DETERMINING OPTIMAL POLICIES FOR

MANAGEMENT OF AN AQUATIC ECOSYSTEM

by

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INTRODUCTION

Throughout the United States, state fish and game agencies have been given legislative mandates to provide sufficient levels of human use of fish and wildlife resources consistent with protecting these renewable natural resources. To achieve such management ends, state agencies allocate substantial quantities of money, time, and personnel to the process of making decisions which govern the extent of resource use. However, substantial agency effort does not always improve management of fish and wildlife systems. Even when improvement in management does occur, the increment of gain does not always justify the coincident increment in agency effort.

Improving management and efficiently allocating agency effort are central problems of a state agency. One means of combating these problems is to make decisions in a systematic and quantitative manner. An attempt can be made to predict quantitative outcomes resulting from decisions and then a methodology employed to systematically find the decision which produces the most desirable outcome.

To predict outcomes resulting from a certain set of decisions, a cause and effect relationship between decisions and the system being managed is required. An efficient and precise means of expressing cause:effect relationships is through use of mathematical models such as those proposed by Ricker (1958) and Beverton and Holt (1957). However, these fisheries models depicted fish populations in isolation from external factors. Van Dyne (1969) suggested that management should encompass the entire ecosystem, i.e., factors external to an exploited population are integral components of the management system. Likewise, the state management agency may provide for human use of the resources. Therefore, characteristics of the human users can also be part of the management system (Moeller and Engelken 1972). Effective prediction of the result of a decision upon the management system may require large models encompassing both the ecosystem and its interaction with man.

A methodology by which the most desirable outcome may be found requires two necessary conditions. First, there must be some measure of system response which the decision-maker wishes to employ to evaluate management effectiveness, i.e., an objective function. The objective function may reflect several different aspects of the system, but it must be expressed as a single quantity. To do so may require use of rather elaborate objective setting techniques (von Neuman and Morgenstern 1948, Halter and Dean 1971, Churchman and Ackoff 1953). The second condition for an effective methodology for determining desirable outcomes is a sequence of instructions which directs the decision-maker toward a better decision after having tested a previous decision. From the sequence, or algorithm, the maximum (or minimum) of an objective function may be found (if it exists), and a decision which produces the maximum (or minimum). The mechanics of maximization or minimization are problems in mathematical programming. Various techniques and approaches to mathematical programming are discussed by Wilde and Beightler (1967).

The need for rational decisions regarding utilization of fish and wildlife resources has been suggested (McFadden 1969, Lackey 1974). The need for a method for determining these decisions has also been suggested (Watt 1968). This dissertation is directed to the end of developing methods for management of an aquatic ecosystem.

Study Objectives

The objective of this dissertation is to develop methods of determining the optimal decisions for management of an aquatic ecosystem. Specifically, the first objective is to develop a theoretical framework which describes causal pathways within the ecosystem and which includes relationships between and among species in space and time. The second objective is to develop an objective function for use on a specific aquatic ecosystem. The third objective of the study is to develop and/or adapt existing methods by which an estimate of the decisions which produce the optimal value of the objective function may be discovered. The fourth objective is to merge the above into a usable procedure for finding Optimal Ecosystem Policies, i.e., for finding the time dependent decision which produce the optimal objective function values and to test the procedure (henceforth OEP) on a specific aquatic ecosystem.

Problem Analysis

Finding optimal decisions for any system, including ecosystems, should consist of at least four distinct phases: systems description, definition of objectives, system solution, and solution sensitivity analysis (Wilde and Beightler 1967: 465). Work in ecosystems analysis has previously focused on system description or modeling (see, for example, Patten 1971) and to a lesser degree upon system sensitivity (Brylinsky 1973). Watt (1968) discussed system solution in some detail, yet he neglected the problem of defining the objective function. However, each of the four phases of optimization will be treated in some detail in OEP.

System Description

A management system consisting of an ecosystem and the interaction between man and the ecosystem has many variables and is very complex. Complexity may be defined as the number of possible relationships between the variables in the system. The complexity of a system increases disproportionally with an increase in the number of variables. To model successfully an ecosystem for management purposes, a method must be used which is capable of coping with complexity.

Ecosystem description should be theoretically sound. A mathematical model which employs an interaction matrix of competition for resources such as space, time, energy, matter, and information is most desirable (Watt 1973). Ideally, the model should have the flexibility to include major interaction between and among animals, but yet be realistic in terms of experimental evidence.

Ecosystem description may consist of a mathematical model from which it is too difficult to obtain numerical results. In this case the model may be coded on a digital computer, so numerical results may be obtained. When the mathematical model is combined with logical relationships available in digital computer programming languages, then the ecosystem can be simulated and years of real-time can be compressed into seconds of computer time. The general approach in the system description aspect of OEP was to combine a theoretical model with the computational power of computer simulation.

Definition of Objectives

In renewable natural resource systems exploitation may occur for a variety of different reasons (Pearse 1969). For example, one person may be using the resource for monetary gain as in a commercial fishery, while another may use it for recreation, such as trout fishing. Often these users are in competition with each other; a gain to one group is a loss to another group. For public renewable natural resources, it is the state agency's responsibility, delegated from society at large, to determine an objective, i.e., a specific, quantitative end toward which effort is directed. This objective may reflect each major user-group according to their relative worth as perceived by that agency.

There are many measures or criteria which may be included in the objective. For example, because the agency may be charged with ecosystem preservation, some measure of ecosystem viability and/or stability might be a decision criterion. Likewise, nonuser-groups may be represented in the objective function. If high populations of deer in a wooded area meant nearby farm crops were subjected to foraging damage, then the agency might wish to include the non-user objective of minimize crop damage as one of several criteria.

Instead of including many criteria in an objective function, some may be considered as constraints, e.g., maximize hunter-benefits subject to the constraint that crop damage will not rise above a certain level; or, maximize the commercial fishing catch subject to the constraint that the measure of ecosystem stability does not decrease below a certain level. However, when a criterion is used as a constraint instead of part of the objective function, the decision-maker is implying that the specified level of that criterion is acceptable. In actuality that level may be detrimental to other portions of the system. Conversely, the specified level may be very much higher without being detrimental. Because the criterion is ignored in the objective function, the situation is not exploited fully. In both cases employing constraints may produce misleading results.

The objective of this portion of the dissertation is to formulate an objective function and constraints for a specific aquatic ecosystem. The objective function will combine several noncommensurable criteria into a single quantity. The constraints will be utilized such that misleading results will be avoided.

System Solution

System solution is the process of determining the optimal decisions. In most decision problems, a single decision variable may take a very large, if not infinite, number of values. Therefore, it is difficult, at best, to compute outcomes for each of these decision variables. It is possible to partition the decision variable, i.e., break the range of the decision variable into relatively wide intervals, and test a single value within each partition, but partial enumeration is extremely inefficient and may be impractical when the region of the optimum outcome is unknown.

When the mathematical programming problem is one of multiple decisions, partial enumeration is often out of the question because of the "curse of dimensionality" (Bellman 1957), e.g., increasing the dimension of a 10 x 10 multidimensional grid system to 10 x 10 x 10 will increase the number of points in the system from 100 to 1000. Even high speed digital computers cannot enumerate outcomes for systems with a moderately high number of variables.

Most of the decisions affecting ecosystems are time-dependent. An increase in creel limit in a fishery in January will likely have a different effect than the same increase in July. Therefore, decision variables must be expressed as a function of continuous time or at discrete points in time, and the dimensionality of the problem is increased by one. One decision variable that changes each month in the year is equivalent to 12 distinct decision variables.

Time-dependent processes are often nonlinear, although they sometimes can be fit to piece-wise linear models and then solved by linear programming (see, for example, Hadley 1962). Dynamic programming (Bellman 1957, Bellman and Dreyfus 1962) is designed for time-dependent nonlinear problems, but with large multivariable systems, solution by dynamic programming is still cumbersome, if possible at all. Using the modern theory of optimal control developed by Pontryagin (Pontryagin et al. 1962) and by associated numerical techniques (Katz 1962), a time-dependent process may be optimized by decomposing the problem into a series of independent optimization problems. This is an extremely efficient procedure, but it requires that the decision and state variables be expressed in strictly analytic (mathematical equation) form. However, computer simulations are employed precisely because analytic models cannot be formed. If an analytic model were to be found which approximated the results of computer simulations of the ecosystem, use of optimal control theory would then be allowable. The approach in this study was to fit an approximating analytic model to the simulation data and then apply optimal control theory.

Sensitivity Analysis

The value of optimization to management is that it reveals the structure of the optimal decisions and the decision problem by forcing the analyst to express his understanding of the system in a quantitative manner. Sometimes the character of the decision may be discerned without going into numerical details. But, when numerical results are necessary, sensitivity analysis (which is the study of the stability and validity of the solution) is important for interpreting the results. Sensitivity analysis can determine the effect that an error in measurement might have on the optimal solution, or on nonoptimal solutions. The solution's validity and reliability may be assessed by an analysis of decision and parameter sensitivity.

OEP Design Criteria

Effective design of an ecosystem management procedure requires that the design criteria (the standards on which design is based) be clearly stated. Design criteria for a management procedure may depend on the general end toward which management is directed, personnel and experience of the management agency, and the decision-maker's perception of the value or relative worth of each component of the system being managed. However, several design criteria are common to management agencies, and the following design criteria were fulfilled so that OEP can be useful to an agency.

OEP is conceived as a total management procedure consisting of the four components of: a methodology for developing an objective function, a system description using simulation, and optimization algorithm, and sensitivity analysis. It is desirable that the simulation and optimization procedures be included within a single computer program.

A well designed OEP methodology and computer program should supply the decision-maker (a manager employed by a state fish and game agency who is responsible for the fisheries resources within a certain region) with an approximation of the optimal policy, i.e., the optimal set of decisions, for managing an aquatic ecosystem. The design of the program should be flexible so that, with relatively small changes in the program, many aquatic environments and management problems may be depicted. Flexibility should be a criterion whenever possible, so that differences between specific ecosystems and management problems may be easily incorporated.

The program should be user-oriented. If estimates of parameters of complex ecological functions are required, these parameters (estimated for a variety of species) should be included in the computer program itself. If the species for which these estimates were made do not coincide with the species existing in the decision-maker's specific ecosystem, he may supply his own estimates. But, if the user does not or cannot supply input values, the program should default to generalized estimates built directly into the program.

Some estimates of ecological parameters must be inputs supplied by the decision-maker. These parameters will be expressed in a manner which is compatible with an ecologist's or manager's intuition and in a scale which is conducive to subjective estimate (such as a probability scale). OEP should not require an information base which exceeds the agency's ability to provide it. The program may be implemented using existing data and the agency personnel's experience as inputs.

The final design criterion is that the results of an OEP application must supply the decision-maker with information about his particular ecosystem, the science of ecology, and the practice of resource management. By presenting ecosystems management problems in an organized and quantitative manner, it is hoped that fisheries and wildlife management will begin to employ management science techniques that presently exist in other management disciplines such as industrial engineering.

Overview

The following chapters will emphasize the specific methodology in meeting the objectives of the study. As such, the OEP design will be explained in detail including literature reviews, mathematical developments, and solution techniques. Although much of this development is specific to the case study of an aquatic ecosystem management problem in West Virginia, the method of solving management problems should be observed. However, because an integral part of the OEP procedure is application, a fairly rigorous review of the results of the case study will also be presented. From this exposition and results, recommendations for improving the OEP procedure and ecosystem management will be discussed.

METHODS AND PROCEDURES

The presentation of the OEP procedure, including the methodologies employed and the structure of the computer program, will be presented within the context of a specific case study. The presentation will include a description of the case study system, a description of OEP design and a discussion of application of OEP and sensitivity analysis.

Rich Creek--The Case Study System

The National Marine Fisheries Service and the West Virginia Department of Natural Resources contracted with Virginia Polytechnic Institute and State University to study the effect of various harvest regimes on baitfish populations within Rich Creek. Although commercial fishing for bait species did not occur regularly in Rich Creek, the creek was chosen because it was typical of the streams in which seines and traps are used to capture baitfish. Field studies, designed to mimic an actual commercial baitfishing operation (Brandt and Schreck 1975), were performed in conjunction with the study reported herein.

Rich Creek begins as a spring rising out of the wooded northern slope of Peters Mountain, Monroe County, West Virginia. The stream runs 17.7 km south passing through Peterstown, West Virginia, and the town of Rich Creek, Virginia, and drains into the New River. The Rich Creek watershed has an area of 85 km^2, the majority of which is pasture land, although some of it is planted in corn. The stream is characterized by average flow water depths of 0.5-0.8 m and an average width of 4.7 m (Brandt 1974, Brandt and Schreck 1975). Water temperatures range from a low of 4 C in midwinter to 24 C in July (Bailey et al. 1973, Bailey 1974). The stream substrate primarily consists of gravel beds with some silt deposits.

The creek is classified as a marginal trout stream by the West Virginia Department of Natural Resources (Bailey et al. 1974). Trout are available from two sources: (1) the State of West Virginia regularly stocks the stream in the late winter months; and (2) a few trout escape during high waters from a commercial trout hatchery located at the headwaters. The rest of the fish fauna consists of centrarchid-cyprinid complexes and other associated species common to warmwater streams (Table 1) (Brandt 1974). All fin fish and crayfish, except centrarchids and trout, were considered to be baitfish.

The gear allowed by the State of West Virginia for baitfishing included seines no longer than 1.83 m (6 ft), no deeper than 1.22 m (4 ft), and with a mesh size of 0.64 cm (0.25 in). Minnow traps had to be 60.9 cm (2 ft) or less in length with an opening diameter of 2.54 cm (1 in) or less. Field studies tested a range of exploitation levels possible by baitfishing.

The recreational fisheries of Rich Creek included heavy angling effort for the stocked trout, and relatively little fishing for bluegill and smallmouth bass (Bailey et al. 1974).

OEP Design

To design any management procedure constraints on the procedure must be defined. The first constraint is the planning or time horizon

Table 1. Common names, scientific names, and computer simulation category names for species in Rich Creek as found by Brandt (1974).

Common Name	Scientific Name	Category Name
Particulate Organic Matter		POM
Macroinvertebrates		MACROINV
Rainbow trout	*Salmo gairdneri*	TROUT
Brown trout	*Salmo trutta*	
Brook trout	*Salvelinus fontinalis*	
Bluegill sunfish	*Lepomis* spp.	BLUEGILL
Rock bass	*Ambloplites repestris*	
Smallmouth bass	*Micropterus dolomieai*	SMOUTHBS
Spotted bass	*Micropterus punctulatus*	
Crayfish	*Cambarus* spp.	CRAYFISH
Crayfish	*Orconectes spinosus*	
White shiner	*Notropus albeolus*	SHINERS
Telescope shiner	*Notropus telescopus*	
Greenside darter	*Etheostoma blennioides*	
Fan-tail darter	*Etheostoma flabellare*	
Bluehead chub	*Hybopsis leptocephala*	CHUBS
Creek chub	*Semotilus atromaculatus*	
Mottled sculpin	*Cottus bairdi*	
Stone roller	*Campostoma anomalum*	STONERLS
Bluntnose minnow	*Pimephales notatus*	
Fathead minnow	*Pimephales promelas*	
White sucker	*Catostomus commersoni*	SUCKERS
Northern hogsucker	*Hypentelium nigricans*	

(the length of time into the future that the decision-maker wishes to make predictions). Ecological planning, it is generally agreed (see, e.g., Anderson 1972), should employ long time horizons because short term effects may mask important changes in the system. However, the further into the future that a prediction is made, the less accurate and reliable that predictions will be and the more risks will be taken.

The time horizon for OEP was chosen to be one year, running from January 1 to December 31. Exploitation could occur throughout the year. At the end of each year, the system was to be returned to the beginning state of that year or to a state specified by the decision-maker. This specified desired state becomes a terminal constraint on the system. The system will not degrade below a specified level at the end of the year. Therefore, by planning for sequential short term epochs (using OEP), a desired state of the system is achieved for the long term. However, improper choice of the specified state may produce suboptimal results in the long term. The exact form for this terminal constraint will be discussed in the section on Management Objectives.

Each year was divided into decision-maker-specified stages of equal length. Most of the applications of OEP in this study were for 24 stages of 15 days each. The number of stages is determined by characteristics of the study system (how often decisions are made in the study system), and the memory capabilities of the decision-maker's computer.

OEP was designed to compute interactions between and among as many as 10 species with each species being divided into as many as five age classes. The program could also handle as many as five different types of fisheries of fishermen. The categories used for the Rich Creek study were: (1) trout fishermen; (2) bluegill fishermen; (3) smallmouth bass fishermen; (4) the seine fishermen; and (5) the trap fishermen.

A management policy, D, consists of decision activity j at time i. Therefore, the policy, D, may be expressed as a matrix of order N x Q

$$D = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1Q} \\ \vdots & \vdots & d_{ij} & \vdots \\ d_{N1} & d_{N2} & \cdots & d_{NQ} \end{bmatrix} .$$

where: Q = number of activities,

N = number of time stages, and

d_{ij} = decision activity j at time i.

In OEP, 13 decision activities (Table 2) were included in the computer program (Q = 13). If N = 24, i.e., if the number of time stages equals 24, then the management policy consists of 13 x 24 elements or 312 decision variables.

The design of OEP will be discussed in the following four categories: ecosystem dynamics, fishermen dynamics, management objectives, and the optimization procedure.

Table 2. Decision activities incorporated into the OEP computer program.

Activity Number (Q)	Definition
1	Proportion of total area that is open for fishing
2	Biomass trout (g/m^2) to be planted
3	Mesh size of seine or trap (cm)
4	Maximum length of seine (m)
5	Maximum number of baitfish in possession per seine operation
6	Density of commercial fishermen (No/m^2)
7	Maximum number of trout in possession per angler
8	Minimum size of bluegill (g) in possession
9	Maximum size of bluegill (g) in possession
10	Maximum number of bluegill in possession per angler
11	Minimum size of smallmouth bass (g) in possession
12	Maximum size of smallmouth bass (g) in possession
13	Maximum number of smallmouth bass in possession per angler

Ecosystem Dynamics

Models of ecosystem dynamics should depict interaction among ecosystem components and exhibit some degree of realism, generality, and precision. Such a model should (at a minimum) include effects of predator-prey relationships, reproduction, mortality and aggressive behavior, and the flexibility to include other important interaction processes. Some modelers have decomposed the dynamics of ecosystems into individual ecological processes in a manner similar to Holling (1965) with his model of predator attack. Timin (1973) extended Holling's approach by modeling a multispecies consumption system which can be integrated as a subprogram into a generalized ecosystem simulator. Interaction between animals has also been incorporated into reproduction models (Fujita 1954). This dissertation reports on an effort in queueing theory which expands on Timin's work to include several types of intra- and interspecific interaction.

Queueing model development. Consider an animal of the vth type moving through its environment. When another animal of the rth type enters v's sphere of influence, i.e., when it enters the area in which it can be detected by v, v must react in one of three ways: (1) recognize and react toward r; (2) recognize and avoid r; or (3) recognize and totally ignore r.

In the state in which v is reacting toward (chasing) animal r, assume another animal (s) enters v's sphere of influence while v is chasing r. The presence of s might change v's action. If s is unpalatable, it may be ignored. But, if s is a potential predator, its presence will take preemptive priority over that of r and v will attempt to avoid (escape) s.

Generally, an animal has a more complex priority set than simply chasing, escaping, or ignoring. A more complex priority set may include, for example, escaping a predator, escaping an aggressive dominant, spawning (reproducing), chasing a subdominant, and chasing a prey. An animal's actions may always be characterized with preemptive priorities, i.e., arrival of an item or stimuli of a higher priority will stop action on or behavior toward (termed "service") items or stimuli of lower priority. In essence, animal v is the single server in a queueing system in which the service discipline is governed by preemptive priorities and the maximum number allowed in the system is 1 (maximum queue length equals zero).

So that this relationship may be formalized, let n be the number of response priorities for a particular animal with the highest priority being 1. Associated with each priority i there is an arrival rate λ_i and a service rate μ_i. These rates are the expected number of trespassers of priority i into v's sphere of influence per unit time and the expected number of services of priority i that v can perform per unit time, respectively.

Given n priorities, at any time t animal v can be in the process of servicing an animal of priority i (i=1, 2, ..., n) with a probability $P_i(t)$; it can be idle having just completed service of priority type i [$P_{oi}(t)$], or it can be idle having not interacted with any other animal in the ecosystem [$P_{oo}(t)$]. Thus, the animal can be in one of 2n + 1 mutually exclusive and exhaustive states.

Let Δt be an arbitrarily small time increment in which the probability of more than one arrival or service occurring is extremely small. Then the following equation can be developed:

$$P_{oi}(t + \Delta t) = P_i(t)\ [\mu_i \Delta t + o(\Delta t)] + P_{oi}(t)[1 - \sum_{j=1}^{n} \lambda_j\ \Delta t - o(\Delta t)] \qquad (1.1)$$

$$(i=1,\ 2,\ \ldots,\ n)$$

where $o(\Delta t)$ is an arbitrary function of Δt, many orders of magnitude less than $\lambda_i \Delta t$ [as $\Delta t \to 0$, $(o(\Delta t)/\Delta t) \to 0$]. Equation (1.1) formalizes the relationship that the probability of v being idle in the interval Δt, having just completed a service of priority i [$P_{oi}(t + \Delta t)$] is equal to the probability that a service of the ith priority was completed (the first term in 1.1) plus the probability that there were no arrivals (the second term in 1.1).

Since $$\lim_{\Delta t \to 0} \frac{P_{oi}(t + \Delta t) - P_{oi}(t)}{\Delta t} = P'_{oi}(t),$$

equation (1.1) can be manipulated to produce

$$P'_{oi}(t) = \mu_i P_i(t) - (\sum_{j=0}^{n} \lambda_j)\ P_{oi}(t). \qquad (1.2)$$

As t approaches infinity, $P'_{oi}(t)$ approaches zero, and $P_{oi}(t)$ approaches P_{oi} (steady state conditions). Therefore,

$$P_{oi} = \frac{\mu_i P_i}{\sum_{j=1}^{n} \lambda_j} \tag{1.3}$$

In a similar manner,

$$\begin{aligned} P_i(t + \Delta t) = {} & [\sum_{j=0}^{n} P_{oj}(t)][\lambda_i \Delta t + o(\Delta t)] \\ & + P_i(t)[1 - \mu_i \Delta t - \sum_{j=i+1}^{n} \lambda_j \Delta t - o(\Delta t)] \\ & + [\sum_{j=1}^{i-1} P_j(t)][\lambda_i \Delta t + o(\Delta t)]. \end{aligned} \tag{1.4}$$

If we define $\sum_{m=z}^{w} a_m = 0$ when $z>w$, then in the steady state

$$P_i = \frac{\lambda_i}{\mu_i + \sum_{j=1}^{i-1} \lambda_j} (\sum_{j=0}^{n} P_{oj} + \sum_{j=i+1}^{n} P_j). \tag{1.5}$$

Let γ_i $(i=1, 2, \ldots, n)$ be new variables such that

$$\gamma_n = \frac{\lambda_n}{\mu_n + \sum_{j=1}^{n-1} \lambda_j} \tag{1.6}$$

Substituting (1.6) into (1.5) gives

$$P_n = \gamma_n \sum_{j=0}^{n} P_{oj}. \tag{1.7}$$

Then using (1.7) and (1.5) and by back substituting,

$$P_{n-1} = \frac{\lambda_{n-1}}{\mu_{n-1} + \sum_{j=1}^{n-2} \lambda_j} \left(\gamma_n \sum_{j=0}^{n} P_{oj} + \sum_{j=0}^{n} P_{oj}\right) \tag{1.8}$$

or

$$P_{n-1} = \gamma_{n-1} \left(\sum_{j=0}^{n} P_{oj}\right)$$

where

$$\gamma_{n-1} = \frac{\lambda_{n-1}}{\mu_{n-1} + \sum_{j=1}^{n-2} \lambda_j} (1 + \gamma_n). \tag{1.9}$$

By continuing to back substitute, the general result is

$$P_i = \gamma_i \sum_{j=0}^{n} P_{oj} \qquad (i=1,\ 2,\ \ldots,\ n) \tag{1.10}$$

where

$$\gamma_i = \frac{\lambda_i}{\mu_i + \sum_{j=1}^{i-1} \lambda_j} \left(1 + \sum_{j=i+1}^{n} \gamma_j\right). \tag{1.11}$$

Since the 2n + 1 states are mutually exclusive and exhaustive,

$$\sum_{i=0}^{n} P_{oi} + \sum_{i=1}^{n} P_i = 1.$$

Note that $P_{oo} = 0$ for any non-zero arrival rate. Using (1.10),

$$\sum_{i=0}^{n} P_{oi} + \sum_{i=1}^{n} (\gamma_i \sum_{j=0}^{n} P_{oj}) = 1.$$

and

$$\sum_{i=0}^{n} P_{oi} = \frac{1}{1 + \sum_{i=1}^{n} \gamma_i} \qquad (1.12)$$

Substituting (1.12) into (1.10) produces

$$P_i = \frac{\gamma_i}{1 + \sum_{j=1}^{n} \gamma_j} \qquad (1.13)$$

and using (1.3)

$$P_{oi} = \frac{\mu_i \gamma_i}{(\sum_{j=1}^{n} \lambda_j)(1 + \sum_{j=1}^{n} \gamma_j)} \quad . \qquad (1.14)$$

P_{oi} is defined as the probability the animal is in the idle state having completed a service of priority i, or as the proportion of time that the animal is in that state. This does not mean, however, that the service was completed successfully. The probability of success, given completion, would be $\mu_i/(\mu_i + \mu\tilde{\gamma}_i)$, where $\mu\tilde{\gamma}_i$ is the service rate of the other animal performing the complementary service; e.g., if μ_i was rate of prey capture, then $\mu\tilde{\gamma}_i$ would be the rate of escape by that prey.

P_i and P_{oi} are steady state probabilities of a Markov chain in which the expected recurrence time of a state is the reciprocal of the steady state probability. Therefore, the expected number of completed services of priority i (X_i) is the product of P_{oi}, the probability of success and the total time being considered (T). If we assume the P_{oi} calculated for the individual are an adequate representation of those of its species or age class, then (1.14) may be incorporated into an ecosystem model.

In such a model the detection by species v of the proportion of species r that are in the ith priority (λ_{ir}) may be calculated using an analog from statistical mechanics (Timin 1973),

$$\lambda_{ir} = 2\ D\ R_i\ N_r (S_v^{\ 2} + S_r^{\ 2})^{1/2} \tag{1.15}$$

where,

D = distance (m) over which a fish perceives stimuli

N_r = density of species r

S = searching speed of the server (v) and of species r

R_i = proportion of species r which are in the ith priority

Then λ_i would be the sum of λ_{ir} over all r. It is expected that R_i would depend on factors such as time of year, preferences for food items, and the species. Arrival rates could then be adjusted for each time period, each species and each age class. Given that μ_i is known, the P_{oi} may be calculated for each animal type v (equation 1.14).

<u>Example of queueing model application</u>. In order to examine the model, consider two consumers (consumer 1 and consumer 2) which compete for a

single prey item and are themselves potential prey of a single predator. Assume the prey item is immobile ($S=0$, $\mu=0$), that $R_i = 1/4$ (chosen for computational convenience) for all species and all i, and priority sequences for the two consumers are as follows:

Consumer 1

1. Escape predator
2. Escape dominant
3. Chase prey

Consumer 2

1. Escape predator
2. Chase prey
3. Chase subdominant

For the example the parameters for the two consumers will be identical except that the priorities are realigned (Table 3). The probability of being idle having completed a capture is also given in Table 3. Due to the dominant behavior of consumer 2 (indicated in the above priority sequences), consumer 1 is less likely to have completed the capture process than consumer 2. To further evaluate the relationships, P_{o3} for consumer 1 (the probability of prey capture) is plotted against the service rate of chasing prey and the speed of search, and is compared to the same probability (P_{o2}) for consumer 2 (horizontal line in Fig. 1). In order for consumer 1 to increase its capture probability, it must increase its speed or service rate, or both. But if the speed is increased greatly, the chance of encountering a predator or a dominant

Table 3. Parameter values for 4-species system in queueing example.

Parameter	Prey	Consumer 1	Consumer 2	Predator
N (m^{-2})	10.0	0.50	0.50	0.10
S (m/sec)	0.0	0.02	0.02	0.04
D (m)		0.30	0.30	
μ_i (sec^{-1})				
i=1		0.20	0.20	
2		0.25	0.30	
3		0.30	0.25	
		P_{o_3} = 0.815	P_{o_2} = 0.829	

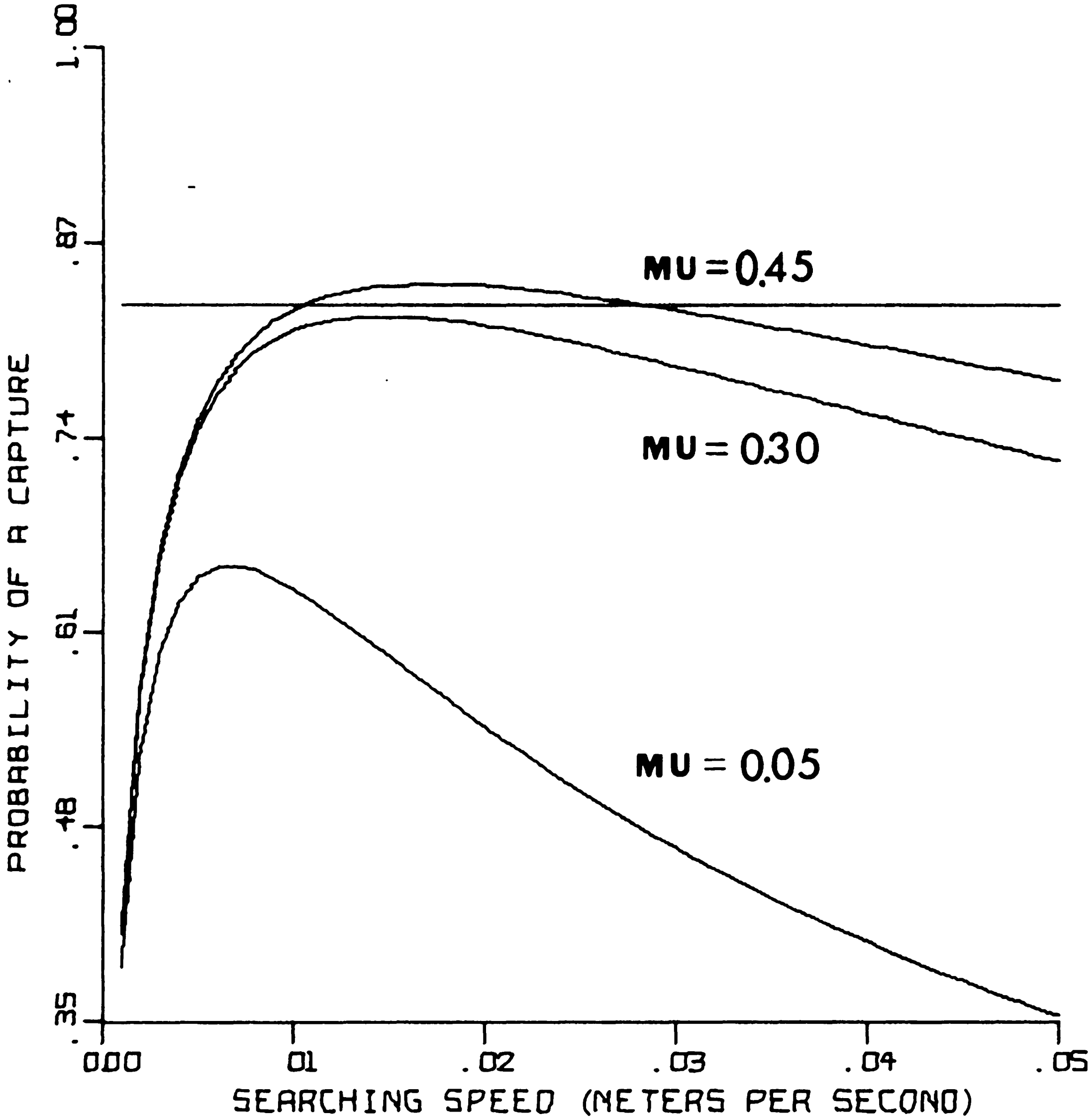

FIGURE 1. PROBABILITY OF A CAPTURE OF A FOOD ITEM BY CONSUMER 1 GIVEN SEARCHING SPEED AND CAPTURE RATE (MU) IN 1/SEC. THE HORIZONTAL LINE IS THE PROBABILITY OF A CAPTURE OF A FOOD ITEM BY CONSUMER 2.

will increase and the gains in capture probability are nullified. Hence, the dominant behavior of consumer 2 leads to an advantage in capture of prey. Interference in predatory action reduces the amount of prey captured as suggested by Holling (1965).

The queueing model in OEP. The priority sequence for fish and crayfish which was employed in this study is as follows:

(1) Escape from predator;

(2) Escape from aggressive dominant;

(3) Spawn with receptive mate;

(4) If server in spawning condition, chase of subdominant;

(5) Chase of food item; and

(6) If server not in spawning condition, chase of subdominant.

Priorities (4), (5), and (6) imply that when an animal is in spawning condition, aggressive social behavior takes precedence over chasing a food item. This appears to be true for many fishes (Nikolsky 1968).

Each arrival rate was weighted by proportions (R_i) in (1.15). The R_i used in OEP were calculated using what will be termed interaction matrices. These matrices are estimates of the proportion (or probability) of the interacting animals that fall into a certain interaction category. The product of the appropriate proportions equal R_i. The following interaction matrices were used (using FORTRAN variable names):

(1) $PPRED_{ijkl...}$ The probability that an animal of species i, age class j will attack an animal of species k, age class l.

(2) $PSPWN_{in...}$ The probability that an animal of species i will be in spawning condition during the nth month of the year.

(3) $PSPGR_{i...}$ The proportion of the total area which is available for use as a spawning ground for species i.

Two other indices of interaction were employed. The first was a binary matrix (all elements equal to zero or one):

$NDOM_{ik...}$ Does a member of species i ever display territorial or aggressive behavior toward a member of species k? (1 equals yes; 0 equals no).

This was converted to PA_{ijkl} (the probability of aggressive behavior by a member of species i, age class j, toward a member of species k, age class l):

$$PA_{ijkl} = (NDOM_{ik})(W_{ij})/(W_{ij} + W_{kl}),$$

where W is the average weight.

The other index matrix was PAG_{ij}, an index of aggregation of species i, age class j with others of its own kind (as in schooling behavior). The range of the PAG scale was arbitrarily set at 0.0 to 10.0 with 10.0 being high aggregation. The index PAG was a subjective estimation of a weighting factor to account for congregation of the fish species.

The set of matrices served to define biological relationships between species and also to define the physical environment. A review of the literature provided gross estimates for the elements of these matrices and for other parameters to be discussed later. This estimation is termed subjective estimation because of the inaccuracy. An entirely different set of matrices may be used. For example, each probability, or index number, might be made time-dependent, or a matrix governing the proportion of covered area available to each species for escape from predators might be included. However, the set of matrices chosen were sufficiently detailed for this study. Therefore, the arrival rates of each priority were weighed by these interaction matrices.

The queueing process (equations 1.14 and 1.15) was iterated for each species and age class, i.e., each age class had a priority sequence, arrival rates, and service rates reflecting the abundance of all the other species. The expected number of successful completions of each priority (X_i) by each number of an age class was computed for each time period. When X_5 was multiplied by the average weight of the prey, the product was ration size. If the ration size exceeded the maximal ration, then ration size was set equal to the maximal ration and the mortality rates were reduced accordingly.

The maximum ration was derived from the equation

$$RMAX = UPS(WEIGHT)^{EPS} ,$$

where

WEIGHT = Wet weight (g) of the consumer

UPS = 0.146

EPS = 0.849

Parameter estimates are modifications of those reported for bluegill by Kitchell _et_ _al_. (1972)

Other statistics computed by the queueing process are the number of eggs spawned (the product of X_4, eggs/female, and the number of females), and the mortality (the product of the number of unsuccessful escapes and the age class abundance). Calculation of these statistics (and the ration size) required definition of several subroutines dealing with temperature, productivity in the lower portions of the food web, searching speed (S in equation 1.15), fecundity, and growth and metabolism.

Productivity. The productivity subroutine calculates water temperature (T) in degrees C, the density of particulate organic matter (POM), and the density of macroinvertebrates (MACRO). Each value is assumed to be a function of the time of the year:

$$T = PRP_1 + PRP_2 EXP[-PRP_3 (TIME - \frac{NSTAGE}{2})^2],$$

$$POM = PRP_4 + PRP_5 \{EXP[-PRP_6 (TIME - \frac{NSTAGE}{3})^2]$$

$$+ EXP[-PRP_7 (TIME - \frac{2(NSTAGE)}{3})^2]\}, \text{ and}$$

$$MACRO = PRP_8 + PRP_9 EXP[-PRP_{10} (TIME - \frac{NSTAGE}{2})^2],$$

where:

TIME = time stage under consideration,

NSTAGE = total number of time stages in the year, and

PRP_i = parameter values (i=1, 2, ..., 10).

Curves derived from the three equations were chosen because they are unimodal, bimodal, and unimodal, respecively. Default values for the parameters, physical interpretations, data source (if available) and methods of estimation are given in Appendix I.

Fecundity. The fecundity subroutine calculates the number of eggs per female (FEC) as a function of water temperature (T) and the weight of the fish (W):

$$FEC = FP_1[1\text{-}EXP(-FP_2W)]\{EXP[-FP_4(T\text{-}FP_3)^2]\},$$

where FP_i (i=1, 2, ..., 4) are species dependent parameters (default values are given in Appendix I with interpretations, data source and method of estimation). The relationship expresses the notion that fecundity approaches a maximum as temperature approaches an optimum (FP_3) and as weight (W) increases.

Searching Speed. The species-dependent searching speed (SPEED) in cm/sec was calculated as a function of temperature (T) and the weight of the fish in grams (W):

$$SPEED = \frac{SP_1(T + 273)EXP(\frac{-SP_2}{T + 273})}{1 + SP_4EXP(\frac{-SP_5}{T + 273})} W^{SP_3}$$

where SP_i (i=1, 2, ..., 5) are parameters. The mathematical model of the temperature effect was derived from studies on reaction rate kinetics (see, for example, Belehradek 1957) and applied in an ecological context by Watt (1968: 278). Parameters (Appendix I) were estimated by applying Marquardt's iterative least squares algorithm (1963) to data taken from Wohlschlag and Juliano (1959).

Metabolism and growth. The growth model was a function of temperature (T) and body weight in grams (W),

$$\text{Growth/day} = \text{Energy Intake} - \text{Standard Metabolism} - \text{Active Metabolism.}$$

The species-dependent standard metabolism model (METAB) used the reaction-rate model of temperature and the common power function of oxygen consumption (see, for example, Paloheimo and Dickie 1965):

$$\text{METAB} = \frac{(115.7)(GP_1)(T + 273)\text{EXP}\left(\frac{-GP_2}{T + 273}\right)}{1 + GP_4\text{EXP}\left(\frac{-GP_5}{T + 273}\right)} W^{GP_3}$$

where GP_i (i=1, 2, ..., 5) are parameters and the number 115.7 is a factor converting oxygen consumption in mg/hr to calories consumed per day. The function was fit to a variety of data by iterative least squares regression: bluegill (data from Pierce and Wissing 1974); goldfish (data from Beamish and Mookherjii 1964); and brook trout, white suckers, and carp (all data estimated from graphs in Beamish 1964).

Species-dependent active metabolism (AM) was computed by

$$AM = GP_6(\text{SPEED}),$$

where SPEED is the searching speed (cm/sec) as calculated in the previous section. The parameter GP_6 was estimated by averaging the conversion rate from cruising speed to active metabolism (calories) taken from Pierce and Wissing (1974).

Energy intake (E) was the ration size (g) as calculated in the queueing process multiplied by a factor converting wet weight to usable energy in calories (350.625 cal/g). Finally, growth in grams was found by:

$$\text{GROWTH} = (\text{E} - \text{AM} - \text{METAB})/750,$$

where 750 equals the number of calories/gram. Estimates of GP_i (i=1, 2, ..., 5) for a variety of species are given in Appendix I. Some species present in Rich Creek are not represented in the metabolism data, but an attempt was made to match the species which have similar characteristics, i.e., use was made of available information.

Stochastic elements in ecosystem dynamics. Initially in OEP the estimates of parameters and the estimates of the probabilities in the interaction matrices were considered to be deterministic. It is possible to consider these estimates to be "most likely" estimates and then make subjective estimates as to the high and low points in the range. From this subjective information, a Weibull distribution may be constructed (Lamb 1967, Clark and Lackey 1975). Random variables may then be generated (using pseudorandom numbers). Random variables can take the place of the deterministic estimates and each simulation is a stochastic or Monte Carlo simulation. The extra storage requirements for high and low estimates of the interaction matrices and the extra computations were excessive for this particular study. Monte Carlo simulations were produced in OEP in the following manner. Estimates of the standard deviations of temperature, particulate organic matter density, macroinvertebrates density, growth, searching speed, and angler density (to be discussed later) are included as input parameters for each of these functions. A random normal variate was generated using the input standard deviation and the deterministic function value as the mean (expected value), using the method of Schmidt and Taylor (1970: 265-267). Random "noise" introduced by several factors is encompassed into a relatively small number of variance estimates.

Fishermen Dynamics

Functional characteristics of both recreational and sport fishermen were included within the queueing subprogram. To do so, it was important to note the difference between the methods by which fish are caught in Rich Creek. Angling and trapping are passive acts by the fishermen: the fishermen wait for the fish to "catch" themselves. On the other hand, seining is an active process: the fishermen are actively striving to capture fish. The distinction reflects where the fishermen enters into a fish's priority sequence. Until the time when the fish is actually hooked or trapped, the fish is in the process of obtaining prey [priority (5)]. But, when confronted with a seine, a fish tries to escape [priority (1)]. Using appropriate priorities, the man-fish interaction was included in the queueing process.

Arrival rates and service rates of fish and fishermen within a unit area were also multiplied by interaction matrices. These were:

$PREF_{ij}$...the probability that a member of species i will take the bait of a fisherman of type j.

PHOOK....the probability that a fish will be hooked given that it will take the bait.

PCAPT....the probability that a fish will be captured given that it is hooked.

These interaction probabilities specify the physical and biological relationships between the fishermen and fish populations.

<u>Angler density</u>. Computation of arrival rates [equation (1.15)] requires that the density of the interacting organisms be defined. Because the fishermen are included within the queueing system, their density must also be defined. The density of commercial fishermen was specified to be a decision variable (Table 2), and, as such, no functional equation for this variable is necessary.

However, the density of recreational fishermen is a dynamic process and its change was assumed to be a result of several important variables (Bailey 1974): temperature conditions (TC); time of year (TY); opening day anticipation (AN); and the catch in the immediate prior history (CA). Therefore, angler density (ANG) was:

$$ANG = (POP)(PLIC)(TC)(TY)(AN)(CA)/AREA,$$

where: POP = the number of people that have access to the stream,

PLIC = the proportion of these people who have fishing licenses, and

AREA = the area of the stream (m^2).

TY was expressed as a function of the number of time stages (NSTAGE) and the time stage of concern (TIME):

$$TY = EXP[-AP_1(\frac{TIME}{NSTAGE} - AP_2)^2].$$

The equation mathematically states that there was one time of year (AP_2) which produces a maximum amount of fishing.

TC was expressed as a function of temperature (T):

$$TC = EXP[-AP_3(T - AP_4)^2],$$

i.e., there was an optimum temperature (AP_4).

AN was a function of the number of consecutively previous days in which no fishing occurred (OFF):

$$AN = 1 - AP_5 EXP[-AP_6(OFF + 1)],$$

i.e., as OFF increased, AN approached a maximum.

Finally, CA was a function of the catch-per-angler-day during the previous time period (CPUE):

$$CA = 1 - AP_7 EXP[-AP_8(CPUE)].$$

As CPUE increased, CA approached a maximum. AP_i (i=1, 2, ..., 8) were constants estimated by regression (Appendix III).

Although fishing was allowed year round in West Virginia, functionally there was an opening day due to lack of angler interest in the early winter and due to publicizing of trout stocking schedules (Bailey, personal communication).

Both CPUE and OFF were three element vectors consisting of an element for each of the three recreational angler-types: trout fishermen, bluegill fishermen, and smallmouth bass fishermen. Therefore, an angler density equation was calculated for each of the three angler-types and weighted by the proportion of each angler-type within the total population (POP).

The parameters for the angler density equation(AP_i: i=1, 2, ..., 8) were fit by iterative least squares regression to creel census data obtained by sampling the anglers of Rich Creek (Bailey 1974). Data and the parameter estimates are given in Appendices II and III, respectively.

Capture parameters. The efficiency of the seining gear and the traps were considered to be a function of the weight (g) of fish (W) and the mesh size (MS) in cm. Thus, the proportion of the susceptible fish that will be captured by the seine)PRT) is:

$$PRT = CP_3 EXP\{-CP_1[W - CP_2(MS)]^2\}.$$

This equation assumes that the optimal mesh size for catching fish of weight W is W/CP_2. For the efficiency of the seine alone, PRT is further multiplied by another factor (F) which is a function of the length of the seine (LS) in m

$$F = 1 - EXP[-CP_4(LS)].$$

The equation assumes catch will assymptotically increase with the length of the seine. Estimates of CP_i (i=1,2,3,4) are given in Appendix III.

Other parameters (CP_i: i=5,6,7,8) were used to complete the fishermen-fish description in the queueing process. These were:

CP_5 ... the probability that a fish will not escape an angler or a seine given that it has been hooked or enclosed by the angler or seine, respectively

CP_6 ... the probability that a fish will not escape from a trap given that it has entered the trap

CP_7 ... the average speed (m/sec) that an angler moves during a day of fishing

CP_8 ... the average speed (m/sec) that the seine is moved during a day of seining.

