




```
EXTERNAL     INFLUENCE OUTSIDE DECISION-MAKERS

DEC IMP --- HOW IMPORTANT IS THE DECISION?
INFLUENC --- WHAT IS THE POTENTIAL FOR INFLUENCING A DECISION?
DAT NEED --- WHAT IS THE NEED FOR DATA TO SUPPORT A DECISION?

EXTREME --- EXTREMELY IMPORTANT
IMPORT  --- MODERATELY IMPORTANT
FAIR IMP --- FAIRLY IMPORTANT
SLIGHT  --- SLIGHTLY IMPORTANT
NONE    --- NOT IMPORTANT

GREAT   --- GREAT INFLUENCE OVER DECISION
SIGNIF  --- SIGNIFICANT INFLUENCE OVER DECISION
SOME INF --- SOME INFLUENCE OVER DECISION
SML INFL --- SMALL INFLUENCE OVER DECISION
NO INFL --- NO INFLUENCE OVER DECISION

SEVER   --- SEVERE NEED FOR DATA
MODERATE --- MODERATE NEED FOR DATA
SOME ND --- SOME NEED FOR DATA
LITTLE  --- LITTLE NEED FOR DATA
NO NEED --- NO NEED FOR DATA
```

**Figure 4.** The second objective in the I&M hierarchy contains three criteria, each with a corresponding rating scale.

### Satisfy Legal Mandates (Objective 3)

The three most important criteria for determining how well a project satisfies legal requirements are (Figure 5):

1. The degree to which legal mandates are binding requirements.
2. Whether alternative ways to satisfy the legal mandates are available.
3. Whether data from the project will be sufficient to satisfy the legal mandates.

### Maintain Familiarity with Park Resources (Objective 4)

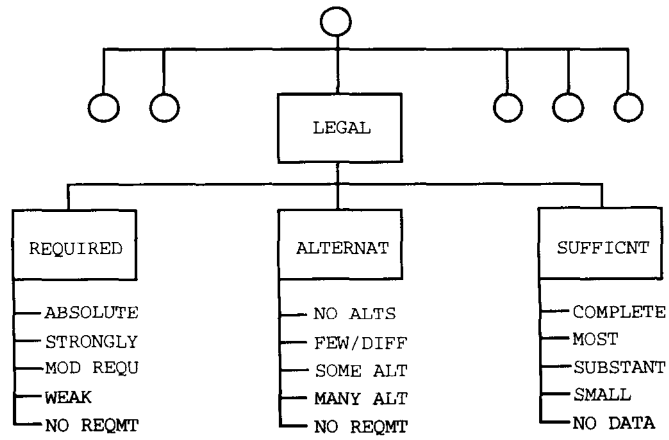
This is the first of three objectives that give resource managers a better understanding of natural resources. The four most important criteria for determining how well a project helps managers stay familiar with the resources with which they work are (Figure 6):

1. The importance of the resource involved in the project.
2. Whether the resource is changing.
3. The amount of current knowledge of the resource.
4. The degree to which the project will fill gaps in current knowledge.

### Understand Ecosystem Function (Objective 5)

This is the second of three objectives that give resource managers a better understanding of natural resources. The three most important criteria for determining how well a project helps improve understanding of ecosystem function are (Figure 7):

1. The importance of the resource involved in the project.
2. The amount of current knowledge of the resource.
3. The degree to which the project being considered will fill in gaps in current knowledge.




```
LEGAL    --- SATISFY LEGAL MANDATES

REQUIRED --- IS PROJECT REQUIRED BY LAW?
ALTERNAT --- ARE THERE ALTERNATIVE WAYS TO SATISFY THE LEGAL
             MANDATE?
SUFFICNT --- IS PROJECT SUFFICIENT TO SATISFY LEGAL
             MANDATE?

ABSOLUTE --- PROJECT ABSOLUTELY REQUIRED BY LAW
STRONGLY --- LEGAL REQUIREMENT IS QUITE STRONG
MOD REQU --- ONLY A MODERATE LEGAL REQUIREMENT
WEAR     --- PROJECT SATISFIES ONLY A WEAK LEGAL REQUIREMENT
NO REQMT --- NO LEGAL REQUIREMENT

NO ALTS  --- NO ALTERNATIVE WAYS TO MEET REQUIREMENT AVAILABLE
FEW/DIFF --- FEW ALTERNATIVES EXIST AND THEY ARE DIFFICULT OR
             EXPENSIVE
SOME ALT --- SOME ALTERNATIVES EXIST
MANY ALT --- MANY ALTERNATIVES EXIST
NO REQMT --- NO LEGAL REQUIREMENT

COMPLETE --- COMPLETE -- NO FURTHER DATA NEEDED
MOST     --- PROVIDES MOST NEEDED DATA
SUBSTANT --- PROVIDES A SUBSTANTIAL AMOUNT OF NEEDED DATA
SMALL    --- PROVIDES ONLY A SMALL AMOUNT OF NEEDED DATA
NO DATA  --- DOES NOT PROVIDE DATA TO SUPPORT DECISION
```

