Application of Renewable Natural Resource Modeling in the Public Decision-making Process

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APPLICATION OF RENEWABLE NATURAL RESOURCE MODELING IN THE PUBLIC DECISION-MAKING PROCESS

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SUMMARY. Renewable natural resource management (e.g., fisheries, forestry, and wildlife) is the practice of analyzing, making, and implementing decisions to maintain or alter the structure, dynamics, and interactions of habitat, biota, and man to achieve specific human goals and objectives *through* the natural resource. The purpose of this paper is to place ecosystem modeling into a natural resource management framework. Managers usually predict the consequences of a proposed decision in a number of ways, including rules of thumb, past experience, population models, experimentation, trial and error, and pure guess. A key problem in making accurate predictions of the consequences of a proposed management decision is the complexity of most natural resource systems. Historically, arithmetical calculation has been the major problem with using mathematical models in management, but this problem has been solved to some degree by simulating fisheries, forests, or wildlife resource systems. Most natural resource and ecosystem models are quite similar in approach and philosophy, but there is substantial variation between models when viewed according to their intended purpose. Models used in natural resources management may be classified as to habitat, biological, or social type, or combinations of these three categories. Natural resource systems, when viewed holistically, include ecological and social aspects. The future role of modeling in all types of management may or may not be great and depends in large measure on the relationship between modelers and decision-makers.

KEY WORDS. Modeling, decision-making, management, fisheries, wildlife.

1. INTRODUCTION

Natural resource management is the practice of analyzing, making, and implementing decisions to maintain or alter the structure, dynamics, and interactions of habitat, biota, and man to achieve human goals and objectives through the natural resource. When one considers the number and diversity of components which constitute a renewable natural resource system, a fishery for example (i.e., fishes, plankton, bottom animals, rooted plants, chemical and physical water characteristics, various types of anglers, and related commercial activities), the true complexity becomes apparent. A slight change in part of a fishery may result in substantial changes in another, seemingly unrelated part. To use the example of a fishery further, they are particularly complex when a recreational component is present. There are often many game fish populations to consider (e.g., bass, bluegill, crappie, catfish, and miscellaneous sunfishes in warmwarter systems). Angler diversity is also large. Some anglers exclusively pursue a single fish species, while many exhibit little species preferences. Management strategies for a trophy fishery may very much differ from those of a multispecies, family type fishery.

Prediction is the essence of natural resource management. Managers usually predict the consequences of a proposed decision in a number of ways, including rules of thumb, past experience, population models, experimentation, trial and error, and pure guess. None of these ways is totally acceptable as a predictive tool, but all have a place in fisheries management.

A key problem in making accurate predictions of the consequences of a proposed management decision is the complexity of most natural resource systems. Even if some components of a system are well understood, the number of interrelationships makes accurate prediction difficult. The dynamic aspects of a system are also important because *rates* of change in components are as important as the components themselves. For example, the growth rate of an *individual* fish is affected by *all* components of the fishery, even though some of those linkages may be obscure.

1.1. Definitions.

A good point to start an analysis of renewable natural resource management and models is by defining the system of concern: a natural resource system (either recreational or

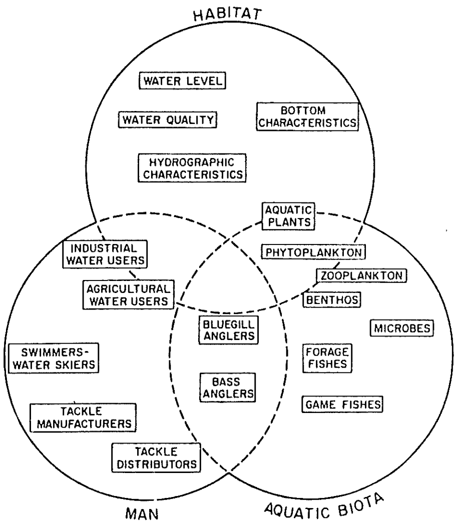


FIG. 1: Graphical model of a generalized freshwater recreational fishery. Only major system components are included.

commercial) is a system composed of *habitat*, animal and plant populations (*biota*), and *man* (Figure 1). In a broad sense, fisheries, wildlife, and forestry are the study of the structure, dynamics, and interactions of habitat, biota, and man, and the achievement of human goals and objectives through use of the resource. Management is the analysis and implementation of decisions to meet human goals and objectives through use of the resource (Lackey, 1974).

Another concept needs to be clarified for the purpose of subsequent discussion: in a general sense, a *model* is simply an abstraction of a system. Models may be verbal, graphical, physical, or mathematical (including computer-implemented models). However, renewable natural resource modeling nowadays usually connotes modeling of a mathematical nature.

Time is a constraint in attempting to predict the consequences of management decisions. Given that a number of potential decisions are being considered, considerable time would be needed to adequately investigate each alternative. Time and cost are related: how much of a budget is available for predicting the consequences of management decisions? Any method which can facilitate decision analysis in management would be highly useful, especially if additional funding were not required. Realistically, a manager may have several major systems to manage with the assistance of an assistant or two.