Since the queueing process calculates the catch by the average fishermen, skill of the fishermen is not included in the model. The estimates of the CP parameters are given in Appendix III.

With a dynamic approach to quantifying the states of the system, OEP generates statistics such as the number of fishermen, the number, size, and species of fish caught, and the means by which the fish were caught. However, if an optimal policy is to be found, catch statistics (as well as other criteria) must be developed into a set of management objectives.

Management Objectives

Many different criteria may be included in an ecosystem management objective function. Criteria may reflect several system aspects such as benefits which are accrued by the users of the resource, maintenance and/or conservation of the resource, and benefits derived by the management agency, itself. When managing multiple-use ecosystems, a decision-maker may consider several criteria within the objective function. Perhaps all of the above criteria could be included, but problems arise when the decision-maker attempts to quantify these criteria. Quantifying user-benefits in a recreationally oriented resource is especially difficult. The following sections show the development of quantification schemes for objectives for the recreational fishery of Rich Creek.

Utility function for a recreational fishery. Rational management of a recreational fishery by a public agency requires optimization of an objective function which reflects benefits to the users. An objective function often used is the user-days measure (McFadden 1969, Lackey 1974), which primarily reflects benefits to the survival conscious agency. However, many other attributes may enter into recreational fishing benefits.

In a recreational fishery, important attributes of an individual's fishing experience may include water quality, scenic beauty of the area, size, number, and species of fish caught, privacy, support facilities, and access to the fishing area (Bailey et al. 1974). Moeller and Engelken (1972) found that in their sample, anglers consistently ranked privacy more important than either number or size of fish in the catch. Results such as those of Moeller and Engelken and others (Stankey 1973) lead one to question user-days as a proper management objective function for all cases, because more user-days is equivalent to less privacy.

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 decision-maker would prefer the alternative with the greatest expected utility. The utility function (UF) is an expression of preference of the decision-maker and sufficient conditions for its existence may be verified [see, e.g., Henderson and Quandt (1971: 13)]. This utility concept may be expanded to include multiple measures of effectiveness using Keeney's model (1973, 1974).

Because the UF represents the decision-maker's views as to his <u>own</u> preferences, there is no "right" or "wrong" associated with it. When the decision-maker (a public natural resouce manager) attempts to formulate a UF using attributes which primarily reflect benefits to the resource <u>user</u>, and only secondarily to himself, he is put in the position of making value judgements about what <u>he</u> feels the public desires. In all likelihood the decision-maker's utility preferences 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 (Raiffa 1970: 228-229). The group utility function may be derived by taking the mean, median, mode, or some other measure of central tendancy of the coefficients of the individuals' utility functions. This does not, however, overcome problems of interpersonal comparisons of utility (Halter and Dean 1971: 246-248). One must recognize the distinction between the meaning of an expert's responses to a decision-maker and those same responses to the expert himself (Morris 1974: 1241). To the expert the utility function is a representation of his preferences; to the decision-maker the expert's UF is information.

The approach taken herein was to define a sample of the users of the recreational resource as the panel of experts, measure the UF of each, and aggregate these UF's into a single utility function. The advantages of this procedure often outweigh the disadvantages (Halter and Dean 1971: 248). The aggregate UF (termed group UF) is an expression of information which may be employed by the decision-maker. In OEP the decision-maker's utility function is defined to be the same as the group UF. However, the decision-maker may modify his UF to include his own preferences or input from sources other than the group utility function. These modifications may be easily implemented. The following is a discussion of the construction of the UF using the Keeney utility model and its application to Rich Creek.

The Keeney utility model. The Keeney model (1974) follows directly from the axioms of rational behavior specified by von Neumann and Morgenstern (1948). Let $\underline{X} = X_1 \times X_2 \times \ldots \times X_i \times \ldots \times X_n$ be the Cartesian product of the n attributes; i.e., the consequence space.

Then, a specific consequence is $\underline{x} = (x_1, x_2, \ldots, x_i, \ldots, x_n)$, where x_i is a specific amount of X_i. We assume preferences over $\underline{X}$ are bounded; therefore, let $\underline{x}^o$ be the least desirable consequence, and $\underline{x}^*$ be the most desirable. Also, X_{ij-} (read as "ex not ij") is $X_1 \times X_2 \times \cdots \times X_{i-1} \times X_{i+1} \times \cdots \times X_{j-1} \times X_{j+1} \times \cdots \times X_n$ and x_{ij-} is a member of X_{ij-}. Likewise, $X_{i-} = X_1 \times X_2 \times \cdots \times X_{i-1} \times X_{i+1} \times \cdots \times X_n$ and x_{i-} is a member of X_{i-}. Finally the utility function $u(\underline{x}) = u(x_1, x_2, \ldots, x_n)$ is equal to a function of $[u_1(x_1), u_2(x_2), \ldots, u_n(x_n)]$, where $u_i(x_i)$ is the utility of the ith attribute scaled from 0 to 1; i.e., $u_i(x_i^o) = 0$ and $u_i(x_i^*) = 1$. Also, $u(\underline{x}^o) = u(x_1^o, x_2^o, \ldots, x_n^o) = 0$ and $u(\underline{x}^*) = u(x_1^*, x_2^*, \ldots, x_n^*) = 1$.

The Keeney model relies on the assumptions of preferential independence and utility independence of the attributes. The former assumption implies that the indifference curves over $X_i \times X_j$ are the same, regardless of the value of X_{ij-}. The latter assumption implies that the conditional utility function over X_i, given X_{i-} fixed at any value, will be a positive linear transformation of the conditional utility over X_i, given X_{i-}, fixed at any other value.

If the two assumptions hold for all i and $i \times j$, then the model can be stated as either,

$$u(\underline{x}) = \Sigma_{i=1}^{i=n} k_i u_i(x_i), \tag{2.1}$$

or

$$1 + Ku(\underline{x}) = \pi_{i=1}^{i=n} [1 + Kk_i u_i(x_i)], \tag{2.2}$$

where k_i and K are scaling constants ($0<k_i<1$, $K>-1$, $K \neq 0$). If $\Sigma_{i=1}^{i=n} k_i=1$, then (2.1) is the proper relationship; otherwise, relationship (2.2) is appropriate.

The above utility model, because of its associated assumptions, permits development of a utility function of several attributes by measuring the utility of each attributes separately, and then measuring the scaling constants. The methods of verifying the assumptions, measuring $u_i(x_i)$, and measuring the scaling factors (k_i and K) will be presented in subsequent sections in the context of the study.

Definition of Rich Creek utility attributes. The utility problem can be formulated in such a way as to include attributes of importance and yet in a form in which assumptions of independence are valid. Measures of effectiveness for recreational fishing at Rich Creek which were used were:

X_1 = fish species appearing in the catch;

X_2 = average fish size (in) in the catch;

X_3 = average number of fish caught/angler/day; and

X_4 = angler abundance/day (no/500 yd^2), a measure of crowding.

The species attribute, X_1, was defined to be a vector (X_1^{TR}, X_1^{SMB}, X_1^{BG}) corresponding to trout, smallmouth bass, and bluegill, respectively, where X_1^j (j=TR, SMB, BG) can only take the values 0 and 1 (Table 4). Thus, if trout appear in the catch, then x_1^{TR} = 1, regardless of the number caught. Similarly, when no trout are caught, x_1^{TR} = 0. Therefore,

Table 4. Utility attributes and their bounds as used in OEP

Attribute	Least desirable amount	Most desirable amount
Species in catch (Yes=1, No=0)		
X_1^{TR}: trout	0	1
X_1^{SMB}: smallmouth bass	0	1
X_1^{BG}: bluegill	0	1
X_1: scaled	0	1
Length of fish caught (inches)		
trout	8	14
smallmouth bass	9	16
bluegill	5	12
X_2: scaled	0	1
Number fish caught/angler/day		
trout	0	20
smallmouth bass	0	20
bluegill	0	30
X_3: scaled	0	1
Angler abundance (No/500 yd^2/day)	50	0
X_4: scaled	0	1

$u_1^j(0) = 0$, $u_1^j(1) = 1$ for j = TR, SMB, BG; and $u_1(\underline{x}_1^*) = u_1(x_1^{TR*}, x_1^{SMB*}, x_1^{BG*}) = u_1(1,1,1) = 1$. The utility function $u_1(\underline{x}_1)$ may then be expressed in a fashion analagous to (2.1) and (2.2); i.e.,

$$u_1(x_1^{TR}, x_1^{SMB}, x_1^{BG}) = \sum_{j=TR,SMB,BG} [c_j u_1^j(x_j)] \tag{2.3}$$

or

$$1 + Cu_1(x_1^{TR}, x_1^{SMB}, x_1^{BG}) = \prod_{j=TR,SMB,BG} [1 + Cc_j u_1^j(x_1^j)] \tag{2.4}$$

where C anc c_j are scaling constants equivalent to K and k_i of (2.1) and (2.2).

X_2 and X_3 are the scaled attributes of fish size and number, respectively. The scaled value of x_3 was calculated in the following fashion: let us say an angler caught 13 trout, 1 smallmouth bass, and 3 bluegill. The maximum number he could have caught would be 20 trout, 20 smallmouth bass, and 30 bluegill (Table 4). When each of these is expressed as a percentage of the maximum and then averaged, we have $x_3 = (13/20 + 1/20 + 3/30)/3 = (.80)/3 = 0.267$.

Similarly, x_2 was calculated by a weighted average. Assume an angler caught 3 trout, each 10 inches long, 4 smallmouth bass, each 11 inches long, and 5 bluegill, each 7 inches long. A 10-inch trout, when expressed as a percentage of the possible range, is equivalent to (10-8)/(14-8) or 0.333 (Table 4). Likewise, an 11-inch smallmouth equals (11-9)/(16-9) or 0.286 and a 7-inch bluegill is (7-5)/(12-5) =

0.286. The mean scaled length for all fish caught is x_2 = [3(0.333) + 4(0.286) + 5(0.286)]/(3 + 4 + 5); i.e., x_2 = 0.295.

The measure of crowding (or conversely, privacy) which was used was angler abundance/day which was converted to a 0 to 1 scale (Table 4). If angler abundance was 15 people/500 yd^2/day, then x_4 = *50-15)/50 = 0.700, because 15 is 70% of the range from 50 anglers per 500 yd^2 to 0 anglers per 500 yd^2. The range of zero to 50 anglers per 500 yd^2 was developed after discussions with Bailey (personal communication).

Assumptions of preferential and utility independence of the attributes were verified by discussions with graduate students at VPI & SU who were also licensed anglers. The method of verification follows that of Keeney (1973, 1974) and is explained in the following section. Utility assessments and assessments of the scaling factors were made via questionnaires mailed to residents of Monroe County who had obtained fishing licenses for the 1973-1974 year. An example of the questionnaire is given in Appendix IV.

Verification of assumptions. If the preferential independence of two attributes (let us say X_2 and X_3) was to be verified, then X_{14} ($X_1 \times X_4$) was fixed and the respondent was asked for an (x_2, x_3) and (x'_2, x'_3) which would make him indifferent to the two consequences of (x_2, x_3, x_{14}) and (x'_2, x'_3, x_{14}). Next, the respondent was asked if he was indifferent to (x_2, x_3, x'_{14}) and (x'_2, x'_3, x'_{14}). If the answer was affirmative, the procedure was repeated with other members of X_{23}, and with X_{14}

fixed at various levels. If the answers continued to be affirmative, the respondent was asked if his indifference to (x_2, x_3, x_{14}) and (x_2', x_3', x_{14}) would hold for every choice of x_{14}: a yes answer implied that $X_2 \times X_3$ was preferentially independent of X_{14}.

In questioning anglers, care had to be exercised to make sure that the respondent understood that a 10-inch bluegill and a 10-inch trout were not equivalent on the X_2 scale (Table 4). Similarly, 10 bluegill were not equivalent in X_3 to 10 smallmouth bass. Once this was understood, the questioning became easier. After testing all combinations of $X_i \times X_j$, the assumption of preferential independence was deemed sound.

Similar procedures were used to test for utility independence. For example, to test for utility independence of X_4, the respondent was asked for a certainty equivalent x_4 such that (x_4, x_{4-}) is indifferent to the lottery yielding (x_4', x_{4-}) and (x_4'', x_{4-}), each with equal probability. If the certainty equivalent did not change with x_{4-}, then x_4' and x_4'' were set at different values and the question was repeated. When a range of x_4' and x_4'' had been tested and the certainty equivalents had not changed with changes in x_{4-}, then X_4 was concluded to be utility independent of X_{4-}. When the angler realized the relationship of length and number of fish of different species, questioning proceeded rapidly. After testing all four attributes, the assumption of utility independence was accepted.

Utility assessment over each attribute. Because $u_1(\underline{x}_1) = u_1(x_1^{TR}, x_1^{SMB}, x_1^{BG})$ and because x_1^{TR}, x_1^{SMB}, x_1^{BG} can only equal 0 or 1, assessing $u_1(\underline{x}_1)$

simply requires evaluating the scaling constants C and c_j. These constants will be discussed in a later section; therefore, X_2, X_3, X_4 were the only attributes for which direct utility assessment had to be undertaken.

Individual utilities were found from responses to three questions in the mailed questionnaires. The exact questions as they appear in the questionnaires are in Appendix IV. The essence of these three questions were:

(1) What certainty equivalent of length of trout (in inches) would make you indifferent to the lottery offering a 14-inch trout and an 8-inch trout, each with equal probability?

(2) What certainty equivalent of number of bluegill will make you indifferent to a lottery offering 30 bluegill and 0 bluegill, each with equal probability?

(3) What certainty equivalent of number of other fishermen within 50 yards of you will make you indifferent to a lottery offering 50 other fishermen within 50 yards of you and 0 other fishermen within 50 yards of you, each with equal probability?

If we let responses to the three questions (after being scaled) be x_2, x_3, and x_4, respectively, then

$$u_i(x_i) = 0.50\ u_i(0) + 0.50\ u_i(1) = 0.5 \quad \text{for } i = 2,3,4.$$

The model that was assumed for $u_i(x_i)$ was

$$u_i(x_i) = x_i^{b_i}, \tag{2.5}$$

where b_i are constants (i=2, 3, 4). The reasons for choosing this model were primarily pragmatic: It fit the boundary condition of $u_i(0) = 0$ and $u_i(1) = 1$. Also, since short, simple questionnaires were desired, only a single value of x_i was determined for each respondent. By assuming (2.5), which has only one parameter, one can solve for the parameter using that single data point; i.e., $b_i = \ln[u_i(x_i)]/\ln(x_i)$ which is solvable because $u_i(x_i)$ and x_i are known.

Evaluation of scaling factors. The scaling factors c_j (j=TR, SMB, BG) and C were determined by responses to questionnaires in the following manner. If $x_1 = (x_1^{TR}, x_1^{SMB}, x_1^{BG})$, to determine c_{TR}, the probability p_{TR} was found at the level where the respondent was indifferent to $x_1 = (1,0,0)$ for certain, and a lottery offering $x_1 = (1,1,1)$ with a probability p_{TR} or $x_1 = (0,0,0)$ with a probability $1-p_{TR}$. From (2.3) and (2.4), $c_{TR} = p_{TR}$. Similarly, c_{SMB} was determined by finding the probability p_{SMB} at which the respondent was indifferent to $x_1 = (0,1,0)$ for certain and the lottery of $x_1 = (1,1,1)$ with probability p_{SMB} or $x_1 = (0,0,0)$ with probability $1-p_{SMB}$; then, $c_{SMB} = p_{SMB}$. The value c_{BG} was found using the same procedure.

If $\Sigma_j c_j \neq 1$, then (2.4) is the proper model and C can be found by solving

$$1 + C = \pi_j \ (1 + Cc_j) \tag{2.6}$$

by trial and error. If $\Sigma_j \ c_j > 1$, then $-1 < C < 0$; if $\Sigma_j \ c_j < 1$, then $0 < C$. Equation (2.6) is derivable from (2.4) when each attribute is offered at its most preferred amount; i.e., when $x_1 = x_1^*$.

The factors k_i and K could have been found in an analagous fashion, but some modifications were made to simplify questionnaires. Because the respondents had difficulty in converting length or number of one to the appropriate length or number of another species, the questions were worded to avoid conversions. The following [remembering $x_1 = (x_1^{TR}, x_1^{SMB}, x_1^{BG})$] were determined by questionnaire response:

(1) Find p_1 such that the respondent was indifferent to [$x_1 = (1,0,0)$, x_{1-}^o] for certain, or a lottery offering [$x_1 = (1,0,0)$, x_{1-}^*] with a probability p_1 and [$x_1 = (0,0,1)$, x_{1-}^o] with a probability $1-p_1$.

(2) Find p_2 such that the respondent was indifferent to [$x_1 = (0,0,1)$, x_2^*, x_{34}^o] for certain, or a lottery offering [$x_1 = (1,0,0)$, x_{1-}^*] with a probability p_2 and [$x_1 = (0,0,1)$, x_{1-}^o] with a probability $1-p_2$.

(3) Find p_3 such that the respondent was indifferent to [$x_1 = (0,0,1)$, x_3^*, x_{24}^o] for certain, or a lottery offering [$x_1 = (1,0,0)$, x_{1-}^*] with a probability p_3 and [$x_1 = (0,0,1)$, x_{1-}^o] with a probability $1-p_3$.

(4) Find p_4 such that the respondent was indifferent to [$x_1 = (0,0,1)$, x_4^*, x_{23}^o] for certain, or a lottery offering [$x_1 = (1,0,0)$, x_{1-}^*] with a probability p_4 and [$x_1 = (0,0,1)$, x_{1-}^o] with a probability $1-p_4$.

There was never more than one non-zero element in $\underline{x}_1$. Therefore, the respondent did not have to convert number and length scales from one species to another; e.g., the respondent did not have to know that 15 bluegill and 10 smallmouth bass were equal quantities in the number scale (X_3)

From the four questions, four equations could be formulated. Also, when $\underline{x} = \underline{x}^*$, using (2.2) gives another equation:

$$1 + K = \pi_{i=1}^{i=4} (1 + Kk_i). \tag{2.7}$$

The five equations in the five unknowns, K and k_i (i=1, 2, 3, 4) were solved by a numerical technique (Conte 1965: 43). The equations used and their formulation for solution are included in Appendix V. Because $\Sigma_i k_i$ was greater than unity, the utility model appropriate to the Rich Creek case was the multiplicative one; i.e., equation (2.2).

Group utility. Of the 225 questionnaires mailed, only 25 were returned in a usable form. The low response rate (approximately 10%) is probably due to the length and complexity of questions, although an attempt was made to minimize both. The median was calculated for each question response, and the parameter values for the utility function were computed (Table 5).

Ordinal ranking of the constants k_i (i=1, 2, 3, 4) (Table 5) is contrary to the ordinal ranking of importance of these attributes expressed in other studies (Moeller and Engelken 1972); i.e., privacy (k_4) was not found to be greater in magnitude than the other attributes. The ranking is, however, not too surprising for the following reason. Most fishing in Rich Creek is for trout and trout do not reproduce in Rich Creek. Anglers have become accustomed to catchable-sized trout

Table 5. Parameter values for the utility function based on 25 completed questionnaires, Monroe County, West Virginia.

Parameter	Value	Parameter	Value	Parameter	Value
k_1	0.384	c_{TR}	0.800	b_2	1.710
k_2	0.473	c_{SMB}	0.750	b_3	0.387
k_3	0.449	c_{BG}	0.600	b_4	34.314
k_4	0.424	C	- 0.976		
K	- 0.833				

stocking and, indeed, they anticipate stockings. As such, anglers have been observed congregating in large numbers in the area of a recent stocking (Bailey, personal communications).

In Table 6 are the utility values for the eight outcomes of $u_1(x_1)$. The shapes of the $u_i(x_i)$ for i=2, 3, and 4 are shown in Figures 2, 3, and 4 respectively. Size of fish and privacy display increasing marginal utilities (MU's) with privacy being strongly increasing. Hence, a unit increase in the size of fish or privacy quantities will result in a somewhat greater than one unit increase in utility. This is particularly noticeable in the attribute X_4. When crowding is fairly low, an additional decrease in crowding will produce a large increase in utility. But, when crowding is high, a further reduction in crowding will not have a significant effect on $u_4(x_4)$. The increasing MU of X_2 and the fact that k_2 is greater than the other k_i's imply that strategies which would produce larger fish are important. Examples of such strategies include stocking larger trout and setting aside areas for catch and release fishing for trophy-sized fish. The MU of X_3 is shown to be decreasing (Figure 3), which means that at high catches further additions to the catch will not significantly increase the utility. With the information on each independent utility and on scaling constants representing tradeoffs between these utilities, the multiattribute utility function may be formed for application in OEP.

Other decision criteria. The previous decision criterion reflects benefits derived by specific users of Rich Creek, namely the recreational fishermen. But other criteria exist and are important considerations

Table 6. Utility for the eight outcomes of $u_1(\underline{x}_1)$.

Species in catch				
trout	smallmouth bass	bluegill	$\underline{x}_1$	$u_1(\underline{x}_1)$
No	No	No	(0,0,0)	0.000
No	No	Yes	(0,0,1)	0.600
No	Yes	No	(0,1,0)	0.750
Yes	No	No	(1,0,0)	0.800
No	Yes	Yes	(0,1,1)	0.911
Yes	No	Yes	(1,0,1)	0.932
Yes	Yes	No	(1,1,0)	0.964
Yes	Yes	Yes	(1,1,1)	1.000

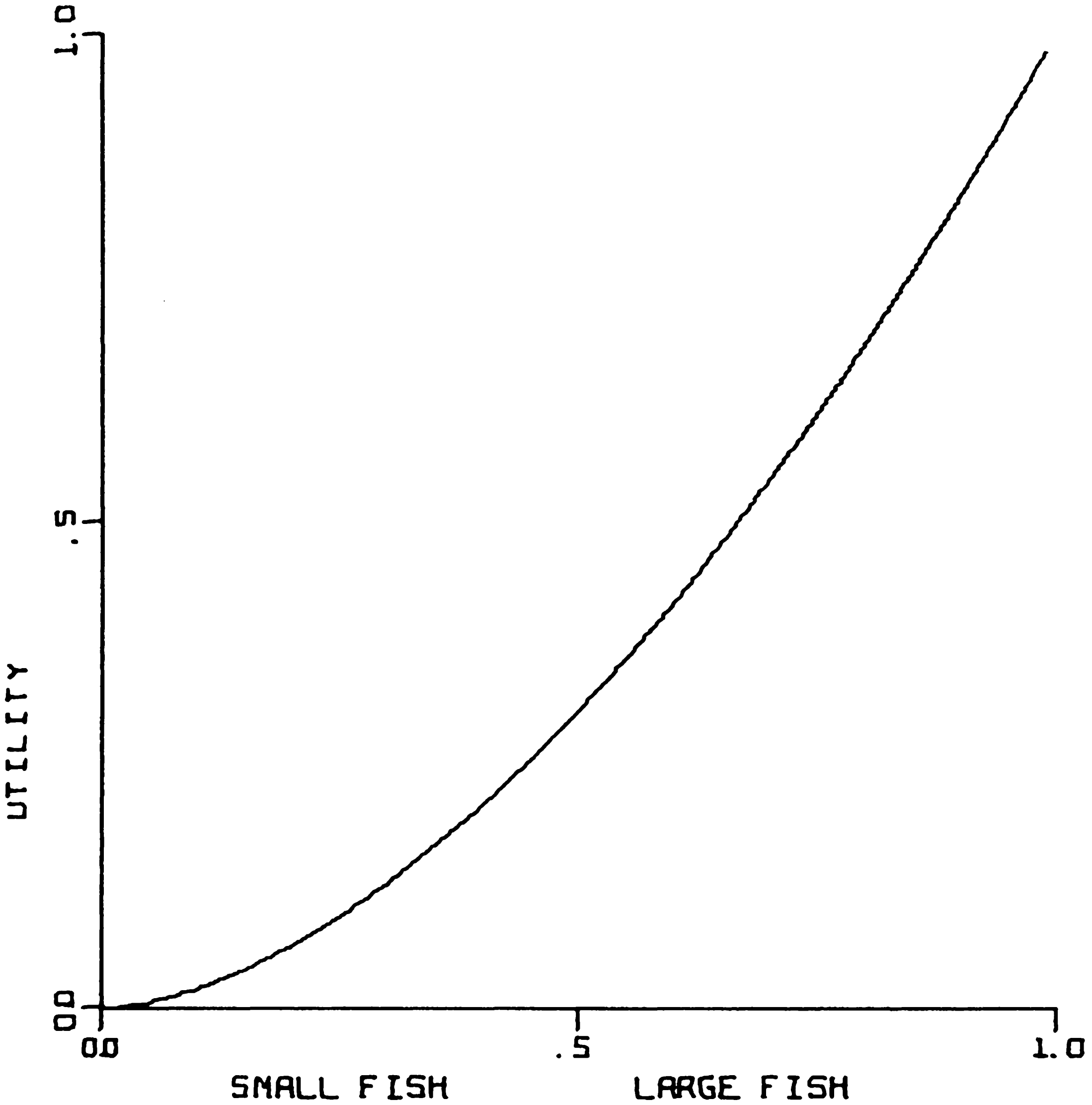

FIGURE 2. UTILITY FOR THE ATTRIBUTE OF FISH SIZE WHERE X2 (SIZE) IS SCALED FROM ZERO TO ONE.

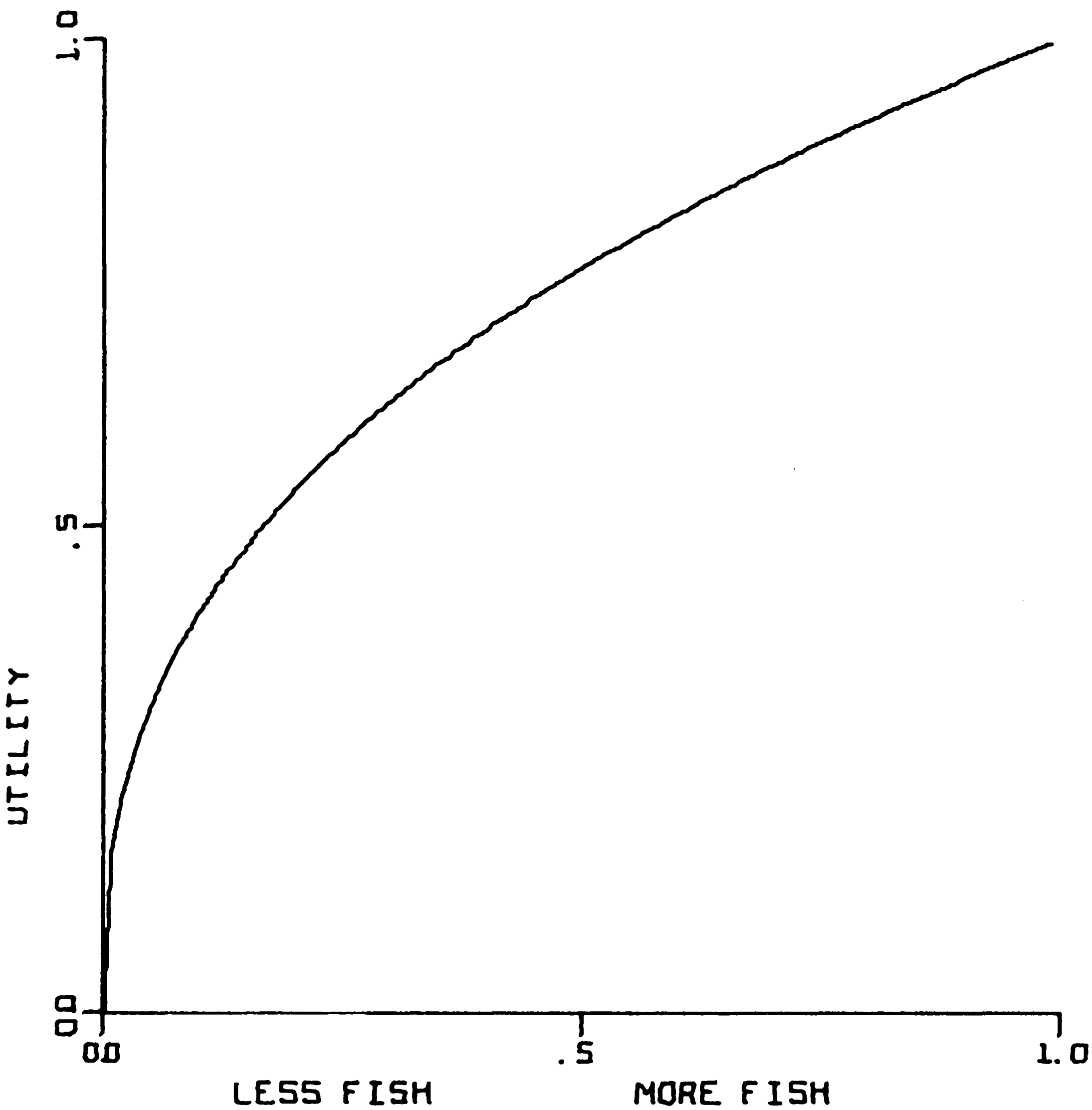

FIGURE 3. UTILITY FOR THE ATTRIBUTE OF NUMBER OF FISH WHERE X3 (NUMBER) IS SCALED FROM ZERO TO ONE.

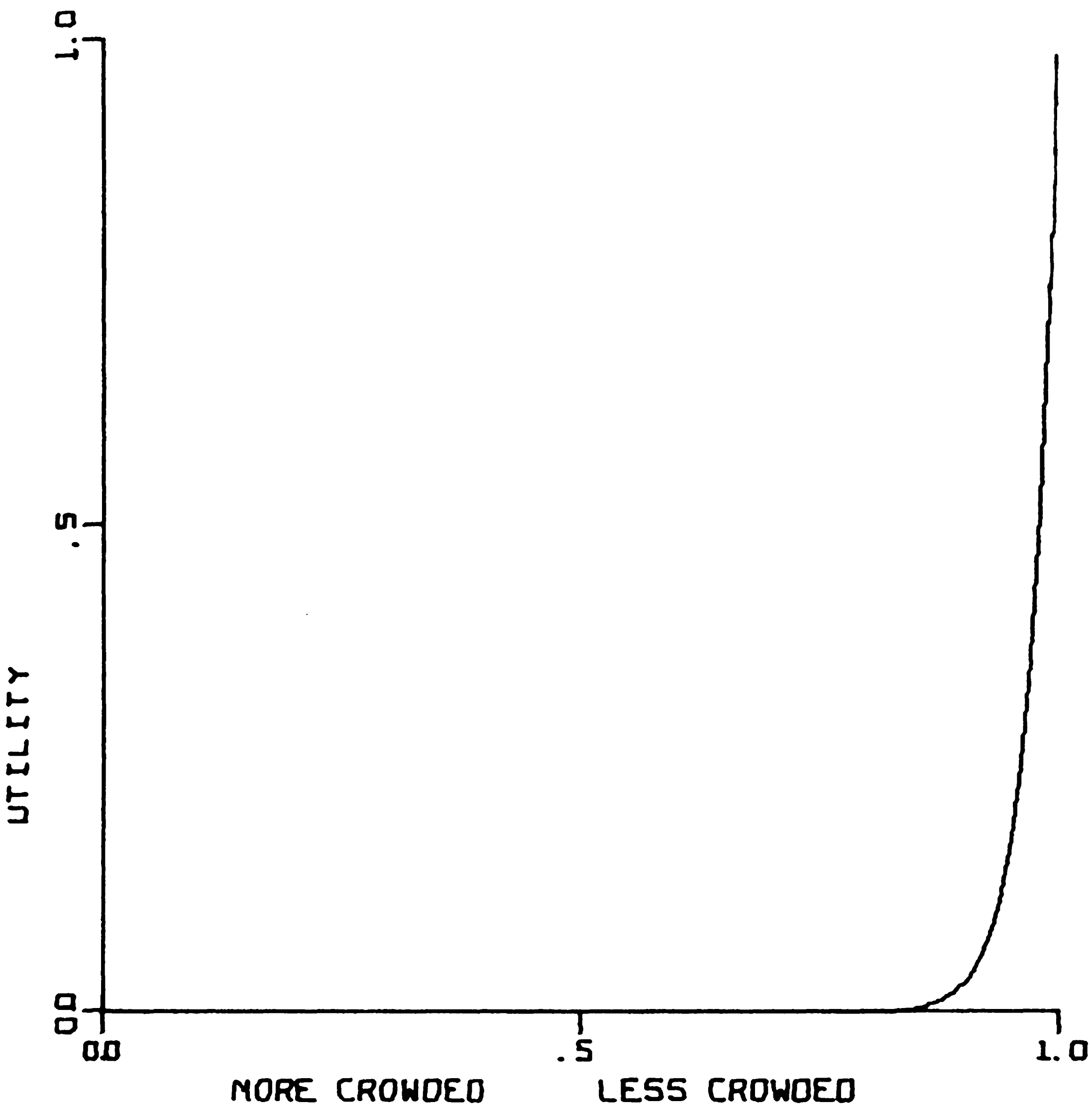

FIGURE 4. UTILITY FOR THE ATTRIBUTE OF ANGLER CROWDING WHERE X4 (CROWDING) IS SCALED FROM ZERO TO ONE.

in ecosystem management.

Another decision criterion may be a measure of ecosystem diversity. Many ecologists have equated stability with ecosystem health (e.g., MacArthur 1955, Margalef 1958) and then proceeded to use diversity indices as indicators of stability. A popular diversity index is the information theory index (Brillouin 1962):

$$\text{Diversity} = 1.433 \ln \frac{NUM!}{NUM_1!NUM_2!\ldots NUM_n!}$$

where: NUM = total number of individuals in the system

n = number of species, and

NUM_i = number of individuals in species i (i=1, 2, ..., n).

Brillouin's index measures the information content (negentropy) of the network represented by this configuration of species and individuals. However, as suggested by Pielou (1969: 232), this analogy may not be completely relevant to ecology. Also, Brillouin's index is not independent of the total number of individuals (NUM). Therefore, it is invalid to compare indices between ecosystems when diversity is expressed in this manner (Watt 1974).

Despite the drawbacks associated with all diversity indices, Brillouin's index was used as an indicator of ecosystem diversity in this study. Maintaining a certain level of diversity would prevent overexploitation. The diversity of fish and crayfish was used as a measure of this criteria. Trout were not included because they are not "natural" components of the Rich Creek ecosystem, i.e., essentially all of the trout in Rich Creek are planted by the West Virginia Department of Natural Resources. Calculation of the diversity index was simplified by using Stirling's second-order approximation for ln NUM! (see Watt 1968: 345).

Another decision criterion was the benefits derived by the commercial fishermen who harvested the baitfish species in Rich Creek. Catch-per-unit-effort measured in number of fish caught per seining operation per day was the index used to reflect their derived benefits. A seining operation consists of the seine, six minnow traps, and associated personnel (Brandt 1974). The average catch-per-unit-effort was calculated for each time period in the simulation model, and the sum of these over all time periods (over the entire year) was the commercial fishery criterion of this study.

The last criterion considered in the decision problem was what may be termed an agency benefit. This measure was an index of the volume of use that the recreational fishing public made of Rich Creek, i.e., the average number of anglers per day multiplied by the number of fishing days in the year (angler-days). As was discussed in the section on the utility function, this may be detrimental to an individual angler's recreational experience, but many states require this type of criterion when allocating monies (Lackey 1974).

Constraints. Several terminal system constraints were built into the OEP computer program. A terminal constraint implies that the value of the constrained state variable had to be greater than (less than, or equal to) a specified level at the terminal stage of the decision problem, i.e., at the end of the year.

The first of the terminal constraints dealt with budgetary expenditures. Since the only variable costs of decisions in Rich Creek arose from the stocking of trout, the budget reflects the cost of stocking trout, only (assumed to be $0.0022 per gram of trout delivered to the stream or $0.40 per fish). Budget expenditures of the year were constrained to be below a specified level, i.e., a limit was set on the amount of money spent per year.

Two other terminal constraints were included in OEP. These criteria mentioned previously in conjunction with the decision criteria were: the diversity index calculated for the fish and crayfish; and the commercial catch-per-unit-effort summed over all time periods. These criteria were constrained such that year-end values were to remain above a specified level.

In many cases the decision-maker will have no _a priori_ judgements about the level at which the constraints should be set. Therefore, testing the constraints at different levels through sensitivity analysis is needed and this will be discussed later. After this testing, the decision-maker will be more able to set the constraint levels.

OEP objective function. Thus far, four criteria have been considered in the decision problem: recreational utility, commercial catch-per-unit-effort, diversity, and angler-days. The three terminal constraints of commercial catch, diversity, and budget were discussed as well. The OEP computer program was designed such that any one of the four measures may be used as an objective function, i.e., the objective of OEP may be to maximize any of the four criteria.

Conceivably, each of the four criteria could have been considered independent attributes and a utility function could have been developed using the same methods as previously discussed. The OEP program has the option of including a linear combination of the four attributes as an objective function, and this is equivalent to a linear utility model in which each attribute has a linear utility function [equation (2.1)]. This option, does, however, assume that the attributes are not multiplicative. Future modifications of OEP might concentrate on including a multiplicative utility function as a possible objective function.

Application of OEP to the Rich Creek system included the optimization problem using each of the four measures as an objective, and several linear combinations of the four. Various values for the three terminal constraints were also tested. Although the recreational utility objective function will be stressed, optimal policies will be presented for each of the objective functions.

OEP Optimization Procedures

Many techniques exist for finding the optima of mathematical models (Taha 1971) and some of these techniques are very powerful and efficient. However, computer simulations are not expressed in analytic form so most methods do not apply. Direct searching methods do exist (Wilde 1964, Wilde and Beightler 1967) in which an optimum may be found using nothing but objective function evaluations. Computer simulation is one means of providing objective function evaluations. These methods require a substantial increase in the number of function evaluations, especially in multidimensional systems, and the risk of converging to a local optima is fairly high.

Schmidt and Taylor (1971) suggested a simple approach which bridged the gap between mathematical models and computer simulation results. Their method was to fit an approximating mathematical model (such as a quadratic equation) to results of the computer simulation by linear regression. The optimum for this model was then found analytically. The solution was then used by the computer simulation to produce new results and the process was iterated until convergence occurred.

When the mathematical model is of sufficiently large dimensions and is time-dependent, even solving for an analytic optimum may be difficult. Pontryagin, et al. (1962) developed the theory of optimal control to handle optimal problems in time-dependent systems. The theory was called Pontryagin's Maximum Principle for his introductory work. This theory was expanded to include systems in which time was expressed in discrete stages by Chang (1961), hence the name discrete maximum principle. Katz (1962) developed a computational procedure for using the discrete maximum principle and this was used successfully by Fan and Wang (1964) in real-world problems.

The procedure used in OEP to obtain an optimum is a combination of Schmidt and Taylor's search by regression method and the policy iteration technique of Katz. In order to describe this procedure, the discrete maximum principle will be discussed using the development and notation of Wilde and Beightler (1967: 427).

The discrete maximum principle. Consider a serial optimization problem of N discrete time stages with P state variables and Q decision variables. Let s_{np} be state variable p (p=1, 2, ..., P) at stage n (n=1, 2, ..., N) and let d_{nq} be the qth decision variable (q=1, 2, ..., Q) at stage n.

Let there be NP continuously differentiable transition functions $T_{np}(\underline{s}_n, \underline{d}_n)$ relating the output states of each stage to the input state vector $(\underline{s}_n)$ and decision vector $(\underline{d}_n)$

$$s_{n+1,p} = T_{np}(\underline{s}_n, \underline{d}_n). \tag{3.1}$$

Introduce N new state variables (s_{n0}) which depict the value of the objective function at each stage, and:

$$s_{n+1,0} = T_{n0}(\underline{s}_n, \underline{d}_n) = s_{n,0} + R_n(\underline{s}_n, \underline{d}_n), \tag{3.2}$$

where R_n is the gain to the objective function of the nth stage. Note that (3.2) is a cumulative sum objective function.

To maximize the return of the objective function at the end of the Nth stage, the problem is one of terminal control and can be expressed as:

$$\max s_{N+1,0} = s_{N0} + R_N(\underline{s}_N, \underline{d}_N) \tag{3.3}$$

subject to the NP equality constraints

$$s_{n+1,p} - T_{np}(\underline{s}_n, \underline{d}_n) = 0. \tag{3.4}$$

Using classical optimization techniques, a Lagrangian function L may be defined by

$$L \equiv s_{N+1,0} - \sum_{n=1}^{N} \sum_{i=0}^{P} \lambda_{n+1,i}[s_{n+1,i} - T_{ni}(\underline{s}_n, \underline{d}_n)]. \tag{3.5}$$

where the λ are Lagrangian multipliers in classical optimization. They are termed state derivatives in control problems.

The optimal solution to (3.3) and (3.4) occurs when L is stationary relative to the state, i.e., the first derivatives of L with respect to the state variables must equal zero. Therefore,

$$\frac{\partial L}{\partial s_{N+1,0}} = 1 - \lambda_{N+1,0} = 0,$$

and

$$\lambda_{N+1,0} = 1. \tag{3.6}$$

Also, for $i \neq 0$

$$\frac{\partial L}{\partial s_{N+1,i}} = - \lambda_{N+1,i} = 0,$$

and

$$\lambda_{N+1,i} = 0. \tag{3.7}$$

These conditions hold whenever there are no terminal constraints on the states. If a terminal constraint does exist, then $\lambda_{N+1,i} \neq 0$ for the constrained state i ($i \neq 0$). Methods to handle this problem will be discussed later.

By taking $\partial L/\partial s_{n0}$ for all n [equations (3.2) and (3.6)], it is easily seen that $\lambda_{n0} = 1$ for all stages. The rest of the state derivatives may be found from derivatives of (3.5):

$$\frac{\partial L}{\partial s_{np}} = -\lambda_{np} + \sum_{i=0}^{P} \lambda_{n+1,i} \left(\frac{\partial T_{ni}}{\partial s_{np}}\right) = 0, \qquad (3.8)$$

or for $n \neq 1$ and $p \neq 0$

$$\lambda_{np} = \sum_{i=0}^{P} \lambda_{n+1,i} \left(\frac{\partial T_{ni}}{\partial s_{np}}\right) . \qquad (3.9)$$

Equation (3.9) is a straightforward recursive formula for calculating each state derivative (λ_{np}) backward from stage N to stage 1.

Define the Hamiltonian function at the nth stage to be

$$H_n \equiv \sum_{i=0}^{P} \lambda_{n+1,i} T_{ni}. \qquad (3.10)$$

Notice that if L is to be maximized

$$\frac{\partial L}{\partial d_{nq}} = \sum_{i=0}^{P} \lambda_{n+1,i} \left(\frac{\partial T_{ni}}{\partial d_{nq}}\right) = 0.$$

To express this equivalently

$$\frac{\partial L}{\partial d_{nq}} = \frac{\partial H_n}{\partial d_{nq}} = 0. \qquad (3.11)$$

Equation (3.11) states: if L is to be stationary, then H_n must also be stationary for all n. Since the λ and s can be calculated, H_n is a function of decisions of the nth stage only, and the terminal control problem is decomposed into n optimization problems of finding the new decision set $(\underline{d}_n^*)$ such that $\partial H_n/\partial \underline{d}_n^* = 0$ in a neighborhood of $\underline{d}_n^*$.

Just as the Lagrangian multipliers have an economic interpretation in classical optimization, so do the state derivatives (λ_{np}). The value λ_{np} is the per unit cost to the objective function $(s_{N+1,0})$, that results from meeting the constraint $s_{n+1,p} = T_{np}(\underline{s}_n, \underline{d}_n)$. As such these values contain information as to the sensitivity of the mathematical model (Peterson 1974).

<u>Katz's policy improvement algorithm</u>. Katz's method of obtaining numerical results to the terminal control problem proceeds as follows: first a guess is made as to the values of d_{nq}. Then, using the initial state variables and decisions, $s_{n+1,p}$ are calculated for all n and p using (3.1). Next λ_{np} are calculated recursively using (3.8). Finally, all of the Hamiltonians are formed and made stationary (3.10). From the new decision set, new state variables are computed, and the process is repeated. This procedure does not always converge and often it is better to adjust each decision in the direction of the new stationary point rather than set the decision equal to the value at the new stationary point.

Katz's method presupposes that $\lambda_{N+1,i}$ can be calculated which is not the case when some terminal states are constrained. When terminal constraints exist, an indirect decision inversion method may be used in which $\lambda_{N+1,i}$ can be estimated for each constrained state i by solving as many simultaneous equations as there are constraints by the Newton-Raphson method (see: Wilde and Beightler 1967: 441-442). Then Katz's alforithm can proceed as before.

RAMP search. The search procedure in OEP will be termed: search by Regression and Application of the Maximum Principle (RAMP search).

First, eleven outputs of the simulator were chosen as state variables of the Rich Creek ecosystem. The variables were:

1. Cumulative commercial catch (No/seine/day)
2. Budget expenditure
3. Diversity index value
4. Time of the year (time stage number)
5. Biomass of POM and MACROINV in the stream
6. Biomass of trout in the stream
7. Biomass of bluegill in the stream
8. Biomass of smallmouth bass in the stream
9. Biomass of baitfish in the stream
10. Angler density
11. Cumulative sum objective function

Before applying the algorithm, states 1 through 10 were multiplied by a scaling factor (100) and state 11 was multiplied by another scaling factor (1×10^{-8}). This was done so that overflow problems could be avoided in computation of the state derivatives.

