Research Technical Completion Report
Project A-063-IDA

AN APPLIED COUPLED SIMULATION-OPTIMIZATION MODEL OF WATER USE EFFICIENCY IN INTENSIVE FISH CULTURE SYSTEMS

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March 1982

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October 1978 - September 1981

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Submitted to

Office of Water Research and Technology

United States Department of the Interior

Washington, D.C. 20240

March 1982

This project was supported primarily with funds provided by the Office of Water Research and Technology as authorized under the Water Resources Act of 1964, as amended.

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PREFACE

The funds for this study during FY79-82 were provided by the Office of Water Research and Technology through the Idaho Water Resources Research Institute, University of Idaho, Moscow, Idaho. The material presented in this report, in large part, forms the basis for a doctoral dissertation, "A Systems Approach to Aquaculture Management: A Production Forecasting Model" by Philip Carleton Downey.

ABSTRACT

An aquaculture system consists of a number of biotic and abiotic factors which act alone and/or interactively in defining systems behavior and impacting the allowable growth rate (AGR) of the fish. The bioenergetics approach, as presented, provides the necessary common denominator linking the quantitative effects of the biotic and abiotic dependencies of systems operation.

Computer implementation of the mathematical models of quantitative relationships in aquaculture systems is a dynamic process which provides a conceptual framework for understanding systems behavior. These models can provide useful information on variable significance to systems functioning, thereby directing research resources into areas which will most benefit further understanding of the system. Furthermore, as aquaculture systems research progresses, the composite model can be modified to incorporate new technology. Modelling therefore is a cyclic process, a means for understanding the system, evaluating the system, and using the model to incorporate the new technology.

The conceptual framework of the model presented is not only applicable to rainbow trout, but is an acceptable conceptual model for all aquaculture systems. Reparameterization of specific components results in valid models for other species.

This computer implemented mathematical model has addressed one of the significant limitations of aquaculture systems management; namely, production forecasting, by providing a method of using current technology for the predictions of allowable growth rates and systems production forecasting. The use of the model in aquaculture operations would serve as a valuable aid to production forecasting, resulting in more efficient and profitable aquaculture systems operations.

I. INTRODUCTION

Facilities employing intensive aquaculture technologies produce millions of pounds of food and game fish annually the world over. The most abundant group of fish raised is the salmonids; i.e., trout, charr, and Pacific salmon. The channel catfish industry in the United States is rapidly becoming an intensive aquaculture industry, having been a semi-intensive process since its inception in the 1960's.

Among the several indentifiable constraints to productivity, water use and growth forecasting are mong those needing concerted attention. The equally significant constraints of increasing production costs and loss of production potential through infectious and noninfectious diseases are, in the majority of cases, the effect of suboptimum practices of water use and growth forecasting. Thus, the utilization of validated methods and methemathical models for optimizing water use and production forecasting could have a measurable impact on reducing production costs through decreasing the loss of production potential.

Several mathematical and/or computer models have been developed for aquaculture, particularly salmonids, but for the most part they are neither sufficiently comprehensive nor flexible to accomplish the dual goal of being a tool for production forecasting and/or for hatchery design.

HATCH, a computer simulation model of a holistic fishery, simulates the downstream migrations of coho smolts, the harvest of fish by the ocean commercial fishery, adult returns to freshwater and the hatchery rearing of eggs and fry to smolt size (Rasch 1972; Johnson 1974). The growth of salmon to smolt size is predicted by a growth model developed by Stauffer (1973). Stauffer's growth model recognizes three variables; namely, fish size, feeding rate, and water temperature, as the important variables in predicting fish growth.

Jorgenson (1976) developed a model applicable to salmonid hatcheries. The difficulty of using this model arises with parameter estimation; many of which were obscure and/or are poorly defined. In addition, predictive abilities of this model did not consider important variables such as the effect of pond design on systems operation.

Kerr (1971a, b, c) developed a growth model for lake trout in natural environments. Although this model contains many parameters associated with natural environments, portions of this model pertaining to fish metabolism are applicable to hatchery systems.

The objective of this study is to present a computerized systems model, based on current technology, for increasing capabilities of production forecasting in aquaculture systems. This proposed model is relatively comprehensive and includes major variables, constraints and interactions inherent in most fish culture operations. The anticipated usage of the predictive and evaluative capabilities of the model are many and include:

1. Long-range production forecasting information for managing water use in aquaculture systems more effectively;
2. A method for testing alternate management strategies for determining the most efficient process for raising fish at a specified facility;
3. An aid in designing new facilities and/or renovating existing facilities. Application of the model for design and management will result in better use of the water supply;
4. Assessment of hatchery effluents. Water treatment facility requirements necessary for meeting present and future water quality standards can be estimated more precisely;
5. A tool for training fish culturists at the middle and upper managerial levels;
6. An aid in the epidemiology and treatment of noninfectious and infectious diseases.