1.2. Models. There is nothing inherently exotic about modeling or models; we all use models intuitively. A model may be simply a *verbal* abstraction, such as once fish reach a certain size, that age class will die at a fairly constant rate (Figure 2). Fisheries may also be described via *graphical* models (Figure 1 and 2). The importance of verbal and graphical models in management lies in their initial simplifying description of complex phenomena. Modeling breaks a complex system, a natural resource system, into components. In this way we can begin to realize what parts are related and the general trends of these relationships (inverse relationship or direct relationship). Using graphical models (Figure 2), the relationship is more vividly expressed so that they may be useful in preliminary decision analysis.

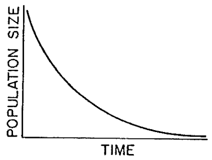
MODEL TYPE	EXAMPLE
VERBAL	"ONCE FISH REACH A CERTAIN SIZE, THAT AGE CLASS WILL DIE AT A FAIRLY CONSTANT RATE."
GRAPHICAL	
MATHEMATICAL	$N_t = N_0 e^{-Zt}$ WHERE, N_t = POPULATION SIZE AT TIME = t N_0 = POPULATION SIZE AT TIME = 0 e = NATURAL BASE Z = TOTAL MORTALITY RATE t = TIME (GREATER THAN 0)

FIG. 2. Verbal, graphical, and mathematical models of population change over time. Each model can be useful in management, depending on the desired use.

Another kind of model utilized *physical* representation of the system under consideration. For example, a laboratory model of a reservoir may be built to test waterflow patterns resulting from various water release schemes. Some scientists have utilized aquaria to study fish population dynamics. In fact, almost all laboratory studies in fisheries science are controlled such that the effect of an isolated few may be discerned. Though controlling variables highly simplifies the system, the laboratory model is still a useful physical representation of the real system in some kinds of management situations.

The most rigorous type of model is that utilizing mathematics to describe a system (Figure 2). *Mathematical* models, until the last decade or two, have been relatively simple largely because analytical tools have not been available to solve complex systems of equation. It is often stated that a certain amount of calculation, which could be done by many workers over several months using calculators, can be accomplished on a computer in few minutes. Practically speaking, hand calculation is often impossible in all but the simplest modeling work.

Arithmetical calculation has been a major problem with using mathematical models in natural resource management, but it has been solved to some degree by simulating systems. Simulation is done by coding mathematical relationships in computer language for numerical analysis. In this way, time can be expanded or contracted to investigate important aspects of the system. For example, 10 years of fish catch may be simulated in seconds; and seconds of a physiological process concerning a fish may be simulated in minutes.

Closely related to the analytical capability of computers is the option to use logic statements in arithmetical analyses. For example, in a computer program you may hypothesize: IF we fertilize this lake with phosphorus, THEN the growth of largemouth bass can be predicted by the following relationship . . . IF not, THEN the relationship will be . . . . Using computer programming logic statements, we can approximate relationships over the range of the variables with which we are concerned.

The purposes of computer simulation in natural resource management are to improve understanding of the system, enhance decision analysis, and, in turn, benefit management. Computer simulation is characterized by: (1) providing a framework for describing complex systems; (2) allowing rapid and inexpensive evaluation or alternative management strategies; (3) identifying gaps in available data; and (4) forcing the modeler to organize his thoughts into formal statements.

Providing a framework for describing complex systems can be a very useful role of simulation. Each component of a system is in itself relatively simple. For example, changes in individual populations may show that the population level of one age class of a species affects young-of-the-year of another species. Similar relationships between other components may also be determined. Very rapidly, however, the model becomes extremely complex. The relationships must be systematically written in logical and arithmetic statements (computer simulation) for bookkeeping by computer.

A manager is continuously faced with the question: "What will happen *if* I follow a particular management strategy?" Often computer simulation is the tool best suited to address such a question. For example, if we had constructed a good simulation of a fishery, a manager could examine the probable impact of changing angling regulations, stocking schemes, or habitat alteration.

One of the least appreciated aspects of modeling and simulation is their relation to raw data. Deciding which and how much data to collect is a difficult decision in management. Data are expensive to collect, analyze, and interpret. Simulation is a clear and formal statement about current understanding of the system at hand. In use, a simulation may make one painfully aware of gaps in the data base and how useful various pieces of data are. Simulation can thus serve to identify the type of data to be collected, and its location and frequency of collection.

Developing computer simulators are very definitely learning experiences (Titlow and Lackey, 1974). A modeler must state his perhaps hazy thoughts in a very exact manner. Relationships that the modeler had never considered must now be addressed and his best estimates provided. The self-teaching aspects of modeling may well be its most beneficial aspect.

2. GOALS AND OBJECTIVES

A management *objective* is a statement of the desired result of a decision or set of decisions. At least in classical management terminology, an objective is not equated with a *goal*, which is defined as the end toward which a design tends; that is, an ideal or aim which is usually expressed in general and abstract terms. A few examples of goals in renewable natural resource management are: best or wisest use of resources, conservation, protection, and enhancement of the resource; and providing the greatest amount of recreational opportunity for the greatest number of people. A goal is a value to be sought, not an object to be achieved. Goals provide general direction to agency programs and are useful in public relations, but clear, sound objectives are vital to fulfilling goals.