A number, k, of initial decision policies, d_{nq}, were randomly generated and, using these decisions, k simulations were performed. The values of s_{np} (p=1, 2, ..., 11) and d_{nq} (q=1, 2, ..., 13) were recorded from each of the k simulation experiments. Approximating models for T_{np} were fit to the recorded data by linear regression analysis. The approximating models used were quadratic equations with no crossproducts:

$$s_{n+1,p} = T_{np}(\underline{s}_n, \underline{d}_n) = \sum_{i=1}^{11} (a_{ip}s_{ni} + b_{ip}s_{ni}^2)$$
$$+ \sum_{j=1}^{13} (c_{jp}d_{nj} + r_{jp}d_{nj}^2), \tag{3.12}$$

where $\underline{a}_p$, $\underline{b}_p$, $\underline{c}_p$, and $\underline{r}_p$ are constants estimated by regression. Some of these parameters were assumed to be zero before regression if there was no logical connection between the variable and the particular transition function. Quadratics with no crossproducts were chosen as approximating models because they have a single maximum or minimum for which a solution can be obtained analytically. The transition functions were time-dependent through the state variable s_{n4} (the time stage number). The choice of k was determined by the number of data points needed to fit the transition functions in (3.12).

From (3.12) the state derivatives can be calculated and the Hamiltonians formed. The Hailtonians are themselves quadratic equations which can be expressed in the form:

$$H_n = v_o + \sum_{q=1}^{13} (v_q d_{nq} + w_q d_{nq}^2), \tag{3.13}$$

where v and w are constants (constant functions of the state variables and state derivatives). The stationary points may be easily found from (3.13) yielding:

$$d_{nq} = -v_q/2w_q, \qquad (3.14)$$

for q=1, 2, ..., 13 and n=1, 2, ..., N.

Remember that the necessary (but not sufficient) conditions for a maximum are that the H_n are stationary with respect to d_{nq}. Thus any maximum, minimum, saddle point, or boundary point is a candidate for the optimal policy. The strategy taken in RAMP search was to define bounds to d_{nq} ($0 \leq d_{nq} \leq DMAX_{nq}$). If the new policy (3.14) was exterior to these bounds, then d_{nq} was set equal to the bound that was exceeded.

Thus (3.14) provides a new approximation to the optimal decision policy which is returned to the simulation model for use in a new simulation experiment. From this simulation a new value of the objective function is calculated. The search procedure may then be summarized in the following steps:

1. If the value of the objective function calculated from the new simulation experiment is greater than the lowest value of the objective function of the k previous simulation experiments, then replace the state and decision variables of the lowest value of the objective function with the values obtained from the new experiment and go to step 3. Otherwise go to step 2.

2. If the new objective function value is lower than any of the previous values, then find the difference (Δ_{nq}) between the new decision variables and those decision variables which resulted in the highest value of the objective function in the k previous experiments. Multiply Δ_{nq} by a step size ρ ($0<\rho<1$) and add the result to the new decision variables. Return them to the simulation for another experiment. If still no improvement occurs, then reduce the step size (reduce ρ). Repeat until improvement occurs (Go to step 3) or until a prespecified number of step size reductions have taken place (go to step 5).
3. If improvement occurs, test the convergence criterion. Is the difference between the high and low values of the objective function found from the k simulations less than some prespecified ε? Yes--go to 5. No--go to 4.
4. Using the k simulation results, fit the transition functions, apply the discrete maximum principle, and find a new policy (d_{nq}). Test this policy by simulation. Return to 1.
5. Print results.

It was necessary to fit new transition functions at each iteration for two reasons: 1) storage capacity of the computer limits the number of data sets (k) which can be stored; 2) equation (3.12) is an approximating model and there is no _a priori_ reason to believe that this is the correct relationship. It is assumed that (3.12) becomes a better approximation as the data points cluster around the optimum. Therefore, only k data sets are kept because previous data points may reduce the fit around the optimum.

To handle terminal constraints in the calculation of the objective function from the simulation, a penalty function technique was used. If S is the terminal value of the objective function calculated from the simulation, then the penalized objective (OBJ) was calculated as:

$$\text{OBJ} = \begin{cases} \text{S if constraints are met} \\ \text{S}-\Phi \text{ if constraints are not met,} \end{cases}$$

where Φ is a large number much greater than the maximal value which S may attain.

Computational experience with RAMP search showed that there were limitations to the application of the algorithm. First, since the algorithm was based on a heuristic approximation approach, a global optimum cannot be guaranteed. Fairly frequently the program converged to a local optimum, but use of different starting points for the algorithm usually showed when local optima occurred. However, one can never be sure that what was presumed to be a global optimum was not in reality a local optimum.

Also, care had to be taken to be certain that at least one of the k original experiments met all three of the terminal constraints. If all of the k experiments were infeasible, the algorithm was incapable of establishing a proper trajectory toward a feasible maximum.

OEP Design Overview

The OEP program was designed as a user-oriented program to find optimal management strategies for a stream ecosystem. Flow charts (Figures 5 and 6) summarize the structure of the OEP program and simulation as discussed in this section on OEP design. The computer program is coded in FORTRAN, has been documented and appears in Appendix VI. It requires 180 K bytes of storage on an IBM 370/155 computer. Execution times were approximately 5 minutes for a single terminal control problem, with a single simulation of 24 time-stages taking approximately 10 seconds depending on the printed output specified.

OEP Sensitivity Analysis

Included within the general framework of sensitivity analysis are the sources of information as to the validity and stability of a decision model. The methods by which this information is accumulated conventionally takes the following forms:

1. <u>Comparisons</u> of model outputs with real-world outputs;
2. <u>Repetitions</u> of the analysis using different inputs;
3. <u>Postoptimality analysis</u> - modifications of the analysis that produced an optimal decision; and
4. <u>Analytical calculations</u> performed as a by-product of optimization.

The first method is the standard method of validity check in which model variables are tested using statistical or subjective

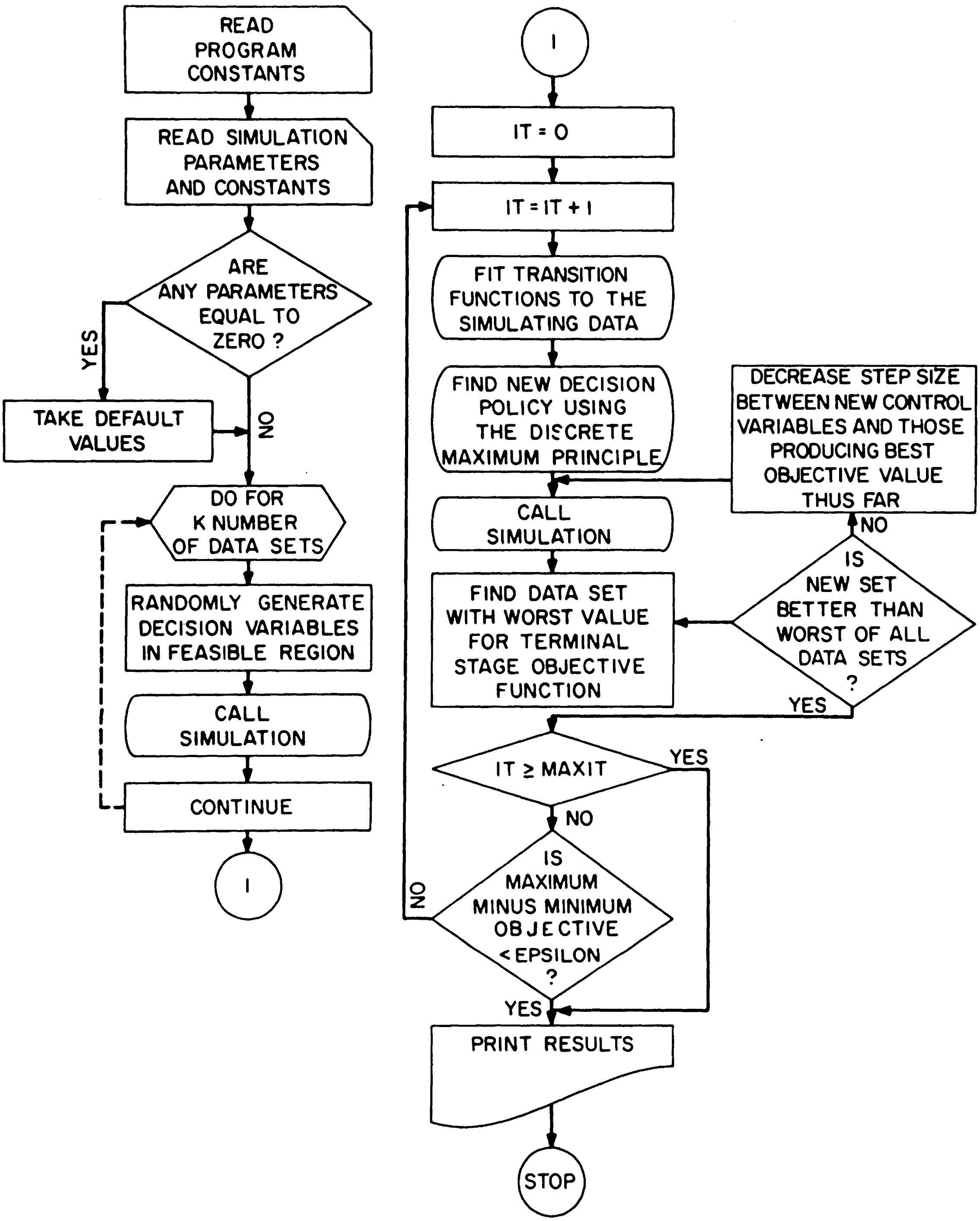

FIGURE 5. GENERALIZED FLOW DIAGRAM FOR OEP PROGRAM AND RAMP SEARCH.

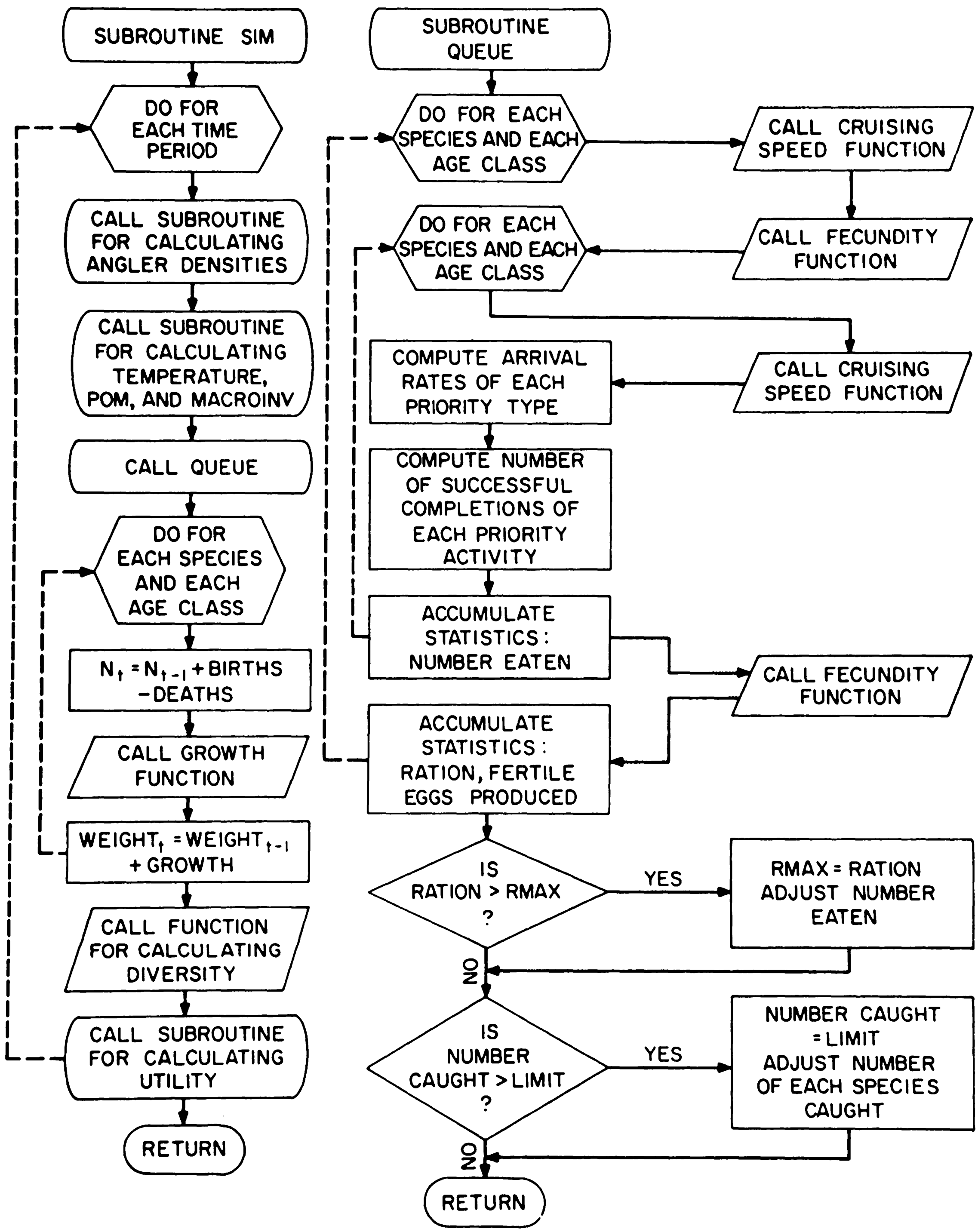

FIGURE 6. GENERALIZED FLOW DIAGRAM FOR THE ECOSYSTEM SIMULATION IN THE OEP PROGRAM.

criteria against the same variables as they were observed in the real system. It is often difficult (if possible) to obtain data from the real system. In such cases the criterion of "goodness of fit" between model and system outputs are often subjective.

The second method in sensitivity analysis is to repeat the analysis using different random inputs. Then the model outputs for a number of experiments can be averaged and a variance computed. This is a measure of stability of the estimate and of the model.

The third method is to investigate changes in the optimal value of the objective function which results from changes in inputs. Does a small change in input drastically alter the structure of the optimal decision policy? This procedure supplies information on the stability of the decision policy and on those areas of the system which upon alteration will improve (or impair) the results the most.

The fourth method is to recognize the value of analytic calculations that arise in analysis. Examples of these calculations in OEP include the marginal utilities and the state derivative (λ_{np}). Each of these provide insight into results of increments in system variables.

In the context of OEP, there are three different levels of sensitivity statements. The first level is that dealing with the ecosystem itself. What ecosystem variables affect the output most significantly? This question is answered with sensitivity information from the second level, i.e., the simulation model. Assuming the model has been accepted as a valid abstraction of the system, it will answer the question: what <u>simulation</u> variables affect the <u>simulation</u> output most significantly?

The third level of sensitivities are derived from the approximating models used in RAMP search, such as the state derivatives, λ_{np}. The sensitivities found from level two and three are not exact replicas of the sensitivities of the ecosystem and some realism is lost at each level. However, they do provide information to the decision-maker as to the results of a decision policy and this is a form of feedback in the model analysis.

The sensitivity analysis of OEP as it was applied to the Rich Creek ecosystem includes the following: comparisons of simulated system with the observed system in 1973, stability assessments of the observed system of 1973, stability assessments of the optimal policy as found by RAMP search, postoptimality results of modifying terminal constraints, postoptimality results of modifying key system variables, and assessment of the state derivatives and other analytic calculations. Much of this was done for several objective functions. With sensitivity analysis techniques of experimentation, some understanding of the processes acting on Rich Creek system dynamics was illuminated--an understanding that otherwise may have been obscure.

RESULTS AND DISCUSSION[1]

Application of OEP to the Rich Creek decision problem required input information as discussed in OEP Design. In many cases this information was in the form of subjective estimation by the author. However, validity checks can help to determine how useful the program is. One means of testing validity of a model is to compare predicted outputs with outputs observed from the real system. In the Rich Creek ecosystem most of the system variables were not actually observed. However, two variables were observed. The first was the catch by seines and traps that resulted from field studies in the summer of 1973 (Brandt and Schreck 1975). Using decision variables which were in effect in 1973, these field studies were mimicked by OEP. Both deterministic and Monte Carlo predictions of the baitfish and crayfish catch by seine and trap were made (Table 7). The cumulative catch as observed from the summer of 1973 compared favorably with the output of the seven Monte Carlo predictions. The second variable was the annual recreational fishing pressure in Rich Creek estimated as 300-500 angler hours/acre/year (Bailey et al. 1974). This was equivalent to 2778-4630 angler-days per year in Rich Creek. The mean number of angler-days/year predicted by seven OEP Monte Carlo simulations was 4719. Once again, the results were comparable. These results may be

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[1] All of the multistage decision problems discussed in these results were parsed into 24 time stages of 15 days each, i.e., a twice monthly schedule, unless otherwise specified in the discussion.

Table 7. Catch of baitfish (No.) as observed (Brandt and Schreck 1975) and as predicted by OEP simulation.

Time	Observed	Deterministic Prediction	Monte Carlo Predictions						
May 16-May 31	164	113	120	107	22	36	79	81	43
June 1-June 15	182	114	184	84	478	39	82	102	37
June 16-June 30	148	111	128	50	413	178	68	57	535
July 1-July 15	204	109	912	56	307	39	152	50	106
July 16-July 31	191	107	257	52	335	21	56	47	32
Aug 1-Aug 15	319	106	310	47	266	22	34	55	34
Aug 16-Aug 31	276	104	81	49	224	19	42	48	33
Sept 1-Sept 16	244	102	75	45	20	17	33	24	14
Totals	1728	866	2067	496	2065	371	546	464	834
			Mean = 977.5						

considered as indices of OEP validity. However, they are only comments on the validity of two portions of the simulator and only under existing (1973) conditions. Because no guarantee can be made as to the simulator's ability to predict future events, it is imperative that relationships between variables be investigated in the analysis.

The results of OEP application will be discussed in the context of each of the decision criteria in turn: utility maximization, diversity maximization, commercial catch maximization, angler-day maximization, and maximization of linear combinations of these four. To facilitate this discussion, some notation will be introduced here. Let

BDG = the value ($) at which the terminal budget constraint is set

COM = the value (number of fish per seine-day summed over all time stages) at which the terminal commercial fishing constraint is set

DV = the value (diversity units) at which the terminal diversity constraint is set

B = the yearly expenditures in a single year

C = the value of cumulative commercial catch-per-seine-day in a single year

DIV = the value of the diversity index at the end of the year

Also let

UT = the year-end value of cumulative utility

AD = the number of angler-days in a single year

OB = the value of the objective function

Therefore, the optimal Rich Creek management problem may be expressed as:

$$\max OB = a_1 UT + a_2 DIV + a_3 C + a_4 AD \qquad (4.1)$$

subject to

$$DIV \geq DV$$

$$C \geq COM$$

$$B \leq BDG,$$

where a_i (i=1, 2, 3, 4) are constants ($a_i \geq 0$) specified by the decision-maker.

Utility Maximization

Utility maximization is the optimization problem of (4.1) when a_1=1 and a_i=0 (i=2, 3, 4). Initially the terminal constraints were set such that

$$BDG = \$6{,}960 \geq B$$

$$COM = 5{,}000 \leq C$$

$$DV = 100{,}000 \leq DIV.$$

The optimal value of utility (UT*) derived from this program was 7.668 and this deterministic prediction resulted from the 312 (13x24) decision variables derived by OEP (Table 8). The commercial catch, budget expenditures, and diversity in this prediction were B=\$6,512, C=5,701, and DIV=494,300. Therefore, it appears that the system was not greatly constrained under these terminal conditions. The total number of an-

TABLE 8. VALUES OF OPTIMAL DECISION VARIABLES, D(N,Q) (N=1,2,...,24 TIME STAGES; Q=1,2,...,13 DECISION ACTIVITIES), AS DETERMINED BY APPLYING RAMP SEARCH TO UTILITY MAXIMIZATION OBJECTIVE FUNCTION. SEE TABLE 2 FOR DEFINITIONS OF THE 13 DECISION ACTIVITIES.

STAGE 1		STAGE 2		STAGE 3		STAGE 4	
1	0.2144E 00*	1	0.8898E-02	1	0.2790E 00	1	0.1085E-01
2	0.8271E 00	2	0.1012E 01	2	0.2406E 01	2	0.3303E 01
3	0.2560E 00	3	0.9931E-01	3	0.1725E 01	3	0.1532E 01
4	0.5643E 01	4	0.9552E 01	4	0.1699E 02	4	0.1305E 02
5	0.5519E 04	5	0.4305E 04	5	0.3355E 04	5	0.2506E 03
6	0.3844E-04	6	0.1402E-04	6	0.1820E-04	6	0.1357E-04
7	0.6523E 01	7	0.8169E 01	7	0.1748E 01	7	0.4162E 01
8	0.9859E 02	8	0.3697E 02	8	0.7600E 02	8	0.4531E 01
9	0.2482E 02	9	0.3912E 03	9	0.4500E 03	9	0.2390E 03
10	0.6849E 01	10	0.1351E 02	10	0.2548E 01	10	0.1189E 02
11	0.6419E 02	11	0.1463E 03	11	0.4611E 01	11	0.2464E 03
12	0.5469E 03	12	0.5147E 03	12	0.7373E 03	12	0.9812E 03
13	0.3229E 01	13	0.2074E 01	13	0.3856E 01	13	0.8434E 01

* 0.2144E 00 = 0.2144 TIMES 10 TO THE ZERO POWER

TABLE 8. (CONTINUED).

	STAGE 5		STAGE 6		STAGE 7		STAGE 8
1	0.5177E-02	1	0.4585E-01	1	0.4550E 00	1	0.4629E 00
2	0.2364E 01	2	0.2908E 01	2	0.2923E 01	2	0.2807E 01
3	0.1478E 01	3	0.1363E 01	3	0.6556E 00	3	0.9483E-01
4	0.3703E 01	4	0.1747E 02	4	0.1409E 02	4	0.4597E 01
5	0.4617E 04	5	0.8745E 03	5	0.2850E 04	5	0.9637E 04
6	0.4987E-05	6	0.3289E-04	6	0.1826E-04	6	0.3569E-04
7	0.4517E 01	7	0.1726E 01	7	0.6364E 01	7	0.6107E 01
8	0.8020E 02	8	0.1043E 02	8	0.5223E 02	8	0.2324E 02
9	0.3407E 03	9	0.3660E 02	9	0.1860E 03	9	0.4058E 03
10	0.4972E 01	10	0.8380E 01	10	0.1179E 02	10	0.5011E 01
11	0.4482E 02	11	0.1583E 03	11	0.1926E 01	11	0.2223E 03
12	0.1254E 03	12	0.9747E 03	12	0.1214E 04	12	0.4266E 03
13	0.9950E 01	13	0.9854E 01	13	0.7762E 01	13	0.4629E 00

TABLE 8. (CONTINUED).

	STAGE 9		STAGE 10		STAGE 11		STAGE 12
1	0.1142E 00	1	0.4130E 00	1	0.2147E 00	1	0.3154E 00
2	0.4701E 01	2	0.1758E 01	2	0.1313E 01	2	0.3546E 01
3	0.1212E 01	3	0.1371E 01	3	0.1449E 01	3	0.1154E 01
4	0.3435E 01	4	0.1906E 02	4	0.1982E 02	4	0.1605E 01
5	0.5830E 04	5	0.5530E 04	5	0.4274E 04	5	0.2936E 04
6	0.4746E-04	6	0.3688E-04	6	0.3206E-04	6	0.1707E-05
7	0.4546E 01	7	0.4550E 01	7	0.9386E-01	7	0.5726E 01
8	0.1754E 02	8	0.8276E 01	8	0.2725E 02	8	0.1195E 02
9	0.4346E 03	9	0.1833E 03	9	0.2532E 03	9	0.2554E 03
10	0.3490E 01	10	0.1067E 02	10	0.1401E 02	10	0.5148E 01
11	0.1759E 03	11	0.1528E 03	11	0.1376E 03	11	0.2390E 03
12	0.1752E 03	12	0.3419E 03	12	0.1125E 04	12	0.8259E 03
13	0.5107E 01	13	0.1447E 01	13	0.4529E 01	13	0.3618E 01

TABLE 8. (CONTINUED).

	STAGE 13		STAGE 14		STAGE 15		STAGE 16
1	0.1202E 00	1	0.1827E 00	1	0.1983E 00	1	0.3663E-01
2	0.9388E 00	2	0.1559E 01	2	0.2404E 01	2	0.1343E 01
3	0.1912E 01	3	0.1155E 01	3	0.6620E 00	3	0.1950E 01
4	0.1133E 01	4	0.1332E 02	4	0.1321E 02	4	0.8630E 01
5	0.7351E 04	5	0.8012E 04	5	0.9907E 04	5	0.8272E 04
6	0.4494E-04	6	0.4064E-04	6	0.7561E-07	6	0.2825E-05
7	0.7809E 01	7	0.6691E 01	7	0.9579E 00	7	0.8962E 01
8	0.5889E 02	8	0.6915E 02	8	0.5478E 02	8	0.8696E 02
9	0.2299E 03	9	0.6081E 02	9	0.1972E 03	9	0.6568E 02
10	0.1158E 02	10	0.8855E 01	10	0.1058E 02	10	0.7661E 00
11	0.1130E 02	11	0.8479E 01	11	0.7477E 02	11	0.2562E 03
12	0.4040E 03	12	0.9091E 03	12	0.5627E 03	12	0.7030E 03
13	0.5424E 01	13	0.3208E 01	13	0.1729E 00	13	0.3678E 01

TABLE 8. (CONTINUED).

STAGE 17

1	0.8232E-01
2	0.3319E 01
3	0.1042E 01
4	0.3048E 01
5	0.2314E 04
6	0.5524E-06
7	0.9940E 01
8	0.8583E 02
9	0.9400E 02
10	0.7945E 01
11	0.7698E 02
12	0.1221E 03
13	0.8170E 01

ALL DECISIONS FOR TIME STAGES 18 TO 24 ARE EQUAL TO ZERO

gler-days was fairly large relative to 1973 conditions, i.e., AD = 6,843 as compared to 4,630 given by Bailey et al. (1974).

Optimal predicted results showed (Figure 7) that fishing only occurred between days 75 and 240 of the year (March to September). The characteristics of the optimal utility functions for each of the independent attributes (Figure 7) show that species utility (u_1) is constant through the fishing season (trout only), except when bluegill fishing occurs in late spring and early summer.

The utility derived from the size of fish (u_2) was high in the early parts of the fishing season and declined throughout the year due to the decline in average trout size. In the early season , as predicted by OEP, fishing pressure was low and water temperatures were low, which meant that there was some plant-to-plant growth and survival of the stocked trout. Later in the year, the water became warmer and more people began to fish. No trout survived; i.e., the fishery became a "put and take" fishery and all trout were caught. Therefore, size became constant at a relatively low level, because all stocked trout were approximately the same size.

The contribution of the other attributes to the multiattribute utility may be seen as well. Utility from numbers of fish (u_3) had a general upward trend during the year attributable to the increased number of stocked fish. Utility derived from privacy (u_4) decreased drastically in late spring and summer due to good weather and increased leisure time. More people fished and less privacy resulted, but the trend was reversed in the late summer and fall. The high number of

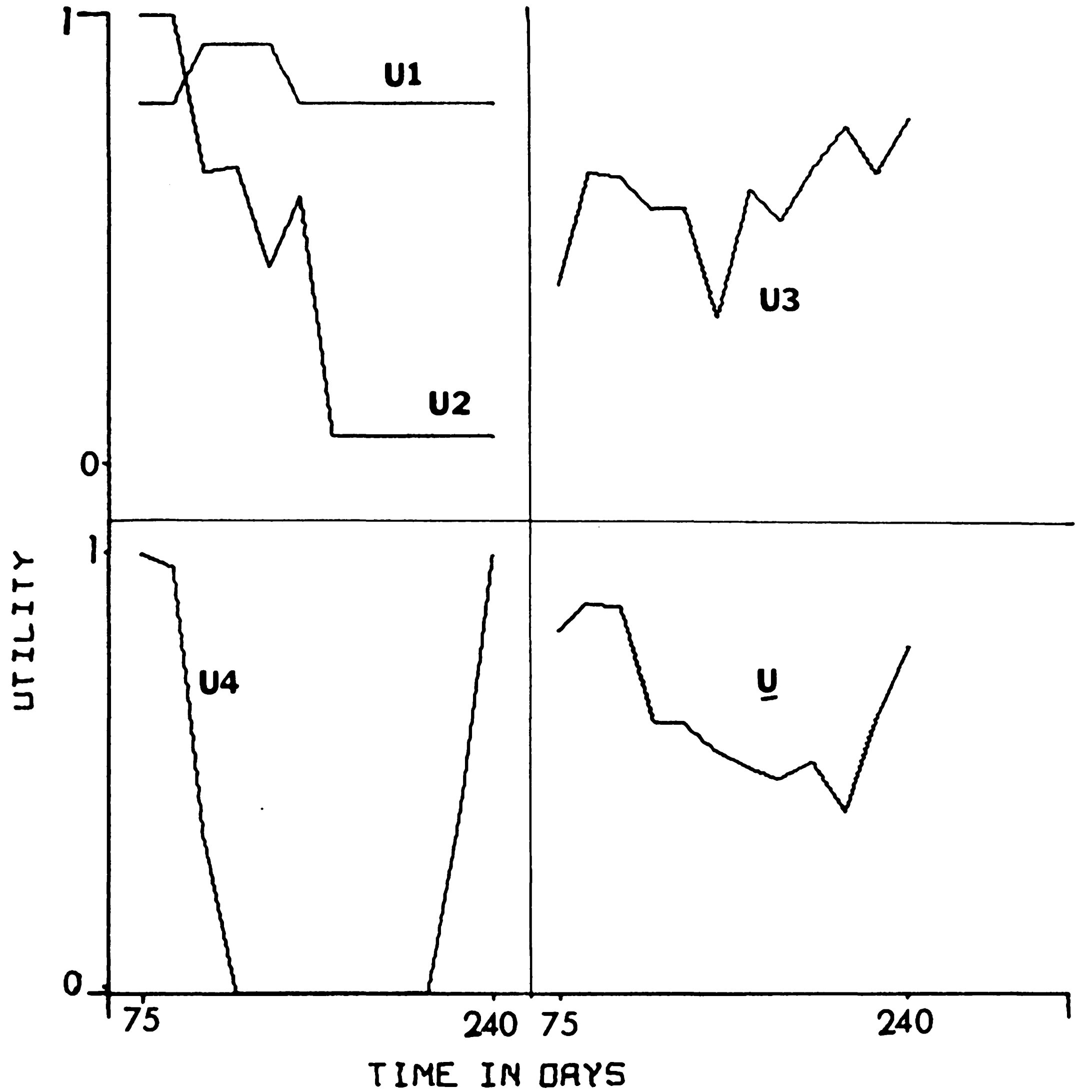

FIGURE 7. UTILITY DERIVED FROM SPECIES CAUGHT (U1), UTILITY DERIVED FROM SIZE OF FISH CAUGHT (U2), UTILITY DERIVED FROM NUMBER OF FISH CAUGHT (U3), UTILITY DERIVED FROM PRIVACY (U4), AND THE OPTIMAL MULTIATTRIBUTE UTILITY FUNCTION (U) VERSUS TIME OF YEAR.

people fishing in early summer also meant that there were fewer fish caught per person and thus there was a decrease in u_3 at this point in time.

The net effect of the four factors on the predicted optimal multiattribute utility function (u) was that there were low values of u in midsummer and high values in late winter and late summer. The high marginal utility of privacy (Figure 4) did, indeed, affect the dynamics of u. However, these effects were offset by an increase in u_3 (numbers of fish) during the time when u_2 and u_4 were low.

The relationship of the three attributes of size, number, and privacy may be explored using the marginal utilities, i.e., the partial derivatives of u with respect to each attribute (Figures 8 and 9). The marginal utilities are interpreted as the increase in utility resulting from a unit increase in the attributes. Utility is relatively insensitive to changes in the size of fish and to changes in number of fish during spring and fall. However, reductions in privacy will markedly reduce utility in the early spring and late fall. During summer there was an increase in the marginal utility with respect to numbers of fish. At this time number of fish becomes the dominant factor in utility.

Stability of the Utility Optimum

The stability of the optimum was investigated in two ways: (1) using the optimal decisions, Monte Carlo simulations were performed; and (2) the optimal decisions were perturbed for several simulations.

In the first case four Monte Carlo simulations were run using the optimal decisions. The mean of UT was found to be 7.253 with a stan-

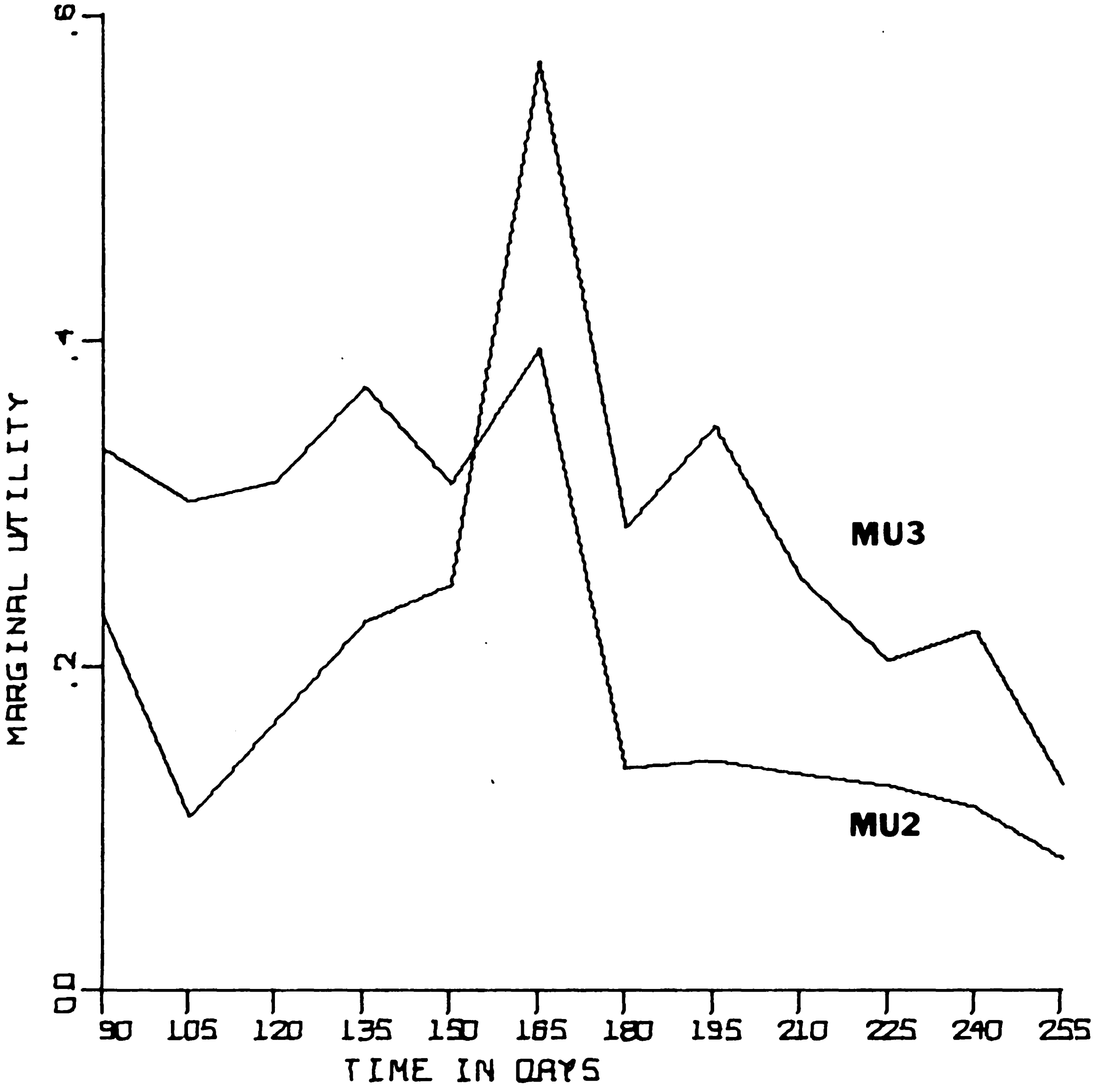

FIGURE 8. MARGINAL UTILITY WITH RESPECT TO SIZE OF FISH (MU2) AND WITH RESPECT TO NUMBER OF FISH (MU3) VERSUS TIME.

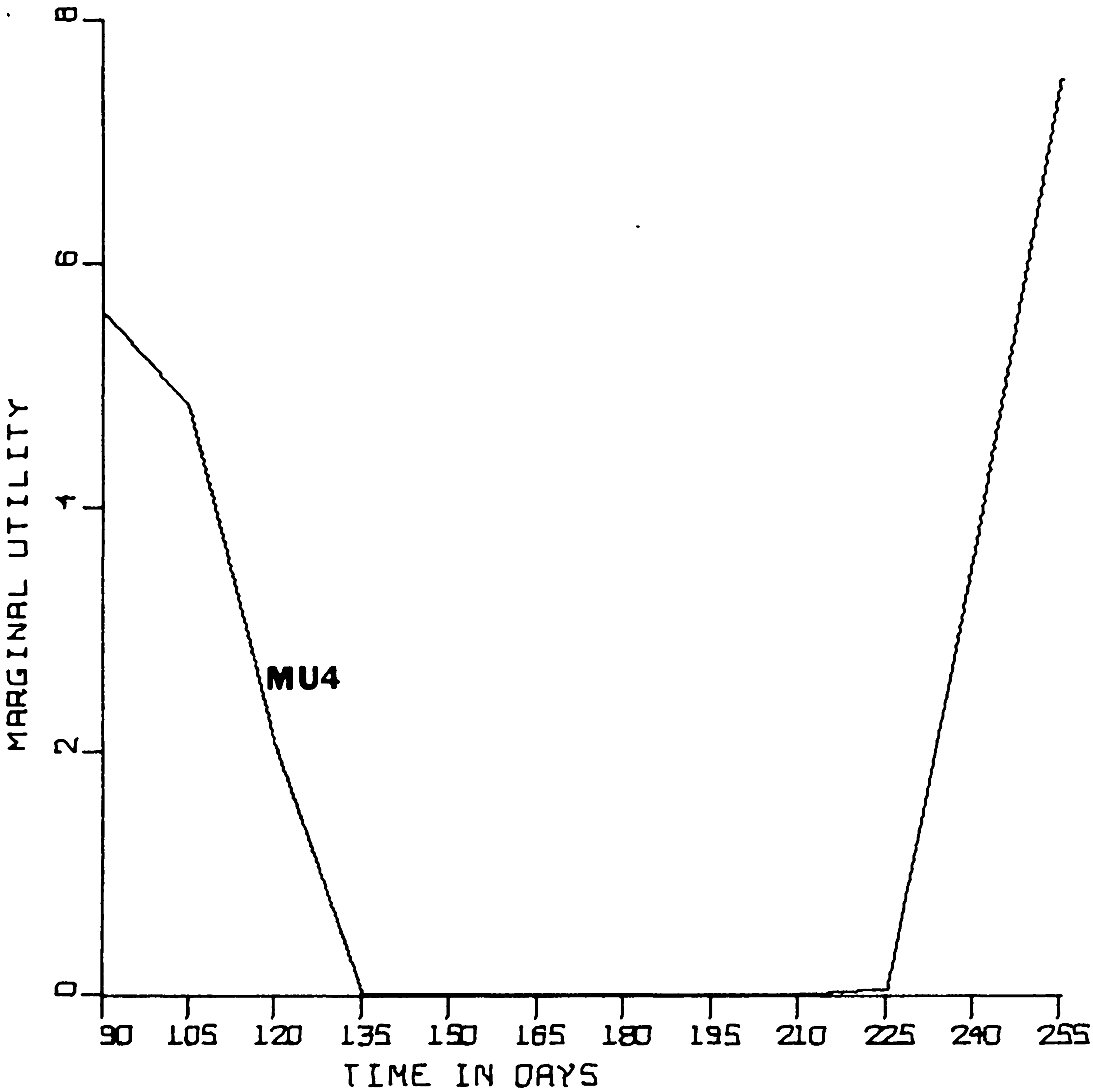

FIGURE 9. MARGINAL UTILITY WITH RESPECT TO PRIVACY (MU4) VERSUS TIME.

dard deviation of 0.577. Mean UT can be compared to the deterministic prediction of optimal UT which was 7.668. The difference between this and the utility derived from OEP predictions of the 1973 Rich Creek system was also observed. Using 1973 inputs and seven Monte Carlo simulations, the mean UT was 4.413 with a standard deviation of 0.293. It appears that the optimal decisions produce a significant increase in utility over the OEP prediction of existing conditions.

Simulating results of each of the 312 decision variables perturbed independently would be very costly. Therefore, the stability of these decisions was investigated in a more general way. Each row vector in the decision matrix was altered simultaneously, i.e., all of the 24 elements (for 24 time periods) in the vector for decision i (i=1, 2, ..., 13) were altered at the same time. This alteration consisted of a 1% change of the optimal decisions given previously in Table 8. A 1% perturbation was chosen to approximate the partial derivatives of utility with respect to the decisions. The effect of these alterations are shown to be insignificant in predicting UT (Table 9).

Postoptimality Analysis of Utility Maximization

In a strict sense postoptimality analysis consists of sensitivity analysis on the optimum derived after the original optimization has occurred and without solving another optimization problem. In this study the term postoptimality analysis is used in a broader context to include sensitivity information on the constraints and other vari-

Table 9. Effect of altering each decision activity plus one percent (+), minus one percent (-), or no alteration (0) for all time periods. See Table 2 for definitions of the decision numbers.

Alteration	Decision Number	UT	DIV	C	AD
0	—	7.668	494300	5701	6843
-	1	7.666	495400	5700	6911
+	1	7.669	493900	5700	6774
+	2	7.669	494300	5700	6843
-	2	7.666	494300	5700	6843
+	3	7.668	493200	5701	6843
+	4	7.668	493500	5701	6843
+	5	7.668	494300	5756	6843
+	6	7.668	493500	5700	6843
-	7	7.664	494600	5700	6840
+	7	7.672	494300	5700	6844
+	8	7.668	493500	5701	6843
-	9	7.668	493500	5701	6843
-	10	7.667	494300	5701	6843
-	11	7.668	493500	5701	6843
-	12	7.668	493500	5701	6843
-	13	7.668	493500	5701	6843

ables found by any means <u>including</u> repetition of the optimization problem using perturbed variables.

Experimenting with the simulator showed that the approximate maximum level of cumulative commercial catch per seine-day which could be reached was 6,000 fish, while the maximum DIV was 1×10^6. These figures are dependent upon input variables (primarily the estimates of initial population sizes). Subjective estimates were made for many of these variables, but these OEP outputs serve as reference points for the postoptimality analysis.

In investigating the sensitivities of the terminal constraints, the first situation tested was: BDG = $50,000, COM = 0, DV = 0. In effect, this was the problem of <u>unconstrained</u> utility maximization and the resulting optimal utility (UT*) was 8.891. This UT* was accompanied by B = $26,044, C = 5,692, and DIV = 101,400, showing the diminishing returns to scale of the budget expenditures. These three numbers partially define the bounds of the constrained region. If the terminal constraints are within these bounds, these constraints will not be active in the solution.

The feasible region bounded by commercial catch and diversity is a product of the interaction of these two components. If COM is high, then diversity cannot reach as high a level as when COM is low. Conversely when DV is high, commercial catch cannot reach as high a level. In terms of the optimization problem, this meant that under most circumstances the constraints of commercial catch and diversity were not tight unless the feasible region was rather narrowly defined.

When the shape and structure of the utility function was defined, it was found that (all else being equal) the angler received more utility from a unit of trout than from a unit of either bluegill or smallmouth bass. Therefore, when BDG was high, more money could be spent, more trout could be planted, and UT* primarily reflected the gain in utility of trout fishing. But, when BDG was low, not as many trout could be planted and, thus, the other types of angling took on increased importance. The same relationship between angler satisfaction and budget was noted by Bailey (1974) from field studies. The optimal decisions and the role of other constraints are, themselves, affected by this switch in importance.

When BDG was approximately \$3,500, the optimal solution occurred when diversity was greater than 5×10^5; i.e., decreasing DV to 1×10^5 did not increase UT* (Figure 10). But when BDG was high (greater than \$6,000) a decrease in DV to 1×10^5 would increase UT*. Also, for equal UT* and equal BDG (e.g., UT* = 6.5 and BDG = \$4,500), COM is higher when DV = 1×10^5 than when DV = 5×10^5.