**Figure 5.** The third objective in the I&M hierarchy contains three criteria, each with a corresponding rating scale.

### Provide Background Information for Use by Other Projects and Programs (Objective 6)

This is the third of three objectives that give resource managers a better understanding of natural resources. The two most important criteria for determining how well a project provides useful background material are (Figure 8):

1. How useful the information will be.
2. Whether alternative sources of the information are available.

### Provide an Early Warning of Global or Regional Problems (Objective 7)

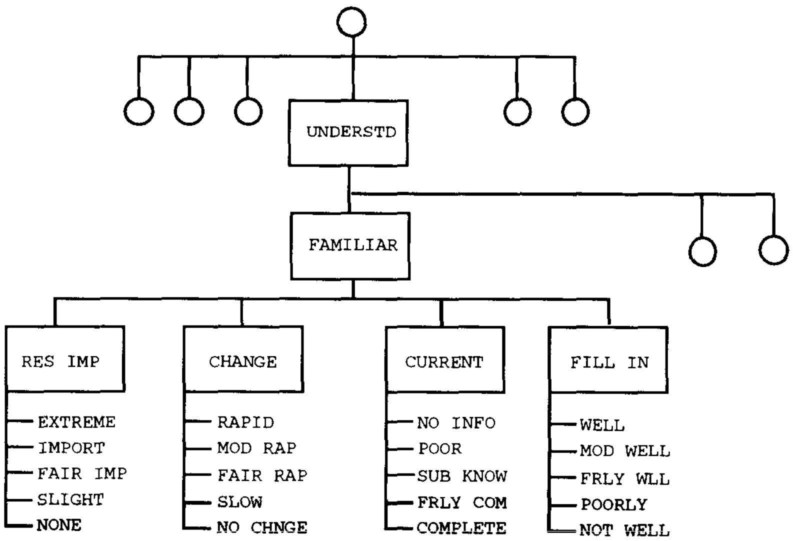
The three most important criteria for determining how well a project helps give an early warning of global or regional problems are (Figure 9):

1 The probability of the problem occurring.
2. The availability of alternative warnings.
3. The adequacy of the warning in providing early information about the problem.

### Provide Background Information against which Exploited Areas Outside the Park Can Be Compared (Objective 8)

The four most important criteria for determining how well a project helps provide background information for other areas are (Figure 10):

1. The regional importance of the resource involved in the project.
2. Whether alternative areas are available for the project.
3. How valuable the comparative information would be.




| | |
|---|---|
| FAMILIAR --- | MAINTAIN FAMILIARITY WITH RESOURCES |

| | |
|---|---|
| RES IMP --- | HOW IMPORTANT IS THE RESOURCE? |
| CHANGE --- | IS RESOURCE IN A STATE OF CHANGE? |
| CURRENT --- | HOW COMPLETE IS CURRENT KNOWLEDGE OF THE RESOURCE? |
| FILL IN --- | HOW WELL WILL THIS PROJECT FILL IN GAPS IN KNOWLEDGE? |

| | |
|---|---|
| EXTREME --- | EXTREMELY IMPORTANT |
| IMPORT --- | MODERATELY IMPORTANT |
| FAIR IMP --- | FAIRLY IMPORTANT |
| SLIGHT --- | SLIGHTLY IMPORTANT |
| NONE --- | NOT IMPORTANT |

| | |
|---|---|
| RAPID --- | CHANGE IS RAPID AND POTENTIALLY DRASTIC |
| MOD RAP --- | CHANGE IS MODERATELY RAPID OR POTENTIALLY DRASTIC |
| FAIR RAP --- | CHANGE IS FAIRLY RAPID OR SIGNIFICANT |
| SLOW --- | CHANGE IS PROBABLY SLOW OR UNIMPORTANT |
| NO CHNGE --- | NO CHANGE EXPECTED |

| | |
|---|---|
| NO INFO --- | NO INFORMATION CURRENTLY EXISTS CONCERNING THIS RESOURCE |
| POOR --- | CURRENT KNOWLEDGE IS POOR |
| SUB KNOW --- | SUBSTANTIAL KNOWLEDGE EXISTS CONCERNING RESOURCE |
| FRLY COM --- | FAIRLY COMPLETE -- RESOURCE IS WELL UNDERSTOOD |
| COMPLETE --- | COMPLETE -- NO FURTHER DATA NEEDED |

| | |
|---|---|
| WELL --- | DATA WILL SUPPLY MISSING PIECES WELL |
| MOD WELL --- | DATA WILL FILL GAPS MODERATELY WELL |
| FRLY WLL --- | DATA WILL FILL GAPS FAIRLY WELL |
| POORLY --- | DATA WILL NOT FILL GAPS OR WILL DUPLICATE EXISTING KNOWLEDGE |
| NOT WELL --- | DATA WILL DUPLICATE EXISTING INFO AND NOT ADD NEW KNOWLEDGE |