To develop this model, the following tasks were defined:

1. To identify the qualitative and quantitative interrelationships among the major variables in aquaculture systems;
2. To construct a quantitative computerized model reflecting the interrelationships among major variables, constraints and interactions in aquaculture systems.

This study, based upon a total systems concept, ordered the identified variables into cause and effect relationships. Although this conceptual framework was developed from facilities raising rainbow trout (*Salmo gairdneri*), the general approach and concepts developed are applicable to *all* aquaculture systems.

II. AQUACULTURE SYSTEMS CONCEPTS

The opinion that no two finfish culture facilities are physically alike is held by most knowledgible aquaculture professionals. However, conceptually they are all alike qualitatively with the differences being qualitative. Klontz et al. (1979) have identified 56 interacting, dependent, and independent, biotic and abiotic factors, which taken together constitute a functional aquaculture system. For the sake of simplifying the system complexity, the 56 factors have been grouped into five major components; namely, Fish, Water, Nutrition, Pond, and Management (Table 1).

The majority of the factors intrinsic to an aquaculture system, particularly those factors directly impinging on productivity, can be arranged into qualitatively ordered cause and effect relationship; thus defining the system (Figure 1). In such a system a quantitative change in any of the factors sets into motion a sequential series of changes through the system which cannot be altered unless another change is introduced (Downey 1978; Klontz et al. 1979). The net effect of this "domino-effect" is a change in growth rate of the fish in the system. Thus, to forecast systems behavior requires the predictibility of growth in terms of the systems constraints. This process begins with the product definition and setting into motion those management practices necessary to achieve the product definition. The management practices are modified by the systems constraints intrinsic within the Fish, Water, Nutrition, and Pond components.

Table 1. Factors affecting the productivity of trout and salmon raising facilities (Klontz et al. 1979).

	A. Fish Associated		
1.	Ammonia-nitrogen	7.	Infectious disease history
2.	Behavior	8.	Length-weight relationship
3.	Nutritional requirements	9.	Cannibalism
4.	Environmental requirements	10.	Oxygen uptake
	a. physical	11.	Oxygen demand
	b. chemical	12.	Fecal solids
5.	Product definition	13.	CO_2
6.	Growth Rate Potential		
	B. Water Associated		
1.	Dissolved oxygen	12.	Municipal contaminants
2.	Nitrite-nitrogen	13.	Natural contaminants
3.	Alkalinity		a. N_2
4.	pH		b. CO_2
5.	Inflow		c. H_2S
6.	Suspended solids	14.	Utilization
7.	Settleable solids	15.	Salinity
8.	Temperature	16.	Hardness (Ca^{++})
9.	Carrying capacity	17.	B.O.D.
10.	Agricultural contaminants	18.	Viscosity
11.	Industrial contaminants		
	C. Container Associated		
1.	Water volume	5.	Water replacement time
2.	Water velocity	6.	Outfall design
3.	Composition	7.	Shape
4.	Water flow pattern		
	D. Nutrition Associated		
1.	Feeding rate	4.	Nutritional quality
2.	Feed efficiency		a. proximate analysis
3.	Feed style		b. metabolizable energy
		5.	Feed Storage
	E. Management Associated		
1.	Fish sampling techniques	5.	Pond cleaning
2.	Feeding frequency	6.	Fish size grading techniques
3.	Feeding techniques	7.	Management programming
4.	Record keeping	8.	Management objectives