The above analysis shows that a high diversity (which we assume to be an indicator of ecosystem stability and/or organization and complexity) occurs at low budget expenditures. This implies that a more stable system is needed when the natural portions of the ecosystem (smallmouth bass and bluegill) are being exploited at a higher rate. An increase in complexity will provide more opportunities for the remaining species to grow and reproduce. Conversely, at high budgets the maintenance of high diversity will result in an indirect output

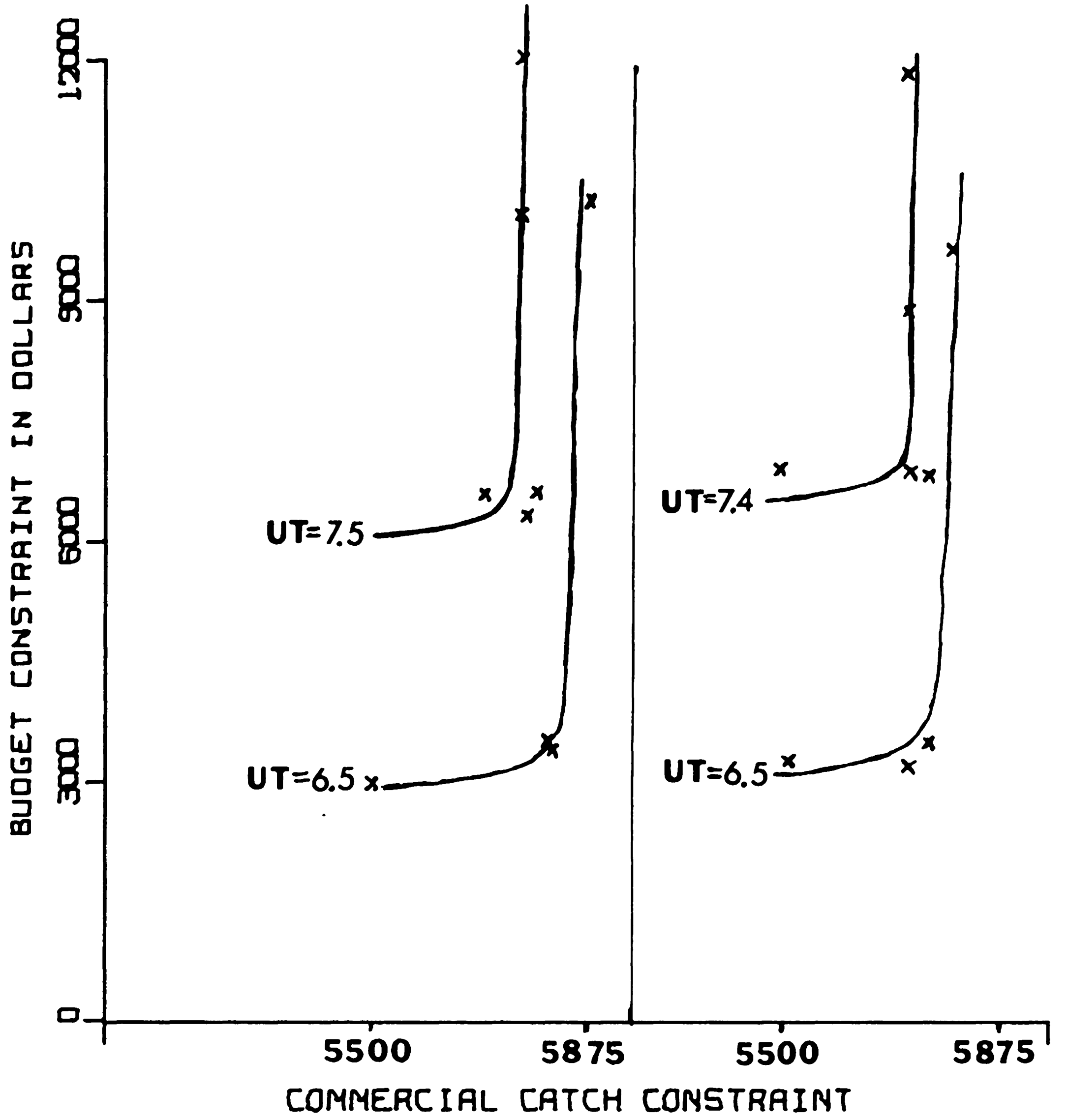

FIGURE 10. COMMERCIAL CATCH CONSTRAINT IN CUMULATIVE CATCH PER SEINE-DAY VERSUS BUDGET CONSTRAINT GIVEN TWO VALUES OF THE DIVERSITY CONSTRAINT, DV=100000 ON THE LEFT AND DV=500000 ON THE RIGHT. CONTOUR LINES OF EQUAL OPTIMAL UTILITY (UT) WERE FIT BY EYE.

loss from the trout portion of the ecosystem. Therefore, at high budgets, a high diversity can only occur when there is an associated loss in utility; i.e., diversity becomes an active constraint.

Since utility reflects the preferences of the human component of the system, sensitivity analysis should especially include those variables and parameters which depict the man-biota interaction. Human population size (POP) has a negative effect on UT* (Figure 11). This is a logical situation because one attribute in the utility function is privacy. Increasing the population size will mean more people will fish, yielding less privacy and less utility per angler. The effect of the population size is not too great, because at the population sized expressed in Figure 11, privacy is at the range in the scale at which the marginal utility is still small (Figure 4). At population sizes less than 10,000, the effect on utility would be more extreme.

The number of angler days predicted from OEP was fairly high (AD = 6,843), therefore, an investigation of the angler density equation is in order. Perturbations of this equation are fairly sensitive (Table 10). Alterations of the parameters produced a substantial reduction in utility ranging from 1.342 to 1.963 utility units per year (a reduction of 18-25% from UT* = 7.668).

The aquatic faunal portions of the ecosystem were affected primarily by three major factors: (1) the water temperature; (2) the standard metabolic rate of the fish and crayfish; and (3) the productivity of the particulate organic matter (POM) and of the macroinvertebrates (MACROINV). When the entire water temperature function

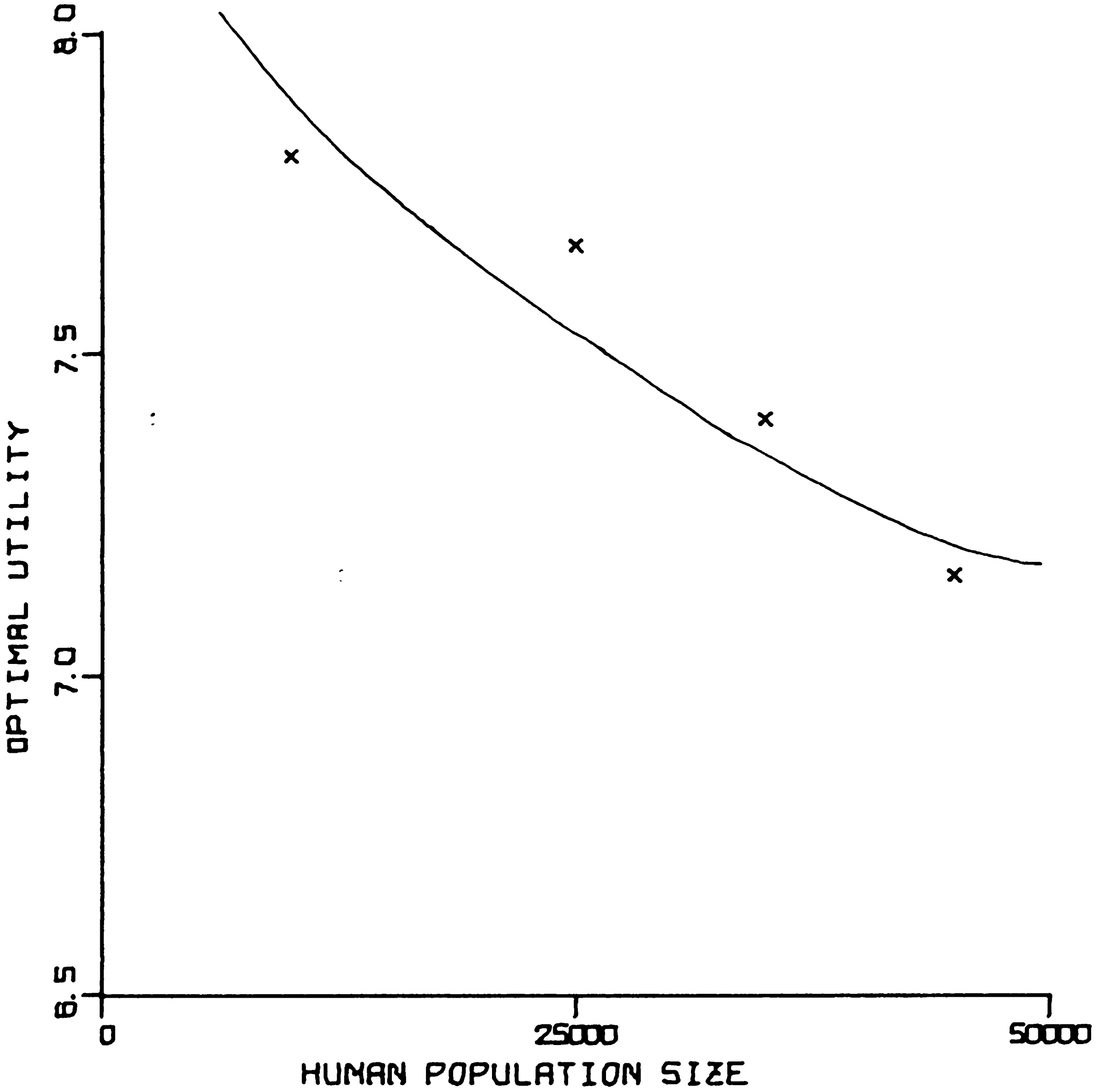

FIGURE 11. OPTIMAL CUMULATIVE UTILITY OBTAINED FROM VARIOUS HUMAN POPULATION SIZES. CURVE FIT BY EYE.

Table 10. Effects on optimal utility (UT*) of varying the angler dynamics equation parameters away from estimated values

Parameter	Estimated Value	Perturbed Value	Resulting UT*
AP_1	231.4490	236.0000	5.850
AP_2	0.4834	0.4500	5.732
AP_3	0.0013	0.0011	5.992
AP_4	19.5152	21.0000	5.831
AP_5	0.3530	0.1500	6.065
AP_6	0.9423	1.1500	5.800
AP_7	0.5553	0.7500	6.326
AP_8	1.1192	1.3500	6.072

was shifted 2 C higher (PRP_1=6 instead of 4), the optimal utility was 8.112 achieved with DIV = 809,700. When the temperature function was shifted 2 C down (PRP_1=2), the diversity constraint could not be met at DV = 100,000, hence no solution was possible.

When the standard metabolic rate was reduced 10% [$GP_1^{(now)} = 0.9 \times GP_1^{(before)}$] for all fish and crayfish, the effect on utility was not great (UT* = 7.454). However, when the metabolic rate was <u>increased</u> 10%, once again, the diversity constraint could not be met at DV = 100,000 and no solution existed.

The difference between the causative mechanisms associated with the temperature and metabolic rate variables are these: when temperature increases, it increases the metabolic rate. However, it also increases the swimming speed, hence, the animal is more likely to be successful as a predator. This gain apparently outweighs the energy losses to metabolism. The gain is reflected in faster growth, more reproduction and subsequently a gain in diversity <u>and</u> utility. On the other hand, increasing the standard metabolic rate alone without an associated increase in prodatory efficiency results in a net energy loss and, therefore, a reduction in diversity.

The "lower" portions of an ecosystem (POM and MACRO) may be important because stresses placed on these components may manifest themselves in higher components, such as fish and/or man. Therefore, the production density curves of POM and MACROINV were decreased (PRP_4= 5, PRP_8 = 2.5) as a test. The result was a utility equal to 5.970.

This was a substantial decrease from UT* = 7.668, which tends to corroborate the importance ecologists place on the food organisms low in the food web.

Another question (and particularly relevent to the practicing manager) which might be asked is, "How important are the initial estimates of the fish population abundance?" This question was investigated by (1) halving and (2) doubling all of the initial subjective population estimates. It must be remembered that doing this will alter the diversity index such that comparisons are invalid. This problem was somewhat circumvented by (1) doubling and (2) halving the population sizes at the end of each simulation <u>before</u> the diversity was calculated. This still does not make comparisons valid, but differences between diversities <u>are</u> suppressed so that the same diversity constraint could be used in both cases. The results showed that doubling the initial population estimates produced UT* = 7.584 and halving produced UT* = 8.381. With the error in the diversity constraint, the calculated utilities are comparable.

Other Sensitivity Information for Utility Maximization

All of the previous decision problems consisted of 24 time stages. To test an alternative structure the decision problem was decomposed into 12 time stages of 30 days each, which amounts to a monthly decision schedule instead of twice-monthly schedule. The optimal utility was found to be 3.282 which is equivalent to 6.564 on a 24 time stage schedule. However, the optimum could only be achieved by reducing the diversity constraint to DV = 10,000. Apparently, 30-day time periods are too long, while the 24 stage schedule allows decisions to change to meet the short-term demands of the system.

The state derivative calculated in the process of RAMP search showed that by far the most sensitive of the approximating transition functions is the one associated with the biomass of trout. As defined, a state derivative, λ_{np}, is the cost to the objective function of meeting the constraint implied by transition function "np." The cost associated with the trout biomass transition function shows an exponential decrease over time (Table 11), a formalization of the intuitive concept that outcomes predicted well into the future are most sensitive to decisions made at the present. It also indicates that more information would be beneficial about the relationship of the state and decision variables to trout biomass.

The optimal strategy for utility maximization forces the commercial fishing to occur early in the year. To test the effects of an alternative commercial fishing strategy on utility, the following decision policy was used:

$$d_{n3} = 0.25$$

$$d_{n4} = 15.00$$

$$d_{n5} = 8{,}000$$

$$d_{n6} = 1.173 \times 10^{-5},\ 5 \leq n \leq 20,$$

$$d_{ni}\ (i=3,\ 4,\ 5,\ 6) = 0,\ \text{elsewhere.}$$

All other decisions are the same as in Table 8. The above decisions are the most efficient levels of activities in terms of commercial

Table 11. The values of the state derivatives associated with the trout biomass transition function calculated in RAMP search, i.e., $\lambda_{n+1,6}$

Time Period (n)	$\lambda_{n+1,6}$	Time Period (n)	$\lambda_{n+1,6}$
1	0.2147E 06[a]	13	0.1422E-07
2	0.8105E 05	14	0.1376E-08
3	0.7524E 04	15	0.1360E-09
4	0.6488E 03	16	0.1385E-10
5	0.4871E 02	17	0.1407E-11
6	0.3984E 01	18	0.1357E-12
7	0.2368E 00	19	0.1297E-13
8	0.1372E-01	20	0.1202E-14
9	0.8818E-03	21	0.1060E-15
10	0.5721E-04	22	0.9820E-17
11	0.2975E-05	23	0.1466E-17
12	0.1932E-06	24	0.0

[a] 0.2147E 06 = 0.2147×10^6

fishing. However, they have been limited so that no commercial fishing occurs before time period five and after time period 20. The resulting UT under these conditions was unchanged from standard conditions (UT = 7.668). With this decision policy, commercial catch per seine-day decreased to 74.6. It appears that when no commercial fishing occurs in early winter, it will be a loss to the commercial fishermen and not to recreational fishermen.

Utility Maximization Overview

The optimal strategy for utility maximization has several characteristics. Because diversity and commercial catch are conflicting constraints, a policy had to be found which would satisfy both. OEP results indicate that commercial catch should be concentrated at the beginning of the year. This leaves the rest of the year (including the reproductive period) for the fish populations to recover and for diversity to build up to pre-exploitation levels. Such a policy may be infeasible in the real world, because it is doubtful if commercial seiners will harvest at a high rate if no market exists for their fish. In the early winter no market would exist because there is little recreational fishing. But, recreational fishing does start to increase in late winter and the demand for baitfish is assumed to increase concurrently. Therefore, a policy which emphasizes baitfish exploitation early in the year might still be successful. However, if this strategy was not emphasized, it would not greatly affect utility, only the commercial fishery.

The optimal strategy found by OEP stresses exploitation of trout (if the budget allows it). The size of the trout is the most important attribute of utility. However, the number of fish caught can be a compensating factor in the summer when the size attribute tends to decrease. Perhaps the most important aspect of utility maximization is the marginal utility associated with privacy. An attempt should be made to maintain low angling pressure as long as possible in the late winter and to regain this low angling pressure as quickly as possible in autumn.

In terms of research needs, information accumulation should focus on the function which predicts angling pressure (better estimates are needed for the parameters of this function). Also temperature, metabolism, and particulate organic matter and macroinvertebrate productivity are important to optimal utility. Finally, the relationship of the decisions to trout biomass is integral to utility, therefore, the initial fish population estimates for nontrout species do not have to be very accurate when deriving the optimal policy for utility maximization.

Diversity Maximization

Diversity maximization is the optimization problem expressed in 4.1 in which $a_2 = 1$ and $a_i = 0$ $(i \neq 2)$, namely

$$\max OB = a_2 DIV$$

subject to:

$$DIV \geq DV$$

$$C \geq COM$$

$$B \leq BDG.$$

Initially, terminal constraints were set at BDG = \$6,960, COM = 3,000, and DV = 100,000. Because the objective is DIV maximization, the diversity constraint seldom takes an active part in the solution. The optimal value of diversity derived from this formulation was DIV* = 526,000 with UT = 7.0, C = 4,460, and B = \$6,931. There was also a fairly low number of angler-days (AD = 5,905). It is significant that the budget constraint is active and utility is fairly high even though recreational fishing is neglected in the objective. A reason for this phenomenon is as follows: some fishing is bound to occur even with the diversity objective. If the diversity is to reach a high level, the fishing that does occur must be shifted away from the "natural" components of the ecosystem, i.e., away from smallmouth bass and bluegill. A method of getting this shift is to spend more money on stocking trout and thus, a moderately high utility is achieved as a by-product. Using such reasoning, a decrease in the budget constraint (BDG) should decrease DIV*, and to some degree it does (Figure 12).

An obvious question may now be asked: why not eliminate fishing and thereby let the ecosystem remain in its "natural" and presumably highly diverse state? When the simulation was run with all decisions set at zero, the terminal diversity was found to be DIV = 114,300. This less than optimal diversity level is indicative of the need for

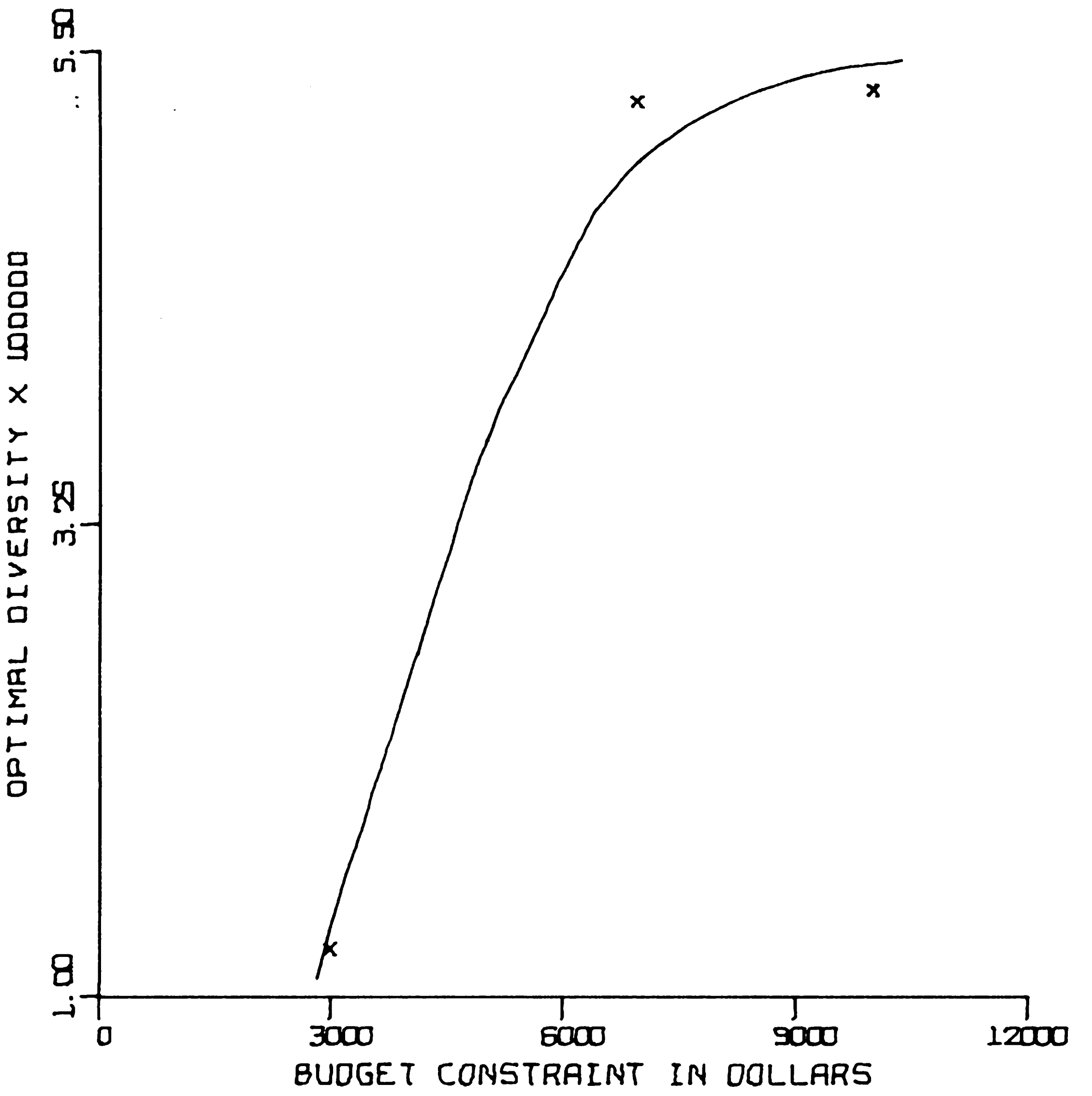

FIGURE 12. OPTIMAL DIVERSITY FOR SEVERAL BUDGET CONSTRAINTS. CURVE FIT BY EYE.

some cropping of the exploited fish populations to bring the age-structure into balance. However, if better estimates of initial population sizes were made, the results might show that the age-structure is, indeed, in balance, and a no-fishing policy might be best for maximizing diversity. Diversity maximization, unlike utility maximization, is dependent on initial population estimates.

The decisions which produced DIV* = 526,000 (Table 12) are the expression of a general policy in which angling pressure is discouraged and what angling exists is channeled into trout fishing. The time sequence of DIV (Figure 13) shows the expected increase due to reproduction in the spring and summer and a gradual decline thereafter.

Postoptimality Analysis of Optimal Diversity

Variations in the human population level (POP) did not produce significant alterations in optimal diversity. A population size of 35,000 gave DIV* = 531,000 and DIV* = 521,600 was achieved with a population of 15,000 as compared to the DIV* = 526,000 when the population size was 25,000. Likewise, the commercial catch constraint does not alter DIV*. When COM was set equal to 5,000, the resulting DIV* was 516,400 (a result well within the reliability of the search procedure). Also, small changes in the productivity of particulate organic matter and macroinvertebrates did not affect diversity (if $P_4 = 12$ and $P_i = 7$, then DIV* = 518,300; and if $P_4 = 8$ and $P_8 = 3$, then DIV* = 501,000). Apparently diversity maximization does not depend to any great extent on these variables.

TABLE 12. VALUES OF OPTIMAL DECISION VARIABLES, D(N,Q) (N=1,2,...,24 TIME STAGES; Q=1,2,...,13 DECISION ACTIVITIES), AS DETERMINED BY APPLYING RAMP SEARCH TO DIVERSITY MAXIMIZATION OBJECTIVE FUNCTION. SEE TABLE 2 FOR DEFINITIONS OF THE 13 DECISION ACTIVITIES.

	STAGE 1		STAGE 2		STAGE 3		STAGE 4
1	0.8406E 00*	1	0.7260E 00	1	0.4223E-01	1	0.8778E 00
2	0.9583E 00	2	0.3351E 00	2	0.3603E 01	2	0.9452E 00
3	0.1169E 01	3	0.1735E 01	3	0.1887E 01	3	0.4680E 00
4	0.1564E 02	4	0.1206E 02	4	0.3512E 01	4	0.1406E 02
5	0.4316E 04	5	0.8090E 04	5	0.5621E 04	5	0.1103E 04
6	0.5512E-04	6	0.4268E-04	6	0.7925E-04	6	0.3372E-04
7	0.8447E 01	7	0.5594E 01	7	0.1392E 02	7	0.6104E 00
8	0.1147E 03	8	0.1673E 03	8	0.8441E 01	8	0.2968E 02
9	0.5750E 03	9	0.4521E 03	9	0.8924E 03	9	0.5542E 03
10	0.2020E 02	10	0.1454E 02	10	0.1709E 02	10	0.1077E 02
11	0.1451E 03	11	0.1935E 03	11	0.2467E 03	11	0.3061E 03
12	0.1704E 04	12	0.2402E 04	12	0.2085E 04	12	0.1105E 04
13	0.9532E 01	13	0.5628E 01	13	0.1128E 02	13	0.2829E 01

* 0.8406E 00 = 0.8406 TIMES 10 TO THE ZERO POWER

TABLE 12. (CONTINUED).

STAGE 5		STAGE 6		STAGE 7		STAGE 8	
1	0.8711E 00	1	0.4494E-01	1	0.9111E-01	1	0.7610E-01
2	0.4767E 01	2	0.1776E 01	2	0.2239E 01	2	0.7921E 00
3	0.1762E 01	3	0.1454E 01	3	0.1734E 01	3	0.5314E 00
4	0.1411E 02	4	0.3299E 01	4	0.3414E 01	4	0.3370E 01
5	0.3025E 04	5	0.4465E 04	5	0.2228E 04	5	0.6193E 04
6	0.4670E-04	6	0.1941E-04	6	0.8004E-04	6	0.1998E-04
7	0.1590E 01	7	0.2927E 03	7	0.1594E 02	7	0.1249E 02
8	0.5476E 02	8	0.2627E 02	8	0.1158E 03	8	0.1900E 03
9	0.8346E 03	9	0.4240E 03	9	0.2711E 03	9	0.6988E 02
10	0.2994E 01	10	0.1933E 02	10	0.1784E 02	10	0.2748E 02
11	0.1264E 03	11	0.3133E 03	11	0.4286E 03	11	0.3986E 03
12	0.1546E 04	12	0.2440E 04	12	0.1979E 04	12	0.1349E 04
13	0.8699E 01	13	0.2442E 01	13	0.6625E 00	13	0.1230E 01

TABLE 12. (CONTINUED).

STAGE 9		STAGE 10		STAGE 11		STAGE 12	
1	0.5136E 00	1	0.2261E 00	1	0.6752E 00	1	0.8441E 00
2	0.2640E 01	2	0.1425E 01	2	0.1598E 01	2	0.2895E 01
3	0.1092E 01	3	0.1350E 01	3	0.1683E 01	3	0.1755E 01
4	0.1045E 02	4	0.9706E 01	4	0.3416E 01	4	0.1086E 01
5	0.2215E 04	5	0.8356E 04	5	0.4530E 04	5	0.4277E 04
6	0.6287E-04	6	0.6463E-04	6	0.1810E-04	6	0.7760E-05
7	0.1558E 02	7	0.7139E 01	7	0.1744E 00	7	0.1232E 02
8	0.3021E 01	8	0.6504E 02	8	0.8471E 02	8	0.1995E 03
9	0.7240E 02	9	0.6649E 03	9	0.4164E 03	9	0.3976E 03
10	0.1040E 02	10	0.1517E 02	10	0.2893E 02	10	0.2016E 02
11	0.1781E 03	11	0.1922E 03	11	0.3111E 03	11	0.2788E 02
12	0.4306E 02	12	0.1892E 04	12	0.1332E 03	12	0.7178E 03
13	0.1794E 02	13	0.1626E 01	13	0.1441E 02	13	0.4417E 01

TABLE 12. (CONTINUED).

STAGE 13		STAGE 14		STAGE 15		STAGE 16	
1	0.7412E 00	1	0.5106E-01	1	0.2290E 00	1	0.6491E 00
2	0.2297E 01	2	0.3707E 00	2	0.1324E 01	2	0.3592E 01
3	0.1706E 00	3	0.1990E 01	3	0.1055E 01	3	0.9953E 00
4	0.7552E 01	4	0.5761E 01	4	0.1566E 02	4	0.1039E 02
5	0.4980E 04	5	0.7737E 04	5	0.9488E 04	5	0.6382E 04
6	0.5895E-04	6	0.4995E-05	6	0.6474E-04	6	0.1538E-04
7	0.1106E 01	7	0.6720E 01	7	0.6897E 01	7	0.3584E 01
8	0.5269E 01	8	0.1133E 03	8	0.4858E 02	8	0.1381E 03
9	0.5945E 03	9	0.3380E 03	9	0.3186E 03	9	0.4779E 03
10	0.2179E 02	10	0.4614E 01	10	0.2813E 02	10	0.2911E 02
11	0.2061E 03	11	0.2713E 03	11	0.2197E 03	11	0.2151E 02
12	0.2343E 04	12	0.2179E 04	12	0.4978E 03	12	0.1314E 04
13	0.1829E 02	13	0.6909E 01	13	0.4793E 01	13	0.1535E 02

TABLE 12. (CONTINUED).

	STAGE 17		STAGE 18		STAGE 19		STAGE 20
1	0.8724E 00	1	0.7799E 00	1	0.2379E 00	1	0.9351E 00
2	0.1640E 01	2	0.1914E 01	2	0.1822E 01	2	0.4061E 01
3	0.2334E 00	3	0.5563E 00	3	0.8944E-01	3	0.9141E 00
4	0.1495E 02	4	0.4461E 01	4	0.1978E 02	4	0.8648E 01
5	0.4359E 04	5	0.8350E 04	5	0.5318E 04	5	0.4809E 04
6	0.8862E-04	6	0.2769E-06	6	0.2895E-04	6	0.9940E-04
7	0.7883E 01	7	0.1003E 02	7	0.1901E 02	7	0.1271E 02
8	0.7783E 02	8	0.1970E 03	8	0.1946E 02	8	0.1737E 03
9	0.7088E 03	9	0.3549E 03	9	0.2688E 02	9	0.4395E 03
10	0.6687E 01	10	0.1508E 02	10	0.9108E 01	10	0.3458E 01
11	0.1248E 03	11	0.2331E 03	11	0.2765E 03	11	0.1485E 03
12	0.1227E 04	12	0.6864E 03	12	0.1462E 04	12	0.1860E 04
13	0.1399E 01	13	0.9030E 01	13	0.1066E 02	13	0.1583E 02

TABLE 12. (CONTINUED).

STAGE 21

1	0.5431E-01
2	0.1002E 01
3	0.1428E 01
4	0.9579E 01
5	0.4495E 04
6	0.3865E-04
7	0.5468E 01
8	0.3244E 02
9	0.4612E 03
10	0.1844E 02
11	0.3847E 02
12	0.2322E 04
13	0.1760E 02

ALL DECISIONS FOR TIME STAGES 22 TO 24 ARE EQUAL TO ZERO

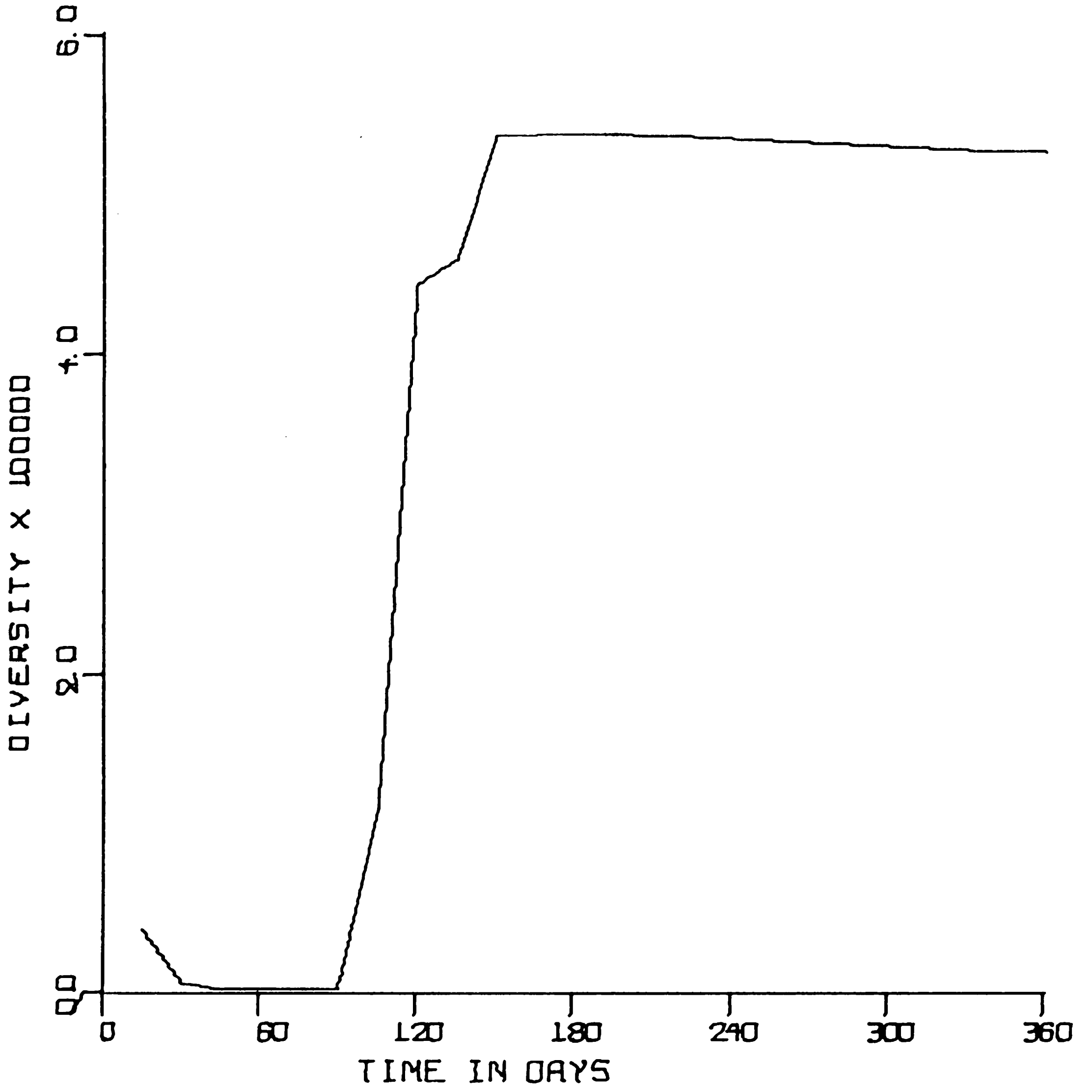

FIGURE 13. TIME SEQUENCE OF OPTIMAL DIVERSITY

The diversity objective was by far the most sensitive to the variables: metabolic rate of the fish and the water temperature. Increasing the temperature function (by incrementing PRP_1) greatly increased the optimal diversity (Figure 14). Similar to analysis of the diversity constraint in utility maximization, when the metabolic rate was decreased 10%, diversity was not greatly changed. However, when the metabolic rate was increased 10%, the constraint DV = 50,000 could not be met, even for diversity maximization. The temperature equation is functioning in OEP as the "driver" of system metabolism. Reproduction, predation, growth, and angling success are directly dependent upon water temperature in the simulation model. The culmination of all of these processes are reflected in the diversity index. Hence, the temperature is an important part of optimal diversity prediction, and so is the relationship of temperature to the other processes.

Overview of Diversity Maximization

The intent of using diversity as a criterion in management of the Rich Creek ecosystem was to group all of the objectives of conservation and maintenance into a single index. With this one index function by which ecosystem diversity was judged, computational problems were diminished. However, any one diversity index may not reflect the "true" stability of the ecosystem.

The information theory index was used because it expressed two separate concepts in a single quantity: (1) the diversity of species,

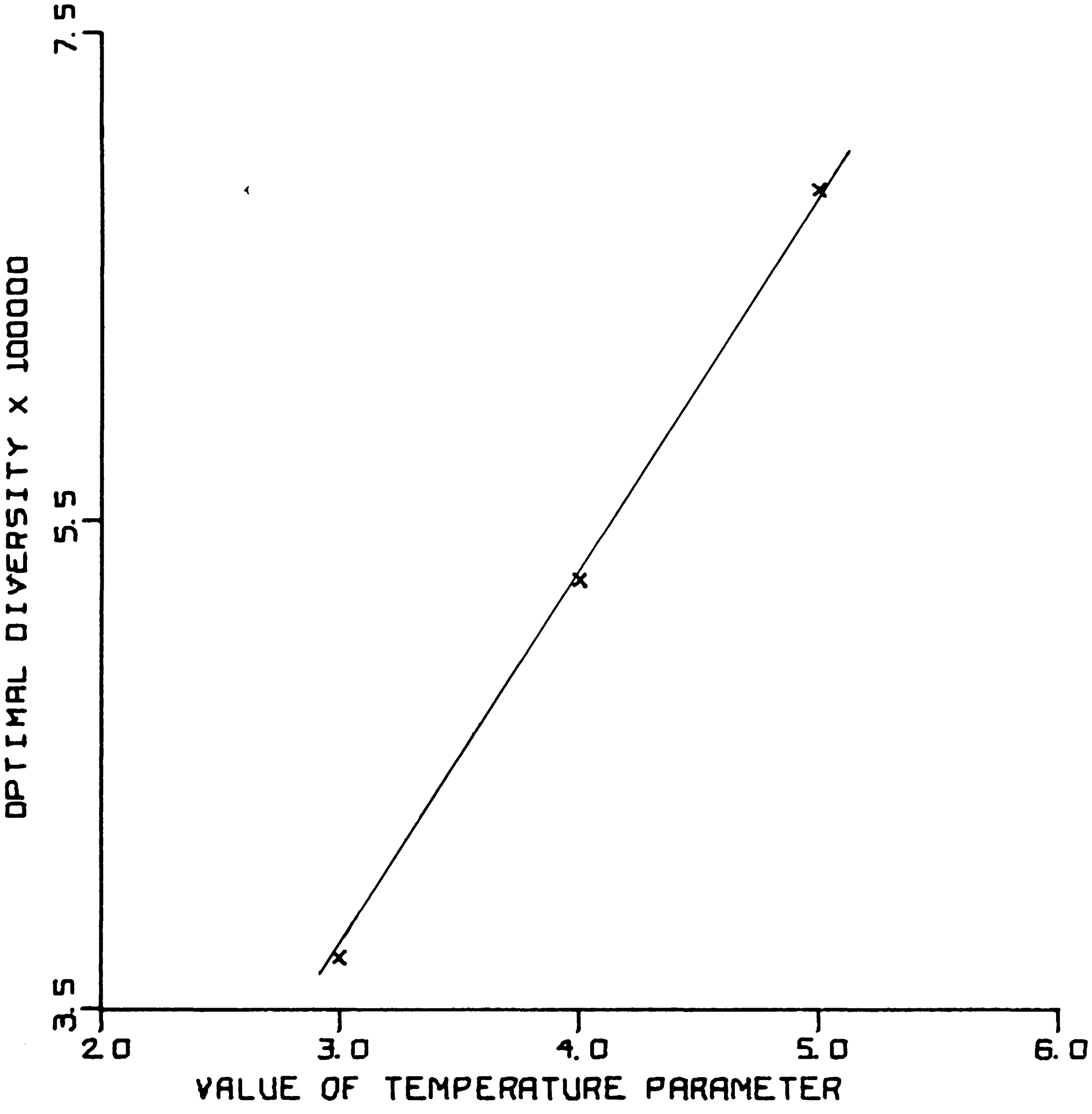

FIGURE 14. OPTIMAL DIVERSITY VERSUS VARIOUS VALUES OF THE TEMPERATURE PARAMETER (PRP 1) IN DEGREES C. CURVE FIT BY EYE.

and (2) the number of individuals within each species. Sometimes the index as used in this study would be dominated by this second concept, i.e., a large number in one species would produce a fairly large value for the diversity index. The result would be a high diversity for a situation which was intuitively undiverse. When the solution to an optimization problem took this form, it was eliminated from consideration in the analysis. Most of the time this elimination was unnecessary because pathologic diversity values oftentimes produces infeasible results. Other diversity indices could have been used in OEP and further modifications of OEP might include such indices.

The relationship of the diversity index to the system was most sensitive to the temperature of the ambient environment. Therefore, if diversity maximization is the objctive, temperature prediction should receive high priority when future data aquisition projects are planned. Such investigations might not be deemed worthwhile by management agencies because it is unlikely that an agency would manage a fishery on the single criterion of diversity maximization. However, the preceding arguments have shown the usefulness of diversity concepts as one of several criteria and/or constraints. Therefore, scientific studies on temperature relations and on measuring ecosystem "health" can be fruitful to management.

Commercial Catch Maximization

Maximization of cumulative commercial catch-per-seine-day is expressed by equation (4.1) when $a_3 = 1$ and $a_i = 0$ $(i \neq 3)$, i.e.,

$$\max OB = a_3 C$$

subject to

$$DIV \geq DV$$

$$C \geq COM$$

$$B \leq BDG$$

The commercial catch maximization problem was initially formulated with BDG = \$6,960, DV = 100,000, COM = 3,000. After applying RAMP search, the results obtained were C* = 5,835 with B = \$6,526, DIV = 118,400, UT = 4.242, and AD = 6,584. Optimal decisions for this objective (Table 13) show that all commercial or recreational exploitation occurs before time stage 14, i.e., before the middle of July, and no exploitation occurs after the middle of July.

Examination of the seine effort decision (Decision 6) shows this to be expressed in numbers/m^2/day. The portion of Rich Creek which is of concern to this study is 75,000 m^2 (15,000 m in length by 5 m wide), and when this figure is multiplied by the seine densities, the products range from 0.0277/day to 0.8789/day. Therefore, the average density is less than one seining operation per day on the stream. The manner in which the state agency might regulate this stream would be to sell one baitfishing license for this area and then regulate the number of days per time period in which seining could occur. In this optimization problem the one seining operation in Rich Creek was active between 0.42 and 13.20 days per 15 day period (Figure 15). The maximum seine density during the year is 0.1173×10^{-4}, implying that the maximum number of licenses per stream length should be one for every 17 km of

TABLE 13. VALUES OF OPTIMAL DECISION VARIABLES, D(N,Q) (N=1,2,...,24 TIME STAGES; Q=1,2,...,13 DECISION ACTIVITIES), AS DETERMINED BY APPLYING RAMP SEARCH TO COMMERCIAL CATCH MAXIMIZATION OBJECTIVE FUNCTION. SEE TABLE 2 FOR DEFINITIONS OF THE 13 DECISION ACTIVITIES.

STAGE 1		STAGE 2		STAGE 3		STAGE 4	
1	0.7866E-01*	1	0.9777E-01	1	0.5250E-01	1	0.1156E 00
2	0.4060E 01	2	0.4889E 01	2	0.2108E-01	2	0.1259E 01
3	0.4169E 00	3	0.1655E 01	3	0.4907E 00	3	0.3807E 00
4	0.1886E 02	4	0.3302E 01	4	0.8682E 01	4	0.1752E 02
5	0.7807E 04	5	0.5426E 04	5	0.3966E 04	5	0.5417E 04
6	0.2491E-05	6	0.9616E-05	6	0.5908E-05	6	0.4593E-05
7	0.4241E 00	7	0.1832E 01	7	0.6658E 00	7	0.8245E 00
8	0.5608E 01	8	0.1163E 02	8	0.8607E 01	8	0.1679E 02
9	0.9216E 02	9	0.2340E 02	9	0.7521E 02	9	0.6863E 01
10	0.3361E 01	10	0.7605E 00	10	0.3424E 01	10	0.1209E 01
11	0.3490E 00	11	0.1564E 01	11	0.2881E 02	11	0.2410E 02
12	0.3019E 03	12	0.1015E 03	12	0.1715E 03	12	0.1287E 03
13	0.1865E 01	13	0.1810E 01	13	0.3598E 00	13	0.1270E-02

* 0.7866E-01 = 0.7866 TIMES 10 TO THE -1 POWER

TABLE 13. (CONTINUED).

	STAGE 5		STAGE 6		STAGE 7		STAGE 8
1	0.3697E-01	1	0.2727E-01	1	0.8985E-01	1	0.5001E-01
2	0.3850E 01	2	0.3268E 01	2	0.4276E 01	2	0.1110E 01
3	0.1915E 01	3	0.1916E 01	3	0.1324E 01	3	0.1462E 01
4	0.1634E 02	4	0.1730E 02	4	0.5519E 01	4	0.7788E 01
5	0.2825E 04	5	0.5696E 04	5	0.6961E 04	5	0.7557E 04
6	0.4288E-05	6	0.7903E-05	6	0.8661E-05	6	0.3693E-06
7	0.1289E 01	7	0.1667E 01	7	0.2231E 01	7	0.9402E 00
8	0.1447E 00	8	0.7761E 01	8	0.2962E 01	8	0.2477E 02
9	0.4439E 02	9	0.9702E 02	9	0.7640E 02	9	0.6286E 02
10	0.1183E 01	10	0.1425E 01	10	0.3261E-01	10	0.1640E 01
11	0.2134E 02	11	0.3245E 02	11	0.5875E 02	11	0.3717E 02
12	0.6547E 02	12	0.2171E 03	12	0.1754E 03	12	0.1980E 03
13	0.4599E 00	13	0.1238E 01	13	0.2272E 01	13	0.1120E 01

TABLE 13. (CONTINUED).

STAGE 9		STAGE 10		STAGE 11		STAGE 12	
1	0.1233E 00	1	0.8559E-01	1	0.1102E 00	1	0.4558E-01
2	0.4430E 01	2	0.2769E 01	2	0.1611E 01	2	0.3019E 01
3	0.8785E 00	3	0.3199E 00	3	0.1994E 01	3	0.6853E 00
4	0.1323E 02	4	0.1952E 02	4	0.1646E 01	4	0.1245E 02
5	0.1612E 03	5	0.4150E 04	5	0.5219E 04	5	0.6525E 04
6	0.1737E-05	6	0.8848E-05	6	0.4880E-05	6	0.3878E-05
7	0.1781E 01	7	0.1281E 01	7	0.1614E 01	7	0.2473E 01
8	0.2472E 02	8	0.1758E 02	8	0.8997E 01	8	0.3578E 01
9	0.5842E 02	9	0.6840E 02	9	0.3928E 02	9	0.1075E 03
10	0.8188E 00	10	0.1203E 01	10	0.3211E 01	10	0.1664E 01
11	0.3978E 02	11	0.2825E 02	11	0.6216E 02	11	0.4065E 01
12	0.2668E 03	12	0.2560E 03	12	0.8185E 02	12	0.1238E 03
13	0.9874E 00	13	0.2214E 01	13	0.1551E 01	13	0.1981E 01

TABLE 13. (CONTINUED).