Objectives have been described from many vantage points. Uleck (1971) defined what he called "ends" as aspirations for preferred states or conditions. Meier and Thornton (1973) defined an objective as an end point to be reached, and capable of attainment and measurement. Anderson (1972) states that an objective is simply a more specific goal. Goals and objectives are not absolutes, but decision elements in a system. Besides serving as targets for management, goals and objectives give identity to the agency, imply its system of values, define the type of information required in decision-making, help describe the most effective personnel, and provide inspiration to personnel.

However, defined, objectives have some very important properties which affect their use in natural resource management and modeling: (1) objectives are clearly stated; (2) objectives are specific and not filled with broad, general terms; (3) objectives are quantifiable, if not empirically, then subjectively; and (4) objectives have a performance measure in order to evaluate progress (Anderson 1972). Objectives and goals may also be arranged in hierarchies or chains. In a goal chain, a goal or objective is an end when viewed from the lower end of the chain, and a means when viewed from higher in the chain. Uleck (1971) combines the properties of objectives in the term "operational," which implies that progress toward objectives can be measured objectively and that all costs and benefits of striving toward objectives can be foreseen and estimated. Objectives are made operational, according to Uleck, by: (1) making objective statements clear and specific; and (2) stating objectives in terms which indicate constraints, benefits, and costs. Uleck also emphasized that objectives must be capable of being utilized in all planning steps and, most importantly, be acceptable to the affected public. Objectives must be oriented toward satisfying people through use of the natural resource.

Effective management of any system is based upon clear and formally stated objectives. However, many natural resource management agencies may have no formal objectives or may have ambiguous statements such as best or wisest use of a particular resource system (Lackey, 1974). The soft objectives serve well as broad goals and are acceptable to the general public, but sound objectives need to accompany goals for effective management to occur.

Most managers have recognized the inherent difficulties of operating without functional objectives, and have also tried to substitute measurable objectives. Historically, the most common objective has been to maximize pounds or numbers of fish, ducks, or deer on a sustained basis. Some common variants are to maximize yield of a certain species or to maximize catch or harvest of a certain size. Desirable properties of this type of objective are: (1) it is conceptually simple; and (2) it is an objective-oriented approach to management. However, maximum sustained yield has some inherent disadvantages. The main undesirable property is that most hunters and anglers regard harvest or catch as only one of several measures of output from a natural resource system. Other aspects important to the hunter or angler are the outdoor experience, environmental aesthetics, and the sporting challenge.

Coomber and Biswas (1973) suspected that the public received benefits of a psychic or convenience nature which might in total amount be larger than the more tangible benefits received from recreation. Hunting or fishing may be an escape to solitude, a social enterprise, a vigorous physical challenge, or an occasion of relaxation. McFadden (1969) viewed the sporting experience as being composed of two basic factors: the quest--an adventure in fishing or hunting methodology; and the attainment of a tangible reward, such as a fish or a deer. However, the basic core experience may be enjoyed in a variety of natural and social environments and consequently, the sports must mean different things to different people. Obviously there are a number of important physical, social, and psychological factors related to a fishing or hunting experience which are neglected by the maximum sustained yield concept.

Among more recent efforts to institute hard objectives have been attempts to measure quantities such as man-days of use. The assumption is that measuring the number of man-days of recreation on a particular resource is a valid index of output. Some may also go further and assume that the approach could be used to maximize recreational benefit. However, maximizing angler days may result in an amusement park situation.

A possible objective in renewable natural resource management is maximizing aesthetics. This is a very altruistic approach, but not currently practical. Due to lack of a functional pricing system, the value of various recreational factors cannot be easily determined by a market survey conducted on the angling or hunting public. Leopold (1969) has used a quantitative scheme for making comparisons of aesthetic factors on rivers, a first step which could be applied to management for recreational benefits.

Another possible objective is maximizing quality-ranked user-days. Quality is an extremely vague and variable parameter to measure, but certain factors which contribute to the quality of the fishing or hunting experience could be delineated and measured. The number of potential variables is large, but specific areas may only have a few aspects which determine quality.

Some popular fisheries and wildlife management objectives (such as maximizing catch) are often not adequate measures of output and may well be replaced or modified to meet present needs (Clark and Lackey, 1975). The aspect of quality needs to be integrated into management if optimal output from recreational-oriented resources is to be realized.

2.1 Setting Objectives. Practically speaking, the identification, selection, articulation, and ranking of objectives are not easily achieved. There are many problems concerning the quantification and measurement of aesthetic and environmental factors. Because of the complexity of natural resources systems, establishment of management objectives may tend to be ignored by some managers. Possible reasons why decision-makers may be unwilling to formulate objectives are fear that some of the real objectives would be disapproved under scrutiny by the public, and fear that some objectives might not be approved by all interested parties. Miller (1970) states that decision-makers may be unable to formulate objectives because of three difficulties: incomplete problem awareness; incomplete knowledge of the intracacies of the problem; and inability, due to time, money, and/or manpower constraints, to devote sufficient thinking effort. Often the objective setting methodology is not sufficient to be of use to the manager. Most authors stress only the importance of objectives without providing means for determining or detailing them. However, several techniques are available and when used in combination should provide a sound framework for determining objectives. The strawman/discussion technique, tree structures, relevance trees, the brainstorming technique, Delphi method, and attitude surveys are just six objective and goal determination procedures.