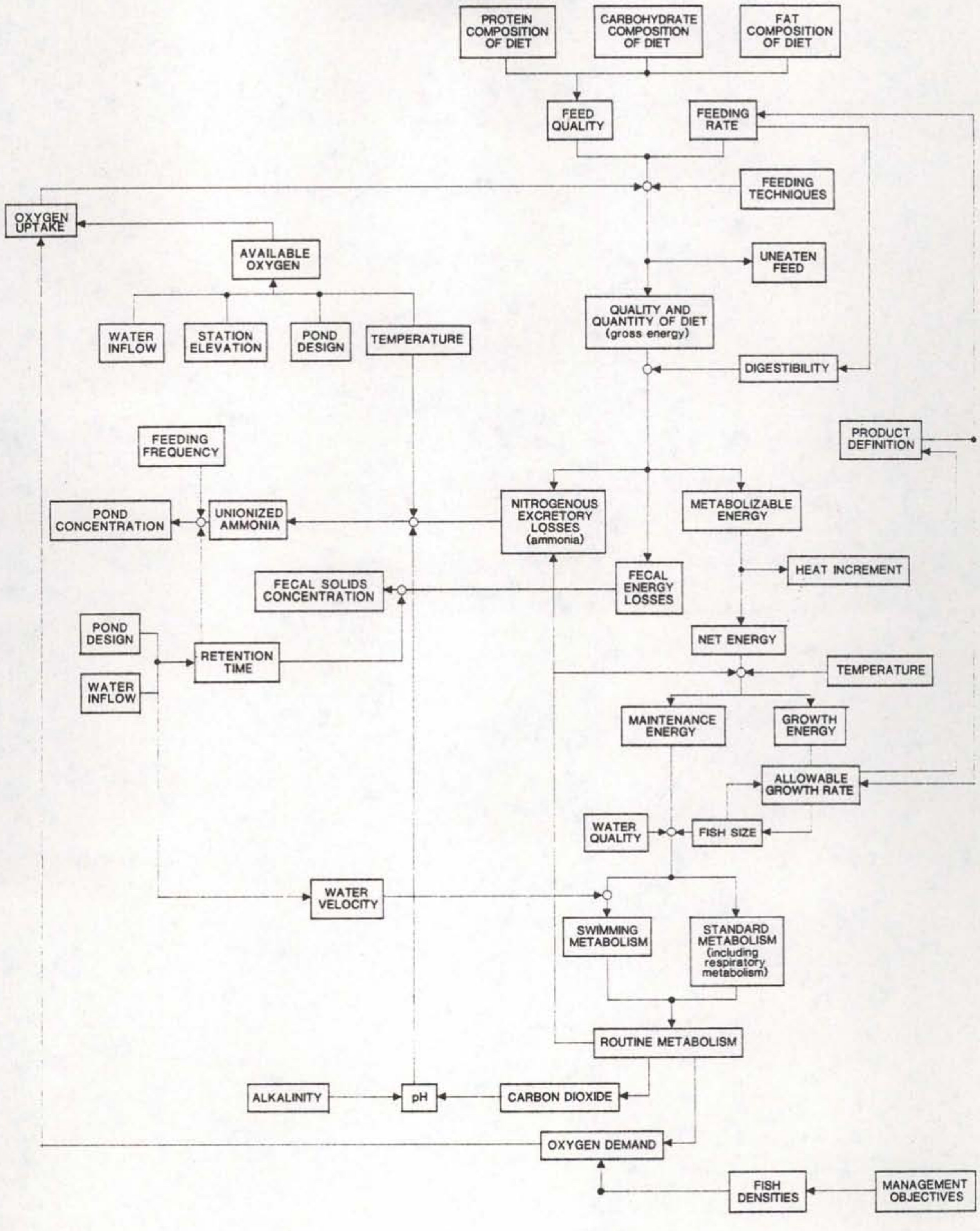

Fig. 1: Diagrammatic representation of the interrelationships among the abiotic and biotic factors within an aquaculture system.

III. MANAGEMENT OF AQUACULTURE SYSTEMS

Conceptually, the entire systems operation and production are under the complete control of facility management. Management personnel can control the variables and interactions of the system and therefore can directly and indirectly affect systems operation through manipulation of input variables to assure an optimum environment for production. Management activities consist of defining management goals and objectives of the system (= product definition) and manipulating the interactions among the variables to meet management objectives.

A. PRODUCT DEFINITION

One of the underlying principles of an aquaculture system simply states: "The ends prescribe the means." That is, the type of fish to be produced by the system (Product Definition) dictates the methods used to attain this product (Klontz et al. 1979).

A product definition consists of setting criteria which define the goal(s) of the system. These criteria include the species of fish, quality of fish, date the product is to be harvested, size of fish to be produced, the number of fish required, what size the fish will be at the start of the rearing process, and when will the rearing process begin.

With the product definition established (the ends), systems management considerations (the means), such as growth rates, feeding rates, space and water requirements, are, for the most part, defined within very narrow limits. This process of defining management objectives and systems operation is called <u>production forecasting</u>.