STAGE 13

1	0.2355E-01
2	0.4989E 01
3	0.5814E 00
4	0.1529E 02
5	0.9696E 04
6	0.1173E-04
7	0.2261E 01
8	0.2449E 02
9	0.8306E 02
10	0.2307E 01
11	0.2893E 01
12	0.2316E 03
13	0.7364E-01

ALL DECISIONS FOR TIME STAGES 14 TO 24 ARE EQUAL TO ZERO

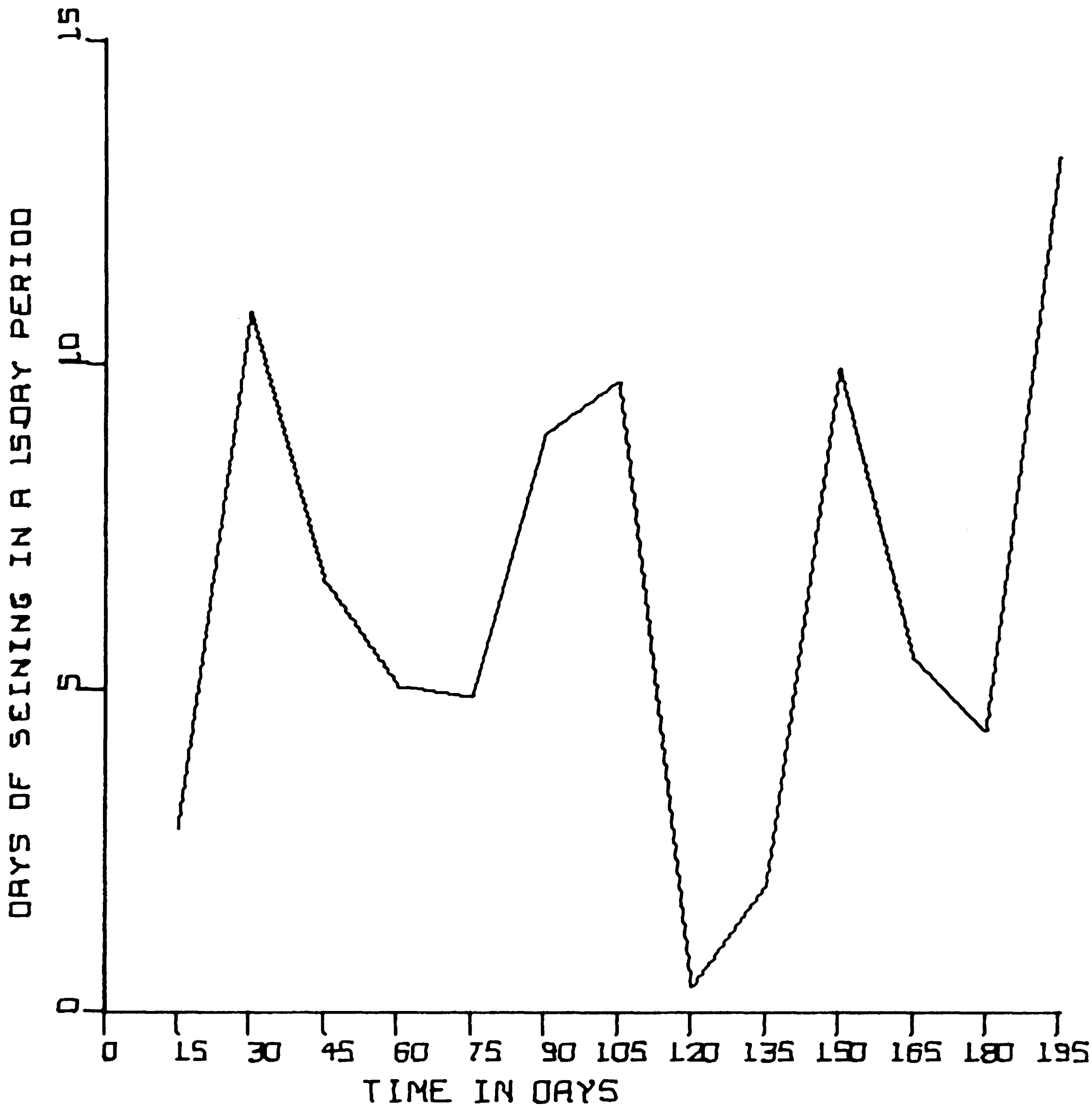

FIGURE 15. NUMBER OF DAYS OF COMMERCIAL FISHING ALLOWED DURING EACH 15-DAY PERIOD.

harvestable stream ($1/0.1173 \times 10^{-4}$ approximately equals 17×10^3). Therefore, there should be only one license in Rich Creek (17.7 km).

The maximum number of baitfish in possession (Decision 5) ranged from 161 to 9,696. However, this limit was never active, i.e., the limit was never reached during any of the time periods. Therefore, inclusion of this decision in the regulatory policy is not needed. The other two decisions dealing directly with baitfish harvest were mesh size (Decision 3) and seine length (Decision 4). Great variability exists within each decision when compared over time (Table 13). The reason for this variability apparently is related to the basic strategy used in getting high commercial catches. The catch is concentrated at the beginning of the year leaving the rest of the year for the system to recover and for diversity to be maintained. To achieve this end, the seine length is initially quite long, the mesh size is small and the seine-density is low. The long seine allows large numbers of fish to be caught and the small mesh size means that all sizes of fish are caught. In the late winter mesh size is somewhat larger to select for larger fish. When reproduction occurred in the spring, mesh size is smaller again to allow harvest of the young fish. This explanation is based on the trends in the decisions. However, better estimates are needed to improve explanation of the relationship between the probability of capture and mesh size and seine length.

Postoptimality Analysis of Commercial Catch Maximization

Postoptimality analysis of OEP using the cumulative commercial catch per seine-day objective function included perturbations of the human population size, the productivity functions for particulate organic matter and macroinvertebrates, the temperature function, and the budget constraint. In <u>none</u> of these cases was the effect on C* significant. The rationale for such results relates to the exploitation occurring primarily at the beginning of the year. Most of the effects of the above variables are observed in the system later in the year. Therefore, for perturbations of moderate magnitude, they have little effect on the commercial catch which has already reached near-optimal proportions.

Analysis of changes in the diversity constraint did not produce significant changes in C* either. However, it did produce some interesting effects on the structure of the decision policy. In the original commercial catch optimization problem in which C* = 5,835 and DV = 100,000, no exploitation occurred after time period 13. All of the subsequent decisions were zero. When DV was increased to 500,000, exploitation of both commercial and recreational species occurred up to and including time period 12, but it did not include time period 13. In order for the diversity constraint to be met, exploitation had to be stopped one time period earlier. Conversely, when DV was reduced to 50,000, exploitation continued into time period 17. The diversity constraint defines the time when the system terminates. But this termination time does not affect C* greatly, because the commercial catch has already closely approached the maximum.

Overview of Commercial Catch Maximization

The optimal strategy for maximization of cumulative commercial catch per seine-day implies an intense harvest regime at the beginning of the year followed next by exploitation at a less severe rate and followed last by a period of no exploitation. The optimal catch was not affected by moderate changes in most system variables. However, the actual decisions found by RAMP search are sensitive to the equations predicting probability of capture as a function of mesh size and seine length. Future improvements to OEP should include updated parameter estimates for these equations.

Another possible improvement to OEP's commercial catch maximization objective relates to the basic strategy. An intense baitfish harvest may be infeasible at the beginning of the year. A state agency will not be able to induce people to seine for baitfish when there are no recreational fishermen to purchase the product. Another constraint which might be added to the optimization problem is to allow baitfish fishing only between specified time periods or to allow no baitfish fishing when there is no recreational fishing. These changes could easily be implemented into the simulation. The changes required in the search procedure would be more substantial, but still possible.

Angler-Days Maximization

Angler-days maximization is equation (4.1) with $a_4 = 1$ and $a_i = 0$ ($i=1, 2, 3$), i.e.,

$$\max OB = a_4\ AD$$

subject to:

$$C \geq COM$$

$$DIV \geq DV$$

$$B \leq BDG$$

The original optimization problem for AD maximization was formulated with COM = 3,000, DV = 100,000 and BDG = \$6,960. The results of this optimization (AD* = 6,990, UT = 6.574, C = 3,193, DIV = 515,700, and B = \$6,603) were achieved by the decisions in Table 14. The trend of these decisions is to allow large creel limits (Decisions 7, 10, and 13 in Table 14) and to keep a large proportion of the area open to fishing (Decision 1). By this policy the angling public is induced to come out and fish, hence, more angler-days.

It is noteworthy that AD* is accompanied by a fairly high utility (6.574). Also, remember that when utility was the objective, the angler days predicted way 6,361. Apparently high numbers of angler-days and high utility do not <u>have</u> to be mutually exclusive. The explanation for this lies with the marginal utility associated with the attribute of fishermen crowding. At high angler densities the utility of the attribute is zero and it would take a rather large decrease in crowding before the utility for privacy would be non-zero. Therefore, a large number of angler-days are accumulated with the other attributes taking up the slack in utility. When angler-days are naturally low in winter and fall, utility increased to a fairly high level. This relationship does not hold for all budget levels. Perturbations of BDG will be discussed in the next section.

TABLE 14. VALUES OF OPTIMAL DECISION VARIABLES, D(N,Q) (N=1,2,...,24 TIME STAGES; Q=1,2,...,13 DECISION ACTIVITIES), AS DETERMINED BY APPLYING RAMP SEARCH TO ANGLER-DAYS MAXIMIZATION OBJECTIVE FUNCTION. SEE TABLE 2 FOR DEFINITIONS OF THE 13 DECISION ACTIVITIES.

STAGE 1		STAGE 2		STAGE 3		STAGE 4	
1	0.3737E 00*	1	0.6944E-01	1	0.3853E 00	1	0.5470E 00
2	0.1209E 01	2	0.1229E 01	2	0.1899E 01	2	0.3906E 01
3	0.1745E 00	3	0.1699E 01	3	0.1623E 01	3	0.1528E 01
4	0.6961E 01	4	0.1769E 02	4	0.8990E 01	4	0.1106E 02
5	0.3029E 04	5	0.6624E 04	5	0.3957E 04	5	0.4438E 04
6	0.6852E-04	6	0.1526E-05	6	0.3285E-04	6	0.6848E-04
7	0.7697E 01	7	0.2602E 01	7	0.8196E 01	7	0.2303E 01
8	0.2853E 02	8	0.1287E 03	8	0.1005E 03	8	0.1055E 03
9	0.3531E 03	9	0.6198E 03	9	0.2938E 03	9	0.1149E 03
10	0.2106E 01	10	0.1028E 02	10	0.1310E 02	10	0.6070E 00
11	0.4450E 03	11	0.4289E 03	11	0.3409E 03	11	0.4862E 03
12	0.1772E 04	12	0.1581E 03	12	0.4038E 03	12	0.1631E 04
13	0.4824E 01	13	0.1318E 02	13	0.1667E 02	13	0.3250E 01

* 0.3737E 00 = 0.3737 TIMES 10 TO THE ZERO POWER

TABLE 14. (CONTINUED).

	STAGE 5		STAGE 6		STAGE 7		STAGE 8
1	0.1037E 00	1	0.6032E 00	1	0.9187E 00	1	0.3973E 00
2	0.7998E 00	2	0.2929E 01	2	0.1177E 01	2	0.1701E 01
3	0.5205E-01	3	0.1718E 00	3	0.2880E 00	3	0.9324E 00
4	0.1433E 02	4	0.4863E 01	4	0.1492E 02	4	0.1470E 02
5	0.6535E 03	5	0.6856E 04	5	0.1804E 04	5	0.2130E 04
6	0.9427E-04	6	0.9252E-04	6	0.3676E-04	6	0.6649E-04
7	0.1364E 01	7	0.7619E 01	7	0.1165E 02	7	0.1449E 01
8	0.1849E 03	8	0.1918E 03	8	0.3706E 02	8	0.9010E 02
9	0.8407E 03	9	0.2918E 03	9	0.7845E 03	9	0.4594E 02
10	0.8482E 01	10	0.9486E 01	10	0.1686E 02	10	0.7554E 01
11	0.1449E 03	11	0.4896E 03	11	0.2639E 03	11	0.2568E 02
12	0.4868E 03	12	0.7382E 02	12	0.2680E 03	12	0.1051E 03
13	0.1119E 02	13	0.7281E 01	13	0.1787E 02	13	0.1580E 02

TABLE 14. (CONTINUED).

	STAGE 9		STAGE 10		STAGE 11		STAGE 12
1	0.3619E 00	1	0.1212E 00	1	0.8804E 00	1	0.7706E 00
2	0.3043E 00	2	0.4745E 01	2	0.1059E 01	2	0.4256E 01
3	0.2163E 00	3	0.1205E 01	3	0.6946E 00	3	0.3451E 00
4	0.2024E 01	4	0.1489E 01	4	0.3555E 01	4	0.7477E 01
5	0.6337E 04	5	0.2465E 03	5	0.9408E 04	5	0.6903E 04
6	0.8915E-04	6	0.4780E-04	6	0.4481E-05	6	0.7769E-04
7	0.1291E 02	7	0.1293E 02	7	0.1604E 02	7	0.8982E 01
8	0.1698E 03	8	0.1152E 03	8	0.8167E 02	8	0.1404E 03
9	0.2573E 03	9	0.5738E 03	9	0.2094E 03	9	0.1535E 03
10	0.2225E 01	10	0.1930E 02	10	0.2162E 02	10	0.2113E 02
11	0.4359E 03	11	0.6129E 02	11	0.1154E 03	11	0.3460E 03
12	0.1407E 04	12	0.2361E 04	12	0.2244E 04	12	0.2031E 04
13	0.1062E 02	13	0.1127E 02	13	0.6160E 01	13	0.1291E 02

TABLE 14. (CONTINUED).

STAGE 13		STAGE 14		STAGE 15		STAGE 16	
1	0.5615E 00	1	0.9263E 00	1	0.9505E 00	1	0.2647E 00
2	0.2798E 01	2	0.1842E 01	2	0.3622E 01	2	0.1163E 01
3	0.6079E 00	3	0.1748E 01	3	0.1584E 01	3	0.2643E-01
4	0.1575E 02	4	0.1858E 02	4	0.4632E 01	4	0.1972E 02
5	0.9907E 04	5	0.7074E 04	5	0.2630E 04	5	0.7983E 04
6	0.8544E-04	6	0.8822E-04	6	0.4933E-04	6	0.9140E-04
7	0.4209E 01	7	0.1853E 02	7	0.1187E 02	7	0.5983E 01
8	0.1146E 03	8	0.1241E 03	8	0.2397E 02	8	0.1138E 03
9	0.4899E 03	9	0.3438E 03	9	0.3415E 03	9	0.6502E 03
10	0.3262E 01	10	0.2128E 02	10	0.5931E 01	10	0.6364E 01
11	0.3766E 03	11	0.4088E 03	11	0.3857E 03	11	0.3856E 03
12	0.1352E 04	12	0.1306E 04	12	0.2122E 04	12	0.1796E 04
13	0.9309E 01	13	0.1551E 02	13	0.3012E 01	13	0.7381E 01

TABLE 14. (CONTINUED).

	STAGE 17		STAGE 18
1	0.7483E 00	1	0.3312E 00
2	0.8420E 00	2	0.4540E 01
3	0.5509E 00	3	9335E 00
4	0.2746E 01	4	0.1259E 02
5	0.3445E 04	5	0.5749E 04
6	0.8316E-04	6	0.7859E-04
7	0.1777E 02	7	0.1083E 02
8	0.1694E 03	8	0.3532E 02
9	0.7706E 02	9	0.1666E 03
10	0.2671E 02	10	0.1565E 02
11	0.2855E 03	11	0.2315E 03
12	0.1034E 04	12	0.2100E 03
13	0.6843E 01	13	0.6732E 01

ALL DECISIONS FOR TIME STAGES 19 TO 24 ARE EQUAL TO ZERO

Postoptimality Analysis of Angler-Days Maximization

Population size of the surrounding area is an obvious variable upon which the number of angler-days depends. If only a few people have easy access to the ecosystem, relatively few people will be able to use the resource. When the human population size was raised from 25,000 to 40,000 the optimal number of angler-days increased from 6,990 to 11,255. Likewise, when the population was 15,000, AD* = 4,197. The population variable defines the order of magnitude of angler-days to be expected.

Dollar expenditures for planting trout show decreasing returns to scale when plotted against angler-days (Figure 16). Increasing the budget past $6,906 does not produce a substantial rise in angler-days, but lowering the budget <u>does</u> produce a substantial decrease. More importantly, when BDG = $3,000 and angler-days maximization was the objective, a low utility (UT = 2.467) was obtained along with few angler-days. At low budgets both angler-days <u>and</u> utility decrease. Less money means less trout to be caught and less interest in angling, a loss to both UT and AD. The importance of trout was reiterated when the state derivatives were calculated. The λ_{np} associated with the trout biomass transition function was many orders of magnitude greater than the other λ_{np}'s.

Changing the temperature function and the particulate organic matter and macroinvertebrate functions did very little to the optimal number of angler-days. Increasing the productivity functions (PRP_4 = 15 and PRP_8 = 7.5) raised the objective to AD* = 7,034 and increasing

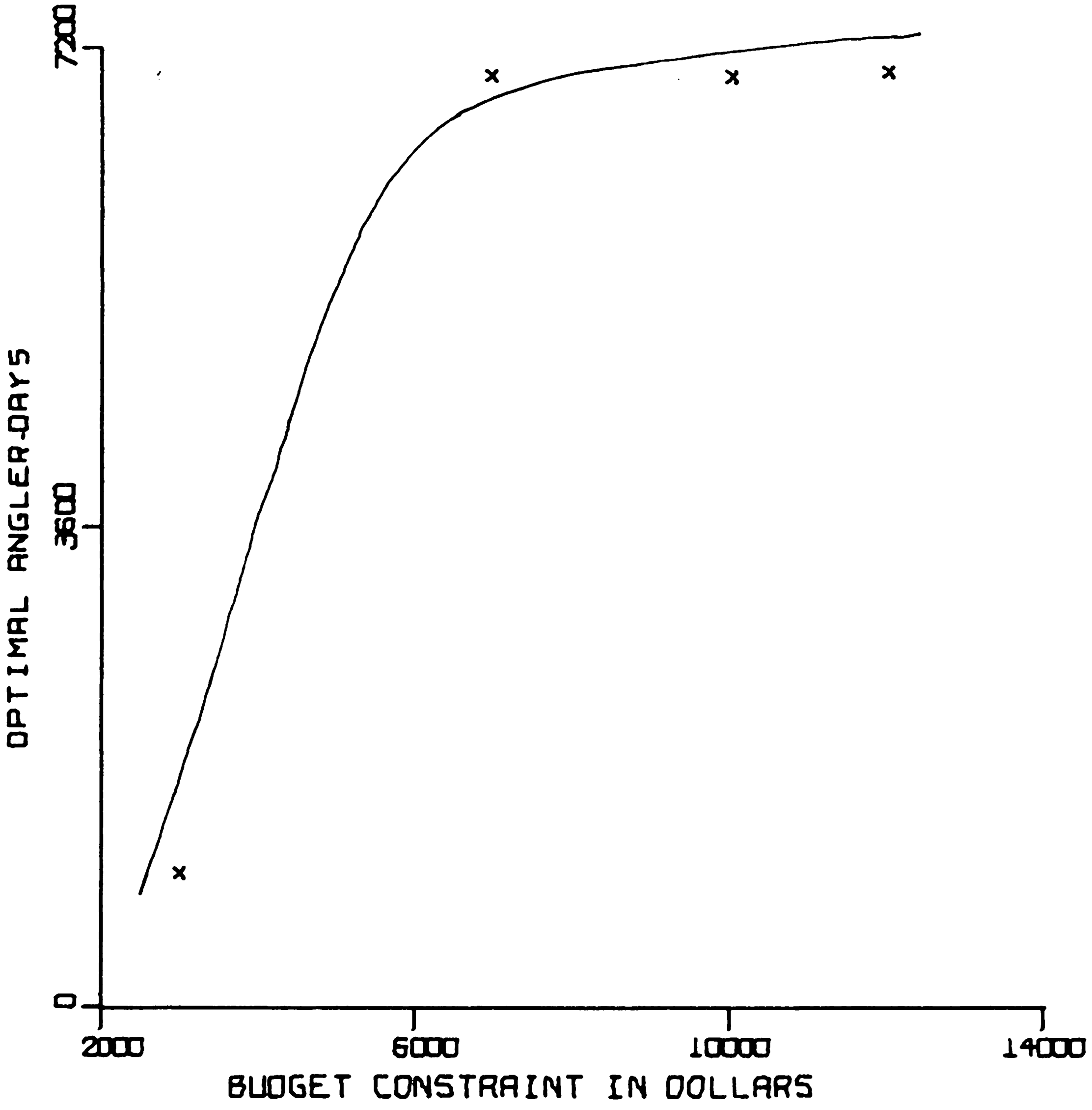

FIGURE 16. OPTIMAL ANGLER-DAYS VERSUS BUDGET CONSTRAINT. CURVE FIT BY EYE.

temperature (PRP_1 = 5) gave AD* = 6,981. Neither appear to be different than AD* = 6,990 found under standard conditions.

Overview of Angler-Days Maximization

Postoptimality analysis has shown that the numbers of angler-days and utility objectives can be compatible when coupled with adequate budget expenditures. The utility function is an expression of utility per individual. When the utility function was designed with the attribute angler density as an expression of crowding, it was thought that conceivably the optimal strategy for utility maximization might eliminate all but one angler. Likewise the optimal policy for angler-days maximization might result in a greatly reduced utility. The analysis shows the opposite, i.e., a fairly high utility will induce more angler-days and conversely a high number of angler days has an acceptable value for utility associated with it.

The necessary conditions for the coupling of utility and angler-days are two. First there must be an adequate amount of money spent on planting trout. Without these expenditures angler-days is a poor objective. Secondly, angler preferences should not change substantially from that measured, i.e., trout is the preferred species and privacy has a highly increasing marginal utility. If trout is not the preferred species, the budget does not play as important a role. Also if privacy's marginal utility was less increasing, then changes in angler-days at higher levels would have a more significant effect on utility. However, for the Rich Creek system as observed, the two objectives of angler-days and utility can be compatible.

Maximization of Linear Combination

The discussion in the previous paragraph is an introduction to multiple-objective optimization in relation to Rich Creek. Such an objective can be a linear combination of the decision criteria. This was expressed by equation (4.1) and reiterated here:

$$\max OB = a_1\, UT + a_2 DIV + a_3 C + a_4 AD \tag{4.1}$$

subject to:

$$C \geq COM$$

$$DIV \geq DV$$

$$B \leq BDG.$$

The a_i are the "values" or "worth" received from a unit of the ith decision criteria. It is the decision-maker's responsibility to supply numerical values to these coefficients, i.e., deciding which criterion is "worth" more to the agency or to himself and how much more. The methods given in the section of development of utility functions could be used to determine the coefficients (scaling factors). Ramifications of the choice of a_i were determined by supplying several sets of values for a_i (i=1, 2, 3, 4) and applying the search procedure to each set. The a_i were chosen using the following method: a factor b_i was picked which reduced the ith criterion to a zero-one scale. Then the values of a_i tested were various percentages of b_i. Thus, for the second criterion DIV, the multiplier $b_2 = 10^{-6}$ reduced DIV to a zero-one scale. Then the a_2 tested were 5%, 10%, 25% and 50% of b_2.

Results (Table 15) show that there is not a linear relation between an increase in a_i and the resulting change in that decision

Table 15. Results of using linear combinations of UT (utility), DIV (diversity), C (commercial catch), and AD (angler-days); i.e., maximization of $a_1UT + a_2DIV + a_3C + a_4AD$

Criterion	Coefficient Value (a_i)	Resulting Value of Criterion	Objective Function Value
UT	2.500×10^{-1}	6.778×10^{0}	
DIV	2.500×10^{-7}	4.060×10^{5}	2.198
C	4.168×10^{-5}	5.764×10^{3}	
AD	2.500×10^{-5}	6.456×10^{3}	
UT	3.500×10^{-1}	7.091×10^{0}	
DIV	5.000×10^{-7}	4.174×10^{5}	2.792
C	1.667×10^{-5}	4.068×10^{3}	
AD	5.000×10^{-6}	6.753×10^{3}	
UT	2.500×10^{-1}	7.681×10^{0}	
DIV	1.000×10^{-7}	4.950×10^{5}	2.520
C	3.334×10^{-5}	5.777×10^{3}	
AD	4.500×10^{-5}	6.293×10^{3}	
UT	4.500×10^{-1}	7.631×10^{0}	
DIV	5.000×10^{-8}	4.492×10^{5}	3.811
C	8.335×10^{-6}	5.743×10^{3}	
AD	4.500×10^{-5}	5.831×10^{3}	

Table 15. (continued)

Criterion	Coefficient Value (a_i)	Resulting Value of Criterion	Objective Function Value
UT	5.000×10^{-2}	7.018×10^{0}	
DIV	5.000×10^{-8}	4.566×10^{5}	1.118
C	7.502×10^{-5}	5.780×10^{3}	
AD	4.500×10^{-5}	6.911×10^{3}	

criterion. For example, decreasing a_1 (the coefficient for UT) from 0.45 to 0.25 can actually increase utility. The reason for this apparent anomaly lies with the values of the other coefficients and the relationships between the criteria. If one criterion has a fairly large coefficient (a_i), it may dominate the objective function such that a change in another coefficient may make no significant difference in the overall objective. Also, fairly high values of utility, number of angler-days, and diversity can go hand-in-hand, i.e., an increase in one will increase the other two. Therefore, a particular criterion might change in the objective independently from the coefficient. Before the multiple-objective function (4.1) is implemented, the relationships within and among criteria and constraints should be explored using single objectives and sensitivity analysis.

Improvements of OEP might include dropping the assumption of a linearly additive objective function and develop a multiplicative utility model [equation (2.2)] for these four criteria. Other criteria such as budget expenditures could be implemented as well. Neither modification would require extensive changes in the OEP program.

RECOMMENDATIONS

This section includes the summary and conclusions of application of OEP to the Rich Creek fishery system for management and research specifically, and recommendations for modifications of OEP for future applications specifically to Rich Creek.

The OEP program was applied to fisheries management problems of Rich Creek using the four management objectives: maximize utility, maximize diversity, maximize commercial catch-per-unit-effort, and maximize number of angler-days. Objectives were employed in conjunction with three terminal or year-end constraints: budget expenditures for the year shall not exceed BDG dollars; the cumulative catch of baitfish per seine-day for the year shall not be less than COM; and the year-end value of the diversity index shall not be less than DV.

Successful management strategies for utility maximization require a substantial budget so that the preferred species (trout) may be planted. By doing so, angling pressure is induced, hence a high value of angler-days. Angling pressure should be inhibited for as long as possible in late winter and discouraged as soon as possible in autumn. If this is done, fishing at these times will be high in privacy and more utility will be derived. In the spring and summer fishing pressure naturally increases and drives privacy low. There should then be a compensatory increase of size and numbers of fish caught which can be accomplished by allowing trout to grow in the winter in the stream and by planting larger numbers of fish in the summer.

The commercial catch constraint for utility maximization is met using the same basic strategy as is used for commercial catch maximization. In this strategy long seines with small mesh sizes are used in the winter to increase harvest efficiency of fish of all sizes. Seining operation density is kept fairly low so there is a large value for catch-per-unit-effort. Later in the year mesh sizes are increased to select for larger fish. As reproduction occurs and fish grow to harvestable size, mesh size decreases, once again, so that these fish may be exploited. Modifications to this scheme affect commercial catch much more than they affect utility.

The diversity constraint as well as diversity maximization is achieved by shifting the focus of recreational fishing away from smallmouth bass and bluegill which enter into diversity calculations. With adequate budgets more trout are planted and trout are the primary recreational species, a recommendation also suggested by Bailey (1974).

The diversity factor is also the rationale for the majority of commercial catch occurring early in the year. By allowing extensive harvests in early winter, a high value of cumulative catch per seine-day is achieved very early in the year. Later in the year, all fishing stops to allow recovery of the exploited populations and ultimately an increase in diversity.

Strategies to maximize the number of angler-days are not unique as compared to those for maximizing utility, at least when the budget constraint is high enough. Successful fishing gives a high utility and will induce more angling pressure. High angling pressure (angler-days) will suppress some utility, but not substantially. Conversely, optimal utility is accompanied by a fairly high number of angler-days. At lower budgets this relationship does not hold because the utility attributes of size and number of fish cannot increase enough to compensate for the lost privacy due to high angler-days.

Research studies on Rich Creek and modifications of OEP for application to Rich Creek should center on three key relationships. First a clear definition of the effect of the people who have access to Rich Creek is needed. Human population size significantly alters both utility and angler-days. Also the parameters for the equation which predicts angling pressure are in need of improvement. These parameters can be provided by creel census information. A regime of monitoring angler utility would be useful, so that the utility function reflects more anglers' attitudes and so that changes in preferences could be discovered.

The second key relationship is water temperature function's role as "driver" of the OEP program. Errors in temperature prediction can cause significant changes in utility and diversity. A more elaborate temperature function, fit to historical data of the area should limit some of the resulting variability.

The third key relationship deals with trout biomass. Those factors of the queueing subroutine which deal with trout, such as bait preference, searching speed, metabolism, and service rates are especially important. The same factors for the other species are not as important in terms of the objectives of utility maximization and number of angler-days maximization. Therefore, further data acquisition should focus on the trout species rather than the other recreational species.

SUMMARY AND CONCLUSIONS

Techniques have been developed by which optimal decision policies may be derived for regulating the exploitation and use of an aquatic ecosystem. Optimal Ecosystem Policies (OEP) is a complete system of definition of objectives, ecosystem description, ecosystem optimization, and ecosystem sensitivity analysis designed to produce the optimal time sequence of decisions given an existing information base similar to that available to a state fish and game agency. To achieve these design criteria, parameters of ecological interactions are expressed in OEP in a probability scale. With a probability scale, a decision-maker may use his intuition to make subjective probability estimates of subjective probability distribution estimates.

OEP employs a theoretical model of ecosystem interaction in which the ecological processes are time and density dependent and priorities are placed on each action. Such a model may be depicted as a queueing system with a preemptive priority service discipline.

The objective function was developed to include aspects of benefits to recreational and commercial users of ecosystems, indices of ecosystem stability, and indices of the volume of use by recreational exploiters. This objective was coupled with a budget constraint and constraints on minimum commercial exploitation and minimum diversity. The criterion developed to describe recreational benefits was a multiattribute utility function. Using the Keeney method, the importance of each attribute (that is, the scaling factors) may be determined in a rational manner which is consistent with the decision-maker's perception of preferences. Potentially the Keeney utility model can be used for heirarchies of objectives in which multiattribute utility functions are the attributes for higher level utility functions.

Ecosystem optimization was achieved by RAMP search (search by Regression and Application of the Maximum Principle) in which results of simulation experiments were fit to mathematical equations. Then a numerical optimum was found for the system of equations by employing a policy improvement algorithm derived from the discrete maximum principle. The policy was then an input into the simulation for further experimentation.

Sensitivity information of several different types was used to judge the effects of random or nonrandom alteration of key variables upon the objective function. This information can be used to understand intricacies of the decision policy, to refine OEP for application to a specific case study, and to plan data acquisition so that information is produced which describes the portions of the system which are most sensitive to perturbation.

The OEP program is user-oriented, but for application to ecosystems other than the case study, some degree of user-intervention is required. Future modifications might be directed toward fully automating the selection of state and decision variables to be included in the simulation, but it is suspected that the modifications will never achieve a closed loop. A completely automated program may be undesirable, especially when one is dealing with complex and rather subjectively designed simulations.

The possible benefits to be derived from an applied research program are fourfold: (1) results are produced which are directly applicable to a case study; (2) a methodology is developed or refined which can be used to solve similar problems; (3) in order to obtain applied solutions, a theory is described which organizes existing knowledge into a logical framework and from that framework interesting properties are discovered; and (4) results show needs for future research both for the particular case study and for scientific development in general. The research reported herein has attained each of these benefits (1) by applying OEP to Rich Creek; (2) by developing RAMP search and refining the multiattribute utility function for use in fisheries; (3) by describing the priority queueing system; and (4) by sensitivity analysis, thereby accomplishing the objectives of the research.

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Appendix I. Parameters values, method of estimation, source of data, species from which parameters were estimated, and interpretation of the parameters for ecosystem dynamics subroutines.

Appendix I. Parameter values, method of estimation, source of data, species from which parameters were estimated and interpretation of the parameters for ecosystem dynamics subroutines.

Parameter	Species	Value	Estimation Method	Data Source	Interpretation
PRP_1	NA[a]	4000E-03[b]*	Subj[c]	Brandt and Schreck (1975)	Minimum mean monthly temperature in ^oC
PRP_2	NA	1800E-02*	Subj	Brandt and Schreck (1975)	$PRP_1 + PRP_2$ is the maximum mean monthly temperature
PRP_3	NA	1900E-04*	Subj	Brandt and Schreck (1975)	Temperature time variance parameter
PRP_4	NA	1000E-02*	Subj	-	Minimum density (No./m^2) of POM
PRP_5	NA	7000E-02*	Subj	-	$PRP_4 + PRP_5$ is the maximum POM density
PRP_6	NA	4000E-05*	Subj	-	Spring time variance parameter
PRP_7	NA	4000E-05*	Subj	-	Autumn time variance parameter
PRP_8	NA	5000E-03*	Subj	-	Minimum density (No./m^2) of MACROINV

[a] Not applicable

[b] 4000E-03 = 4000×10^{-3}

[c] Subjective estimation

* Default value for OEP computer program

Appendix I. (continued)

Parameter	Species	Value	Estimation Method	Data Source	Interpretation
PRP_9	NA	1500E-02*	Subj	-	$PRP_8 + PRP_9$ is the maximum MACROINV density
PRP_{10}	NA	1700E-02*	Subj	-	MACROINV time variance parameter
PRP_{11}	NA	5000E-03	Subj	-	Standard deviation of POM
PRP_{12}	NA	2500E-03	Subj	-	Standard deviation of MACROINV
PRP_{16}	NA	3000E-03	Subj	Brandt and Schreck (1975)	Standard deviation of temperature
FP_1	NA	1000E 01*	Subj	-	Maximum eggs per female
FP_2	NA	4600E-06*	Subj	-	Size rate constant
FP_3	NA	1800E-02*	Subj	-	Optimal spawning temperature
FP_4	NA	8000E-06*	Subj	-	Temperature variance constant
SP_1	Bluegill	6867E-08*	NLR[f]	Wohlschlag and Juliano (1959)	Swimming rate constant
SP_2	Bluegill	3595E-01*	NLR	Wohlschlag and Juliano (1959)	Temperature constant

[f] Nonlinear regression using Marquardt's algorithm (1963)

Appendix I. (continued)

Parameter	Species	Value	Estimation Method	Data Source	Interpretation
SP_3	Bluegill	7299E-04*	NLR	Wohlschlag and Juliano (1959)	Weight exponent
SP_4	Bluegill	3911E-01*	NLR	Wohlschlag and Juliano (1959)	Denominator coefficient
SP_5	Bluegill	1714E-01*	NLR	Wohlschlag and Juliano (1959)	Temperature constant
SP_6	Bluegill	9340E-05	NLR	Wohlschlag and Juliano (1959)	Standard deviation
GP_1	White sucker	5910E-04*	NLR	Beamish (1964)	Metabolic rate
GP_2	White sucker	2526E-01*	NLR	Beamish (1964)	Temperature constant
GP_3	White sucker	8140E-04*	NLR	Beamish (1964)	Weight exponent
GP_4	White sucker	4900E-01*	NLR	Beamish (1964)	Denominator coefficient
GP_5	White sucker	1553E-01*	NLR	Beamish (1964)	Temperature constant
GP_6	Bluegill	9500E-03*	Subj	Pierce and Wissing (1974)	Active metabolism conversion
GP_7	NA	1750E-02	Subj	-	Standard deviation
GP_1	Bluegill	5688E-04	NLR	Pierce and Wissing (1974)	-

Appendix I. (continued)

Parameter	Species	Value	Estimation Method	Data Source	Interpretation
GP_2	Bluegill	3038E-01	NLR	Pierce and Wissing (1974)	-
GP_3	Bluegill	8113E-04	NLR	Pierce and Wissing (1974)	-
GP_4	Bluegill	4760E-01	NLR	Pierce and Wissing (1974)	-
GP_5	Bluegill	9902E-02	NLR	Pierce and Wissing (1974)	-
GP_1	Brook trout	3486E-04	NLR	Beamish (1964)	-
GP_2	Brook trout	9454E-02	NLR	Beamish (1964)	-
GP_3	Brook trout	8874E-04	NLR	Beamish (1964)	-
GP_4	Brook trout	4903E-01	NLR	Beamish (1964)	-
GP_5	Brook trout	2067E-01	NLR	Beamish (1964)	-
GP_1	Carp	3988E-04	NLR	Beamish (1964)	-
GP_2	Carp	2666E-01	NLR	Beamish (1964)	-
GP_3	Carp	7972E-04	NLR	Beamish (1964)	-
GP_4	Carp	4686E-01	NLR	Beamish (1964)	-
GP_5	Carp	1433E-01	NLR	Beamish (1964)	-

Appendix I. (continued)

Parameter	Species	Value	Estimation Method	Data Source	Interpretation
GP_1	Goldfish	7940E-04	NLR	Beamish and Mookherjii (1964)	-
GP_2	Goldfish	2519E-01	NLR	Beamish and Mookherjii (1964)	-
GP_3	Goldfish	7980E-04	NLR	Beamish and Mookherjii (1964)	-
GP_4	Goldfish	4903E-01	NLR	Beamish and Mookherjii (1964)	-
GP_5	Goldfish	1551E-01	NLR	Beamish and Mookherjii (1964)	-

Appendix II. Data used to fit the angling pressure prediction function.

Appendix II. Data used to fit the angling pressure prediction function

Time of Year (0=Jan 1, 1=Dec 31)	Temperature (degrees C)	Number Consecutive Days of No Fishing	Catch-per-Angler-Day	Angler Density (No./m^2/day)
0.23	6.5	38	1.53	964E-06[a]
0.25	8.6	0	0.48	273E-06
0.27	10.2	0	0.09	125E-06
0.29	11.3	0	0.83	367E-06
0.31	13.9	0	1.12	599E-06
0.33	15.6	0	0.42	413E-07
0.35	21.2	0	0.05	238E-06
0.37	18.5	0	1.59	884E-06
0.39	19.4	0	0.13	780E-07
0.41	20.5	0	0.11	147E-07
0.43	22.3	0	0.00	167E-07
0.46	21.7	0	1.95	651E-06
0.48	21.6	0	0.23	147E-07
0.50	23.2	0	0.00	000E 00
0.52	21.5	0	0.00	000E 00

[a] 964E-06 = 964×10^{-6}

Appendix III. Parameter values, data source, method of estimation, and interpretation of fishing parameters.

Appendix III. Parameter values, data source, method of estimation and interpretation of fishing parameters

Parameter	Value	Estimation Method	Data Source	Interpretation
AP_1	2315E-01*[a]	NLR[b]	Appendix II	Time-variance of parameter
AP_2	4834E-04*	NLR	Appendix II	Optimal time of year for angling
AP_3	1313E-06*	NLR	Appendix II	Temperature variance parameter
AP_4	1952E-02*	NLR	Appendix II	Optimal temperature for angling
AP_5	3530E-04*	NLR	Appendix II	Maximum proportion of population fishing on opening day
AP_6	9423E-04*	NLR	Appendix II	Rate constant for anticipation variable
AP_7	5553E-04*	NLR	Appendix II	Proportion of population fishing after a day with maximum catch-per-unit-effort
AP_8	1119E-03*	NLR	Appendix II	Rate constant for catch-per-unit-effort variable
AP_9	1120E-05	NLR	Appendix II	Standard deviation of angler density

* Default values in OEP computer program

[a] 2315E-01 = 2315×10^{-1}

[b] Nonlinear regression using Marquardt's algorithm (1963)

Appendix III. (continued)

Parameter	Value	Estimation Method	Data Source	Interpretation
CP_1	3600E-07*	Subj[c]	Brandt and Schreck (1975)	Exponential rate constant for mesh size
CP_2	2000E-02	Subj	Brandt and Schreck (1975)	Conversion factor between fish weight and optimal mesh size
CP_3	1250E-04*	Subj	Brandt and Schreck (1975)	Proportion of fish caught when mesh size is optimal
CP_4	5000E-04*	Subj	Brandt and Schreck (1975)	Maximum proportion of fish caught by seine
CP_5	6200E-04*	Subj	-	Probability of not escaping angler or seiner given fish has been hooked or enclosed by seine
CP_6	2080E-04*	Subj	-	Probability of not escaping trap, given fish has entered trap
CP_7	6900E-06*	Subj	-	Average speed (m/sec) that an angler moves in a day of fishing
CP_8	6000E-05*	Subj	-	Average speed (m/sec) that a seine is moved in a day of seining

[c] Subjective estimation

Appendix IV. Utility function questionnaire as presented to licensed anglers of Monore County, West Virginia.

ANGLER SURVEY

In the following questions I am asking you to tell me when you are "indifferent" to two situations. By "indifferent" I mean you do not care which situation that occurs, <u>either one is fine with you</u>. The following example will explain further.

EXAMPLE

Fill in the blank with a number (the number of fish) that will make you

<u>indifferent</u> to the two situations

```
          Situation 1                                      Situation 2
*****************************                  *****************************
*  Fish at a place where    *                  *  Fish at a place where    *
*  you will catch ______    *                  *  there is a 50% chance of *
*  trout for certain        ************************  catching 30 trout and a   *
*                           *                  *  50% chance of catching   *
*                           *                  *  no trout                 *
*****************************                  *****************************
```

I will fill in the blank with "20." See below:

```
*****************************                  *****************************
*                           *                  *  Fish at a place where    *
*  Fish at a place where    *                  *  there is a 50% chance of *
*  you will catch __20__    *                  *  catching 30 trout and a  *
*  trout for certain        *                  *  50% chance of catching   *
*                           *                  *  no trout                 *
*****************************                  *****************************
```

By putting "20" in the blank, I have said that I do not care shether I get 20 trout for certain or a 50-50 chance of 30 trout or no trout.

Note that if I were offered 21 trout for certain or the 50-50 chance of 30 or no trout, then I would prefer 21 trout.

But, if I were offered 19 trout for certain or the 50-50 chance of 30 or no trout, then I would prefer the 50-50 chance.

Please fill in the blanks of the following questions in the same manner as that above. Remember to read each question carefully.

You may now begin

The following question is designed to measure how important the length of the fish is to you. Fill in the blank with a number (the number of inches of fish) that would make you indifferent to the two situations.

Situation 1	Situation 2
Fish at a place where the average length of trout that you catch will be _____ inches for certain.	Fish at a place where there is a 50% chance that the average length of trout that you catch will be 14 inches and a 50% chance that the average length of trout will be 8 inches.

The following question is designed to measure the importance of the number of fish that you catch. Fill in the blank with a number (the number of fish) that will make you indifferent to the two situations.

Situation 1	Situation 2
Fish at a place where you will catch ______ bluegill for certain.	Fish at a place where there is a 50% chance of catching 30 bluegill and a 50% chance of catching no bluegill.

The following question is designed to measure the importance of privacy to you. Fill in the blank with a number (the number of fishermen) that will make you indifferent to the two situations.

Situation 1	Situation 2
Fish at a place where there will be ______ other fishermen within a 50 yard radius of you for certain.	Fish at a place where there is a 50% chance of there being 50 other fishermen within a 50 yard radius of you and a 50% chance of there being no other fishermen within a 50 yard radius of you.

ANGLER SURVEY

In the following questions I am asking you to tell me when you are "indifferent" to two situations. By "indifferent," I mean you do not care which situation that occurs, either one is fine with you.

Also, I use the term "% chance" of some event occurring. By saying some event has a "20% chance" or occurring, I mean that this event will occur 20 times out of 100. If there is also an "80% chance" of some other event occurring, then these two events are the only possible ones to occur (20% + 80% = 100%, where 100% means all possibilities). The following example will explain further.

Example

Fill in the blanks with the two percents (%) that will make you <u>indifferent</u> to the two situations. Remember, the two percents must add to 100.

Situation 1	Situation 2
Fish at a place where you will catch 20 bluegill, for certain.	Fish at a place where there is a ____% chance of catching 30 bluegill and a ____% chance of catching 0 bluegill.

I will fill in the blanks with 45% and 55%. See below:

Situation 1	Situation 2
Fish at a place where you will catch 20 bluegill for certain.	Fish at a place where there is a <u>45</u> % chance of catching 30 bluegill and a <u>55</u> % chance of catching 0 bluegill.

By putting 45% and 55% in the blanks (note 45% + 55% = 100%), I have said that I do not care whether I get 20 bluegill for certain or the 45-55% chance of getting 30 or 0 bluegill.

Note that if the chances offered were 44$ chance of 30 bluegill and 56% chance of 0 bluegill, then I would prefer 20 bluegill for certain. If I were offered a 46% chance of 30 bluegill and a 54% chance of 0 bluegill, then I would prefer to take the chance rather than take 20 for certain.

Please fill in the blanks in the following questions in the same manner as that above. Remember to read the questions carefully and also remember the two percents must add up to 100.

You may now begin

The following question is designed to measure how important catching trout is to you. Fill in the blanks with the two percents that will make you indifferent to the two situations. Remember, the two percents must add up to 100.

Situation 1	Situation 2
Fish at a place where you will catch one trout 8 inches long and there will be 50 other fishermen within a 50 yard radius of you. All of this will occur for certain.	Fish at a place where there is a ____% chance of catching 20 trout with an average length of 14 inches and of there being no other fishermen within a 50 yard radius of you. There is a ____% chance of catching one bluegill which will be 6 inches long and of there being 50 other fishermen within a 50 yard radius of you.

The following question is designed to measure how important privacy in fishing is to you. Fill in the blanks with the two percents that will make you indifferent to the two situations. Remember, the two percents must add up to 100.

Situation 1	Situation 2
Fish at a place where there are no other fishermen within a 50 yard radius of you and you will catch 1 bluegill which is 6 inches long. All of this will occur for certain.	Fish at a place where there is a ____% chance of catching 20 trout with an average length of 14 inches and of there being no other fishermen within a 50 yard radius of you. There is a ____% chance of catching one bluegill which will be 6 inches long and of there being 50 other fishermen within a 50 yard radius of you.

The following question is designed to measure the importance of the size of fish that you catch. Fill in the blanks with the two percents that make you indifferent to the two situations. Remember the two percents must add up to 100.