The purpose of the strawman/discussion technique are to elicit ideas from a group and promote consensus through discussion. The participants simply bring a list of proposed objectives to a committee meeting for review and discussion. The strawman/discussion technique fits well with the traditional committee approach to planning, but has some disadvantages, such as the unwillingness of some people to alter their ideas. Psychological factors, such as the bandwagon effect and the dominant personality bias, are also negative features. Also, the strawman/discussion technique may not provide participants with enough detail for selecting best decisions. However, this procedure may be especially well-suited for establishing general goals.

Tree structures provide a strong framework for problem analysis by retaining focus on the overall goal. The structure is composed of branches arranged in successive levels, with the highest level representing the goal and succeeding levels representing subgoals on down to specific objectives. Phenicie and Lyons (1973) present a lucid discussion and explanation of this procedure with special reference to fisheries and wildlife management.

Relevance trees are tree structures modified by providing values representing the relative importance of each branch at each level. The purpose and advantages are similar to trees, except an ordinal ranking of subgoals and objectives is generated, which may be particularly useful in allocating money and effort to the most important management objectives.

Another method, the brainstorming technique, is best suited for broad goal determination. A basic decision problem is stated to a group and potential solutions solicited from the participants. All suggestions are reviewed.

The Delphi method involves use of individual questionnaires to survey participants, followed by feedback of a computed consensus of the group's opinions. This procedure eliminates many psychological biases and tends to promote group consensus. When used alone, it is best for determining goals, but used in conjunction with a tree, it can be a useful tool for setting objectives.

Attitude or opinion surveys can provide useful input from the public. Telephone, personal, or mail interviews may be used. The procedure provides a means for natural resource agencies to provide the greatest amount of user satisfaction from the resource. These survey techniques may eventually lead to the development of a management benefit unit as proposed by Lackey (1974), which would provide a common denominator to evaluate natural resource management decisions.

2.2 Objective Functions. Rational management of a natural resource by a public agency requires optimization of an objective function which reflects benefits to the user, as well as to society as a whole. The objective most often used by public agencies to depict recreational user-benefits is the user-day, but many other attributes may enter into the recreational experience.

An alternative procedure is for the decision-maker to specify certain measures of effectiveness and then develop a utility function governing explicit measures or attributes. Given such a utility function, the expected utility may be calculated and would be the objective function; i.e., the decision-maker would prefer the alternatives with the greatest expected utility.

Because the utility function represents the decision-maker's views as to his own preferences, there is no right or wrong associated with it. Problems arise when the decision-maker (a public natural-resource manager) attempts to formulate a utility function using attributes which primarily reflect benefits to the resource user, and only secondarily to himself. The manager is put in the position of making value judgments as to what he feels the public desires. In all likelihood the decision-maker's utility preference for an attribute will not coincide with the preferences of the public.

To provide the decision-maker with information about the resource and the public, consultants or a panel of experts may develop a group utility function. The group utility function may be derived by taking the mean, median, or mode of the utility functions of the individual members of the panel; i.e., mean, median, or mode of the coefficients of the individual's utility functions. This does not, however, overcome problems of interpretive comparisons of utility. To the expert, the utility function is a representation of his *preferences*; to the decision-maker the expert's UF is *information*.

2.3 Institutional Considerations. Natural resource managers must decide who should set objectives, agency personnel, the general public, or a combination of the two. Historically, natural resource decisions have been arrived at by the consultation of professionals in institutional roles and positions, an elitist planning process which allows those who are best qualified and most knowledgeable to make decisions. However, many agencies now advocate use of public input in decision-making because of Meier and Thornton (1973) state, ". . . a more informed and concerned general public is currently seeking a greater role in the allocation of economic and physical resources." One of the most urgent social needs in fisheries and wildlife management is the determination of the needs and preferences of the public. Much of the poor planning in the past is due to the inability of planners to consider the needs and desires of certain segments of the public.

An informed and concerned public is essential for natural resource decision-making in the current social climate in the United States. A planning process involving the public is more nearly a democratic process and, as such, may have a higher probability for success because it provides representation from those who are affected. Management personnel cannot rely solely on public opinion in formulating decisions, but public opinion is valuable input because light may be shed on public response to management actions. The interaction between managers and the public may bring greater appreciation for both sides' points of view and problems. Greater understanding should ultimately lead to improved resource management.

The administrative expertise type of decision-making is characterized by a complex division of labor around functional specialties and the recritment of trained personnel capable of responding to narrow problems efficiently and competently. Advantages of this type of process are that it employs professional ethics and standards, and it uses rational decision-making processes in which objectives are often clearly defined, pertinent data collected, and alternatives surveyed and selected. This theory is appealing in principle but open to question in practice. Goal-setting involves value judgments concerning desirable or undesirable consequences of alternative management programs. It is often felt, especially in the public sector, that scientifically trained personnel are no more qualified than the general public to make these value-based decisions.

Public involvement is a basic cultural value which may not be compatible with efficiency through technological expertise, another basic cultural value. A prominent view among natural resource personnel is that environmental decisions must be entrusted to experts. However, a trend toward participatory democracy exists and citizen participation has often been proclaimed as a means to perfect the democrat process. Public demand is not forcing agencies to modify traditional procedures. Agencies must seek methods to bring greater citizen input into program judgments. However, incorporating public input into the planning and decision-making process is not a simple task.