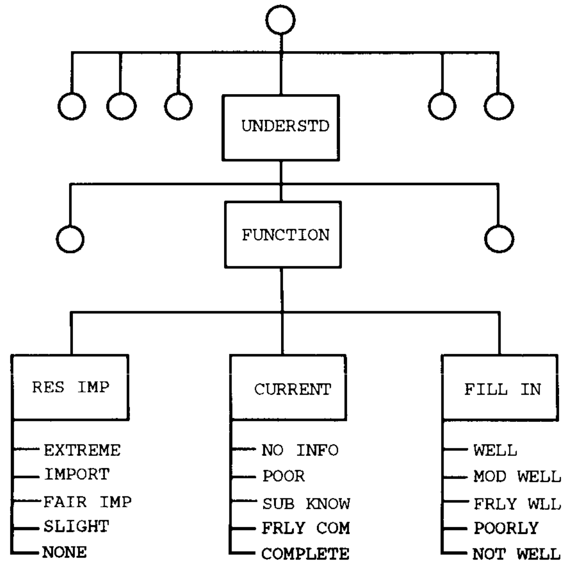
**Figure 6.** The fourth objective in the I&M hierarchy contains four criteria, each with a corresponding rating scale.

4. How well the park compares to the outside area involved.

## Rating I&M Projects

To illustrate how AHP/EC can be used to calculate rankings, we developed an example using projects that could be part of a national park's I&M program. The intention was to have a realistic range of projects with different scores for different objectives, and to establish project priorities for potential management scenarios. Twelve projects were used in the exercise: (1) status of rare plant populations, (2) ambient ozone concentrations (air quality), (3) status of large mammal populations (wildlife), (4) status of anadromous fish populations, (5) damage to alpine plants by hikers and campers, (6) maintenance of weather stations for collecting meteorological data, (7) wet and dry acidic deposition (atmospheric deposition), (8) nutrient cycling characteristics in a specific watershed, (9) avalanche forecasting in avalanche-prone areas, (10) collection and maintenance of herbarium specimens, (11 ) salmon carcass availability for bears and eagles, and (12) snowpack depth in various watersheds. These projects are listed in abbreviated style in Tables 4-6.

All pairs of objectives were compared with respect to the I&M program goal, and all pairs of criteria were




FUNCTION --- UNDERSTAND ECOSYSTEM FUNCTION

RES IMP --- HoW IMPORTANT IS THE RESOURCE?
CURRENT --- HOW COMPLETE IS CURRENT KNOWLEDGE OF THE RESOURCE?
FILL IN --- HoW WELL WILL THIS PROJECT FILL IN GAPS IN KNOWLEDGE?

EXTREME --- EXTREMELY IMPORTANT
IMPORT --- MODERATELY IMPORTANT
FAIR IMP --- FAIRLY IMPORTANT
SLIGHT --- SLIGHTLY IMPORTANT
NONE --- NoT IMPORTANT

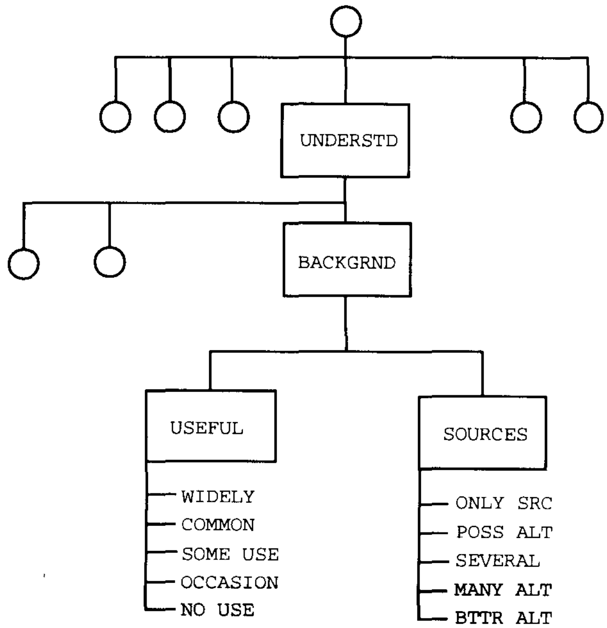
NO INFO --- NO INFORMATION CURRENTLY EXISTS CONCERNING THIS RESOURCE
POOR --- CURRENT KNOWLEDGE IS PoOR
SUB mow --- SUBSTANTIAL KNOWLEDGE EXISTS CONCERNING RESOURCE
FRLY COM --- FAIRLY COMPLETE -- RESOURCE IS WELL UNDERSTOOD
COMPLETE --- COMPLETE -- NO FURTHER DATA NEEDED