Situation 1	Situation 2
Fish at a place where you will catch 1 12 inch bluegill and there will be 50 other fishermen within q 50 yard radius of you. All of this will occur for certain.	Fish at a place where ther is a ____% chance of catching 20 trout with an average length of 14 inches and of there being no other fishermen within a 50 yard radius of you. There is a ____% chance of catching one bluegill which will be 6 inches long and of there being 50 other fishermen within a 50 yard radius of you.

The following question is designed to measure the importance of the number of fish that <u>you</u> catch. Fill in the blanks with the two percents that will make you indifferent to the two situations. Remember the two percents must add up to 100.

Situation 1	Situation 2
Fish at a place where there will be 50 other fishermen within 50 yards of you and you will catch 30 bluegill of average length 6 inches. All of this will occur for certain.	Fish at a place where there is a ____% chance of catching 20 trout with an average length of 14 inches and of there being no other fishermen within a 50 yard radius of you. There is a ____% chance of catching one bluegill which will be 6 inches long and of there being 50 other fishermen within a 50 yard radius of you.

Appendix V. Determining the scaling factors k_i and K for the multi-attribute utility function.

First, remember that if a respondent is indifferent to x for certain, and a lottery of x' with a probability p and x" with a probability 1-p, then

$$u(x) = p[u(x')] + (1-p)[u(x'')]. \tag{A-1}$$

The values of k_i (i=1,2,3,4) and K were found from the following four questions [remembering $\underline{x}_1 = (x_1^{TR}, x_1^{SMB}, x_1^{BG})$]:

1. Find p_1 such that the respondent was indifferent to $[x_1=(1,0,0), x_{1-}^o]$ for certain, or a lottery offering $[x_1=(1,0,0), x_{1-}^*]$ with a probability p_1 and $[x_1=(0,0,1), x_{1-}^o]$ with a probability $1-p_1$.
2. Find p_2 such that the respondent was indifferent to $[x_1=(0,0,1), x_2^*, x_{34}^o]$ for certain, or a lottery offering $[x_1=(1,0,0), x_{1-}^*]$ with a probability p_2 and $[x_1=(0,0,1), x_{1-}^o]$ with a probability $1-p_2$.
3. Find p_3 such that the respondent was indifferent to $[x_1=(0,0,1), x_3^*, x_{24}^o]$ for certain, or a lottery offering $[x_1=(1,0,0), x_{1-}^*]$ with a probability p_3 and $[x_1=(0,0,1), x_{1-}^o]$ with a probability $1-p_3$.
4. Find p_4 such that the respondent was indifferent to $[x_1=(0,0,1), x_4^*, x_{23}^o]$ for certain, or a lottery offering $[x_1=(1,0,0), x_{1-}^*]$ with a probability p_4 and $[x_1=(0,0,1), x_{1-}^o]$ with a probability $1-p_4$.

From the first question and using (A-1), we obtain:

$$u[x_1=(1,0,0),\ x^o_{1-}] = p_1(1 + Kk_1c_{TR})(1 + Kk_2)(1 + Kk_3)$$
$$(1 + Kk_4) + (1 - p_1)(1 + Kk_1c_{BG}) \qquad \text{(A-2)}$$

From equation (2.2) in the body of the dissertation, it can be stated that

$$1 + Ku[x_1=(1,0,0),\ x^o_{1-}] = 1 + Kk_1c_{TR}$$

or

$$u[x_1=(1,0,0),\ x^o_{1-}] = k_1c_{TR} \qquad \text{(A-3)}$$

(A-3) is another expression for u and when (A-3) and (A-2) are equated, we get:

$$k_1c_{TR} = p_1(1+Kk_1c_{TR})(1+Kk_2)(1+Kk_3)(1+Kk_4) + (1-p_1)(1+Kk_1c_{BG}) \qquad \text{(A-4)}$$

Similarly, responses to question 2, 3, and 4 in the scaling factor evaluation section produce probabilities p_2, p_3, and p_4; therefore,

$$u[x_1=(0,0,1),\ x^*_i,\ x^o_{1i-}] = p_i(1+Kk_1c_{TR})(1+Kk_2)(1+Kk_3)(1+Kk_4)$$
$$+ (1-p_i)(1+Kk_1c_{BG}) \qquad \text{(A-5)}$$

for i = 2,3,4. To express u in another form, we know from (2.2) that

$$1 + Ku[x_1=(0,0,1),\ x^*_i,\ x^o_{1i-}] = (1 + Kk_1c_{BG})(1 + Kk_i)$$

or

$$u[x_1=(0,0,1),\ x_i^*,\ x_{1i-}^o] = k_1 c_{BG} + k_i + k_1 k_i c_{BG} K \tag{A-6}$$

for i = 2,3,4. Equating (A-5 and (A-6) gives

$$k_1 c_{BG} + k_i + k_1 k_i c_{BG} K = p_i (1+Kk_1 c_{TR})(1+Kk_2)(1+Kk_3)(1+Kk_4) + (1-p_i)(1+Kk_1 c_{BG}) \tag{A-7}$$

for i = 2,3,4. We also know from (2.2) that

$$1 + K = (1+Kk_1)(1+Kk_2)(1+Kk_3)(1+Kk_4) \tag{A-8}$$

Equations (A-4), (A-7), and (A-8) are five equations in the five unknowns k_i (i=1,2,3,4) and K. These may be solved by an appropriate numerical technique, such as fixed point iteration (Conte 1965: 43). This does not guarantee a unique solution. However, in practice several choices of the initial k_i and K in the solution technique produced the same solution. Also, the bounds on k_i and K are rather closely defined ($0<k_i<1$, $-1<K$). Therefore, with some justification it was assumed that the solution obtained was unique.