Most of the procedures for generating objectives discussed to this point may be modified to incorporate public input. Procedures for establishing broad goals seem quite appropriate for using citizen representatives or panels to collaborate with professionals in decision-making. The attitude and opinion survey techniques offer a promising opportunity for agencies to procure direct public input. Sampling techniques using license records could be used in mail, telephone, or personal interviews or combinations thereof. The methodology developed by Giles and Lee (1975) or similar ranking procedures, could also be utilized. In fact, no single procedure should be emphasized, but combinations of the various techniques used as supplements to one another might prove most useful.

Citizens may participate voluntarily through letter writing, attending public hearings, or joining pressure groups. However, many people fail to participate because they feel their efforts would be in vain. Agencies need to emphasize that the information derived from the public will be used to aid in making decisions. Also, agencies need to solicit public participation from the entire affected group. People who attend public hearings are not representative and, thus, tend to project a distorted view of management issues, but public involvement will help to insure that optimal decisions are made and therefore cannot be neglected by natural resource managers.

3. EVOLUTION OF DECISION MODELS

Most models, even those seemingly unrelated, are quite similar in philosophy and approach, but there is substantial variation between models when they are viewed according to their intended use or function. Models in natural resource systems can be categorized into families that include one or more components (habitat, biota, and man) (Figure 1). The evolution of these models has not followed a discrete path, but rather a disjointed and often circuitous route. The major trends (as exhibited in Figure 3) apply equally to fisheries, wildlife, or forestry, but with different evolutionary trends being of greater importance when evaluated by the scientific effort expended.

Modeling in renewable natural resource management can be justified in many ways, some of which result in benefit/cost ratios much greater than unity and others which do not. As a group, resource modelers have tended to oversell the potential management benefits derivable from modeling, a characteristic

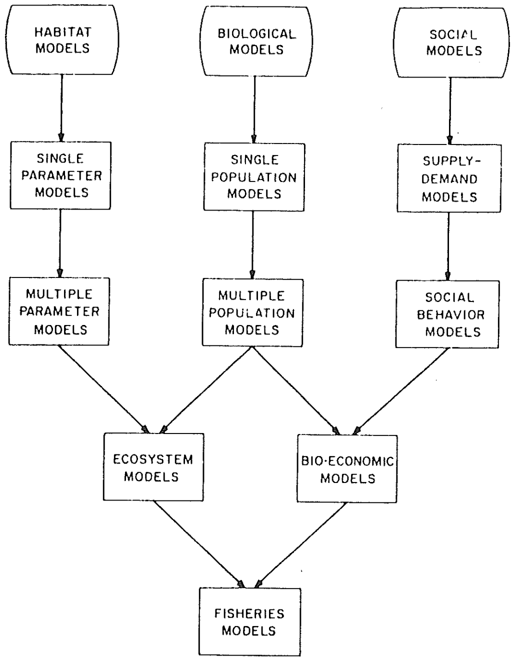


FIG. 3: General relationships and evolution of natural resource system models. Only major types of models and interrelationships are shown. Note that habitat, biological, and social models are necessary components in total natural resource system models.

all too frequent in emerging scientific disciplines. The potential benefits of modeling in management are many, and it is preferable to err on the conservative side as an advocate.

The first and perhaps most obvious potential benefit of modeling in resource management is organization. Resource systems are highly complex systems and modeling (graphical or mathematical) does provide a medium for clarification and organization. Used in the context, a model is a theory about the structure, dynamics, and function of a natural resource system or a component.

A second potential benefit of modeling in management is as a self-teaching device to the builder or user. There may be no better way to develop a feel for a system than to formally model it. Some resource models, particularly computer-implemented models, serve as useful management exercises in universities (Titlow and Lackey, 1974).

Identifying gaps in our understanding of a natural resource system is a third potential benefit from modeling in management. In modeling, the modeler may become painfully aware of areas of missing data. Acquisition of these data may well be top priority for improving management. Sensitivity analysis in modeling will identify the parameters of most importance in determining model output, and data acquisition and/or research effort may be allocated accordingly.

Models as research tools may be considered as a category of potential benefits. Manipulation of the model itself may generate data which are unattainable from the real system. For example, the impact of rainfall and water temperature may each have an impact on certain biotic components, and certain combinations of rainfall and temperature levels have been observed in the field to quantify the impact. Exercising the model may permit a reasonable assessment of the *general* relationship by interpolation (based on existing data combinations).

The fifth and most discussed potential benefit of modeling in management is predicting the impact of alternative management decisions or external influences. Historically, managers of commercial fisheries, for example, have been interested in predicting the impact of a proposed fishing or exploitation rate expressed in the form of a season, mesh size, or quota. Recreational fisheries managers wish to estimate the impact of decisions on the number of realized angler-days, catch, or some other measure (Lackey, 1974). As a very general guide, habitat models will potentially possess relatively good predictive power, biotic models intermediate predictive power, and social models relatively poor predictive power.

3.1 Ecosystem Models. Habitat models include those developed to predict aquatic temperature regimes, toxicant dispersal, and sediment transport (Figure 3). For example, one management problem which exists in freshwater recreational fisheries management is predicting the structure and function of proposed reservoir environments. Managers (and modelers) must first address and solve the problem of predicting future habitat characteristics, including physical and chemical parameters, before ecosystem and fisheries models can be accurately predictive. Predicting habitat characteristics is a difficult endeavor, but because it involves prediction of purely physiocochemical phenomena, it is *relatively* easy.