WELL --- DATA WILL SUPPLY MISSING PIECES WELL
MOD WELL --- DATA WILL FILL GAPS MODERATELY WELL
FRLY WLL --- DATA WILL FILL GAPS FAIRLY WELL
POORLY --- DATA WILL NOT FILL GAPS OR WILL DUPLICATE EXISTING KNOWLEDGE
NOT WELL --- DATA WILL DUPLICATE EXISTING INFO AND NOT ADD NEW KNOWLEDGE

**Figure 7.** The fifth objective in the I&M hierarchy contains three criteria, each with a corresponding rating scale.

compared with respect to each objective. Intensity scores were assigned for all criteria in all objectives of the prototype model (Figures 2–10) for each I&M project. These comparisons and rating scores are not listed here and are not critical to this discussion. They were assigned to maintain reasonable consistency for this exercise. The prototype model was used to rank the projects under five different scenarios with respect to the importance of the model objectives: (1) all objectives equal, (2) "support of management decision making" as the highest priority (other projects having lower priority), (3) "support of management decision making" as the only objective, (4) "influence on external decision makers" as the highest priority (other projects having lower priority), and (5) "influence on external decision makers" as the only objective. There are thousands of possible scenarios, but these are sufficient to illustrate the responsiveness of the model to different objectives.

Project ratings for the different scenarios are shown in Table 4. The table includes summary numerical ratings (with a maximum value of 1), priority values that were calculated by normalizing the rating values, and the ordinal rank for each project. The ratings are weighted scores for each project summed over all criteria. If a particular project scored highest on all criteria, that project would have the maximum value of 1. We can normalize these rating values to provide an estimate of the relative worth of different projects. "Status of rare plants" is the highest priority project when all objectives have equal importance, and its priority rating changes very little across the first four scenarios, even though its ranking varies between one and five. This project drops to a rank of




BACKGRND --- PROVIDE BACKGROUND INFORMATION

USEFUL --- HOW WIDELY WILL INFORMATION BE USED?
SOURCES --- ARE OTHER SOURCES OF INFORMATION AVAILABLE?

WIDELY --- DATA WILL BE WIDELY USED IN MANY APPLICATIONS
COMMON --- DATA WILL BE COMMONLY USED
SOME USE --- INFORMATION WILL BE USED IN SOME APPLICATIONS
OCCASION --- INFORMATION WILL ONLY OCCASIONALLY BE USED
NO USE --- INFORMATION WILL NOT BE USED

ONLY SRC --- THIS PROJECT IS THE ONLY SOURCE OF THIS INFORMATION
POSS ALT --- POSSIBLE ALTERNATIVES, BUT EXPENSIVE OR UNSATISFACTORY
SEVERAL --- SEVERAL POSSIBLE SOURCES OF THIS INFORMATION
MANY ALT --- MANY ALTERNATIVES EXIST
BTTR ALT --- BETTER ALTERNATIVES EXIST

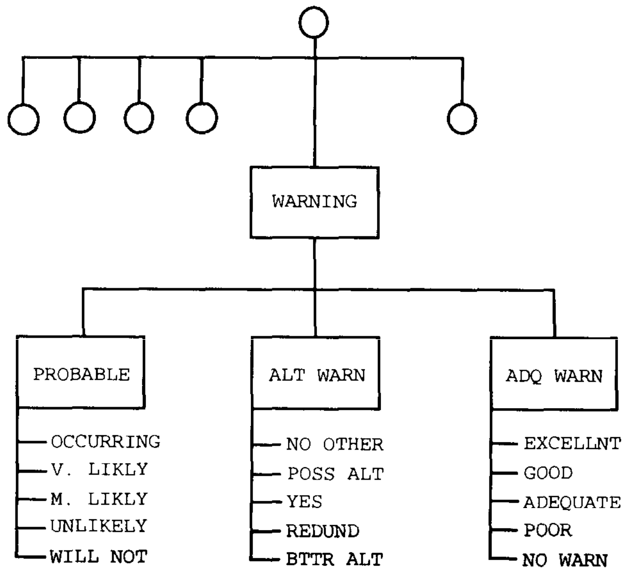
**Figure 8.** The sixth objective in the I&M hierarchy contains two criteria, each with a corresponding rating scale.

fifth when "support of management decision making" is the only objective; "status of large mammal populations (wildlife)" then has highest priority. Other projects, such as "status of anadromous fish populations" and "maintenance of weather stations," vary substantially in rating and priority scores, but do not shift more than two positions in rank across different scenarios.