B. PRODUCTION

As has been stated, the desired product prescribes the methods used in the process of achieving the product. Conceptually, the process consists of the following individual activities: spawn-taking, egg incubation, fry feeding, fingerling feeding, grow-out feeding and processing or distribution (Figure 2). Each activity has its own intrinsic set of criteria and problems. Further, there are no established, routine methods by which each activity is to be accomplished. Nonetheless, there are at least two routine fish culture activities which should be standardized because of their impact, if inaccurately done, on the entire process. These are inventory techniques and record keeping. Each will be discussed separately.

1. Inventory Techniques: The most common method of growth assessment consists of estimating the number of fish per pound (or kilogram) and/or the average length of fish in the population. These data are then expanded to be representative of the entire population. The numbers of samples per lot vary from 3-5 with the mean of the samples constituting the mean of the population. As one could surmise, there could be, and usually is, a great deal of variation and error is this approach is not done with some consideration for statistical validity.

One method found to be highly reliable is the "5-by-5" inventory technique described by Klontz et al. (1978). The method has been severely tested under both laboratory and field conditions and has proven to be statistically valid.

The inventory process begins with the fish not having been fed for a time sufficient to result in an empty gastrointestinal tract. This is quite necessary in many situations because latent bacterial and viral infections are frequently activated by physical stress and fish having empty gastrointestinal tracts are less predisposed to the adverse effects of physical stress (Wedemeyer and Wood, 1974).

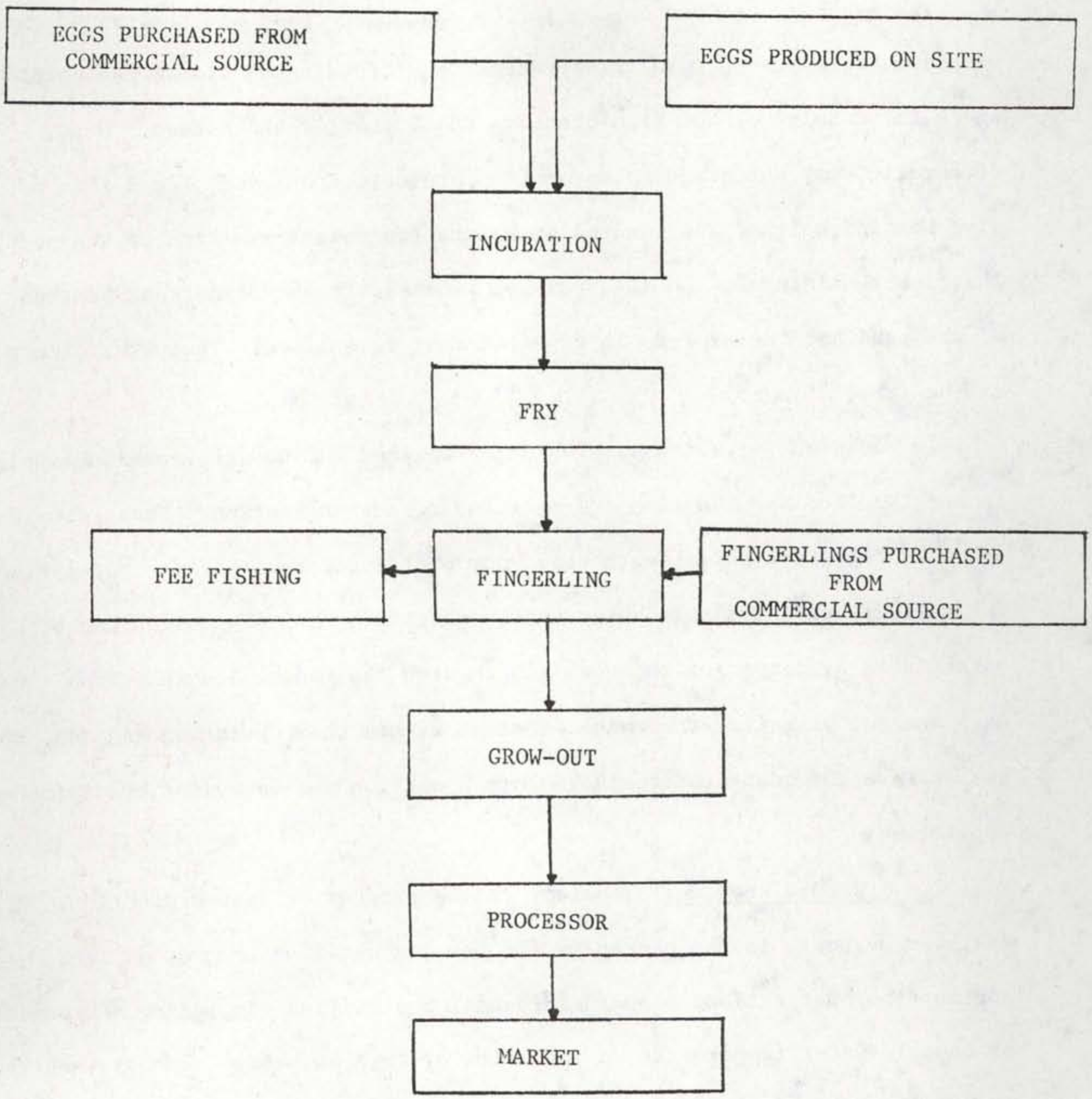

Figure 2. A schematic flow of activities and segments in freshwater food fish production.