Appendix VI. Computer program listing for OEP written in FORTRAN.

```
C      OPTIMAL ECOSYSTEM POLICIES (OEP), A PROGRAM DESIGNED TO FIND THE DECISION
C      POLICIES WHICH WILL MAXIMIZE A SPECIFIED OBJECTIVE FUNCTION FOR AN
C      AQUATIC ECOSYSTEM.......JOSEPH E. POWERS, DEPARTMENT OF FISHERIES AND
C      WILDLIFE SCIENCES, VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY,
C      BLACKSBURG, VIRGINIA 24061......JUNE, 1975.
C
C      MAIN PROGRAM FOR READING PROGRAM PARAMETERS
C
C      NTRY                  NUMBER OF OEP PROGRAMS TO BE RUN
C      TITLE                 TITLE TO BE PRINTED AT TOP OF OUTPUT PAGE
C      PROP1                 COEFFICIENT OF UTILITY IN THE LINEAR SUM OBJECTIVE
C      PROP2                 COEFFICIENT OF COM CATCH IN THE LINEAR SUM OBJECTIVE
C      PROP3                 COEFFICIENT OF DIVERSITY IN THE LINEAR SUM OBJECTIVE
C      PROP4                 COEFFICIENT OF ANGLER-DAYS IN THE LINEAR SUM OBJECTIVE
C      IX                    INITIAL RANDOM NUMBER SEED (5-DIGIT ODD)
C      ND                    NUMBER OF SIMULATION DATA SETS
C      NRAND                 MONTE CARLO SIMULATIONS? 1=YES; 0=NO
C      NSTAGE                NUMBER OF TIME STAGES
C      MAXIT                 MAXIMUM NUMBER OF ITERATIONS FOR OUTER LOOP
C      MNEWT                 MAXIMUM NUMBER OF ITERATIONS IN NEWTON-RAPHSON
C                            PROCEDURE USED IN MEETING TERMINAL CONSTRAINTS
C      MGRAD                 MAXIMIM NUMBER OF ITERATIONS IN THE POLICY IMPROVEMENT
C                            ALGORITHM USING THE DISCRETE MAXIMUM PRINCIPLE
C      IOUT                  OUTER LOOP ITERATIONS FOR WHICH OUTPUT WILL BE PRINTED,
C                            1=PRINT,  0=NO PRINT
C      NOPT                  IS THIS OEP PROGRAM OPTIMIZATION (NOPT=0) OR A
C                            SIMPLE SIMULATION (NOPT=1)?
C      NOUT                  TIME STAGES FOR WHICH RESULTS ARE PRINTED FOR NOPT=1,
C                            (0=PRINT, 1=NO PRINT)
C      DELTA                 CONVERGENCE CRITERION FOR OUTER LOOP
C      DNEWT                 CONVERGENCE CRITERION FOR NEWTON-RAPHSON PROCEDURE
C      DGRAD                 CONVERGENCE CRITERION FOR POLICY IMPROVEMENT ALGORITHM
```

```
C      DMAX                        MAXIMUM VALUE WHICH DECISION VARIABLE MAY ATTAIN
C      SMAX                        MAXIMUM VALUE WHICH STATE VARIABLE MAY ATTAIN
C      INM                         MAXIMUM NUMBER OF REDUCTIONS IN STEP-SIZE ALLOWED
C
       COMMON/APOP/PROP1,PROP2,PROP3,PROP4
       COMMON/BEST/DECIS(5,24,13),ND,STATES(5,25,11)
       COMMON/ATT/NRAND,IX,INM
       COMMON/MAB/ NOUT(24)
       COMMON/ABDF/NSTAGE
       COMMON/ALL/THETA(24,13)
       COMMON/MMOF/MAXIT,MNEWT,DNEWT,DELTA,DGRAD,MGRAD
       COMMON/MM/DMAX(13),SMAX(11),NOPT,IOUT(80),IT
       DIMENSION TITLE(20)
       READ(5,1) NTRY
C      DO FOR ALL OEP PROGRAM DATA SETS
       DO 100 ITRY=1,NTRY
       READ(5,30) TITLE
       READ(5,20)  PROP1,PROP2,PROP3,PROP4
   30  FORMAT(20A4)
       WRITE(6,35) TITLE
       WRITE(6,102)PROP1,PROP2,PROP3,PROP4
  102  FORMAT(1X,8HPROP1 = ,E15.7,5X,8HPROP2 = ,E15.7,5X,8HPROP3 = ,E15.7
      1,5X,8HPROP4 = ,E15.7)
   35  FORMAT(1H1,20A4)
       READ(5,6) IX,ND,NRAND
       READ(5,5) NSTAGE
       READ(5,5) MAXIT,MNEWT,MGRAD
       READ(5,1) (IOUT(I),I=1,MAXIT)
       READ(5,1) NOPT
       READ(5,1) (NOUT(I),I=1,NSTAGE)
    1  FORMAT(80I1)
    5  FORMAT(20I4)
```

```
      READ(5,20) DELTA,DNEWT,DGRAD
   20 FORMAT(10E8.0)
      READ(5,20) DMAX
      READ(5,20) SMAX
    6 FORMAT(16I5)
      READ(5,6) INM
      CALL MJOB
  100 CONTINUE
      STOP
      END
```

```
      FUNCTION RANDU(IX)
C     RANDOM NUMBER GENERATOR
      IY=IX*65539
      IF(IY) 5,6,6
    5 IY=IY+2147483647+1
    6 YFL=IY
      RANDU=YFL*.4656613E-9
      IX=IY
      RETURN
      END
```

```
      FUNCTION RNORM(STD,IX,NBOUND,XMEAN)
C     RANDOM VARIABLE GENERATOR (NORMAL RANDOM VARIABLE)
      RNORM=0.
      IF(XMEAN.EQ.0.0.AND.NBOUND.EQ.0) RETURN
      R=RANDU(IX)
      B=((R-0.5)/ABS(R-0.5))*STD
      V=SQRT(-2.*ALOG((1.-ABS(1.-2.*R))*0.5))
      A=2.515517+(0.802853*V)+(0.01328*V*V)
      D=1.+(1.432788*V)+(0.189269*V*V)+(0.001308*V*V*V)
      RNORM=XMEAN+B*(V-(A/D))
      IF(NBOUND.EQ.0.AND.RNORM.LT.0.0) RNORM=0.
      RETURN
      END
```

```
      SUBROUTINE MJOB
C     DRIVING ROUTINE FOR READING SIMULATION PARAMETERS, INITIALIZING VARIABLES,
C     AND RUNNING THE RAMP SEARCH PROCEDURE
C
C     VARIABLES MARKED WITH * HAVE DEFAULT VALUES BUILT INTO THE OEP PROGRAM
C
C     NSPEC                NUMBER OF SPECIES IN THE ECOSYSTEM
C     NPRIOR*              NUMBER OF PRIORITIES IN THE QUEUEING PROCESS, DEFAULT=6
C     NPHAGE*              LOWEST SPECIES NUMBER THAT IS ACTIVELY DEPICTED
C                          IN THE QUEUEING PROCESS, DEFAULT=2
C     NSPWN*               PRIORITY NUMBER FOR ACT OF SPAWNING, DEFAULT=3
C     NPRD*                PRIORITY NUMBER FOR ACT OF FEEDING, DEFAULT=5
C     NANG*                NUMBER OF DIFFERENT FISHERMEN TYPES, DEFAULT=5
C     MAXAGE               NUMBER OF AGE-CLASSES PER EACH SPECIES
C     N1HEAD               TITLES FOR SPECIES NOT ACTIVELY FEEDING IN QUEUEING
C                          PROCESS
C     NHEAD                TITLES FOR ACTIVELY FEEDING SPECIES IN QUEUEING PROCESS
C     AHEAD                TITLES FOR THE NANG FISHERMEN TYPES
C     UPS*                 COEFFICIENT FOR MAXIMUM RATION FUNCTION (SPECIES
C                          DEPENDENT)
C     EPS*                 EXPONENT FOR MAXIMUM RATION FUNCTION (SPECIES
C                          DEPENDENT)
C     SCALE(I,1,1)         MAXIMUM NUMBER OF SPECIES "I+1" THAT CAN BE CAUGHT
C     SCALE(I,2,1)         MAXIMUM RANGE OF NUMBERS OF SPECIES "I+1" THAT CAN
C                          BE CAUGHT
C     SCALE(I,1,2)         MAXIMUM SIZE (GRAMS) OF AN INDIVIDUAL OF SPECIES "I+1"
C                          THAT CAN BE CAUGHT
C     SCALE(I,2,2)         MAXIMUM SIZE RANGE (GRAMS) OF AN INDIVIDUAL OF SPECIES
C                          "I+1" THAT CAN BE CAUGHT
C                            . THE SCALE VARIABLE IS USED TO CALCULATE THE
C                              ATTRIBUTES FOR THE UTILITY FUNCTION
C     BSPWN*               TIME (SEC) FOR THE ACT OF SPAWNING (SPECIES DEPENDENT)
```

```
C       DAYS*                    NUMBER OF DAYS PER TIME STAGE
C       POP                      HUMAN POPULATION SIZE
C       AREA                     AREA OF THE ECOSYSTEM IN METERS SQUARED
C       PHOOK                    PROBABILITY A FISH IS HOOKED GIVEN IT STRIKES THE HOOK
C       PCAPT                    PROBABILITY THAT A FISH IS CAPTURED GIVEN IT IS HOOKED
C       PCOV                     PROPORTION OF THE AREA WHICH PROVIDES COVER
C       CP*                      CATCH EQUATIONS PARAMETERS
C       SERVE*                   SERVICE RATE (NO/SEC) FOR NON-SPAWNING PRIORITIES
C       PRP*                     PRODUCTION FUNCTIONS AND TEMPERATURE PARAMETERS
C       SPHERE*                  AREA (METERS SQ) IN WHICH AN ANIMAL CAN PERCEIVE ALL
C                                THAT OCCURS
C       AP*                      ANGLER DENSITY FUNCTION PARAMETERS
C       PLIC                     PROPORTION OF HUMAN POPULATION WHO HAVE FISHING LICENSE
C       PFISH(I)                 PROPORTION OF HUMAN POPULATION WHO WILL EVER BE ONE
C                                OF THE "ITH" TYPE OF FISHERMEN, I=1,2,...,NANG
C       NPOP(I,J)                INITIAL POPULATION DENSITY (NO/METER SQ) OF SPECIES I,
C                                AGE-CLASS J
C       WPOP(I,J)                INITIAL AVERAGE WEIGHT PER INDIVIDUAL (GRAMS) FOR
C                                SPECIES I, AGE-CLASS J
C       PREF(I,J)                PREFERENCE PROBABILITY THAT SPECIES I HAS FOR THE GEAR
C                                (BAIT,LURE, ETC.) OF ANGLER-TYPE J
C       GP(I,J)*                 GROWTH FUNCTION PARAMETERS FOR SPECIES I,
C                                I=NPHAGE, NPHAGE+1,...,NSPEC
C       SP(I,J)*                 CRUISING SPEED FUNCTION PARAMETERS FOR SPECIES I,
C                                I=NPHAGE, NPHAGE+1,...,NSPEC
C       FP(I,J)*                 FECUNDITY FUNCTION PARAMETERS FOR SPECIES I,
C                                I=NPHAGE,NPHAGE+1,...,NSPEC
C       PAGR(I,J)                AGGREGATION INDEX FOR SPECIES I, AGE-CLASS J
C       PPRED(I,J,K,L)           PREDATION PREFERENCE PROBABILITY THAT A MEMBER OF
C                                SPECIES I, AGE-CLASS J HAS FOR A MEMBER OF SPECIES
C                                K, AGE-CLASSL
C       NOOM(I,K)                DOES SPECIES I SHOW AGGRESIVE BEHAVIOR TOWARDS SPECIES
```

```
C                             K?  1=YES, 0=NO
C      PSPWN(I,N)             PROPORTION OF SPECIES I WHICH SPAWN DURING "NTH"
C                             MONTH OF THE YEAR
C      EGGWT                  WEIGHT (GRAMS) OF A FERTILIZED EGG (SPECIES DEPENDENT)
C      PSPGR                  PROPORTION OF AREA THAT IS USABLE FOR SPAWNING GROUND
C                             (SPECIES DEPENDENT)
C      UP                     UTILITY FUNCTION PARAMETERS:
C                                1+UP(3)*UTILITY=PRODUCT OVER ALL ATTRIBUTES OF
C                                 (1+UP(8)*UP(I)*U(ATTRIBUTE))
C                                WHERE I=4,5,6,7
C                                U(ATTRIBUTE J+1)=ATTRIBUTE**UP(J),   J=1,2,3
C                                U(ATTRIBUTE 1) CALCULATED AS BELOW
C      UC                     UTILITY FUNCTION PARAMETERS FOR SPECIES ATTRIBUTE:
C                                1+UC(4)*UTILITY=PRODUCT OVER ALL SPECIES OF
C                                   (1+UC(4)*UC(I)*U(SPECIES))
C                                 WHERE I=1,2,3 CORRESPONDS TO SPECIES 2,3,4, RESP.
C      PER                    NUMBER OF CATCHABLE TROUT PER GRAM
C      COST                   COST PER GRAM OF TROUT DELIVERED (DOLLARS)
C      THETA(I,J)             DECISION ACTIVITY J AT TIME I; THETA IS NOT READ IF
C                             NOPT=0
C      BDG                    MAXIMUM YEARLY BUDGET EXPENDITURES IN DOLLARS
C      WELF                   MINIMUM CUMULATIVE SUM OF COMMERCIAL CATCH PER SEINE-DA
C      WELF                   MINIMUM CUMULATIVE SUM OF COMMERCIAL CATCH PER
C                             SEINE-DAY ALLOWED
C      DV                     MINIMUM YEAREND VALUE OF DIVERSITY ALLOWED
C      STATES(I,J,K)          STATE VARIABLE K AT TIME STAGE J FOR THE "ITH"
C                             SIMULATION DATA SET
C      DECIS(I,J,K)           DECISION ACTIVITY K AT TIME STAGE J FOR THE "ITH"
C                             SIMULATION DATA SET
C      S(I,J)                 STATE VARIABLE J AT TIME STAGE I FOR THE NEW
C                             SIMULATION DATA SET
C      DEC(I,J)               DECISION ACTIVITY J AT TIME STAGE I FOR THE NEW
```

```
C                              SIMULATION DATA SET
C       SLACK                  SLACK VARIABLES, I.E., THE DIFFERENCE BETWEEN THE CON-
C                              STRAINT AND ITS ASSOCIATED TERMINAL STATE VARIABLE
C
       COMMON/APOP/PROP1,PROP2,PROP3,PROP4
       COMMON/ATT/NRAND,IX,INM
       COMMON/BEST/DECIS(5,24,13),ND,STATES(5,25,11)
       COMMON/MM/DMAX(13),SMAX(11),NOPT,IOUT(80),IT
       COMMON/MMOF/MAXIT,MNEWT,DNEWT,DELTA,DGRAD,MGRAD
       COMMON/MCGF/DEC(24,13),B1(13),B3(17),B5(3),B6(7),B7(10),B8(10),
      1B9(12),B10(16),B11(19),Z(11),Q(11),DHT(3,4),DTT(3),SLACK(3),BP(19)
       COMMON/MAB/ NOUT(24)
       COMMON/SQ/SSCR(11),BDG,WELF,DV
       COMMON/AB/EGGWT(10),B(10,24),N1HEAD(5,2),NHEAD(10,2),AHEAD(5,2),
      1D(24),ANGLE(24),COM(24),BUDG(24),REC(24),PER
       COMMON/NBH/EPSIL
       COMMON/ABU/SCALE(3,2,2),UC(4),UP(8),UTIL(2)
       COMMON/ABR/ COST
       COMMON/ABC/PPRED(10,5,10,5),NDOM(10,10),PSPGR(10),CP(10),PHOOK,
      1NSPEC,BSPWN(10),PAGR(10,5),NPRICR,NSPWN,NPRD,MAXAGE(10),PSPWN(10,
      212),W(10,5),PREF(10,5),SERVE,SPHERE(10),DAYS,EPS(10),UPS(10),PCAPT
      3,PCCV
       COMMON/ABP/PRP(16)
       COMMON/ALL/ THETA(24,13)
       COMMON/ABH/FP(10,5)
       COMMON/ABE/SP(10,6)
       COMMON/ABCE/NPHAGE
       COMMON/ABCF/PLIC,POP,NANG
       COMMON/ABDF/NSTAGE
       COMMON/ABCD/O(10,5)
       COMMON/ABF/AP(9),AREA,PFISH(5)
       COMMON/ABG/GP(10,7)
```

```
      COMMON/MC/BEST(24,19)
      DIMENSION NPOP(10,5),WPOP(10,5)
      DOUBLE PRECISION S(25,11),LAM(25,11),Y(120),SUM
      REAL NPOP
      EPSIL=10.**(-2)
      READ(5,10) NPRIOR,NPHAGE,NSPWN,NPRD,NANG
    5 FORMAT(80I1)
      IF(NPRIOR.LE.0) NPRIOR=6
      IF(NSPWN.LE.0) NSPWN=3
      IF(NANG.LE.0) NANG=5
      IF(NPHAGE.LE.0) NPHAGE=2
      IF(NPRD.LE.0) NPRD=5
      READ(5,10) NSPEC,(MAXAGE(I),I=1,NSPEC)
      MX=MAXAGE(1)
      READ(5,15) ((N1HEAD(IN,IM),IM=1,2),IN=1,MX)
      READ(5,15) ((NHEAD(I,IN),IN=1,2),I=2,NSPEC)
      READ(5,15) ((AHEAD(I,J),J=1,2),I=1,NANG)
      DO 9 J=1,3
    9 READ(5,21) ((SCALE(J,I,K),K=1,2),I=1,2)
   10 FORMAT(12I5)
   15 FORMAT(10(2A4))
      READ(5,20) (UPS(I),I=1,NSPEC)
      READ(5,20) (EPS(I),I=1,NSPEC)
      READ(5,20) (BSPWN(I),I=1,NSPEC)
      READ(5,20) DAYS
      READ(5,20) PCP,AREA
      READ(5,50) PHOCK,PCAPT,PCOV
      READ(5,20) CP
      IF(CP(1).LE.0.0) CP(1)=0.00036
      IF(CP(2).LE.0.0) CP(2)=20.
      IF(CP(3).LE.0.0) CP(3)=0.125
      IF(CP(4).LE.0.0) CP(4)=0.5
```

```
      IF(CP(5).LE.0.0) CP(5)=0.062
      IF(CP(6).LE.0.0) CP(6)=0.208
      IF(CP(7).LE.0.0) CP(7)=0.0069
      IF(CP(8).LE.0.0) CP(8)=0.06
      READ(5,20)SERVE
      READ(5,20) PRP
      IF(PRP( 1).LE.0.0) PRP(1 )=4.
      IF(PRP(2).LE.0.0) PRP(2)=18.
      IF(PRP(3).LE.0.0) PRP(3)=0.19
      IF(PRP(4).LE.0.0) PRP(4)=10.
      IF(PRP(5).LE.0.0) PRP(5)=70.
      IF(PRP(6).LE.0.0) PRP(6)=0.04
      IF(PRP(7).LE.0.0) PRP(7)=0.04
      IF(PRP(8).LE.0.0) PRP(8)=5.
      IF(PRP(9).LE.0.0) PRP(9)=15.
      IF(PRP(10).LE.0.0) PRP(10)=0.17
      IF(SERVE.LE.0.0) SERVE=0.25
      READ(5,20)(SPHERE(I),I=NPHAGE,NSPEC)
      READ(5,20) (AP(I),I=1,8)
      IF(AP(1).LE.0.0) AP(1)=231.449
      IF(AP(2).LE.0.0) AP(2)=0.483418
      IF(AP(3).LE.0.0) AP(3)=0.00131265
      IF(AP(4).LE.0.0) AP(4)=19.5152
      IF(AP(5).LE.0.0) AP(5)=0.352976
      IF(AP(6).LE.0.0) AP(6)=0.942333
      IF(AP(7).LE.0.0) AP(7)=0.555297
      IF(AP(8).LE.0.0) AP(8)=1.11918
      READ(5,50) PLIC,(PFISH(I),I=1,NANG)
      IF(DAYS.LE.0.0) DAYS=15.
   20 FORMAT(10E8.0)
   21 FORMAT(8E10.0)
      DO 30 I=1,NSPEC
```

```
      IF(UPS(I).LE.0.0) UPS(I)=0.146
      IF(EPS(I).LE.0.0) EPS(I)=0.849
      IF(BSPWN(I).LE.0.0) BSPWN(I)=300.
      IF(SPHERE(I).LE.0.0) SPHERE(I)=0.3
      MAXA=MAXAGE(I)
   25 FORMAT(5E15.0)
      READ(5,25) (NPOP(I,J),J=1,MAXA)
   30 READ(5,25) (WPOP(I,J),J=1,MAXA)
      DO 35 I=1,NSPEC
   35 READ(5,50) (PREF(I,J),J=1,NANG)
      DO 40 I=NPHAGE,NSPEC
      READ(5,21) (GP(I,J),J=1,6)
      IF(GP(I,1).LE.0.0) GP(I,1)=0.591
      IF(GP(I,2).LE.0.0) GP(I,2)=252.573
      IF(GP(I,3).LE.0.0) GP(I,3)=0.814
      IF(GP(I,4).LE.0.0) GP(I,4)=489.983
      IF(GP(I,5).LE.0.0) GP(I,5)=155.274
      IF(GP(I,6).LE.0.0) GP(I,6)=14575.6
   40 CONTINUE
      DO 42 I=NPHAGE,NSPEC
      READ(5,21)(SP(I,J),J=1,6)
      IF(SP(I,1).LE.0.0) SP(I,1)=0.0000686712
      IF(SP(I,2).LE.0.0) SP(I,2)=359.476
      IF(SP(I,3).LE.0.0) SP(I,3)=0.7299
      IF(SP(I,4).LE.0.0) SP(I,4)=391.1
      IF(SP(I,5).LE.0.0) SP(I,5)=171.4
   42 CONTINUE
      DO 44 I=NPHAGE,NSPEC
      READ(5,21)(FP(I,J),J=1,4)
      IF(FP(I,1).LE.0.0) FP(I,1)=10000.
      IF(FP(I,2).LE.0.0) FP(I,2)=0.0046
      IF(FP(I,3).LE.0.0) FP(I,3)=18.
```

```
      IF(FP(I,4).LE.0.0) FP(I,4)=0.008
   44 CONTINUE
      DO 45 I=1,NSPEC
      MAX=MAXAGE(I)
   45 READ(5,50) (PAGR(I,J),J=1,MAX)
   50 FORMAT(20F4.2)
      DO 55 I=1,NSPEC
      MAX=MAXAGE(I)
      DO 55 J=1,MAX
      O(I,J)=NPOP(I,J)
      DO 55 K=1,NSPEC
      MAXL=MAXAGE(K)
      READ(5,50) (PPRED(I,J,K,L),L=1,MAXL)
      DO 55 L=1,MAXL
      PPRED(I,J,K,L)=PPRED(I,J,K,L)*0.1
   55 CONTINUE
      DO 60 I=1,NSPEC
   60 READ(5,5) (NDOM(I,K),K=1,NSPEC)
      DO 65 I=1,NSPEC
      READ(5,50) (PSPWN(I,NT),NT=1,12)
      DO 65 J=1,12
   65 PSPWN(I,J)=PSPWN(I,J)/30.
      READ(5,20) (EGGWT(I),I=1,NSPEC)
      READ(5,50) (PSPGR(I),I=1,NSPEC)
      READ(5,20) UP
      READ(5,20) UC
      READ(5,20) PER,COST
      PROP4=PROP4/AREA
      COST=COST*AREA
      IF(NOPT.EQ.0) GO TO 68
      DO 67 I=1,NSTAGE
      READ(5,20) (THETA(I,J),J=1,13)
```

```
   67 CONTINUE
   68 CONTINUE
      READ(5,20)BDG,WELF,DV
      IF(DV.LE.0.0) DV=DIV(NSPEC,MAXAGE,AREA)
      WRITE(6,70) BDG,WELF,DV
   70 FORMAT(18H0MAXIMUM BUDGET = ,E15.7,5X,38HMINIMUM COMMERCIAL CATCH
     1PER EFFORT = ,E15.7,5X,20HMINIMUM DIVERSITY = ,E15.7)
      IF(NOPT.EQ.1) GO TO 78
      WELF=WELF*100.
      NSS=NSTAGE+1
C     ESTABLISH THE INITIAL VALUES OF THE STATE VARIABLES
      S(1,1)=0.
      S(1,2)=0.
      S(1,3)=DV
      S(1,4)=0.
      DO 71 I=2,4
      II=I+4
      S(1,II)=0.
      MAX=MAXAGE(I)
      DO 71 J=1,MAX
   71 S(1,II)=S(1,II)+WPOP(I,J)*NPOP(I,J)*10.*10.
      S(1,9)=0.
      DO 72 I=5,9
      MAX=MAXAGE(I)
      DO 72 J=1,MAX
   72 S(1,9)=S(1,9)+WPOP(I,J)*NPOP(I,J)
      S(1,9)=S(1,9)*10.*10.
      S(1,10)=EPSIL
      S(1,11)=0.
      XMAX=0.
      DM=1.
C     DO FOR ALL ND DATA SETS
```

```
      DO 92 ISEQ=1,ND
      INUM=0
   89 SUM=0.
      DO 73 I=1,NSTAGE
      IF(NOPT.EQ.0) NOUT(I)=1
      DO 73 J=1,13
C     RANDOMLY GENERATE DECISION VARIABLES
      IF(J.EQ.1.OR.J.GE.6) DECIS(ISEQ,I,J)=RANDU(IX)*DMAX(J)*DM
      IF(J.GE.2.AND.J.LE.5) DECIS(ISEQ,I,J)=RANDU(IX)*DMAX(J)
      IF(J.EQ.2) SUM=SUM+COST*DECIS(ISEQ,I,J)
      IF(SUM.GT.BDG) DECIS(ISEQ,I,J)=0.
   73 THETA(I,J)=DECIS(ISEQ,I,J)
   78 CONTINUE
      DO 80 I=1,NSPEC
      MAX=MAXAGE(I)
      DO 80 J=1,MAX
      O(I,J)=NPOP(I,J)
   80 W(I,J)=WPOP(I,J)
C     PERFORM A SIMULATION EXPERIMENT
      CALL SIM
      IF(NOPT.EQ.1) RETURN
      IF(ISEQ.EQ.1) S(1,5)=B(1,1)*100.
      DO 90 N=1,NSS
      IF(N.EQ.1) GO TO 85
      NN=N-1
C     ESTABLISH THE STATE VARIABLES
      S(N,1)=S(NN,1)+COM(NN)*10.*10.
      S(N,2)=S(NN,2)+BUDG(NN)
      S(N,3)=D(NN)
      S(N,4)=NN
      S(N,5)=B(1,NN)*10.*10.
      S(N,6)=B(2,NN)*10.*10.
```

```
      S(N,7)=B(3,NN)*10.*10.
      S(N,8)=B(4,NN)*10.*10.
      S(N,9)=B(5,NN)+B(6,NN)+B(7,NN)+B(8,NN)+B(9,NN)
      S(N,9)=S(N,9)*10.*10.
      S(N,10)=ANGLE(NN)*10.*10.+EPSIL
      S(N,11)=S(NN,11)+REC(NN)
   85 CONTINUE
      DO 90 J=1,11
C     RECORD STATE VARIABLES
   90 STATES(ISEQ,N,J)=S(N,J)
C     CALCULATE PENALIZED OBJECTIVE FUNCTION AND FIND THE MAXIMUM OF THE ND DATA
C     SETS
   91 F=STATES(ISEQ,NSS,11)
      IF(WELF.GT.STATES(ISEQ,NSS,1)) F=F-10.**(-8)
      IF(BDG.LT.STATES(ISEQ,NSS,2)) F=F-10.**(-8)
      IF(DV.GT.STATES(ISEQ,NSS,3)) F=F-10.**(-8)
C     IF TERMINAL CONSTRAINTS ARE NOT MET, ADJUST DECISIONS
      IF(F.LT.0.0) DM=DM*0.50
      IF(F.LT.0.0) INUM=INUM+1
      IF(F.LT.0.0.AND.INUM.LE.5) GO TO 89
      DM=1.
      IF(F.GT.XMAX) MAX=ISEQ
      IF(F.GT.XMAX) XMAX=F
   92 CONTINUE
      DO 95 I=1,NSTAGE
      DO 95 J=1,13
   95 DEC(I,J)=DECIS(MAX,I,J)
      IT=0
  100 IT=IT+1
      IF(IOUT(IT).EQ.1) WRITE(6,105) IT
  105 FORMAT(1H1,20X,21HRESULTS OF ITERATION ,I3)
      PROP2=PROP2/100.
```

```
      PROP4=PROP4/100.
C     FIT TRANSITION FUNCTIONS TO SIMULATION DATA
      CALL MODEL(S,Y)
C     APPLY POLICY IMPROVEMENT ALGORITHM USING DISCRETE MAXIMUM PRINCIPLE
      CALL OPT(S,LAM,Y,IK,IOPT)
      PROP4=PROP4*100.
      PROP2=PROP2*100.
      WRITE(6,107) IOPT,IK
  107 FORMAT(1X,I2,30H ITERATIONS IN INNER LOOP AND ,I2,21H IN NESTED IN
     1NER LOOP)
      XMIN=10.**30
      DO 110 ISEQ=1,ND
C     CALCULATE PENALIZED OBJECTIVE FUNCTION AND FIND MINIMUM OF ND DATA SETS
      F=STATES(ISEQ,NSS,11)
      IF(WELF.GT.STATES(ISEQ,NSS,1)) F=F-10.**(-8)
      IF(BDG.LT.STATES(ISEQ,NSS,2)) F=F-10.**(-8)
      IF(DV.GT.STATES(ISEQ,NSS,3)) F=F-10.**(-8)
      IF(F.LT.XMIN) MIN=ISEQ
      IF(F.LT.XMIN) XMIN=F
  110 CONTINUE
      INUM=0
  112 CONTINUE
      DO 115 N=1,NSTAGE
      NOUT(N)=1
      DO 115 J=1,13
C     RECORD DECISION VARIABLES RESULTING FROM OPTIMIZATION PROCEDURE
  115 THETA(N,J)=DEC(N,J)
      IF(IOUT(IT).EQ.1) NOUT(NSTAGE)=0
      DO 125 I=1,NSPEC
      MAX=MAXAGE(I)
      DO 125 J=1,MAX
      C(I,J)=NPOP(I,J)
```

```
  125 W(I,J)=WPOP(I,J)
C     PERFORM A NEW SIMULATION EXPERIMENT
      CALL SIM
      DO 130 N=2,NSS
      NN=N-1
C     RECORD STATE VARIABLES RESULTING FROM NEW SIMULATION EXPERIMENT
      S(N,1)=S(NN,1)+COM(NN)*10.*10.
      S(N,2)=S(NN,2)+BUDG(NN)
      S(N,3)=D(NN)
      S(N,4)=NN
      S(N,5)=B(1,NN)*10.*10.
      S(N,6)=B(2,NN)*10.*10.
      S(N,7)=B(3,NN)*10.*10.
      S(N,8)=B(4,NN)*10.*10.
      S(N,9)=B(5,NN)+B(6,NN)+B(7,NN)+B(8,NN)+B(9,NN)
      S(N,9)=S(N,9)*10.*10.
      S(N,10)=ANGLE(NN)*10.*10.+EPSIL
  130 S(N,11)=S(NN,11)+REC(NN)
      F1=S(NSS,11)
      AF=S(NSS,1)
      IF(WELF.GT.AF) F1=F1-10.**(-8)
      AF=S(NSS,2)
      IF(BDG.LT.AF) F1=F1-10.**(-8)
      AF=S(NSS,3)
      IF(DV.GT.AF) F1=F1-10.**(-8)
      IF(F1.GT.XMIN) GO TO 132
      IF(INUM.GT.INM) GO TO 806
      DO 131 I=1,NSTAGE
      DO 131 J=1,13
C     IF NO IMPROVEMENT HAS OCCURED, REDUCE THE STEP-SIZE
      IF(INUM.LE.INM)DEC(I,J)=DEC(I,J)+(0.50**INUM)*(DECIS(MAX,I,J)
     1-DEC(I,J))
```

```
      IF(INUM.EQ.INM.AND.DECIS(MAX,I,J).GE.DEC(I,J))
     1DEC(I,J)= 1.5*DECIS(MAX,I,J)
      IF(INUM.EQ.INM.AND.DECIS(MAX,I,J).GE.DEC(I,J))
     1 GO TO 129
      IF(INUM.EQ.INM.AND.DECIS(MAX,I,J).LT.DEC(I,J))
     1DEC(I,J)=-1.5*DECIS(MAX,I,J)
  129 CONTINUE
      IF(DEC(I,J).GT.DMAX(J)) DEC(I,J)=DMAX(J)
      IF(DEC(I,J).LT.0.0) DEC(I,J)=0.
  131 CONTINUE
      INUM=INUM+1
      GO TO 112
  132 CONTINUE
C     REPLACE OLD STATE AND DECISION VARIABLES WITH THE NEW STATE AND DECISION
C     VARIABLES
      DO 133 N=1,NSS
      DO 133 J=1,11
  133 STATES(MIN,N,J)=S(N,J)
      DO 134 N=1,NSTAGE
      DO 134 J=1,13
  134 DECIS(MIN,N,J)=THETA(N,J)
  806 CONTINUE
      XMIN=10.**30
      XMAX=-10000.
      DO 135 ISEQ=1,ND
C     FIND THE MAXIMUM AND MINIMUM OF THE ND DATA SETS
      F=STATES(ISEQ,NSS,11)
      IF(WELF.GT.STATES(ISEQ,NSS,1)) F=F-10.**(-8)
      IF(BDG.LT.STATES(ISEQ,NSS,2)) F=F-10.**(-8)
      IF(DV.GT.STATES(ISEQ,NSS,3)) F=F-10.**(-8)
      WRITE(6,910) F
      IF(F.GT.XMAX) MAX=ISEQ
```

```
      IF(F.GT.XMAX) XMAX=F
      IF(F.LT.XMIN) XMIN=F
  135 CONTINUE
      DO 140 N=1,NSTAGE
      DO 140 J=1,13
      THETA(N,J)=DECIS(MAX,N,J)
  140 DEC(N,J)=DECIS(MAX,N,J)
      WRITE(6,141) INUM
      IF(INUM.GT.7) GO TO 800
C     HAVE THE MAXIMUM NUMBER OF ITERATIONS BEEN PERFORMED?
      IF(IT.GE.MAXIT) GO TO 800
  141 FORMAT(8H INUM = ,I2)
C     CHECK CONVERGENCE CRITERION
      IF((XMAX-XMIN).GE.DELTA) GO TO 100
  800 CONTINUE
C     PRINT DECISION VARIABLES
      WRITE(6,930) IT
      DO 850 I=1,NSTAGE,2
      II=I+1
      WRITE(6,925) I,II
      IP=II+1
      DO 850 J=1,13
      IF(J.GT.11)WRITE(6,900) THETA(I,J),J,THETA(II,J)
      IF(J.LE.11)WRITE(6,910)THETA(I,J),LAM(II,J),J,THETA(II,J),LAM(IP,J
     1)
  850 CONTINUE
      DO 860 I=1,NSTAGE
  860 NOUT(I)=0
      DO 865 I=1,NSPEC
      MAX=MAXAGE(I)
      DO 865 J=1,MAX
      O(I,J)=NPOP(I,J)
```

```
  865 W(I,J)=WPOP(I,J)
C     PERFORM SIMULATION USING OPTIMAL DECISIONS AND PRINT RESULTS
      CALL SIM
      SUM=0.
C     CALCULATE AND PRINT SLACK VARIABLES
      XMAX=0.
      DO 870 I=1,NSTAGE
      SUM=SUM+COM(I)
  870 XMAX=XMAX+BUDG(I)
      SLACK(1)=SUM-(WELF/100.)
      SLACK(2)=BDG-XMAX
      SLACK(3)=D(NSTAGE)-DV
      WRITE(6,920) SLACK
  900 FORMAT(1X,E13.6,32X,I2,11X,E13.6)
  910 FORMAT(1X,E13.6,8X,D13.6,11X,I2,11X,E13.6,8X,D13.6)
  920 FORMAT(6H SLACK,3(3X,E10.4))
  925 FORMAT(10X,6HSTAGE ,I2,50X,6HSTAGE ,I2/1X,2(9HDECISIONS,8X,17HSTAT
     1E DERIVATIVES,24X))
  930 FORMAT(1H1,10X,19HFINAL VALUES AFTER ,I2,11H ITERATIONS)
      RETURN
      END
```

```
      SUBROUTINE SIM
C     ECOSYSTEM SIMULATION ROUTINE ....   ITERATED OVER ALL TIME STAGES...
C     BIRTHS ARE ADDED , DEATHS ARE SUBTRACTED, AND GROWTH IS ADDED TO EACH
C     AGE-CLASS IN EACH SPECIES
C
C     MTIME                 TIME STAGE NUMBER
C     OFF(I)                NUMBER OF CONCURRENTLY PREVIOUS DAYS IN WHICH NO
C                           FISHING WAS ALLOWED TO ANGLER TYPE I
C     CPUE(I)               CATCH-PER-ANGLER-DAY BY ANGLER TYPE I DURING THE
C                           PREVIOUS TIME STAGE
C     T                     TEMPERATURE IN DEGREES CENTIGRADE
C     W(I,J)                AVERAGE OF SPECIES I, AGE-CLASS J
C     N(I,J)                DENSITY OF SPECIES I, AGE-CLASS J
C     B(I,J)                W(I,J)*N(I,J), I.E., BIOMASS
C     ANGLE                 TOTAL ANGLER DENSITY
C     ANG(I)                ANGLER DENSITY FOR ANGLER TYPE I
C     CATCH(I,J,K)          CATCH PER METER SQ OF SPECIES I, AGE-CLASS J BY
C                           FISHERMEN TYPE K
C     NMORT(I,J)            NATURAL MORTALITY OF SPECIES I, AGE-CLASS J
C     EGG(I,J)              DENSITY OF EGGS PRODUCED BY SPECIES I, AGE-CLASS J
C     EGGS(I)               DENSITY OF EGGS PRODUCED BY SPECIES I
C     RATION(I,J)           RATION SIZE (GRAMS) OF SPECIES I, AGE-CLASS J
C     GRT                   GROWTH IN GRAMS
C     UTIL(I)               UTILITY DERIVED BY ANGLER TYPE I
C     D                     DIVERSITY INDEX VALUE
C     BUDG                  BUDGET EXPENDITURES IN DOLLARS
C     REC                   CUMULATIVE SUM OF UTILITY
C
      COMMON/APOP/PROP1,PROP2,PROP3,PROP4
      COMMON/ATT/NRAND,IX,INM
      COMMON/MAB/ NOUT(24)
      COMMON/AB/EGGWT(10),B(10,24),N1HEAD(5,2),NHEAD(10,2),AHEAD(5,2),
```

```
     1D(24),ANGLE(24),COM(24),BUDG(24),REC(24),PER
      COMMON/ABR/ COST
      COMMON/ALL/ THETA(24,13)
      COMMON/ABC/PPRED(10,5,10,5),NDGM(10,10),PSPGR(10),CP(10),PHOOK,
     1NSPEC,BSPWN(10),PAGR(10,5),NPRIOR,NSPWN,NPRD,MAXAGE(10),PSPWN(10,
     212),W(10,5),PREF(10,5),SERVE,SPHERE(10),DAYS,EPS(10),UPS(10),PCAPT
     3,PCCV
      COMMON/ABP/PRP(16)
      COMMON/ABH/FP(10,5)
      COMMON/ABE/SP(10,6)
      COMMON/BC/EGG(10,5),RATION(10,5),NMORT   , FEC(10,5),CATCH(10,5,5)
     1,EGGS(10)
      COMMON/ABCE/NPHAGE
      COMMON/ABCF/PLIC,POP,NANG
      COMMON/ABDF/NSTAGE
      COMMON/ABCD/N(10,5)
      COMMON/ABG/GP(10,7)
      COMMON/BCF/CPUE(5),ANG(5),OFF(5)
      COMMON/ABF/AP(9),AREA,PFISH(5)
      COMMON/BCDF/MTIME
      COMMON/BCDEF/T
      COMMON/ABU/SCALE(3,2,2),UC(4),UP(8),UTIL(2)
      DIMENSION WMAX(10,5)
      REAL N
      DOUBLE PRECISION NMORT(10,5)
      INTEGER OUTPUT
      DO 60 I=1,NSPEC
      MAX=MAXAGE(I)
      DO 60 J=1,MAX
   60 WMAX(I,J)=0.
      OBJ=0.
      DO 70 I=1,NANG
```

```
      CFF(I)=0.
   70 CPUE(I)=0.
      ADDD=0.
      BUDGG=0.
      COMM=0.
      RECC=0.
C     DO FOR ALL TIME STAGES
      DO 130 MTIME=1,NSTAGE
      MTT=MTIME-1
      OUTPUT=0.
      IF(NOUT(MTIME).GT.0.0) OUTPUT=1.
C     CALL SUBROUTINE FOR CALCULATING TEMPERATURE AND PRODUCTION BY THE LOWER
C     PORTIONS OF THE FOOD WEB
      CALL PROD
      STD=PRP(16)
      IF(NRAND.EQ.1) T=RNORM(STD,IX,0,T)
      TAREA=THETA(MTIME,2)
      DO 72 I=NPHAGE,NSPEC
      MAX=MAXAGE(I)
      DO 72 J=1,MAX
C     IF SPECIES IS TROUT, ADD THE NUMBER PLANTED
      IF(I.EQ.2) N(I,J)=N(I,J)+PER*TAREA
      IF(I.EQ.2.AND.N(I,J).GT.0.0) W(I,J)=(W(I,J)*N(I,J)+TAREA)/N(I,J)
      WA=W(I,J)
      TN=N(I,J)
C     CALCULATE FECUNDITY
   72 FEC(I,J)=FECUND(I,J,TN,WA,T)
      MX=MAXAGE(1)
      IF(OUTPUT.GT.0) GO TO 75
      WRITE(6,90) MTIME,T
      DO 74 JQ=1,MX
      GRT=N(1,JQ)
```

```
      JJ=JQ+10
      STD=PRP(JJ)
      IF(NRAND.EQ.1)N(1,JQ)=RNORM(STD,IX,0,GRT)
   74 WRITE(6,91) (N1HEAD(JQ,IN),IN=1,2),N(1,JQ),W(1,JQ)
      WRITE(6,92)
   75 CONTINUE
      B(1,MTIME)=0.
      DO 77 IN=1,MX
      BMASS=W(1,IN)*N(1,IN)
   77 B(1,MTIME)=B(1,MTIME)+BMASS
C     CALCULATE ANGLER DENSITIES
      CALL ANGLER(DAYS)
      ANGLE(MTIME)=0.
      STD=AP(9)
      DO 82 J=1,3
      AGG=ANG(J)
      IF(NRAND.EQ.1) ANG(J)=RNORM(STD,IX,0,AGG)
      IF(ANG(J).LT.(1./(AREA*DAYS))) ANG(J)=0.
   82 ANGLE(MTIME)=ANGLE(MTIME)+ANG(J)
      ANGLE(MTIME)=ANGLE(MTIME)*AREA*THETA(MTIME,1)
      ADDD=ADDD+ANGLE(MTIME)
      DO 78 I=1,NANG
      OFF(I)=OFF(I)+DAYS
      IF(ANG(I).GT.0.0) OFF(I)=0.
   78 CONTINUE
C     CALL QUEUE, THE ANIMAL INTERACTION SUBROUTINE, FROM WHICH NMORT, EGG,
C     CATCH, AND RATION CAN BE DERIVED
      CALL QUEUE
C     DO FOR ALL ACTIVELY FEEDING SPECIES
      DO 80 I=NPHAGE,NSPEC
      EGGS(I)=EGGS(I)*DAYS
      MAX=MAXAGE(I)
```

```
      B(I,MTIME)=0.
C     DO FOR EACH AGE-CLASS IN THE SPECIES
      DO 80 J=1,MAX
      CT=0.
      DO 83 K=1,NANG
      CATCH(I,J,K)=CATCH(I,J,K)*DAYS
   83 CT=CT+CATCH(I,J,K)
      NMORT(I,J)=NMORT(I,J)*DAYS
      EGG(I,J)=EGG(I,J)*DAYS
      RA=RATION(I,J)
      WT=W(I,J)
      GRT=0.
      IF(J.NE.1) GO TO 76
C     ADD GROWTH AND SUBTRACT MORTALITY
C     ADD BIRTHS SINCE THIS IS AGE-CLASS 0
      N(I,J)=N(I,J)-NMORT(I,J)-CT
      IF(N(I,J).LE.0.0) N(I,J)=0.
      IF(N(I,J).LE.0.0) W(I,J)=0.0
      GRT=GROWTH(RA,WT,T,DAYS,I)
      STD=GP(I,7)
      IF(NRAND.EQ.1) GRT=RNORM(STD,IX,1,GRT)
      W(I,J)=W(I,J)+GRT
      IF(W(I,J).GT.WMAX(I,J)) WMAX(I,J)=W(I,J)
      IF(WMAX(I,J).LE.0.0) WR=0.
      IF(WMAX(I,J).GT.0.0) WR=W(I,J)/WMAX(I,J)
      IF(WR.LT.0.01) W(I,J)=0.
      IF(W(I,J).LE.0.0) WMAX(I,J)=0.
      IF(W(I,J).LE.0.0)W(I,J)=0.0
      IF(W(I,J).LE.0.0)N(I,J)=0.
      BMASS=W(I,J)*N(I,J)+EGGWT(I)*EGGS(I)
      N(I,J)=N(I,J)+EGGS(I)
      IF(N(I,J).LE.0.0) W(I,J)=0.
```

```
      IF(N(I,J).LE.0.0) GRT=0.0
      IF(N(I,J).LE.0.0) GO TO 177
      W(I,J)=BMASS/N(I,J)
      IF(EGGS(I).GT.0.0) WMAX(I,J)=W(I,J)
      GO TO 177
C     ADD GROWTH AND SUBTRACT MORTALITY
   76 N(I,J)=N(I,J)-NMORT(I,J)-CT
      GRT=GROWTH(RA,WT,T,DAYS,I)
      STD=GP(I,7)
      IF(NRAND.EQ.1) GRT=RNORM(STD,IX,1,GRT)
      IF(N(I,J).LE.0.0) N(I,J)=0.
      IF(N(I,J).LE.0.0) W(I,J)=0.0
      IF(N(I,J).LE.0.0) GRT=0.0
      IF(N(I,J).LE.0.0) GO TO 177
      W(I,J)=W(I,J)+GRT
      IF(W(I,J).GT.WMAX(I,J)) WMAX(I,J)=W(I,J)
      IF(WMAX(I,J).LE.0.0) WR=0.
      IF(WMAX(I,J).GT.0.0) WR=W(I,J)/WMAX(I,J)
      IF(WR.LT.0.05) W(I,J)=0.
      IF(W(I,J).LE.0.0) WMAX(I,J)=0.
      IF(W(I,J).LE.0.0)W(I,J)=0.0
      IF(W(I,J).LE.0.0)N(I,J)=0.
  177 BMASS=N(I,J)*W(I,J)
      B(I,MTIME)=B(I,MTIME)+BMASS
C     IF APPROPRIATE, PRINT RESULTS
      IF(OUTPUT.GT.0) GO TO 80
      L=J-1
      IF(J.EQ.1.AND.J.EQ.MAX) WRITE(6,100)(NHEAD(I,IN),IN=1,2),L,BMASS,
     1B(I,MTIME),NMORT(I,J),EGG(I,J),EGGS(I),RATION(I,J),GRT,N(I,J),W(I,
     2J)
      IF(J.EQ.1.AND.J.EQ.MAX) GO TO 80
      IF(J.EQ.1)WRITE(6,93)(NHEAD(I,IN),IN=1,2),L,BMASS,NMORT(I,J),EGG
```

```
     1(I,J),RATION(I,J),GRT,N(I,J),W(I,J)
      IF(J.EQ.MAX)WRITE(6,94)L,BMASS,B(I,MTIME),NMORT(I,J),EGG(I,J),EGGS
     1(I),RATION(I,J),GRT,N(I,J),W(I,J)
      IF(J.NE.1.AND.J.NE.MAX)WRITE(6,99)L,BMASS,NMORT(I,J),EGG(I,J),RATI
     1ON(I,J),GRT,N(I,J),W(I,J)
   80 CONTINUE
C     CALCULATE CPUE
      DO 85 K=1,NANG
      SUM=0.
      DO 84 I=1,NSPEC
      MAX=MAXAGE(I)
      DO 84 J=1,MAX
      SUM=SUM+CATCH(I,J,K)
   84 CONTINUE
      IF(ANG(K).LE.0.0) CPUE(K)=0.
      IF(ANG(K).GT.0.0) CPUE(K)=SUM/(ANG(K)*DAYS)
   85 CONTINUE
C     CALCULATE THE UTILITY DERIVED BY THE FISHERMEN
      CALL UTILTY(DAYS,MAXAGE,ANG,CATCH,CPUE,W)
C     CALCULATE THE DIVERSITY INDEX VALUE
      D(MTIME)=DIV(NSPEC,MAXAGE,AREA)
C     CALCULATE CUMULATIVE SUM OF BUDGET, COMMERCIAL CATCH PER SEINE-DAY,
C     RECREATIONAL UTILITY, ANGLER-DAYS, AND THE WEIGHTED SUM OBJECTIVE FUNCTION
C     PRINT RESULTS OF CATCH DYNAMICS
      COM(MTIME)=UTIL(2)
      COMM=COMM+COM(MTIME)
      BUDG(MTIME)=COST*THETA(MTIME,2)
      BUDGG=BUDGG+BUDG(MTIME)
      REC(MTIME)=UTIL(1)
      RECC=RECC+REC(MTIME)
      OB =PROP1*REC(MTIME)+PROP2*COM(MTIME)
      PRRP3=0.
```

```
      IF(MTIME.EQ.NSTAGE) PRRP3=PROP3
      OB=OB+PRRP3*D(MTIME)
      OB=OB+PROP4*ANGLE(MTIME)*AREA
      REC(MTIME)=OB
      OBJ=OBJ+OB
      REC(MTIME)=REC(MTIME)*10.**(-10)
      IF(OUTPUT.LE.0) WRITE(6,121) D(MTIME)
      IF(OUTPUT.GT.0) GO TO 130
      WRITE(6,95) ((AHEAD(IK,JK),JK=1,2),IK=1,NANG)
      WRITE(6,96) (ANG(IK),IK=1,NANG)
      DO 87 IK=NPHAGE,NSPEC
      MAX=MAXAGE(IK)
      DO 87 JK=1,MAX
      LK=JK-1
      IF(JK.EQ.1) WRITE(6,97)(NHEAD(IK,JQ),JQ=1,2),LK,(CATCH(IK,JK,KK),
     1KK=1,NANG)
      IF(JK.NE.1) WRITE(6,98) LK,(CATCH(IK,JK,KK),KK=1,NANG)
   87 CONTINUE
   90 FORMAT(8H1TIME = ,I2/15H0TEMPERATURE = ,F5.1,10H DEGREES C)
   91 FORMAT(1H0,2A4,3H = ,E10.4,10X,17HAVERAGE WEIGHT = ,E10.4)
   92 FORMAT(///1H0,7HSPECIES,2X,9HAGE CLASS,2X,15HBIOMASS DENSITY,6X,
     1 13HDENSITY EATEN,2X,24HDENSITY OF EGGS PRODUCED,4X,6HRATION,6X,
     2 6HGROWTH,4X,10HPOPULATION,2X,7HAVERAGE/20X,9HAGE CLASS,4X,7HSPECI
     3ES ,19X,9HAGE CLASS,5X,7HSPECIES,29X,7HDENSITY,4X,6HWEIGHT)
   93 FORMAT(1X,2A4,5X,I1,5X,E10.4,15X,E10.4,3X,E10.4,15X,E10.4,2X,E10.4
     1,2X,E10.4,2X,E10.4)
   94 FORMAT(14X,I1,5X,E10.4,2X,E10.4,3X,E10.4,3X,E10.4,2X,E10.4,3X,E10.
     14,2X,E10.4,2X,E10.4,2X,E10.4)
   95 FORMAT(1H1,34X,5(5X,2A4,1X))
   96 FORMAT(1H0,20X,14HANGLER DENSITY,5(4X,E10.4)/14H0CATCH DENSITY,2X,
     17HSPECIES,2X,9HAGE CLASS)
   97 FORMAT(15X,2A4,8X,I1,3X,5(4X,E10.4))
```

```
 98 FORMAT(31X,I1,3X,5(4X,E10.4))
 99 FORMAT(14X,I1,5X,E10.4,15X,E10.4,3X,E10.4,15X,E10.4,2X,E10.4,2X,
   1E10.4,2X,E10.4)
100 FORMAT(1X,2A4,5X,I1,5X,E10.4,2X,E10.4,3X,E10.4,3X,E10.4,2X,E10.4,
   13X,E10.4,2X,E10.4,2X,E10.4,2X,E10.4)
110 FORMAT(22HCCATCH PER UNIT EFFORT,13X,5(4X,E10.4))
120 FORMAT(20HCCUMULATIVE COSTS = ,E15.8, 5X,24HCUMULATIVE RECREATION
   1= ,E15.8, 5X,24HCUMULATIVE COMMERCIAL = ,E15.8)
121 FORMAT(13HCDIVERSITY = ,E10.4,5H BITS)
    IF(OUTPUT.GT.0) GO TO 130
    WRITE(6,110) (CPUE(K),K=1,NANG)
    WRITE(6,120) BUDGG,RECC,COMM
    WRITE(6,125) ADDD,OBJ
125 FORMAT(5X,14HANGLER-DAYS = ,E15.8,10X,12HOBJECTIVE = ,E15.8)
130 CONTINUE
    RETURN
    END
```

```
      SUBROUTINE QUEUE
C     THIS SUBROUTINE, USING A QUEUEING PROCESS AS A BASIS, DEPICTS THE
C     INTERACTIONS BETWEEN AND AMONG ANIMAL SPECIES
C
C     LAM(I)                 ARRIVAL OF AN ITEM OF PRIORITY TYPE I
C     MU(I)                  SERVICE RATE OF AN ITEM OF PRIORITY TYPE I
C     GAMMA(I)               A FUNCTION OF ALL ARRIVAL AND SERVICE RATES
C     P VARIABLES            GENERALLY, VARIABLES BEGINNING IN "P" ARE PROBABILITIES
C                            BY WHICH THE APPROPRIATE ARRIVAL RATES ARE WEIGHTED
C     SP1 & SP2              CRUISING SPEEDS OF THE INTERACTING ORGANISMS
C     XLAM & XL              BASIC ARRIVAL RATES WHICH ARE WEIGHTED BY PROBABILITIES
C                            TO GET ARRIVAL RATES FOR EACH PRIORITY
C     RMAX                   MAXIMAL RATICN
C     SUML                   SUM OF LAM(I)
C     SUMML                  CUMULATIVE SUM OF LAM FROM LAST PRIORITY TO THE FIRST
C     SUMK(I,K)              CATCH-PER-ANGLER-DAY OF SPECIES I BY ANGLER TYPE K
C     XMORT(I,J)             ACCUMULATOR VARIABLE FOR NATURAL MORTALITY OF SPECIES
C                            I, AGE-CLASS J
C     CT(K)                  ACCUMULATOR VARIABLE FOR CATCH BY ANGLER TYPE K
C     TD                     EXPECTED NUMBER OF COMPLETED FEEDING ACTS PER INDIVI-
C                            DUAL PER DAY ( ASSUMED 21600 SECS PER INTERACTION DAY)
C     EG                     EXPECTED NUMBER OF FERTILIZED EGGS PRODUCED PER DAY
C                            (ASSUMED 10800 SECS OF POSIBLE TIME FOR SPAWNING PER
C                            DAY)
C
      COMMON/ATT/NRAND,IX,INM
      CCMMON/ALL/ THETA(24,13)
      COMMON/ABC/PPRED(10,5,10,5),NDOM(10,10),PSPGR(10),CP(10),PHOUK,
     1NSPEC,BSPWN(10),PAGR(10,5),NPRIOR,NSPWN,NPRD,MAXAGE(10),PSPWN(10,
     212),W(10,5),PREF(10,5),SERVE,SPHERE(10),DAYS,EPS(10),UPS(10),PCAPT
     3,PCOV
      CCMMON/BC/EGG(10,5),RATION(10,5),NMORT  , FEC(10,5),CATCH(10,5,5)
```

```
     1,EGGS(10)
      CCMMON/ABE/SP(10,6)
      CCMMON/BCF/CPUE(5),ANG(5),OFF(5)
      CCMMON/ABCE/NPHAGE
      CCMMON/ABCF/PLIC,POP,NANG
      CCMMCN/ABCD/N(10,5)
      CCMMCN/ABDF/NSTAGE
      CCMMON/BCDF/MTIME
      CCMMON/BCDEF/T
      DOUBLE PRECISION SUML,SUMG,SUM,DIV,DIV4,TD,TDN,TDNP,SUMML,MUS,
     1 MU(8),TUP,GAMMA(8),SUMK(10,5),XMORT(10,5),LAM(8),PZ,PC,P4,PD,WM,
     2 PS,PA,PP,PPP,PN,PI,PFSH,PX,PRR,PR,XLAM,PT,PRT,SS,XL,RA,EG,EGS,
     3 RMAX,CT(5),DF,NMORT(10,5)
      REAL N
      P4=1.
      MT=(12*(MTIME-1)/NSTAGE)+1
      NP=NPRIOR+1
C     INITIALIZE ACCUMULATOR VARIABLES AT ZERO
      DO 1 I=1,NSPEC
      EGGS(I)=0.
      MAX=MAXAGE(I)
      DO 1 J=1,MAX
      NMORT(I,J)=0.
      EGG(I,J)=0.
      RATION(I,J)=0.
      DO 1 K=1,NANG
      SUMK(I,K)=0.
    1 CATCH(I,J,K)=0.
      NS=NSPEC+1
      SV=SERVE
C     DO FOR EACH INTERACTIVE SPECIES
      DO 55 I=NPHAGE,NSPEC
```

```
      EGS=0.
      MAX=MAXAGE(I)
      PPP=PSPWN(I,MT)
C     DO FOR EACH AGE-CLASS
      DO 50 J=1,MAX
      EG=0.
      IF(N(I,J).LE.0.0) GO TO 50
      RA=0.
      PCC=PCOV
      PHOOK=PHOUK
      IF(I.NE.2.AND.J.EQ.1) PHOOK=1./(10.0**3)
      IF(I.NE.2.AND.J.EQ.1) PCC=0.1
      WI=W(I,J)
C     DEFINE THE WEIGHTING PROBABILITIES ASSOCIATED WITH THE MESH SIZE DECISION
      PRR=CP(1)*(WI-CP(2)*THETA(MTIME,3))**2
      IF(PRR.GT.20. ) PRT=0.
      IF(PRR.LE.20.) PRT=CP(3)*DEXP(-PRR)
C     DEFINE THE SERVICE RATE FOR EACH PRIORITY
      DO 5 IK=1,NPRIOR
      MU(IK)=SV
      IF(IK.EQ.NSPWN) MU(IK)=1./BSPWN(I)
    5 CONTINUE
      XMU=MU(NPRIOR)
C     CALCULATE SPEED OF THE "I,JTH" INTERACTING ANIMAL
      SP1=SPEED(WI,I,NS)
      STD=SP(I,6)
      IF(NRAND.EQ.1) SP1=RNORM(STD,IX,0,SP1)
      SP3=SP1*SP1
      DO 10 IK=1,NPRIOR
   10 LAM(IK)=0.
      XL=0.
C     DO FOR ALL SPECIES WITH WHICH THE "ITH" SPECIES, "JTH" AGE-CLASS WILL
```

```
C       INTERACT; SPECIES "NS" CORRESPONDS TO THE FISHERMEN, THEREFORE SPECIES NS
C       HAS "NANG" AGE-CLASSES CORRESPONDING TO THE "NANG" FISHERMEN TYPES
        DO 20 IK=1,NS
        IF(IK.NE.NS) MAXIK=MAXAGE(IK)
        IF(IK.EQ.NS) MAXIK=NANG
        IF(IK.EQ.NS) GO TO 13
C       ESTABLISH SHORT NOTATION FOR SOME OF THE WEIGHTING PROBABILITIES
        PP=PSPWN(IK,MT)
        PG=PSPGR(IK)
        PS=0.
        IF(IK.EQ.I) PS=1.
        PN=NDOM(I,IK)
        PD=NDOM(IK,I)
   13   CONTINUE
C       DO FOR ALL AGE-CLASSES WITHIN THE "IKTH" SPECIES
        DO 20 JK=1,MAXIK
        IF(IK.EQ.NS) GO TO 14
        WA=W(IK,JK)
C       CALCULATE SPEED OF "IK,JKTH" ANIMAL
        SP2=SPEED(WA,IK,NS)
        STD=SP(IK,6)
        IF(NRAND.EQ.1) SP2=RNORM(STD,IX,0,SP2)
   14   IF(IK.EQ.NS.AND.JK.LE.3)XLAM=2.*ANG(JK)*SPHERE(I)*SQRT(SP3+CP(7))
        IF(IK.EQ.NS.AND.JK.EQ.4)XLAM=2.*ANG(JK)*SPHERE(I)*SQRT(SP3+CP(8))
        IF(IK.EQ.NS.AND.JK.EQ.5) XLAM=2.*ANG(JK)*SPHERE(I)*SP1
        IF(IK.NE.NS) XLAM=2.*N(IK,JK)*SQRT(SP3+SP2*SP2)*SPHERE(I)
        IF(IK.EQ.NS) GO TO 15
        PC=1.
C       ESTABLISH SHORT NOTATION FOR SOME WEIGHTING PROBABILITIES
        PZ=PPRED(IK,JK,I,J)
        PT=PPRED(I,J,IK,JK)
        PAG=PAGR(IK,JK)
```

```
      IF(PAG.GE.0.9 ) PAG=0.9
      IF(I.EQ.IK.AND.J.EQ.JK) PA=1./(1.-PAG)
      PA=1.0
      WM=0.0
      IF((WI+WA).GT.0.0) WM=1./(WI+WA)
      PX=PT*PA
   15 PR=1.
      IF(IK.EQ.NS.AND.JK.GE.4) PR=PRT
      IF(IK.EQ.NS)PX=PHOOK*PCAPT*PREF(I,JK)*PR
      IF(IK.EQ.NS.AND.JK.EQ.4) PX=0.
      PRR=1.
      IF(IK.EQ.NS.AND.JK.EQ.4) PRR=1.-EXP(-CP(4)*THETA(MTIME,4))
      PFSH=1.0
      IF(IK.EQ.NS) PFSH=CP(5)
      IF(IK.EQ.NS.AND.JK.EQ.5) PFSH=CP(6)
C     CALCULATE ARRIVAL RATES FOR EACH PRIORITY. FOR PRIORITY SEQUENCES OTHER
C     THAN THE ONE USED IN THIS STUDY, THIS CALCULATION SCHEME WOULD HAVE TO BE
C     USER-MODIFIED SO THAT ARRIVAL RATES COULD BE WEIGHTED BY APPROPRIATE
C     PROBABILITIES
      IF(IK.EQ.NS.AND.JK.EQ.4) LAM(1)=LAM(1)+XLAM*PR*PRR*CP(6)
      LAM(5)=LAM(5)+XLAM*PX*PFSH
      IF(IK.EQ.NS) GO TO 20
      LAM(1)=LAM(1)+XLAM*PZ*PC*P4
      LAM(2)=LAM(2)+XLAM*PD*WA*WM*P4*PC
      LAM(3)=LAM(3)+XLAM*PS*PG*PA*PP*PPP*(0.5)*P4
      LAM(4)=LAM(4)+XLAM*PPP*PN*WI*WM*P4*PCC*PA
      LAM(6)=LAM(6)+XLAM*PN*PA*WI*WM*(1.-PPP)
   20 CONTINUE
      SUMG=0.
C     CALCULATE GAMMAS
      DO 25 K=1,NPRIOR
      KI=NP-K
```

```
      SUMML=0.
      NPQ=KI-1
      NMU=0
      IF(MU(KI).LE.0.0) NMU=1
      IF(NMU.EQ.1.AND.KI.EQ.1) GAMMA(KI)=0.
      IF(KI.EQ.1.AND.NMU.EQ.0) GAMMA(KI)=LAM(KI)*(1.+SUMG)/(MU(KI))
      IF(NMU.EQ.1) NMU=0
      IF(KI.EQ.1) GO TO 25
      DO 23 JI=1,NPQ
      SUMML=SUMML+LAM(JI)
   23 CONTINUE
      MUS=MU(KI)+SUMML
      IF(MUS.LE.0.0) GAMMA(KI)=0.
      IF(MUS.LE.0.0) GO TO 25
      GAMMA(KI)=LAM(KI)*(1.+SUMG)/MUS
   25 SUMG=SUMG+GAMMA(KI)
      SUML=0.
      DO 27 IK=1,NPRIOR
   27 SUML=SUML+LAM(IK)
      SUM=SUML*(1.+SUMG)
      DIV=MU(NPRD)*GAMMA(NPRD)
      DIV4=MU(NSPWN)*GAMMA(NSPWN)
      DO 35 IK=1,NS
      IF(IK.NE.NS) MAXIK=MAXAGE(IK)
      IF(IK.EQ.NS) MAXIK=NANG
      DO 35 JK=1,MAXIK
      XMORT(IK,JK)=0.
      CT(JK)=0.
      IF(IK.EQ.NS) GO TO 28
      WA=W(IK,JK)
      SP2=SPEED(WA,IK,NS)
      STD=SP(IK,6)
```

```
      IF(NRAND.EQ.1) SP2=RNORM(STD,IX,0,SP2)
      WA=W(IK,JK)
      PT=PPRED(I,J,IK,JK)*PC
   28 IF(IK.EQ.NS.AND.JK.LE.3)XL   =2.*ANG(JK)*SPHERE(I)*SQRT(SP3+CP(7))
      IF(IK.EQ.NS.AND.JK.EQ.4)XL   =2.*ANG(JK)*SPHERE(I)*SQRT(SP3+CP(8))
      IF(IK.EQ.NS.AND.JK.EQ.5) XL   =2.*ANG(JK)*SPHERE(I)*SP1
      IF(IK.NE.NS) XL   =2.*N(IK,JK)*SQRT(SP3+SP2*SP2)*SPHERE(I)
      PR=1.
      IF(IK.EQ.NS.AND.JK.EQ.4)PR=PRT*CP(6)*(1.-EXP(-CP(4)*THETA(MTIME,4)
     1))
      IF(IK.EQ.NS.AND.JK.EQ.5) PR=PRT*CP(6)
      IF(IK.EQ.NS) PT=PHOOK*PCAPT*PREF(I,JK)*PR
      SS=LAM(NPRD)*SUM
      IF(SS.LE.0.0) TD=0.
C     COMPUTE THE PROBABILITY OF SUCCESSFUL COMPLETIONS OF FEEDING ACT  BY
C     SPECIES I, AGE-CLASS J ON SPECIES IK, AGE-CLASS JK
      IF(SS.GT.0.0) TD=21600.*XL*PT*DIV/SS
      TDN=TD*N(I,J)
      IF(IK.NE.NS) GO TO 30
      TDNP=N(I,J)*PREF(I,JK)*XL*21600.
      PXX=1.
C     IF THE SIZE LIMITS ARE EXCEEDED, NO FISH ARE CAUGHT
C     THESE SHOULD BE USER-MODIFIED TO MAKE THE SPECIES NUMBER CORRESPOND TO
C     THE APPROPRIATE DECISION ACTIVITY
      IF(JK.EQ.2.AND.I.EQ.3.AND.WI.LT.THETA(MTIME,8)) PXX=0.
      IF(JK.EQ.2.AND.I.EQ.3.AND.WI.GT.THETA(MTIME,9)) PXX=0.
      IF(JK.EQ.3.AND.I.EQ.4.AND.WI.LT.THETA(MTIME,11)) PXX=0.
      IF(JK.EQ.3.AND.I.EQ.4.AND.WI.GT.THETA(MTIME,12)) PXX=0.
      IF(JK.EQ.4) TUP=TDNP*PXX
      IF(JK.NE.4) TUP=TDN*PXX
      SUMK(I,JK)=SUMK(I,JK)+TUP
      CT(JK)=CT(JK)+TUP
```

```
      GO TO 35
   30 RA=RA+TD*W(IK,JK)*0.5*(1.-PCOV)
      XMORT(IK,JK)=XMORT(IK,JK)+TDN*0.5*PCOV
   35 CCNTINUE
      DO 37 JK=1,NANG
   37 CATCH(I,J,JK)=CT(JK)
C     COMPUTE THE PROBABILITY OF SUCCESSFUL COMPLETIONS OF SPAWNING BY SPECIES I
C     AGE-CLASS J, WITH SPECIES IK, AGE-CLASS JK
      IF(SUM.GT.0.0) EG=FEC(I,J)*N(I,J)*DIV4*5400./SUM
C     IF THE MAXIMAL RATION IS EXCEEDED, THE RATICN IS SEI EQUAL TO MAXIMUM
C     AND THE MORTALITIES ARE ADJUSTED ACCORDINGLY
      RMAX=UPS(I)*WI**EPS(I)
      DIFF=RA-RMAX
      IF(DIFF.LE.0.0) DF=1.
      IF(DIFF.LE.0.0) GO TO 38
      DF=DIFF/RA
      RA=RMAX
   38 CCNTINUE
      DO 40 IK=1,NSPEC
      MAXIK=MAXAGE(IK)
      DO 40 JK=1,MAXIK
   40 NMORT(IK,JK)=NMORT(IK,JK)+DF*XMORT(IK,JK)
   45 EGG(I,J)=EG
      RATICN(I,J)=RA
   50 EGS=EGS+EG
   55 EGGS(I)=EGS
C     IF THE CREEL LIMITS ARE EXCEEDED, SET THE CATCH EQUAL TO THE LIMIT
C     THESE SHOULC BE USER-MODIFIED TO MAKE THE SPECIES NUMBER CORRESPOND TO
C     THE APPROPRIATE DECISION ACTIVITY
      DO 70 K=1,NANG
      SUM=0.
      DO 60 I=5,NSPEC
```

```
60 SUM=SUM+SUMK(I,K)
   IF(ANG(4).LE.0.0) SUM=0.
   IF(ANG(4).GT.0.0) SUM=SUM/ANG(4)
   DO 70 I=2,NSPEC
   IF(ANG(K).LE.0.0) SUMK(I,K)=0.
   IF(ANG(K).GT.0.0) SUMK(I,K)=SUMK(I,K)/ANG(K)
   MAX=MAXAGE(I)
   DO 70 J=1,MAX
   IF(I.EQ.2.AND.SUMK(I,K).GT.THETA(MTIME,7))
  1  CATCH(I,J,K)=CATCH(I,J,K)*THETA(MTIME, 7)/SUMK(I,K)
   IF(I.EQ.3.AND.SUMK(I,K).GT.THETA(MTIME,10))
  1  CATCH(I,J,K)=CATCH(I,J,K)*THETA(MTIME,10)/SUMK(I,K)
   IF(I.EQ.4.AND.SUMK(I,K).GT.THETA(MTIME,13))
  1  CATCH(I,J,K)=CATCH(I,J,K)*THETA(MTIME,13)/SUMK(I,K)
   IF(I.GE.5.AND.SUM.GT.THETA(MTIME,5))
  1  CATCH(I,J,K)=CATCH(I,J,K)*THETA(MTIME, 5)/SUM
   IF(CATCH(I,J,K).LE.0.0) CATCH(I,J,K)=0.
70 CONTINUE
   RETURN
   END
```

```
      SUBROUTINE PROD
C     SUBROUTINE FOR CALCULATING TEMPERATURE AND PRODUCTIVITY IN THE LOWER
C     OF THE FOOD WEB. THIS ROUTINE ASSUMES NPHAGE EQUALS 2. IF NPHAGE DOES NOT
C     NOT EQUAL 2, THEN PRODUCTION FUNCTIONS SHOULD BE INCLUDED FOR:
C     N(2,J),N(3,J),....,N(NPHAGE-1,J)
C
      COMMON/ABDF/NSTAGE
      COMMON/ABCD/N(10,5)
      COMMON/BCDF/MTIME
      COMMON/BCDEF/T
      COMMON/ABP/PRP(16)
      REAL N
      STAGE=NSTAGE
      TM=MTIME
      TP=(TM-(0.5*STAGE))**2
      TP3=(TM-(STAGE/3.))**2
      TP2=(TM-(2.*STAGE/3.))**2
      T=PRP(1)+PRP(2)*EXP(-TP*PRP(3))
      N(1,1)=PRP(4)+PRP(5)*(EXP(-TP3*PRP(6))+EXP(-TP2*PRP(7)))
      N(1,2)=PRP(8)+PRP(9)*EXP(-TP*PRP(10))
      RETURN
      END
```

```
      FUNCTION GROWTH(R,W,TN,DAYS,I)
C     GROWTH AS A FUNCTION OF TEMPERATURE ( IN DEGREES KELVIN), WEIGHT (W),
C     SPEED, AND RATION (R)
      COMMON/ATT/NRAND,IX,INM
      COMMON/ABE/SP(10,6)
      COMMON/ABG/GP(10,7)
      DOUBLE PRECISION METAB,RA,GR
      T=TN+273.
      IF(R.LE.0.0.AND.W.LE.0.0) GROWTH=0.0
      IF(R.LE.0.0.AND.W.LE.0.0) RETURN
      RA=R
      METAB=DAYS*115.7*GP(I,1)*T*EXP(-GP(I,2)/T)*(W**GP(I,3))/(1.+GP(I,4
     1)*EXP(-GP(I,5)/T))
      SP1=SPEED(W,I,1)
      STD=SP(I,6)
      IF(NRAND.EQ.1) SP1=RNORM(STD,IX,0,SP1)
      METAB=METAB+SP1*DAYS*GP(I,6)
      GR=(DAYS*350.625*RA-METAB)/750.
      GROWTH=GR
      RETURN
      END
```

```
      FUNCTION FECUND(I,J,TN,WA,T)
C     FECUNDITY AS A FUNCTION OF TEMPERATURE (T) AND WEIGHT (WA);  ASSUMES AGE-
C     CLASS 0 WILL NOT REPRODUCE
      COMMON/ABH/FP(10,5)
      TS=T-FP(I,3)
      FECUND=FP(I,1)*(1.-EXP(-FP(I,2)*WA))*EXP(-FP(I,4)*TS*TS)
      IF(I.EQ.4.AND.J.EQ.2.OR.I.EQ.3.AND.J.EQ.2) FECUND=0.
      IF(J.LE.1) FECUND=0.
      IF(TN.LE.0.0) FECUND=0.
      RETURN
      END
```

```
      FUNCTION SPEED(WI,I,NS)
C     CRUISING SPEED AS A FUNCTION OF WEIGHT (WI) AND TEMPERATURE (T IN DEGREES
C     KELVIN)
      COMMON/BCDEF/T
      COMMON/ABE/SP(10,6)
      COMMON/ABCE/NPHAGE
      IF(I.GE.NS) SPEED=0.
      IF(I.GE.NS) RETURN
      IF(WI.LE.0.) SPEED=0.
      IF(WI.LE.0.) RETURN
      IF(I.LT.NPHAGE) SPEED=0.
      IF(I.LT.NPHAGE) RETURN
      TN=T+273.
      SPEED=SP(I,1)*TN*EXP(-SP(I,2)/TN)*(WI**SP(I,3))/(1.+SP(I,4)*EXP(-S
     1P(I,5)/TN))
      RETURN
      END
```

```
      FUNCTION DIV(NSPEC,MAXAGE,AREA)
C     DIVERSITY USING BRILLOUIN'S INFORMATION THEORY INDEX AND STERLING'S SECOND
C     ORDER APPRCXIMATION FOR THE LOG CF N FACTORIAL. INDEX IS EXPRESSED IN BITS
C     OF INFORMATION
      CCMMON/ABCD/N(10,5)
      DIMENSION MAXAGE(10)
      REAL N
      SUM1=0.
      SUM2=0.
      DO 20 I=3,NSPEC
      SUM3=0.
      MAX=MAXAGE(I)
      DO 10 J=1,MAX
   10 SUM3=SUM3+N(I,J)*AREA
      SNN=1.
      IF(SUM3.GT.1.0) SNN=SUM3*ALOG(SUM3-1.)+0.5*ALOG(6.283186*SUM3)
      SUM2=SUM2-SNN
   20 SUM1=SUM1+SUM3
      SN=1.
      IF(SUM1.GT.1.0) SN=SUM1*ALOG(SUM1-1.)+0.5*ALOG(6.283186*SUM1)
      DIV=1.443*(SN+SUM2)+1.
      IF(DIV.LT.1.0) DIV=1.
      RETURN
      END
```

```
      SUBROUTINE ANGLER(DAYS)
C     ROUTINE FOR CALCULATING ANGLER DENSITIES FOR EACH ANGLER TYPE AS FUNCTIONS
C     OF TIME, TEMPERATURE, DAYS OFF, CATCH-PER-PER-UNIT-EFFORT, HUMAN POP-
C     ULATION SIZE, AND PROPORTION HAVING LICENSES. ASSUMES TYPES 4 AND 5 ARE
C     THE COMMERCIAL FISHERMEN. ASSUMES SPECIES 2,3, AND 4 ARE THE RECREATIONAL
C     SPECIES AND ANGLER TYPES 1,2, AND 3 ARE THE RECREATIONAL FISHERMEN
      COMMON/BCDEF/T
      COMMON/ABCF/PLIC,POP,NANG
      COMMON/ABDF/NSTAGE
      COMMON/BCF/CPUE(5),ANG(5),OFF(5)
      COMMON/ALL/ THETA(24,13)
      COMMON/ABF/AP(9),AREA,PFISH(5)
      COMMON/BCDF/MTIME
      IF(THETA(MTIME,1).LE.0.0) GO TO 20
      STAGE=NSTAGE
      TIME=MTIME
      TS=TIME/STAGE
      TS=TS-AP(2)
      AZ=POP*PLIC*EXP(-AP(1)*TS*TS)/(AREA*THETA(MTIME,1))
      IF(AZ.LE.1E-25) AZ=0.
      TS=T-AP(4)
      AZ=AZ*EXP(-AP(3)*TS*TS)
      IF(AZ.LE.1E-25) AZ=0.
      DO 10 I=1,3
      AT=1.-AP(5)*EXP(-AP(6)*(OFF(I)+1.))
      IF(AT.LE.1E-25) AT=0.
      AG=AZ*AT*PFISH(I)
      IF(AG.LE.1E-25) AG=0.
      IF(CPUE(I).LT. 50.) GO TO 8
      ANG(I)=AG*(1.-AP(7))
      GO TO 10
    8 ANG(I)=AG*(1.-AP(7)*EXP(-AP(8)*CPUE(I)))
```

```
10 CCNTINUE
20 ANG(4)=THETA(MTIME,6)
   ANG(5)=ANG(4)*6.
   DO 25 I=1,NANG
   IF(THETA(MTIME,1).LE.0.0) ANG(I)=0.
   IF(ANG(I).LT.(1./(AREA*DAYS))) ANG(I)=0.
25 CCNTINUE
   RETURN
   END
```

```
      SUBROUTINE UTILTY(DAYS,MAXAGE,ANG,CATCH,CPUE,W)
C     ROUTINE FOR CALCULATING UTILITY FOR RECREATIONAL ANGLERS ( UTIL(1) )
C     AND FOR COMMERCIAL FISHERMEN ( UTIL(2) ). UTIL(2) SIMPLY EQUALS
C     THEIR CATCH PER UNIT EFFORT
C
C     AG                    ANGLER DENSITY ATTRIBUTE SCALED FROM ZERO TO ONE
C     SNUM                  ATTRIBUTE OF NUMBER OF FISH SCALED FROM ZERO TO ONE
C     SLEN                  ATTRIBUTE OF SIZE OF FISH SCALED FROM ZERO TO ONE
      COMMON/ABU/SCALE(3,2,2),UC(4),UP(8),UTIL(2)
      DIMENSION SC(2,3),US(3),W(10,5),MAXAGE(10),ANG(5),CATCH(10,5,5),
     1 CPUE(5)
      AG=ANG(1)+ANG(2)+ANG(3)
      IF(AG.LE.0.0) UTIL(1)=0.
      IF(AG.LE.0.0) GO TO 30
      SNUM=0.
      SLEN=0.
      DO 20 I=2,4
      II=I-1
      US(II)=UC(II)
      MAX=MAXAGE(I)
      SC(1,II)=0.
      SC(2,II)=0.
      DO 10 J=1,MAX
      SC(2,II)=SC(2,II)+W(I,J)*CATCH(I,J,II)
   10 SC(1,II)=SC(1,II)+CATCH(I,J,II)
      IF(SC(1,II).GT.0.0) SC(2,II)=SC(2,II)/SC(1,II)
      IF(ANG(II).LE.0.0) SC(1,II)=0.
      IF(ANG(II).GT.0.0) SC(1,II)=SC(1,II)/(DAYS*ANG(II))
      SC(1,II)=(SCALE(II,1,1)-SC(1,II))/SCALE(II,1,2)
      SC(1,II)=1.-SC(1,II)
      IF(SC(1,II).LE.0.0) US(II)=0.
      SC(2,II)=(SCALE(II,2,1)-SC(2,II))/SCALE(II,2,2)
```

```
      SC(2,II)=1.-SC(2,II)
      SNUM=SNUM+SC(1,II)
   20 SLEN=SLEN+SC(2,II)
      IF(SNUM.GT.1.0) SNUM=1.0
      IF(SNUM.LT.0.0) SNUM=0.0
      IF(SLEN.GT.1.0) SLEN=1.0
      IF(SLEN.LT.0.0) SLEN=0.0
      AG=1.-100.*AG
      IF(AG.GT.1.0) AG=1.0
      IF(AG.LT.0.0) AG=0.0
      PROD=(1.+UC(4)*US(1))*(1.+UC(4)*US(2))*(1.+UC(4)*US(3))
      PROD=(((PROD-1.)/UC(4))*UP(8)*UP(7))+1.
      PROD=PROD*(1.+UP(8)*UP(4)*SNUM**UP(1))
      PROD=PROD*(1.+UP(8)*UP(5)*SLEN**UP(2))
      PROD=PROD*(1.+UP(8)*UP(6)*AG**UP(3))
      UTIL(1)=(PROD-1.)/UP(8)
   30 UTIL(2)=CPUE(4)+CPUE(5)
      RETURN
      END
```

```
      SUBROUTINE MODEL(S,Y)
C     ROUTINE FOR FITTING THE TRANSITION FUNCTIONS TO THE ND SIMULATION DATA
C     SETS. FOR A DIFFERENT SET OF STATE VARIABLES, THIS ROUTINE SHOULD BE
C     USER-MODIFIED
C
C     Y                    VECTOR OF DEPENDENT VARIABLES
C     X                    MATRIX OF INDEPENDENT VARIABLES
C     BP                   WORK VECTOR
C     B2,B3,B5,B6,B7,
C     B8,B9,B10,B11        PARAMETERS FOR THE TRANSITION FUNCTIONS
      COMMON/APOP/PROP1,PROP2,PROP3,PROP4
      COMMON/MM/DMAX(13),SMAX(11),NOPT,IOUT(80),IT
      COMMON/BEST/DECIS(5,24,13),ND,STATES(5,25,11)
      COMMON/SMC/NSTOP
      COMMON/NBH/EPSIL
      COMMON/SC/SSQR(11),BDG,WELF,DV
      COMMON/ABDF/NSTAGE
      COMMON/ABR/COST
      COMMON/MCGF/DEC(24,13),B1(13),B3(17),B5(3),B6(7),B7(10),B8(10),
     1B9(12),B10(16),B11(19),Z(11),Q(11),DHT(3,4),DTT(3),SLACK(3),BP(19)
      DOUBLE PRECISION Y(120),X(120,19),S(25,11),SUM
      NMOD=0
      DO 50 J=1,11
   50 SSQR(J)=0.
      NSS=NSTAGE+1
      IF(WELF.LE.0.0.AND.PROP2.LE.0.0) GO TO 72
C     FIT TRANSITION FUNCTION FOR STATE 2
      DO 70 I=1,ND
      DO 70 N=2,NSS
      NN=N-1
      NC=NN+(I-1)*NSTAGE
      Y(NC)=STATES(I,N,1)-STATES(I,NN,1)
```

```
      X(NC,1)=1.
      X(NC,2)=STATES(I,NN,9)
      X(NC,3)=X(NC,2)**2
      X(NC,4)=DECIS(I,NN,1)
      X(NC,5)=X(NC,4)**2
      DO 60 J=3,6
      J3=J+3
      J7=J+7
      X(NC,J3)=DECIS(I,NN,J)
   60 X(NC,J7)=X(NC,J3)**2
   70 CCNTINUE
C     CALL CURVE FITTING ROUTINE
      CALL CURFIT(Y,X,BP,NC,13)
      NMOD=NMOD+1
      IF(NSTOP.EQ.1) WRITE(6,100) NMOD
      IF(NSTOP.EQ.1) STOP
   72 CCNTINUE
      DO 75 N=1,13
      IF(WELF.LE.0.0.AND.PROP2.LE.0.0)B1(N)=0.0
      IF(WELF.GT.0.0.AND.PROP2.GT.0.0)B1(N)=BP(N)
   75 CONTINUE
      IF(DV.LE.0.0.AND.PROP3.LE.0.0) GO TO 87
C     FIT TRANSITICN FUNCTION FCR STATE 3
      DO 85 I=1,ND
      DO 85 N=2,NSS
      NN=N-1
      NC=NN+(I-1)*NSTAGE
      X(NC,1)=1.
      Y(NC)=STATES(I,N,3)-STATES(I,NN,3)
      X(NC,2)=STATES(I,NN,4)
      X(NC,3)=X(NC,2)**2
      SUM=STATES(I,NN,5)+STATES(I,NN,6)+STATES(I,NN,7)+STATES(I,NN,8)+
```

```
     1 STATES(I,NN,9)
      X(NC,4)=SUM
      X(NC,5)=SUM*SUM
      X(NC,6)=DECIS(I,NN,1)
      DO 80 J=3,13
      J4=J+4
      IF(J.GT.7) J4=J+3
      IF(J.EQ.7) GO TO 80
      X(NC,J4)=DECIS(I,NN,J)
   80 CONTINUE
      X(NC,17)=STATES(I,NN,10)
   85 CONTINUE
C     CALL CURVE FITTING ROUTINE
      CALL CURFIT(Y,X,BP,NC,17)
      NMOD=NMOD+1
      IF(NSTOP.EQ.1) WRITE(6,100) NMOD
      IF(NSTOP.EQ.1) STOP
   87 CONTINUE
      DO 90 N=1,17
      IF(DV.LE.0.0.AND.PROP3.LE.0.0) B3(N)=0.
      IF(DV.GT.0.0.AND.PROP3.GT.0.0) B3(N)=BP(N)
   90 CONTINUE
C     FIT TRANSITION FUNCTION FOR STATE 5
      DO 95 I=1,ND
      DO 95 N=2,NSS
      NN=N-1
      NC=NN+(I-1)*NSTAGE
      X(NC,1)=1.
      X(NC,2)=STATES(I,NN,4)
      X(NC,3)=X(NC,2)**2
   95 Y(NC)=STATES(I,N,5)
C     CALL CURVE FITTING ROUTINE
```

```
      CALL CURFIT(Y,X,BP,NC,3)
      NMOD=NMOD+1
      IF(NSTOP.EQ.1) WRITE(6,100) NMOD
      IF(NSTOP.EQ.1) STOP
  100 FORMAT(10H IN CURFIT,I2)
      DO 105 N=1,3
  105 B5(N)=BP(N)
C     FIT TRANSITION FUNCTION FOR STATE 6
      DO 115 I=1,NC
      DO 115 N=2,NSS
      NN=N-1
      NC=NN+(I-1)*NSTAGE
      SUM=0.
      DO 110 J=5,9
  110 SUM=SUM+STATES(I,NN,J)
      Y(NC)=STATES(I,N,6)
      X(NC,1)=1.
      X(NC,2)=SUM
      X(NC,3)=SUM*SUM
      X(NC,4)=DECIS(I,NN,1)
      X(NC,5)=DECIS(I,NN,2)
      X(NC,6)=DECIS(I,NN,7)
      X(NC,7)=STATES(I,NN,10)
      DO 115 J=1,7
  115 X(NC,J)=X(NC,J)*STATES(I,NN,6)
C     CALL CURVE FITTING ROUTINE
      CALL CURFIT(Y,X,BP,NC,7)
      NMOD=NMOD+1
      IF(NSTOP.EQ.1) WRITE(6,100) NMOD
      IF(NSTOP.EQ.1) STOP
      DO 120 N=1,7
  120 B6(N)=BP(N)
```

```
C     FIT TRANSITION FUNCTIONS FOR STATES 7,8, AND 9
      DO 140 IK=7,9
      DO 135 I=1,ND
      DO 135 N=2,NSS
      NN=N-1
      NC=NN+(I-1)*NSTAGE
      SUM=0.
      DO 125 J=5,9
  125 SUM=SUM+STATES(I,NN,J)
      Y(NC)=STATES(I,N,IK)
      X(NC,1)=1.
      X(NC,2)=STATES(I,NN,4)
      X(NC,3)=X(NC,2)**2
      X(NC,4)=SUM
      X(NC,5)=SUM*SUM
      X(NC,6)=DECIS(I,NN,1)
      DO 130 J=1,3
      JI=J+7
      JJ=J+6
      IF(IK.EQ.8) JI=J+10
      IF(IK.EQ.9) JI=J+2
  130 X(NC,JJ)=DECIS(I,NN,JI)
      X(NC,10)=STATES(I,NN,10)
      IF(IK.EQ.9) X(NC,10)=DECIS(I,NN,6)
      DO 134 J=1,10
  134 X(NC,J)=STATES(I,NN,IK)*X(NC,J)
  135 CONTINUE
C     CALL CURVE FITTING ROUTINE
      CALL CURFIT(Y,X,BP,NC,10)
      NMOD=NMOD+1
      IF(NSTOP.EQ.1) WRITE(6,100) NMOD
      IF(NSTOP.EQ.1) STOP
```

```
      DO 140 N=1,10
      IF(IK.EQ.7) B7(N)=BP(N)
      IF(IK.EQ.8) B8(N)=BP(N)
      IF(IK.EQ.9) B9(N)=BP(N)
  140 CCNTINUE
C     FIT TRANSITICN FUNCTION FOR STATE 10
      DC 150 I=1,ND
      DO 150 N=2,NSS
      NN=N-1
      NC=NN+(I-1)*NSTAGE
      SUM=0.
      DO 145 J=6,8
  145 SUM=SUM+STATES(I,NN,J)
      Y(NC)=STATES(I,N,10)
      X(NC,1)=1.
      X(NC,2)=STATES(I,NN,4)
      X(NC,3)=X(NC,2)**2
      X(NC,4)=SUM
      X(NC,5)=SUM*SUM
      X(NC,6)=STATES(I,NN,10)
      X(NC,7)=X(NC,6)**2
      X(NC,8)=DECIS(I,NN,1)
      X(NC,9)=DECIS(I,NN,2)
      DO 150 J=7,13
      J3=J+3
  150 X(NC,J3)=DECIS(I,NN,J)
C     CALL CURVE FITTING ROUTINE
      CALL CURFIT(Y,X,BP,NC,16)
      NMOD=NMOD+1
      IF(NSTOP.EQ.1) WRITE(6,100) NMOD
      IF(NSTOP.EQ.1) STOP
      DO 155 N=1,16
```

```
  155 B10(N)=BP(N)
C     FIT TRANSITICN FUNCTION FOR STATE 11
      DO 170 I=1,ND
      DO 170 N=2,NSS
      NN=N-1
      NC=NN+(I-1)*NSTAGE
      PRRP3=0.
      IF(N.EQ.NSS) PRRP3=PROP3
      Y(NC)=Y(NC)-(PROP2*(STATES(I,N,1)-STATES(I,NN,1))+PRRP3*STATES(I,N
     1,3)+PROP4*STATES(I,N,10))*(10.**(-10))
      IF(PROP1.GT.0.0) Y(NC)=Y(NC)/PROP1
      IF(PROP1.LE.0.0) Y(NC)=0.
      SUM=0.
      DO 160 J=6,8
  160 SUM=SUM+STATES(I,NN,J)
      SUM=SUM/(STATES(I,NN,10)+EPSIL)
      X(NC,1)=1.
      X(NC,2)=DECIS(I,NN,1)
      X(NC,3)=X(NC,2)**2
      X(NC,4)=DECIS(I,NN,2)
      X(NC,5)=X(NC,4)**2
      DO 165 J=7,13
      J1=J-1
      J6=J+6
      X(NC,J1)=DECIS(I,NN,J)
  165 X(NC,J6)=X(NC,J1)**2
      DO 170 J=1,19
  170 X(NC,J)=X(NC,J)*SUM
      IF(PROP1.LE.0.0) GO TO 174
C     CALL CURVE FITTING ROUTINE
      CALL CURFIT(Y,X,BP,NC,19)
      NMOD=NMOD+1
```

```
      IF(NSTOP.EQ.1) WRITE(6,100) NMOD
      IF(NSTOP.EQ.1) STOP
  174 CONTINUE
      DO 175 J=1,19
      IF(PROP1.LE.0.0) B11(J)=0.
      IF(PROP1.GT.0.0) B11(J)=BP(J)
  175 CONTINUE
C     CALCULATE SEQUENCE OF STATE VARIABLES AS PREDICTED BY TRANSITION FUNCTIONS
      DO 200 N=2,NSS
      NN=N-1
      AG=S(NN,2)+COST*DEC(NN,2)
      IF(AG.GE. BDG) DEC(NN,2)=0.
      DO 180 J=1,13
  180 BP(J)=S(NN,J)
      CALL STATE
      DO 185 J=1,13
  185 BP(J)=DEC(NN,J)
      CALL CALC
      BP(1)=Z(1)+Q(1)
      BP(2)=COST*DEC(NN,2)
      BP(3)=Z(3)+Q(3)+S(NN,3)
      BP(4)=1.
      BP(5)=Z(5)
      DO 190 J=6,9
  190 BP(J)=S(NN,J)*(Z(J)+Q(J))
      BP(10)=Z(10)+Q(10)
      BP(11)=Z(11)*Q(11)/(S(NN,10)+EPSIL)
      DO 200 J=1,11
      IF(BP(J).GT.SMAX(J)) BP(J)=SMAX(J)
      IF(BP(J).LT.0.0) BP(J)=0.
      IF(J.EQ.1.OR.J.EQ.2.OR.J.EQ.4.OR.J.EQ.11.OR.J.EQ.3) GO TO 195
      S(N,J)=BP(J)
```

```
      GO TO 200
  195 S(N,J)=S(NN,J)+BP(J)
      IF(J.EQ.11) S(N,J)=S(N,J)+BP(1)*PROP2
      PRRP3=0.
      IF(N.EQ.NSS) PRRP3=PROP3
      IF(J.EQ.11) S(N,J)=S(N,J)+PRRP3*S(N,3)+PROP4*S(N,10)
  200 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE OPT(S,LAM,Y,IK,IOPT)
C     ROUTINE FOR FINDING THE OPTIMAL DECISION POLICY FOR THE TRANSITION
C     FUNCTIONS BY USING A POLICY IMPROVEMENT ALGORITHM AND THE DISCRETE MAXIMUM
C     PRINCIPLE
C
C     AINV                SQUARE MATRIX FOR SOLUTION OF SIMULTANEOUS EQUATIONS
C     DHT(I,J)            PARTIAL DERIVATIVE OF TERMINALLY CONSTRAINED STATE I
C                         (I=1,2,3) WITH RESPECT TO DECISION VARIABLE J (J=1,2,3)
C                         DHT(I,4) EQUALS THE NEGATIVE SLACKS
C     Y                   WORK VECTOR
C     A                   WORK MATRIX
C     AP                  WORK VECTOR
C     BP                  WORK VECTOR
C     Z                   WORK VECTOR OF THE SUM OF THE PRODUCTS OF EACH STATE
C                         VARIABLE (TO ITS APPROPRIATE POWER) AND ITS PARAMETER
C     Q                   WORK VECTOR OF THE SUM OF THE PRODUCTS OF EACH DECISION
C                         VARIABLE (TO ITS APPROPRIATE POWER) AND ITS PARAMETER
C     DTT(I)              PARTIAL DERIVATIVE OF TERMINAL OBJECTIVE STATE WITH
C                         RESPECT TO DECISION I
C     DTS(I,J)            PARTIAL DERIVATIVE OF TRANSITION FUNCTION I WITH
C                         RESPECT TO STATE J
C     LAM(I,J)            STATE DERIVATIVE ASSOCIATED WITH TRANSITION J AT TIME I
C     DCC(I,J)            TEMPORARY MATRIX OF DECISION VARIABLES
      COMMON/APCP/PROP1,PROP2,PROP3,PROP4
      COMMON/MCGF/DCC(24,13),B1(13),B3(17),B5(3),B6(7),B7(10),B8(10),
     1B9(12),B10(16),B11(19),Z(11),Q(11),DHT(3,4),DTT(3),SLACK(3),BP(19)
      COMMON/ALL/CEC(24,13)
      COMMON/MM/DMAX(13),SMAX(11),NOPT,IOUT(80),IT
      COMMON/SMC/NSTOP
      COMMON/SQ/SSQR(11),BDG,WELF,DV
      COMMON/MMOF/MAXIT,MNEWT,DNEWT,DELTA,DGRAD,MGRAD
      COMMON/ABDF/NSTAGE
```

```
      COMMON/ABR/CCST
      COMMON/NBH/EPSIL
      DOUBLE PRECISION AINV(19,19),S(25,11),LAM(25,11),SUM,DTS(11,10),
     1 Y(120)
      DIMENSION A(3,4),AP(24)
      NSS=NSTAGE+1
      IF(IOUT(IT).NE.1) GO TO 25
C     IF APPROPRIATE, PRINT TRANSITION FUNCTION PARAMETERS VALUES
      NMOD=1
      WRITE(6,500) NMOD,(B1(I),I=1,13)
      NMOD=NMOD+2
      WRITE(6,500) NMOD,(B3(I),I=1,17)
      NMOD=NMOD+2
      WRITE(6,500) NMOD,(B5(I),I=1,3)
      NMOD=NMOD+1
      WRITE(6,500) NMOD,(B6(I),I=1,7)
      NMOD=NMOD+1
      WRITE(6,500) NMOD,(B7(I),I=1,10)
      NMOD=NMOD+1
      WRITE(6,500) NMOD,(B8(I),I=1,10)
      NMOD=NMOD+1
      WRITE(6,500) NMOD,(B9(I),I=1,10)
      NMOD=NMOD+1
      WRITE(6,500) NMOD,(B10(I),I=1,16)
      NMOD=NMOD+1
      WRITE(6,500) NMOD,(B11(I),I=1,19)
  500 FORMAT(46H PARAMETER VALUES FOR TRANSITION FUNCTION NO. ,I2/5(3X,E
     115.7))
   25 CONTINUE
C     DO FOR MGRAD NUMBER OF INNER LOOP ITERATIONS ( POLICY IMPROVEMENT ITERA-
C     TIONS)
      DO 2000 IOPT=1,MGRAD
```

```
      DO 35 I=1,NSTAGE
      DO 35 J=1,13
   35 DEC(I,J)=DCC(I,J)
C     ADJUST THE DECISIONS SO THAT THE TERMINAL CONSTRAINTS ARE MET. THIS IS
C     DONE BY PERFORMING THE NEWTON-RAPHSON PROCEDURE FOR SOLVING NONLINEAR
C     SIMULTANEOUS EQUATIONS. THE N-R PROCEDURE IS ITERATIVE AND WILL BE DONE
C     FOR "MNEWT" NUMBER OF ITERATIONS
      DO 315 ITK=1,MNEWT
      DO 272 M=1,3
      SLACK(M)=-1000.
      BP(M)=0.
      DO 272 IR=1,3
      AINV(M,IR)=0.
  272 DHT(M,IR)=0.
C     DEFINE DHT
      DHT(1,1)=B1(4)+2.*B1(5)*DEC(NSTAGE,1)
      DHT(1,3)=B1(6)+2.*B1(10)*DEC(NSTAGE,3)
      DHT(2,2)=COST
      DHT(3,3)=B3(7)
      DHT(3,1)=B3(6)
      DHT(1,4)=WELF-S(NSS,1)
      DHT(2,4)=BDG-S(NSS,2)
      DHT(3,4)=DV-S(NSS,3)
      IF(DHT(1,4).LE.0.0) SLACK(1)=-DHT(1,4)
      IF(DHT(2,4).GE.0.0) SLACK(2)=DHT(2,4)
      IF(DHT(3,4).LE.0.0) SLACK(3)=-DHT(3,4)
      JJ=0
      II=0
      DO 297 I=1,3
      IF(SLACK(I).GE.0.0) GO TO 297
      II=II+1
      JJ=0
```

```
      DO 296 J=1,3
      IF(SLACK(J).GE.0.0) GO TO 296
      JJ=JJ+1
      A(II,JJ)=DHT(I,J)
  296 CONTINUE
      A(II,4)=DHT(I,4)
  297 CONTINUE
      II=II+1
      IF(JJ.EQ.0) GO TO 318
      DO 298 J=1,JJ
  298 A(J,II)=A(J,4)
C     SOLVE SIMULTANEOUS LINEAR EQUATIONS
      CALL SIMULT(AINV,A,AP,JJ,JJ,II)
      IF(NSTOP.EQ.1) GO TO 318
      DO 301 I=1,3
      DO 301 J=1,3
      A(I,J)=AINV(I,J)
  301 AINV(I,J)=0.
      II=0
      DO 305 I=1,3
      IF(SLACK(I).GE.0.0) GO TO 305
      JJ=0
      II=II+1
      DO 302 J=1,3
      IF(SLACK(J).GE.0.0) GO TO 302
      JJ=JJ+1
      AINV(I,J)=A(II,JJ)
  302 CONTINUE
      BP(I)=AP(II)
  305 CONTINUE
      NF=0
      DO 307 I=1,3
```

```
C     ADJUST DECISIONS BY RESULTS OF N-R METHOD
      AP(I)=DEC(NSTAGE,I)+BP(I)
      IF(AP(I).LT.0.0) AP(I)=0.
      IF(AP(I).GT.DMAX(I)) AP(I)=DMAX(I)
C     CHECK N-R CONVERGENCE CRITERION
      IF(ABS(AP(I)-DEC(NSTAGE,I)).GT.DNEWT) NF=1
      DEC(NSTAGE,I)=AP(I)
  307 CONTINUE
      DO 310 J=1,13
  310 BP(J)=DEC(NSTAGE,J)
      CALL CALC
      DO 311 J=1,11
  311 BP(J)=S(NSTAGE,J)
      CALL STATE
      S(NSS,1)=S(NSTAGE,1)+Z(1)+Q(1)
      S(NSS,2)=S(NSTAGE,2)+COST*DEC(NSTAGE,2)
      S(NSS,3)=Z(3)+Q(3)+S(NSTAGE,3)
      IF(NF.NE.1) GO TO 318
  315 CONTINUE
C     DEFINE DTT
  318 DTT(3)=PROP2*(B1(6)+2.*B1(10)*DEC(NSTAGE,3))
      DTT(3)=DTT(3)+PROP3*B3(7)*DEC(NSTAGE,3)
      SUM=S(NSTAGE,6)+S(NSTAGE,7)+S(NSTAGE,8)
      SUM=SUM/(S(NSTAGE,10)+EPSIL)
      DTT(1)=SUM*(B11(2)+2.*B11(3)*DEC(NSTAGE,1))
      DTT(1)=PROP1*DTT(1)+PROP2*(B1(4)+2.*B1(5)*DEC(NSTAGE,1))
      DTT(2)=SUM*(B11(4)+2.*B11(5)*DEC(NSTAGE,2))
      DTT(2)=DTT(2)*PROP1
C     CALCULATE THE FINAL STAGE STATE DERIVATIVES FOR THE TERMINALLY CONSTRAINED
C     STATES
  333 LAM(NSS,11)=1.
      DO 330 J=4,10
```

```
  330 LAM(NSS,J)=0.
      DO 335 IP=1,3
      LAM(NSS,IP)=0.
      DO 335 M=1,3
      DO 335 IR=1,3
      HS=0.
      IF(IR.EQ.IP) HS=1.
  335 LAM(NSS,IP)=LAM(NSS,IP)+DTT(M)*HS*AINV(M,IR)
      DO 340 I=1,11
      DO 340 J=1,10
      DTS(I,J)=0.
      IF(J.EQ.1.OR.J.EQ.2.OR.J.EQ.4.AND.J.EQ.I) DTS(J,J)=1.
      IF(J.EQ.3.AND.J.EQ.I) DTS(I,J)=1.
  340 CONTINUE
C     DO FOR ALL STAGES FROM THE LAST STAGE TO THE FIRST
      DO 1000 N=1,NSTAGE
      PRRP2=PROP3
      NN=NSTAGE+1-N
      NPLUS=NN+1
      DO 465 J=1,13
  465 Y(J)=DEC(NN,J)
  472 NVAR=13
      PRRP3=PROP3
      PROP3=0.
      IF(NN.EQ.NSTAGE)PROP3=PRRP3
C     CALL THE SUBROUTINE WHICH FORMS THE HAMILTONIAN FUNCTION FOR THIS STAGE
C     AND CALCULATES THE STATIONARY POINT
      CALL STATPT(NVAR,NN,LAM,S,AP,Y)
      DO 485 J=1,13
      IF(Y(J).LT.0.0) Y(J)=0.
      AG=Y(J)
      IF(AG.GT.DMAX(J))Y(J)=DMAX(J)
```

```
  485 DEC(NN,J)=Y(J)
      DO 345 J=1,13
  345 BP(J)=DEC(NN,J)
      CALL CALC
      DO 350 J=1,11
  350 BP(J)=S(NN,J)
      CALL STATE
C     CALCULATE THE TRANSITION DERIVATIVES, DTS, FOR THIS STAGE
      DTS(1,9)=B1(2)+2.*B1(3)*S(NN,9)
      DTS(3,4)=B3(2)+2.*B3(3)*S(NN,4)
      SUM=S(NN,5)+S(NN,6)+S(NN,7)+S(NN,8)+S(NN,9)
      DTS(5,4)=B5(2)+2.*B5(3)*S(NN,4)
      DTS(7,4)=S(NN,7)*(B7(2)+2.*B7(3)*S(NN,4))
      DTS(8,4)=S(NN,8)*(B8(2)+2.*B8(3)*S(NN,4))
      DTS(9,4)=S(NN,9)*(B9(2)+2.*B9(3)*S(NN,4))
      DTS(10,4)=B10(2)+2.*B10(3)*S(NN,4)
      DO 355 J=5,9
      DTS(3,J)=B3(4)+2.*B3(5)*SUM
      DTS(6,J)=S(NN,6)*(B6(2)+2.*B6(3)*SUM)
      DTS(7,J)=S(NN,7)*(B7(4)+2.*B7(5)*SUM)
      DTS(8,J)=S(NN,8)*(B8(4)+2.*B8(5)*SUM)
      DTS(9,J)=S(NN,9)*(B9(4)+2.*B9(5)*SUM)
  355 DTS(10,J)=B10(4)+2.*B10(5)*(S(NN,6)+S(NN,7)+S(NN,8))
      DTS(10,5)=0.
      DTS(10,9)=0.
      DTS(10,10)=B10(6)+2.*B10(7)*S(NN,10)
      DB=Q(11)/(S(NN,10)+EPSIL)
      DB=DB*PROP1
      DTS(11,9)=PROP2*(B1(2)+2.*B1(3)*S(NN,9))
      DO 360 J=6,8
  360 DTS(11,J)=DB
      DTS(11,10)=-DB*Z(11)/(S(NN,10)+EPSIL)
```

```
      DTS(11,10)=DTS(11,10)+PROP3*B3(17)
      DTS(11,4)=DTS(11,4)+PROP3*(2.*S(NN,4)*B3(3)+B3(2))
      DTS(11,4)=DTS(11,4)+PROP4*(B10(2)+2.*S(NN,4)*B10(3))
      DTS(11,3)=PRCP3
      DO 361 J=6,9
  361 DTS(J,J)=DTS(J,J)+Z(J)+Q(J)
      DTS(3,10)=B3(17)
      DTS(6,10)=S(NN,6)*B6(7)
      DTS(7,10)=S(NN,7)*B7(10)
      DTS(8,10)=S(NN,8)*B8(10)
      DO 362 J=5,9
  362 DTS(11,J)=DTS(11,J)+PRCP3*(B3(4)+2.*B3(5)*SUM)
      SUM=PROP4*(B10(4)+2.*B10(5)*(S(NN,6)+S(NN,7)+S(NN,8)))
      DC 363 J=6,8
  363 DTS(11,J)=DTS(11,J)+SUM
      DTS(11,10)=DTS(11,10)+PROP4*(B10(6)+B10(7)*2.*S(NN,10))
C     CALCULATE THE STATE DERIVATIVES, LAM, FOR THIS STAGE
      LAM(NN,11)=1.
      DO 370 IP=1,10
      LAM(NN,IP)=0.
      DO 365 I=1,11
  365 LAM(NN,IP)=LAM(NN,IP)+LAM(NPLUS,I)*DTS(I,IP)
      IF(LAM(NN,IP).GT.1D40) LAM(NN,IP)=1D40
      IF(LAM(NN,IP).LT.(-1D40)) LAM(NN,IP)=-1D40
  370 CCNTINUE
      PRCP3=PRRP2
 1000 CONTINUE
 1200 FORMAT(10X,9HDECISIONS,10X,17HSTATE DERIVATIVES,10X,15HSTATE VARIA
     1BLES)
 1300 FORMAT(3X,I2,3X,E13.6,10X,E13.6,14X,E13.6,5X,E13.6,5X,E13.6)
 1350 FORMAT(3X,I2,3X,E13.6,55X,E13.6,5X,E13.6)
C     THE FOLLOWING SECTION CHECKS TO SEE IF IMPROVEMENT IN THE OBJECTIVE HAS
```

```
C      OCCURRED. IF IT HAS NOT, DECISIONS ARE ADJUSTED. THIS ADJUSTMENT WILL BE
C      DONE A MAXIMUM OF 6 TIMES WITHOUT IMPROVEMENT
       IK=-1
 1540  IK=IK+1
C      FIRST CALCULATE STEP-SIZE
       XGRAD=1.1*(0.1**IK)
       IF(IK.LE. 5) GO TO 1545
C      IF 6 ADJUSTMENTS HAVE BEEN MADE WITHOUT IMPROVEMENT, RETURN TO SUBROUTINE
C      MJOB
       DO 1541 I=1,NSTAGE
       DO 1541 J=1,13
 1541  DCC(I,J)=DEC(I,J)
       RETURN
 1545  CONTINUE
       DO 1550 J=1,11
 1550  Y(J)=S(1,J)
       PRRP3=PROP3
       DO 1750 N=2,NSS
       NN=N-1
       DO 1600 J=1,13
       DC=DCC(NN,J)
C      ADJUST THE DECISIONS
       IF(DEC(NN,J).LT.DC) DC=DEC(NN,J)
       DEC(NN,J)=DC+XGRAD*ABS(DEC(NN,J)-DCC(NN,J))
 1600  BP(J)=DEC(NN,J)
C      CALCULATE SEQUENCE OF STATE VARIABLES
       CALL CALC
       DO 1625 J=1,11
 1625  BP(J)=S(NN,J)
       CALL STATE
       AT=Y(1)
       Y(1)=Z(1)+Q(1)
```

```
      Y(2)=Y(2)+COST*DEC(NN,2)
      Y(3)=Z(3)+Q(3)+Y(3)
      Y(4)=Y(4)+1.
      Y(5)=Z(5)
      DO 1650 J=6,9
 1650 Y(J)=Y(J)*(Z(J)+Q(J))
      AZ=Z(11)*Q(11)/(Y(10)+EPSIL)
      Y(10)=Z(10)+Q(10)
      IF(AZ.GT.1E-10) AZ=10.**(-10)
      IF(AZ.LT.0.0) AZ=0.
      DO 1700 J=1,10
      IF(J.EQ.2.OR.J.EQ.4) GO TO 1700
      AG=Y(J)
      IF(AG.GT.SMAX(J)) Y(J)=SMAX(J)
      IF(Y(J).LT.0.0) Y(J)=0.
 1700 CONTINUE
      PROP3=0.
      IF(N.EQ.NSS) PROP3=PRRP3
      AZ=AZ*PROP1+PROP2*Y(1)
      AZ=AZ+PROP3*Y(3)+PROP4*Y(10)
      Y(1)=Y(1)+AT
      Y(11)=Y(11)+AZ
 1750 CONTINUE
      NF=1
      DO 1760 I=1,3
 1760 BP(I)=Y(I)
C     CHECK TERMINAL CONSTRAINTS
      IF(BP(1).LT.WELF) NF=0
      IF(BP(2).GT.BDG) NF=0
      IF(BP(3).LT.DV) NF=0
      AZ=Y(11)-S(NSS,11)
      IF(NF.EQ.0) GO TO 1540
```

```
C     CHECK IMPROVEMENT
      IF(NF.EQ.1.AND.AZ.LT.0.0) GO TO 1540
      DO 1850 I=1,NSTAGE
      DO 1850 J=1,13
 1850 DCC(I,J)=DEC(I,J)
      IF(S(NSS,11).GT.0.0) AZ=ABS(AZ)/S(NSS,11)
      IF(S(NSS,11).LE.0.0) AZ=DGRAD+1.
      IF(IOUT(IT).EQ.1.AND.IOPT.GT.18) WRITE(6,50) IOPT,IK
   50 FORMAT(5X,23HINNER LOOP ITERATION = ,I2,10X,5HIK = ,I2)
      PRRP3=PROP3
      DO 1950 N=2,NSS
      NN=N-1
      NPLUS=N
C     CALCULATE SEQUENCE OF STATE VARIABLES
      DO 1875 J=1,11
 1875 BP(J)=S(NN,J)
      CALL STATE
      DO 1900 J=1,13
 1900 BP(J)=DCC(NN,J)
      CALL CALC
      S(N,1)=Z(1)+Q(1)
      S(N,2)=S(NN,2)+COST*DCC(NN,2)
      S(N,3)=Z(3)+Q(3)+S(NN,3)
      S(N,4)=S(NN,4)+1.
      S(N,5)=Z(5)
      DO 1925 J=6,9
 1925 S(N,J)=S(NN,J)*(Q(J)+Z(J))
      S(N,10)=Z(10)+Q(10)
      S(N,11)=Z(11)*Q(11)/(S(NN,10)+EPSIL)
      DO 1935 J=1,11
      IF(J.EQ.2.OR.J.EQ.4) GO TO 1935
      AG=S(N,J)
```

```
      IF(AG.LT.0.0) S(N,J)=0.
      IF(AG.GT.SMAX(J)) S(N,J)=SMAX(J)
 1935 CONTINUE
      PROP3=0.
      IF(N.EQ.NSS) PROP3=PRRP3
      S(N,11)=S(NN,11)*PROP1+S(N,1)*PROP2
      S(N,11)=S(N,11)+PROP3*S(N,3)
      S(N,11)=S(N,11)+PROP4*S(N,10)
      S(N,1)=S(NN,1)+S(N,1)
C     PRINT RESULTS OF THIS ITERATION, IF APPROPRIATE
      IF(IOUT(IT).NE.1) GO TO 1950
      IF(IOPT.LE.18) GO TO 1950
      IF(IOUT(IT).EQ.1) WRITE(6,1500) NN
 1500 FORMAT(16H STAGE NUMBER = ,I2)
      DO 375 I=1,13
      II=26+I
      Y(I)=DCC(NN,I)
      IF(I.GT.11) GO TO 375
      Y(II)=LAM(NPLUS,I)
  375 CONTINUE
      WRITE(6,1200)
      DO 380 I=1,13
      II=26+I
      IF(I.GT.11) WRITE(6,1350) I,Y(I)
      IF(I.LE.11)WRITE(6,1300)I,Y(I),Y(II),S(NPLUS,I)
  380 CONTINUE
 1950 CONTINUE
C     CHECK CONVERGENCE CRITERION FOR POLICY IMPROVEMENT ALGORITHM
      IF(NF.EQ.1.AND.AZ.LT.DGRAD) RETURN
 2000 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE STATE
C     SUBROUTINE FOR CALCULATING THE WORK VECTOR, Z(I), WHICH IS THE SUM OF THE
C     PRODUCTS OF EACH STATE VARIABLE TO ITS PROPER EXPONENT TIMES ITS PARAMETER
C     FOR THE "ITH" STATE TRANSITION FUNCTION
C
      CCMMON/MCGF/CEC(24,13),B1(13),B3(17),B5(3),B6(7),B7(10),B8(10),
     1B9(12),B10(16),B11(19),Z(11),Q(11),DHT(3,4),DTT(3),SLACK(3), Y(19)
      SUM=Y(5)+Y(6)+Y(7)+Y(8)+Y(9)
      S2=SUM**2
      ST=Y(4)
      ST2=ST*ST
      Z(1)=B1(1)+B1(2)*Y(9)+B1(3)*Y(9)**2
      Z(3)=B3(1)+B3(2)*ST+B3(3)*ST2+B3(4)*SUM+B3(5)*S2+B3(17)*Y(10)
      Z(5)=B5(1)+B5(2)*ST+B5(3)*ST2
      Z(6)=B6(1)+B6(2)*SUM+B6(3)*S2+B6(7)*Y(10)
      Z(7)=B7(1)+B7(2)*ST+B7(3)*ST2+B7(4)*SUM+B7(5)*S2+B7(10)*Y(10)
      Z(8)=B8(1)+B8(2)*ST+B8(3)*ST2+B8(4)*SUM+B8(5)*ST2+B8(10)*Y(10)
      Z(9)=B9(1)+B9(2)*ST+B9(3)*ST2+B9(4)*SUM+B9(5)*S2
      Z(10)=B10(1)+B10(2)*ST+B10(3)*ST2+B10(6)*Y(10)+B10(7)*Y(10)**2
      SUM=Y(6)+Y(7)+Y(8)
      Z(10)=Z(10)+B10(4)*SUM+B10(5)*SUM*SUM
      Z(11)=SUM
      RETURN
      END
```

```
      SUBROUTINE CALC
C     SUBROUTINE FCR CALCULATING THE WORK VECTOR, Q(I), WHICH IS THE SUM OF THE
C     PRODUCTS OF EACH DECISION VARIABLE TO ITS PROPER EXPONENT TIMES ITS
C     PARAMETER FOR THE "ITH" STATE TRANSITION FUNCTION
C
      COMMON/MCGF/CEC(24,13),B1(13),B3(17),B5(3),B6(7),B7(10),B8(10),
     1B9(12),B10(16),B11(19),Z(11),Q(11),DHT(3,4),DTT(3),SLACK(3), Y(19)
      CCMMON/ABR/COST
      Q(1)=B1(4)*Y(1)+B1(5)*Y(1)**2
      DO 10 J=3,6
      J3=J+3
      J7=J+7
   10 Q(1)=Q(1)+B1(J3)*Y(J)+B1(J7)*Y(J)*Y(J)
      Q(2)=COST*Y(2)
      Q(3)=B3(6)*Y(1)
      DO 15 J=3,13
      J4=J+4
      IF(J.GT.7) J4=J+3
      IF(J.EQ.7) GO TO 15
      Q(3)=Q(3)+B3(J4)*Y(J)
   15 CCNTINUE
      Q(6)=B6(4)*Y(1)+B6(5)*Y(2)+B6(6)*Y(7)
      Q(7)=B7(6)*Y(1)+B7(7)*Y(8)+B7(8)*Y(9)+B7(9)*Y(10)
      Q(8)=B8(6)*Y(1)+B8(7)*Y(11)+B8(8)*Y(12)+B8(9)*Y(13)
      Q(9)=B9(6)*Y(1)+B9(7)*Y(3)+B9(8)*Y(4)+B9(9)*Y(5)+B9(10)*Y(6)
      Q(10)=B10(8)*Y(1)+B10(9)*Y(2)
      DO 20 J=7,13
      J3=J+3
   20 Q(10)=Q(10)+B10(J3)*Y(J)
      Q(11)=B11(1)+B11(2)*Y(1)+B11(3)*Y(1)*Y(1)+B11(4)*Y(2)+B11(5)*Y(2)*
     1*2
      DO 25 J=7,13
```

```
      J1=J-1
      J6=J+6
   25 Q(11)=Q(11)+B11(J1)*Y(J)+B11(J6)*Y(J)*Y(J)
      RETURN
      END
```

```
      SUBROUTINE STATPT(N,NN,LAM,S,A,Y)
C     ROUTINE FOR FORMING THE HAMILTONIAN FUNCTION AND CALCULATING THE
C     STATIONARY PCINT
C
C     Y                       STATIONARY POINT ( NEW DECISION VECTOR)
C     A,B                     WORK VECTORS WHERE Y=-A/B
C
      COMMCN/APOP/PROP1,PROP2,PROP3,PRCP4
      COMMON/MCGF/DEC(24,13),B1(13),B3(17),B5(3),B6(7),B7(10),B8(10),
     1B9(12),B10(16),B11(19),Z(11),Q(11),DHT(3,4),DTT(3),SLACK(3),B(19)
      CCMMON/ABDF/NSTAGE
      CCMMON/ABR/COST
      CCMMCN/NBH/EPSIL
      CCMMCN/MM/DMAX(13),SMAX(11),NOPT,IOUT(80),IT
      DIMENSION A(24)
      DOUBLE PRECISION S(25,11),LAM(25,11),S3,S7,S8,S9,Y(120)
      NT=NN+1
      SUM=Z(11)*PRCP1/(S(NN,10)+EPSIL)
C     ESTABLISH A AND B VECTORS
      A(1)=LAM(NT,1)*B1(4)+LAM(NT,3)        *B3(6)+LAM(NT,6)*S(NN,6)*B6(
     14)+LAM(NT,7)*S(NN,7)*B7(6)+LAM(NT,8)*S(NN,8)*B8(6)+LAM(NT,9)*S(NN,
     29)*B9(6)+LAM(NT,10)*B10(8)+SUM*B11(2)*LAM(NT,11)
      A(1)=A(1)+PRCP2*B1(4)
      A(2)=LAM(NT,2)*COST+LAM(NT,6)*S(NN,6)*B6(5)+LAM(NT,10)
     1*B10(9)+SUM*B11(4) *LAM(NT,11)
      S8=LAM(NT,8)*S(NN,8)
      S7=LAM(NT,7)*S(NN,7)
      S9=LAM(NT,9)*S(NN,9)
      S3=LAM(NT,3)
      A(3)=LAM(NT,1)*B1(6)+S3*B3(7)+S9*B9(7)
      A(4)=LAM(NT,1)*B1(7)+S3*B3(8)+S9*B9(8)
      A(5)=LAM(NT,1)*B1(8)+S3*B3(9)+S9*B9(9)
```

```
      A(6)=LAM(NT,1)*B1(9)+S3*B3(10)+S9*B9(10)
      DO 5 J=3,6
      J3=J+3
      J4=J+4
    5 A(J)=A(J)+PRCP2*B1(J3)+PRCP3*B3(J4)
      A(7)=LAM(NT,6)*S(NN,6)*B6(6)+LAM(NT,10)*B10(10)+SUM*B11(6)*LAM(NT,
     111)
      A(8)=S3*B3(11)+S7*B7(7)+LAM(NT,10)*B10(11)+SUM*B11(7)*LAM(NT,11)
      A(9)=S3*B3(12)+S7*B7(8)+LAM(NT,10)*B10(12)+SUM*B11(8)*LAM(NT,11)
      A(10)=S3*B3(13)+S7*B7(9)+LAM(NT,10)*B10(13)+SUM*B11(9)*LAM(NT,11)
      A(11)=S3*B3(14)+S8*B8(7)+LAM(NT,10)*B10(14)+SUM*B11(10)*LAM(NT,11)
      A(12)=S3*B3(15)+S8*B8(8)+LAM(NT,10)*B10(15)+SUM*B11(11)*LAM(NT,11)
      A(13)=S3*B3(16)+S8*B8(9)+LAM(NT,10)*B10(16)+SUM*B11(12)*LAM(NT,11)
      B(1)=LAM(NT,11)*SUM*2.*B11(3)+LAM(NT,1)*2.*B1(5)
      B(1)=B(1)+2.*PROP2*B1(5)
      DO 10 J=8,13
      J3=J+3
   10 A(J)=A(J)+PROP3*B3(J3)
      A(1)=A(1)+PRCP4*B10(8)
      A(2)=A(2)+PROP4*B10(9)
      DC 12 J=7,13
      J3=J+3
   12 A(J)=A(J)+PRCP4*B10(J3)
      B(2)=LAM(NT,11)*SUM*2.*B11(5)
      DC 15 J=7,13
      J6=J+6
   15 B(J)=LAM(NT,11)*SUM*2.*B11(J6)
      DC 20 J=3,6
      J7=J+7
   20 B(J)=LAM(NT,1)*2.*B1(J7)+PROP2*2.*B1(J7)
      CMEGA=-(10.**(-30))
      DO 35 J=1,13
```

```
      IF(B(J).GT.0.0) GO TO 32
      IF(B(J).GT.OMEGA) GO TO 30
C     CALCULATE THE STATIONARY POINT
      Y(J)=-A(J)/B(J)
      GO TO 35
C     IF B(J) APPROXIMATELY EQUALS ZERO, SET STATIONARY POINT AT A BOUNDARY
   30 IF(A(J).GE.0.0) Y(J)=0.
      IF(A(J).LT.0.0) Y(J)=DMAX(J)
      GO TO 35
   32 F=A(J)*DMAX(J)+B(J)*(DMAX(J)**2)/2.
C     IF B(J) IS GREATER THAN ZERO, NO MAXIMUM EXISTS, SO STATIONARY POINT IS
C     SET AT BOUNDARY THAT IS EXCEEDED
      Y(J)=0.
      IF(F.GT.0.0) Y(J)=DMAX(J)
   35 CONTINUE
   40 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SIMULT(   AINV,A,X,NA,NX,NAP)
C     SUBROUTINE FOR SOLVING SIMULTANEOUS LINEAR EQUATIONS FOR NEWTON-RAPHSON
C     PROCEDURE
C
      COMMON/SMC/ NSTOP
      DIMENSION A(3,4),X(24)
      DOUBLE PRECISION AINV(19,19)
      DO 10 I=1,NA
      DO 10 J=1,NA
   10 AINV(I,J)=A(I,J)
      CALL MATINV(AINV,NA)
      IF(NSTOP.EQ.1) WRITE(6,25)
   25 FORMAT(10H IN SIMULT)
      IF(NSTOP.EQ.1) RETURN
      DO 20 I=1,NX
      SUM=0.
      DO 15 J=1,NA
   15 SUM=SUM+AINV(I,J)*A(J,NAP)
   20 X(I)= SUM
      RETURN
      END
```

```
      SUBROUTINE MATINV(A,N)
C     MATRIX INVERSION SUBROUTINE USED BOTH FOR SOLVING SIMULTANEOUS LINEAR
C     EQUATIONS AND FOR THE LINEAR REGRESSION ROUTINE
C
      COMMON/SMC/ NSTOP
      DOUBLE PRECISION A(19,19),DENT(19,19),OMEGA,DENOM,AMULT
      OMEGA=10.**(-30.)
      NSTOP=0
      DO 20 I=1,N
      DO 20 J=1,N
      DENT(I,J)=A(I,J)
      IF(I.EQ.J) GO TO 10
      A(I,J)=0.
      GO TO 20
   10 A(I,J)=1.0
   20 CONTINUE
      DO 50 I=1,N
      IF(DABS(DENT(I,I)).LE.OMEGA) GO TO 60
      DENOM=DENT(I,I)
      DO 30 J=1,N
      DENT(I,J)=DENT(I,J)/DENOM
   30 A(I,J)=A(I,J)/DENOM
      DO 50 K=1,N
      IF(K.EQ.I) GO TO 50
      AMULT=DENT(K,I)
      DO 40 J=1,N
      DENT(K,J)=DENT(K,J)-DENT(I,J)*AMULT
   40 A(K,J)=A(K,J)-A(I,J)*AMULT
   50 CONTINUE
      RETURN
   60 WRITE(6,70)
   70 FORMAT(16H SINGULAR MATRIX)
```

```
NSTOP=1
RETURN
END
```

```
      SUBROUTINE CURFIT(Y,X,BP,ND,NV)
C     MULTIPLE LINEAR REGRESSION ROUTINE BY WHICH TRANSITIONS EQUATIONS ARE FIT
C
      COMMON/SMC/ NSTOP
      DIMENSION BP(19)
      DOUBLE PRECISION XMAT(19,19),YMAT(19),SUM,Y(120),X(120,19)
      DO 20 I=1,NV
      DO 20 J=1,NV
      SUM=0.
      DO 10 K=1,ND
   10 SUM=SUM+X(K,J)*X(K,I)
   20 XMAT(I,J)=SUM
      DO 30 I=1,NV
      SUM=0.
      DO 25 J=1,ND
   25 SUM=SUM+X(J,I)*Y(J)
   30 YMAT(I)=SUM
      CALL MATINV(XMAT,NV)
      IF(NSTOP.EQ.1) RETURN
      DO 40 I=1,NV
      SUM=0.
      DO 35 J=1,NV
   35 SUM=SUM+XMAT(I,J)*YMAT(J)
   40 BP(I)=SUM
      RETURN
      END
```