This example shows that project importance, and hence priority, depends heavily on the relative importance of various model objectives. Furthermore, the prototype model was rather sensitive to the criteria scores used in the example. Rankings vary on both a relative (ordinal) and absolute (numerical) bases. Because we feel that this is a realistic example, we expect similar model sensitivity inmost I&M planning situations.

## Allocation of I&M Program Resources

Continuing with this abbreviated I&M example,we formulated the resource allocation portion of the planning problem. Priority values estimated from the AHP exercise were used as coefficients in the integer programming objective function. Table 5 contains the coefficients for the two constraint equations. Budget and FTE values for each of the 12 projects were borrowed from the 1990 resource management plan of Olympic National Park in Washington, USA. Allocations for 38 funded projects in 1990 were $860,700 and 21.8 FTEs. We calculated the appropriate proportion to approximate these figures for our example with only 12 projects. Integer programming solutions for each of the scenarios of Table 4 are summarized in Table 6, given a total budget of $271,800 and 6.88




WARNING --- EARLY WARNING OF GLOBAL OR REGIONAL PROBLEMS

PROBABLE --- HOW PROBABLE IS IT THAT THE PROBLEM WILL OCCUR?
ALT WARN --- ARE ALTERNATIVE WARNINGS AVAILABLE?
ADQ WARN --- WILL PROJECT PROVIDE ADEQUATE WARNING?

OCCURRNG --- PROBLEM IS ALREADY OCCURRING
V. LIKLY --- PROBLEM IS VERY LIKELY TO OCCUR
M. LIKLY --- PROBLEM IS MODERATELY LIKELY TO OCCUR
UNLIKELY --- PROBLEM IS UNLIKELY TO OCCUR
WILL NOT --- PROBLEM WILL NOT OCCUR OR WARNING IS NOT AN ISSUE FOR THIS PROJECT

NO OTHER --- NO OTHER WARNING EXISTS
POSS ALT --- POSSIBLE ALTERNATIVES, BUT EXPENSIVE OR UNSATISFACTORY
YES --- ALTERNATIVES EXIST, BUT PROJECT WOULD BE A SIGNIFICANT ADDITION
REDUND --- THIS PROJECT WOULD MERELY REPEAT EXISTING WARNINGS
BTTR ALT --- BETTER ALTERNATIVES EXIST

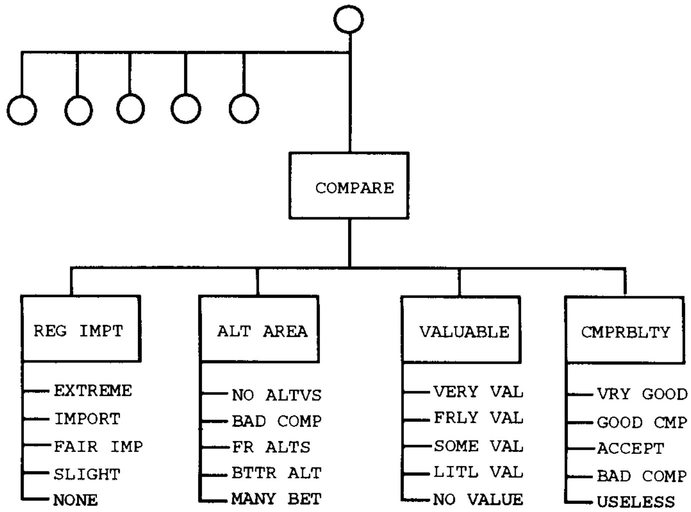
EXCELLNT --- PROJECT WILL PROVIDE EXCELLENT WARNING
GOOD --- PROJECT WILL PROVIDE GOOD WARNING
ADEQUATE --- PROJECT WILL PROVIDE ADEQUATE WARNING
POOR --- PROJECT WILL PROVIDE ONLY A POOR WARNING SYSTEM
NO WARN --- PROJECT WILL NOT SERVE ANY PURPOSE AS AN EARLY WARNING SYSTEM

**Figure 9.** The seventh objective in the I&M hierarchy contains three criteria, each with a corresponding rating scale.

FTEs. Total I&M program values are listed in the last row of the table.

The different l&M program scenarios displayed in Table 6 are optimal-on the basis of the priorities assigned to I&M objectives and criteria, the ratings of each project with respect to criteria intensities, and the constraint coefficients provided. “Rare plants” and “wildlife” projects are implemented in all programs of Table 6. Each has high value to an I&M program and has low to moderate cost. "Nutrient cycling," on the other hand, has low to moderate value to I&M programs and has very high requirements for I&M resources. Therefore, “nutrient cycling” is not implemented in any of these I&M programs for any of the scenarios. In addition to “rare plants” and “wildlife, ” “fish status,” “snowpack,” and “salmon carcass” are each implemented in all optimal programs. The latter two projects have very low cost, while ”fish status” has both high value for I&M and moderate cost. In this formulation, projects with greater relative “bang for the buck” are selectively favored over those with less.