Biological models include classical animal population dynamics models and models of single- and multiple-population systems. In this category we find the classical fish population models of Schaefer and Beverton and Holt (single population models in Figure 3). Nearly all of the extensive literature on population dynamics falls into this category. Also, there has been considerable activity on developing biological models among ecologists.

Ecological or ecosystem models are becoming increasingly common in renewable natural resources management (Lackey, 1974). Ecosystem models combine, in varying degrees, habitat and biological models (Figure 3). Accounting for component interaction is a key point in ecosystem models and much of the profuse literature on the subject deals with interaction characteristics. Freshwater systems have been modeled more frequently than marine systems, in part due to the rather discrete nature of lakes and, to a lesser extent, streams.

In the applied sciences, such as renewable natural resources, models traditionally have been developed which have little basis in reality. Such models have been useful to the natural resource manager because he has been willing to sacrifice realism and generality for precision. Precision has been possible since the systems of concern have been rather narrowly defined entities such as single-stock fisheries or one species wildlife systems. Contemporary systems ecologists have generally preferred to deal with whole ecosystems as a means toward effective management of natural resources. In order to deal with large scale ecosystem models, some ecologists have chosen to model ecological processes in detail. Models developed with such a components approach have tended to be both realistic and precise, but they are often criticized for lack of generality.

Ecosystem models may be either discrete time systems or continuous time systems; but in either case, the experimental component approach may be employed. Examples of this approach may be seen in models of random dispersal, effects of temperature on biological rate processes, density effects on reproduction, predation, and growth models. All of these models may be incorporated into ecosystem simulation in the form of subroutines.

The majority of the time and energy expended in modeling dynamics within an ecosystem is used in depicting interaction among components of that ecosystem to produce models with some degree of realism, generality, and precision. In order to do this, ecologists have factored the dynamics of the ecosystem into individual ecological processes in a manner similar to Holling (1965) with his mode of attack. Timin (1973) extended this approach to a multispecies consumption model which can be integrated as a subprogram into a generalized ecosystem simulator. In a similar vein to Holling's work, interaction has been incorporated into reproduction models (Fujita, 1954). A single mathematical model incorporating interaction between components of an ecosystem has been developed which includes effects of predator-prey relationships, reproduction and aggressive behavior, as well as the flexibility to include other important interaction processes (Powers and Lackey, 1975).

In order to effectively describe a natural resource, a model must be employed which reflects potential actions of the manager. Many of the alternative strategies available to the resource manager are not considered in ecosystem models which do not use the experimental component approach. For example, what will happen to the ecosystem if the manager wishes to improve habitat for certain species? The experimental component approach (illustrated by Powers and Lackey, 1975) allows this question to be considered. In a stream ecosystem, for example, spawning ground improvement would be reflected in the model by increasing the proportion of area available for spawning, which would in turn decrease the probability of the spawning act being interrupted. Removing cover (e.g., aquatic weeds) could also be evaluated, since it decreases the probability that a prey item will escape. These considerations can be directly implemented into the model, making it useful to the resource manager.

Viewing the natural resource as an entire ecosystem has allowed the manager to evaluate secondary effects of a perturbation on other components of that system. Instead of a fishery being seen as a single fish stock, it can now be seen as primary producers, aquatic insects, and fishes which directly or indirectly affect the target fish. Ecological processes may be modeled with a reasonable degree of realism and precision. With this realism and precision the ecosystem model may be effectively integrated into a total natural resource management system.

3.2 Bioeconomic Models. Models which mainly address the third resource component, man, fall into a category which may be termed social models (Figure 3). In commercial fisheries, managers tend to measure fisheries output as pounds of fish or perhaps net income. In recreational fisheries, output is composed of many factors, including aesthetics as well as catch. From a management and modeling standpoint, we must ask such questions as: How do people respond to changes in renewable natural resources? How can human behavior be predicted, or at least the behavior of part of the human population?

Bioeconomic models, as the name implies, include biological and socioeconomic components of resource systems (Figure 3). Bioeconomic models are integral to management of commercial fisheries, but relatively neglected in recreational fisheries. Crutchfield (1973) has clearly illustrated the role of social goals and fisheries management objectives. Managing trends in use of aquatic renewable natural resources may prove to be of much greater importance as human recreational and commercial demands continue to increase.

One of the more difficult problems with which managers are faced is the problem of meeting the needs of competing users of a natural resource (for example, the fishermen who fish for different types of fish and also fish for different purposes). Harvest by one type of fisherman may directly or indirectly affect the harvest by other types of fishermen. Examples of competing users of a fishery might include commercial fishermen who seine for baitfish species within a stream and the recreational fishermen who fish for game species within the same stream. Harvest of the baitfish may remove forage needed by the game fish to grow and reproduce. Thus, there might be a decrease in number and size of these fish and subsequently a reduction in angler satisfaction. Similarly, the sports fisherman, themselves, might be categorized into competing users such as trout anglers, smallmouth bass anglers, and bluegill anglers. Hunters and bird watchers exemplify another well known example of competing users.