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DETERMINING OPTIMAL POLICIES

FOR ECOSYSTEM MANAGEMENT

by

Joseph E. Powers

(ABSTRACT)

A methodology was developed by which a state fish and game agency can determine Optimal Ecosystem Policies (OEP). This methodology consisted of: (1) an ecosystem simulation model which depicted a variety of interactions among and between species; (2) an objective function consisting of several criteria; and (3) a computer implemented optimization procedure designed to find the time sequence of decision activities which maximized the objective function. OEP was applied to a specific case study area, a stream fishery in Rich Creek, Monroe County, West Virginia.

The simulation model consisted of a system of difference equations calculated for discrete time stages (one year time horizon). Interaction was modeled using a special queueing framework, where an animal's actions were governed by a preemptive priority sequence. Using the queueing framework, all interactions become density-dependent, and probability parameters may be estimated subjectively. Ration size, mortality, and reproduction were calculated and were inputs to population abundance, growth, and metabolism calculating routines.

The criteria considered in the objective function in the Rich Creek study were: (1) catch per unit effort by the commercial operators summed over all time stages (a measure of benefits to the commercial fishermen); (2) the environmental stability measured by a diversity index; (3) the number of fishermen visiting the stream during the year (angler-days); and (4) the sum over the year of a measure of angler satisfaction (utility). The utility function was a function of the attributes: size of fish caught, species of fish caught, number of fish caught, and crowding by other anglers. The utility model was empirically determined and it was found to be multiplicative over the attributes. Terminal (year end) constraints in OEP were a budgetary constraint, a diversity constraint, and a commercial catch constraint. Thus, the objective was maximization of a linear combination of the four criteria subject to the three terminal constraints.

The approximate optimal solution was found by search by Regression and Application of the Maximum Principle (RAMP search). Quadratic transition functions were fit to simulated data and the optimal policy was found for these transitions using the discrete maximum principle. This policy was returned to the simulation to generate new data and the procedure was iterated until a convergence criterion was met.

Optimization and sensitivity analysis of the Rich Creek model showed that an adequate budget was needed to maintain levels of stocked trout (the preferred species) to produce relatively high levels of angler utility. At low budgets other species became more important and diversity became an active constraint. Diversity and commercial catch criteria conflicted, therefore optimal catch occurred early in the year so that diversity could recover later. Solutions were most sensitive to three system components: (1) human aspects such as population size, preferences, and angler abundance; (2) the temperature prediction function (it served as a driver for many other variables); and (3) trout biomass variables. Future research on Rich Creek should be directed toward these three components.