Our integer programming algorithm employed a branch and bound solution method. In this procedure, certain branches of the solution space are bounded as particular solutions are tried. When an integer solution in one branch exceeds the upper bound of another branch, then the latter branch is




COMPARE --- PROVIDE COMPARISON WITH UNEXPLOITED AREAS

REG IMPT --- HOW IMPORTANT IS RESOURCE REGIONALLY?
ALT AREA --- ARE ALTERNATIVE UNEXPLOITED AREAS AVAILABLE FOR WORK?
VALUABLE --- HOW VALUABLE WILL THE INFORMATION BE?
CMPRBLTY --- HOW GOOD IS THE COMPARISON OF SITES?

EXTREME --- EXTREMELY IMPORTANT
IMPORT --- MODERATELY IMPORTANT
FAIR IMP --- FAIRLY IMPORTANT
SLIGHT --- SLIGHTLY IMPORTANT
NONE --- NOT IMPORTANT

NO ALTVS --- NO ALTERNATIVE AREAS AVAILABLE
BAD COMP --- ALTERNATIVE AREAS HAVE MAJOR DRAWBACKS
FR ALTS --- FAIR ALTERNATIVES EXIST
BTTR ALT --- BETTER ALTERNATIVES EXIST
MANY BET --- MANY BETTER ALTERNATIVES EXIST

VERY VAL --- PROJECT WILL PROVIDE VERY VALUABLE DATA
FRLY VAL --- PROJECT WILL PROVIDE FAIRLY VALUABLE INFORMATION
SOME VAL --- PROJECT WILL HAVE SOME VALUE
LITL VAL --- PROJECT WILL HAVE LITTLE VALUE
NO VALUE --- DATA WILL HAVE NO VALUE

VRY GOOD --- VERY GOOD COMPARISON
GOOD CMP --- GOOD COMPARISON
ACCEPT --- ACCEPTABLE COMPARISON
BAD COMP --- POOR COMPARISON
USELESS --- USELESS COMPARISON

**Figure 10.** The eighth objective in the I&M hiearchy contains four criteria, each with a corresponding rating scale.

fathomed and does not have to be examined further. When all branches, except one, are fathomed, then the best integer solution of the remaining branch becomes the optimal integer solution for the problem. Because our example has few variables and constraints, there were only six to eight branches created in each analysis. To find a near optimal solution for a particular analysis, we treated each of the other branches in the problem as a new integer programming problem. When we found an integer solution that exceeded the best integer solutions (or upper bounds) of the other branches, we knew that this was the second best objective function solution. Of course, there may be multiple integer solutions that produce the same second-best objective function value. The near optimal program is within 10% of the optimal program in all scenarios. This result may mean that some budget and personnel time can be reserved by using a near optimal program, without substantially reducing I&M program utility.

Total program values (Table 6) are determined by priority ratings that depend on different program objectives as described by the different scenarios. In realistic situations, any particular park has only a single set (scenario) of importance ratings for I&M objectives, although these ratings may change over time. We introduced a variety of scenarios to demonstrate the workings of the approach. For the two scenarios in which there is a single objective, such as management only or external influence only, certain projects that

Table 4. Different scenarios of importance for the eight objectives of the model produce different project ratings, priorities, and rankings[a]