If a complex system, consisting of many user types who have many different motives, is to be managed effectively, the means of analysis must be able to handle this complexity. One method of analysis, computer simulation coupled with optimization procedures, appears to be capable of coping with this complexity (Jester, Garling, and Lackey, 1977).

3.3 Renewable Natural Resource Models. Natural models, in the broadest sense at least, combine the major resource components (habitat, biota, and man) (Figure 2). At such a comprehensive level of analysis, detailed modeling borders on the impossible. And, if certain constraints (i.e., economic, political, and social realities) are added to a comprehensive natural resource model, one has a complete decision-making system.

Few management strategies are explicitly based on models. Most strategies, however, are implicitly based on two widely known single population models: the dynamic pool model (Beverton and Holt 1957) and the logistic model (Schaefer 1954). The dynamic pool model describes a population in terms of the vital statistics of recruitment, growth, and mortality. Each statistic is assumed to be a continuous deterministic function of time. Implementing the dynamic pool model requires a large amount of data and generally can be successful only after substantial information has been collected on an animal (usually fish) population. The logistic model, also called the surplus yield model, combines the effects of recruitment, growth, and natural mortality into a single differential equation for change in population biomass. The logistic model, usually employed when information is relatively scanty, requires only catch and effort data.

Both the dynamic pool and the logistic models have been applied with some success in marine commercial fisheries management. The dynamic pool model has been used in the North Sea plaice fishery and provides an adequate description of the fishery (Gulland, 1972). The logistic model has been useful in managing the Eastern Tropical Pacific yellowfin tuna fishery (Gulland, 1972). Neither, however, has been applied with much success in freshwater sport fisheries.

In large part, the inadequacy of these models is due to their continuous deterministic description of discrete, stochastic population phenomena. Models which incorporate stochastic processes may provide better descriptions of population dynamics, especially when the processes are analogous to biological processes. A stochastic approach is more appropriate where a steady state cannot be assumed, which is the case in most fisheries.

A recent simulation model of a multispecies lake fishery (Zuboy and Lackey, 1975), called STOCKS, is a stochastic model which requires very little input data. STOCKS emphasized dynamic interrelationships among three games fishes: bluegill, black crappie, and largemouth bass. In this model, however, analogous processes are not defined; rather, distributions are generated about some expected value for the vital statistics.

Effective modeling requires clearly stated design criteria. Ideally, a model should cope with the structural and functional complexity of a natural resource system, reflect actual ecological processes, provide broad predictive range and high predictive accuracy when used for analysis of management strategies, and allow sufficient flexibility for general application by managers. As statements of theories, models help us find contexts for our data: as information retrieval schemes, they help us find data for our contexts.

4. TOWARD A THEORY OF NATURAL RESOURCE MANAGEMENT

If, as a basic assumption in renewable natural resource management, we assume that all benefits derivable from management are accruable exclusively to man, then it follows that:

$$Q_{max} = f(X_1, X_2, X_3, \cdots, X_m | Y_1, Y_2, Y_3, \cdots, Y_n),$$

where

Q = a numerical value of total benefit

X_m = management decision (m = the number of all possible decisions)

Y_n = management constraint (n = the number of all possible constraints)

$|$ = "given that."

Controlled or partially controlled decision variables (X's) are those regarded as management activities (stocking, regulations, habitat, improvement, etc.). Non-controlled decision variables (Y's) are random or dependent on other factors (weather, highway development, political changes, recreational attitudes, etc.). Variables may, however, overlap both categories. Within constraints (Y's), the manager tries to select a series of decisions which maximize Q.

A management problem facing all natural resource agencies is evaluating how best to allocate limited financial and personnel resources to meet particular objectives. Given the user-day (or some other quantity) as a measure of output (Q) from a natural resource management program, for example, how can an agency allocate its resources to increase angler-day production within a relatively fixed budget (one of the Y's)? For example, how many angler-days accrue from: (1) building additional lakes; (2) improving support facilities at existing state-owned lakes; (3) stocking various species and number of fish; (4) managing intensively as with lake fertilization and fish population adjustment; (5) educating the angling public; (6) enforcing laws; and (7) improving access to fisheries. Some agencies have additional methods available to fisheries managers for increasing the number of angler-days, while others have fewer alternatives.

Efforts to determine how to best allocate financial resources to achieve particular management objectives are found in many resource management areas. Evaluating decision alternatives requires a system model (conceptual or quantified) in which to make an allocation analysis. Because resource allocation decisions are made in very complex matrix, including uncertainty, time lag, poorly understood and quantified variables, and obscure interrelationships, decision-makers must interact in developing model structure. One example of methodology to predict outputs accruing to state fish and wildlife agency activities and expenditures is an angler-day simulator (PISCES) (Clark and Lackey, 1975).

PISCES is a computer simulation model of a state recreational fisheries management system. It is a methodology for predicting the consequences of alternative budget allocation strategies for a fisheries agency. The measure of performance for each allocation plan is its effect upon the number of angler-days generated within the state. The overall objective of PISCES is to improve investment decisions made by state fisheries agencies. Its planning horizon is one fiscal year.