| | All objectives equal | | | Management has highest priority | | | Management only | | | External influence has highest priority | | | External influence only | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Project | Rating | Priority | Rank | Rating | Priority | Rank | Rating | Priority | Rank | Rating | Priority | Rank | Rating | Priority | Rank |
| Rare plants | 0.629 | 0.130 | 1 | 0.631 | 0.131 | 1 | 0.64 | 0.135 | 5 | 0.603 | 0.130 | 2 | 0.5 | 0.132 | 4 |
| Air quality | 0.597 | 0.123 | 2 | 0.477 | 0.099 | 5 | 0.0 | 0.000 | 10 | 0.637 | 0.137 | 1 | 0.8 | 0.211 | 1 |
| Wildlife | 0.488 | 0.101 | 3 | 0.554 | 0.115 | 2 | 0.82 | 0.173 | 1 | 0.51 | 0.110 | 4 | 0.6 | 0.158 | 3 |
| Fish status | 0.476 | 0.098 | 4 | 0.52 | 0.108 | 3 | 0.7 | 0.148 | 4 | 0.52 | 0.112 | 3 | 0.7 | 0.184 | 2 |
| Alpine plants | 0.455 | 0.094 | 5 | 0.515 | 0.107 | 4 | 0.76 | 0.160 | 2 | 0.363 | 0.078 | 6 | 0.0 | 0.000 | 10 |
| Weather stations | 0.402 | 0.083 | 6 | 0.425 | 0.088 | 6 | 0.52 | 0.110 | 6 | 0.334 | 0.072 | 7 | 0.067 | 0.018 | 8 |
| Atmospheric dep. | 0.375 | 0.077 | 7 | 0.3 | 0.062 | 8 | 0.0 | 0.000 | 10 | 0.38 | 0.082 | 5 | 0.4 | 0.105 | 6 |
| Nutrient cycling | 0.347 | 0.072 | 8 | 0.297 | 0.062 | 9 | 0.1 | 0.021 | 9 | 0.317 | 0.068 | 8 | 0.2 | 0.053 | 7 |
| Avalanche forecast | 0,306 | 0.063 | 9 | 0.396 | 0.082 | 7 | 0.76 | 0.160 | 2 | 0.244 | 0.053 | 10 | 0.0 | 0.000 | 10 |
| Herbarium | 0.28 | 0.058 | 10 | 0.224 | 0.046 | 12 | 0.0 | 0.000 | 10 | 0.224 | 0.048 | 11 | 0.0 | 0.000 | 10 |
| Salmon carcass | 0.257 | 0.053 | 11 | 0.249 | 0.052 | 10 | 0.22 | 0.046 | 7 | 0.305 | 0.066 | 9 | 0.5 | 0.132 | 4 |
| Snowpack | 0.238 | 0.049 | 12 | 0.234 | 0.049 | 11 | 0.22 | 0.046 | 7 | 0.197 | 0.043 | 12 | 0.033 | 0.009 | 9 |

[a]Priority values are normalized rating scores.

Table 5. Budget and FTE values are from 1990 resource management plan of Olympic National Park[a]

| Project | Project cost ($1000) | Project FTE (person-years) |
|---|---|---|
| Rare plants | 24.0 | 0.70 |
| Air quality | 96.5 | 0.30 |
| Wildlife | 57.5 | 1.75 |
| Fish status | 41.0 | 1.75 |
| Alpine plants | 17.5 | 1.00 |
| Weather stations | 42.8 | 0.10 |
| Atmospheric deposition | 42.0 | 1.40 |
| Nutrient cycling | 150.0 | 2.20 |
| Avalanche forecast | 5.5 | 0.15 |
| Herbarium | 15.4 | 0.41 |
| Salmon carcass | 35.0 | 0.80 |
| Snowpack | 8.3 | 0.04 |
| Total available | 271.8 | 6.88 |

[a]These values are used as the coefficients in the integer programming constraint equations.

score high on those "emphasis" areas have very high priority values (see Table 4). These high values, in turn, enable a program to achieve a higher total program value within the limited budget, and fewer projects are required to do so. In the limiting case, the maximum total program value of 1 would be realized when all projects with a priority greater than O could be implemented. From Tables 4 and 6, it appears that maximum program value can most easily be accomplished by selecting I&M objectives that target very narrow emphasis areas.

Assuming reasonably accurate estimates for project costs and FTEs, successive steps in this planning process would revise criteria importance and/or project ratings and then examine their effects on optimal I&M programs.

## Applications

An initial list of projects can be elicited in several ways. First, a standard taxonomy can be used to classify various types of I&M projects (National Park Service 1992, Peterson and others 1993) considered for funding. Second, the AHP itself can be used for project identification. By creating a model for I&M planning, one is forced to conceptualize what the essential features of I&M are for a particular park or region. Once these features have been specified, resource management specialists can identify I&M projects that are valuable for those objectives. Third, a group-think method, such as brainstorming, nominal group technique, or the Delphi technique, can be used with resource management specialists to produce a list of projects. In addition to these approaches, many nongroup methods could be devised to create a list of potential I&M projects.

Most national parks have at least a few components of resource management that can be categorized as I&M. Many parks have a long list of proposed I&M projects, although typically, park management will be able to authorize or fund only a few of them. The prototype model allows managers to list all of their proposed I&M projects, then evaluate them with respect to technical information as well as their own personal judgment. Rankings for the example used in this paper are based on existing information and knowledge, with a minimum of personal bias concerning political or other issues.

Resource management planning by federal agencies is often influenced by various political issues and

Table 6. Integer programming decision variables indicate implemented (1) projects and nonimplemented (0) projects[a]

| | All objectives equal | | Management has highest priority | | Management only | | External Influence has highest priority | | External influence only | |
|---|---|---|---|---|---|---|---|---|---|---|
| Project | Optimal program | Near optimal program | Optimal program | Near optimal program | optimal program | Near optimal program | optimal program | Near optimal program | optimal program | Near optimal program |
| Rare plants | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Air quality | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 1 |
| Wildlife | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Fish status | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Alpine plants | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |
| Weather stations | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 |
| Atmospheric dep. | 0 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| Nutrient cycling | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Avalanche forecast | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| Herbarium | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 |
| Salmon carcass | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 |
| Snow pack | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0 |
| Program value | 0.728 | 0.707 | 0.777 | 0.736 | 0.979 | 0.886 | 0.712 | 0.712 | 0.824 | 0.816 |