Input for the model is arranged in two categories. The first is a data block containing the alternative management decisions. The decision-maker must supply data such as budget expenditures, regulation changes, locations of access areas to be developed, and estimates of the amount of water to be gained or lost to the state's total fisheries resource. The second category consists of data which characterize the state, such as the amount of fishable water, location of access areas, and costs of various management activities. Once the two data blocks are complete, the planner can test alternative budget allocations in the model.

The management programs which must be allocated funds include: (1) pollution control; (2) law enforcement; (3) information and education; (4) coldwater hatcheries; (5) warmwater hatcheries; (6) access area development; (7) research; and (8) state-managed lakes. Other management decisions considered to affect the number of angler-days are: (1) regulation changes including season length and license fees; (2) water gains as from construction of reservoirs or land access and acquisition; and (3) water losses as from pollution or inundation.

The choice of angler-days as the common denominator of output for PISCES was based on its importance in fisheries management. The effects of management upon angler-days considered in PISCES are angler-day production, loss, and migration. PISCES treats an angler-day as a two-dimensional entity. The first dimension, physical location, is partitioned into the state's management regions. Thus, when the output is analyzed, an angler-day in one part of the state can be weighed either more or less than one in another part. The second dimension, fisheries type, is partitioned into the five fisheries types. Thus, an angler-day of bass fishing can be weighed either more or less than an angler-day of trout fishing.

Another example of a tool to aid decision analysis in fisheries and wildlife management is the deer hunter participation simulation (DEPHAS) developed by Bell and Thompson (1973). DEPHAS is a computer simulator designed for predicting outputs resulting from a state fish and wildlife agency activities by allowing state managers to analyze interaction between input and output of their proposed management policies.

Simulation is certainly not the only approach to resource allocation problems and, in fact, it is sometimes regarded as a last resort attack. As another approach to evaluating resource allocation strategies, linear programming has been used (Lobdell, 1972). Salmon management problems have been studied extensively by linear programming and simulation procedures. Salmon management consists of: (1) predicting the number of fish in future runs; (2) selecting a number of salmon to allow to spawn; and (3) allocating the remaining fish to the fishermen throughout the season. Allocation strategies have been used to maximize the value of the catch given the required number of fish reaching spawning grounds. Booth (1972) developed a discrete time maximizing model based on basic fisheries stock-recruitment theory. The essential property of this model is the decision whether a manager invests in spawners (which provide future yield) or sells potential spawners today. A blend of classical fisheries population dynamics (logistic model) and economic theory is often advanced as one solution to meeting management decisions. The key problem has been not so much with modeling, but lack of a clear and generally accepted management objective.

Nearly all natural resource systems consist of two or more game or commercially important species and management activities affect each to a varying degree. Modeling at this level is quite difficult, but modeling energy flow to project trends in the biological components shows promise. Subsystems could be connected by energy flow links, with a computer program performing necessary bookkeeping. Such a modeling strategy could be considered in systems where a common denominator was present, whether it was energy or something else.

The level of use of natural resources is one of the major interactions of man with biota and habitat. Thus, use is a major concern of management agencies, but use-trends in most natural resource systems are generally out of control. In practice, use-trends are nearly always viewed as phenomena *extrinsic* to management, but, in reality, are only partially extrinsic. Virtually all management agency programs and activities have an effect on the location and intensity of natural resource use. Land acquisition, dam construction, pollution control, fish stocking, and access development are common examples in fisheries management.

Natural resource management is largely involved with forecasting the demand and providing an adequate supply for output. Producing or maintaining the necessary supply of resource opportunities may be difficult because all agencies have political, technical, and edological constraints, and limited financial resources. In many cases, use of natural resources threatens to exceed managers' ability to supply use of the desired quality.

Management policies have almost always been designed to respond to use trends but rarely to shape them. If management policies were designed to regulate natural resource use, greater benefits might be accrued from management. Regulation of use could be achieved by limiting licenses, but such a tactic is often not politically or culturally acceptable. A less dictatorial approach, based on subtle relationships between individual management activities and use, might also be effective and perhaps more politically palatable.

Regulations, information distribution, and educational programs address human components in natural resource management, but such efforts alone cannot be relied upon to direct resource use in a desirable direction. One or two actions in a complex management system are invariably inadequate to achieve the desired change. For example, while information and education efforts are working to direct use along a particular course, other agency activities may be working subtly against that course. Multiple actions, each moving in the same direction and with coordinated timing and emphasis, are needed to successfully regulate use.

5. CONCLUSION

The potential benefits of modeling are not universally accepted among scientists or managers. Agencies supporting or proposing to support natural resource modeling will increasingly demand a clear itemization of the expected benefits of modeling. Natural resource management is a very pragmatic discipline and the results of research efforts are generally expected to improve management decisions. All to often researchers have failed to bridge the gap between their work and the decision-making process. This is not to say that we need a public relations campaign to advocate modeling, but rather to present the research results in a usable manner. Research is only one input in the decision-making process and its use depends in part on ease of use.

As a final note about natural resource models and modeling, a much closer involvement between modelers and decision-makers will likely evolve. The distinction between the two groups is purely artificial, but tends to develop at a division of labor approach in structuring an agency. Frequently, those actually making or recommending management decisions perceive, at least subconsciously, modelers as a threat, or worse, a pack of academicians. Modeling offers too much to resource management to fall solely into this category.

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