[a]The different scenarios of importance for the eight management objectives result in different optimal selections of projects to implement. One near optimal program is also included for each scenario.

the personal bias of individual resource managers. The model can be used to incorporate any agenda that a park might wish to include in an I&M program. For example, a park may wish to emphasize "air pollution monitoring" based on its importance as an early warning of damage to vegetation. Scores can be assigned for objectives and criteria such that "air pollution monitoring" will receive a high ranking relative to other projects. Scores within various components of the model can be manipulated so that a desired outcome is obtained. The model quantifies I&M priorities and provides a rational justification for proposed I&M projects and budget requests.

Although one person may have responsibility for administering an I&M program, several people normally provide input to the development of the program. There are so many pieces of information and so many decisions involved in developing a coherent program that it can be difficult to obtain a consensus on all of them. The AHP/EC model can integrate divergent opinions by calculating mean values for each comparison in the model. The final ranking is then truly a group product; it does not reflect the bias of one individual, or require anyone in the group to mediate or make a final judgment. Ratings from individuals can be weighted if that is desirable, perhaps with extra weight given to subject matter experts for different resource areas.

I&M is currently just one component of the resource management plans of most-national parks. It may or may not be identified as a discrete program in a park's plan. The sizes of overall plans and I&M programs vary greatly depending on park size and resource diversity. The I&M programs of some large parks may be larger than the entire resource management program for some small parks. In any case, the evaluation and prioritization required for the development of a resource management plan is nearly identical to that required for an I&M program. Only the scale differs. Because of the parallels between resource management and I&M planning, we feel that the prototype model (or similar AHP approach) can provide an analytical framework for resource management planning, especially for ranking project priorities.

Resource management projects of many kinds are often closely related, logically and practically, over several years. It is therefore important to use a multiple-year horizon for planning. Our example has not explicitly included this aspect of planning, but it can be easily accommodated. Decision variables can be indexed by planning year as well as by project. Projects can then be funded when they become most important for the specified planning objectives.

## Conclusions

This example has dealt with only a small number of I&M projects, but the outcome highlights some important issues. The substantial differences in I&M programs resulting from different I&M objectives suggest that national parks must clearly identify: (1) what I&M is to be used for and (2) how I&M relates to larger resource management objectives. These decisions can have a tremendous impact on which I&M projects can be justified. For example, nutrient cycling projects will have to provide much greater value for the selected objective before their high costs can be justified. The proposed planning process offers a framework in which I&M and resource management planning issues can be explicitly addressed and quantified.

One of the most valuable aspects of AHP/EC is the ease with which users can observe the effects of changes in various components on model output. Values can be changed at will to determine how modifications in objectives change I&M priorities. For example, an emphasis on "support of resource management decision making" could be replaced by an emphasis on "satisfy legal mandates. " The relative change in I&M project rankings would indicate the sensitivity of the model to current inputs. The effect of changing the emphasis of objectives and individual criteria scores can be seen by making large or small changes. This exercise also allows a manager to determine how different management objectives would affect the overall rankings; while one project might be favored by a change in objectives, one or more other projects might drop in priority.

It is mathematically possible to estimate inconsistencies in judgment whenever pairwise judgments are made using AHP. AHP/EC calculates a value that indicates if an inconsistent pattern of judgments is borne out by the user's pairwise rankings. Inconsistencies are sometimes appropriate, and the capability of the model to detect them allows the user to decide if they should be retained.

In some cases, a park may have a strong interest in one particular I&M project, or it may be able to support only a few projects. The huge amount of information contained in the AHP/EC model permits a resource manager to examine the conceptual basis for an I&M project in great detail. Branches and decision structures can be added as necessary for an individual project without affecting the evaluation of other projects. Components can be added or deleted, and criteria can be changed as necessary for different situations. Although the current form of the model is preliminary, a reasonably fixed model structure is preferable as the basis for future I&M planning. Considerable model testing and review will be necessary before this final model structure is determined.

Resource management planning and I&M planning are complex and will never be turnkey processes. AHP permits a systematic treatment of subjective judgments about preferences, priorities, and likelihoods; it does not make decisions, it facilitates decision making. In I&M planning, AHP helps to: (1) organize complexity, (2) incorporate quantitative information as well as knowledge and intuition based on years of experience, (3) consider trade-offs among competing criteria, (4) determine the best program alternatives, (5) communicate the rationale for a decision to others, and (6) incorporate group judgments. The current processes to develop resource management plans and I&M programs can be improved by incorporating the AHP to make them more explicit, rational, analytical, defensible, and consistent.

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