The fish are crowded to the inflow end of the pond and restrained there with a movable screen. In this process, the crowding should be the point where the density of the fish obscures the bottom of the screen. Next, five relitively uniform samples of fish are netted out and placed into a live-box and weighed and counted back into the downstream side of the pond. The fish remaining in the live-box are released to the downstream portion of the pond and the process is repeated four more times. Thus, the origin of the term, "5-by-5."

In addition to the subsamples being weighed and counted, one subsample is anesthetized and the fish are measured to the nearest mm. These data are used to establish a length frequency distribution within the population. The validity of the sample being representative of the population can be established by comparing the mean length with the median length. From these data one can visualize the range of sizes within the population and make some qualitative and quantitative judgements about the necessity for grading the population.

2. Record keeping: Implicit in the process of fish production, for whatever purpose, is the necessity for keeping detailed records of feed consumption, water flow, biomass in ponds, mortalities (including assessments of cause), water temperature, and numbers of fish on hand. Without such records, the application of production forecasting techniques is not feasible, and nearly impossible. Further substantiation of the needs for adequate records of daily activities is reflected in reduced costs of production, according to those who employ record-keeping practices.

IV. FISH IN AQUACULTURE SYSTEMS

A. GROWTH

Fish growth is typically measured as an increase in length (Haskell 1959; Klontz et al. 1978), wet or dry weight gain (Brett and Shelbourn 1975; Stauffer 1973), protein utilization (Nightingale 1974), or as an increase in energy content if the fish (Warren and David 1968; Elliott 1976b; Staples and Nomura 1976). Although many of these measures are interrelated, growth in the context of this discussion is defined as an increase in the energy content of the fish.

Models of fish growth and metabolism have been either descriptive mathematical models, or analysis of the energy components of growth, commonly referred to as the bioenergetics approach (Warren and Davis 1967; Kerr 1971a, b, c; Elliott 1976). The modeling of growth with descriptive models requires the researchers to collect empirical data on fish growth and then fit, using statistical and mathematical techniques, a mathematical equation to the data which best describes the relationship. A bioenergetics approach to growth modeling assumes that the total energy input into a fish system is either retained (= fish growth), used to maintain the fish (= fish metabolism), or is lost from the system (waste) and that these components are additive. Mathematically stated:

$$I = G + M_{rou} + W \quad (1)$$

where:

I = Total intake of energy by the system

M_{rou} = Energy required for fish metabolism

G = Energy used for growth

W = Energy lost from the system as wastes

Equation (1) can be rearranged to solve for growth:

$$G = I - W - M_{rou} \qquad (2)$$

1. Growth Rate

The Potential Growth Rate of fish in aquaculture systems considers the biotic capacity of the fish which occurs largely in an "ideal" system having no constraints to growth and as such is a function of the genetic composition of the fish. Since growth in this "ideal" system is not readily quantifiable, a working definition for growth potential which can realistically be applied to aquaculture systems, must be established. In the context of the systems approach, the growth potential of fish is the expected growth in which the diet quantity and quality, fish species, and life support are specified without any other system constraints (Figure 3).

Growth constraints in aquaculture systems can and do reduce the growth rates of fish in the system. Two components, Pond Design and Management, influence environmental quality, thus affecting metabolic costs to the fish and altering their growth potential. An example of this impact can be seen in water concentrations of ammonia, the chief excretory product of protein metabolism, permitted to exceed 0.0125 mg/l due to high retention times (Pond Design) or high densities of fish (Management). Defining the Pond Design and the Management constraints which impact growth rates yields an Allowable Growth Rate (AGR). Thus, the AGR is the rate of fish growth in a specified system in which constraints are functional.

The Maximum Growth Rate of trout in a constant environment have been shown to be inversely related to the fish size (Paloheimo and Dickie 1965, 1966; Brett 1976b). These empirical maximum growth rates (inches) can be converted to energy content in rainbow trout if:

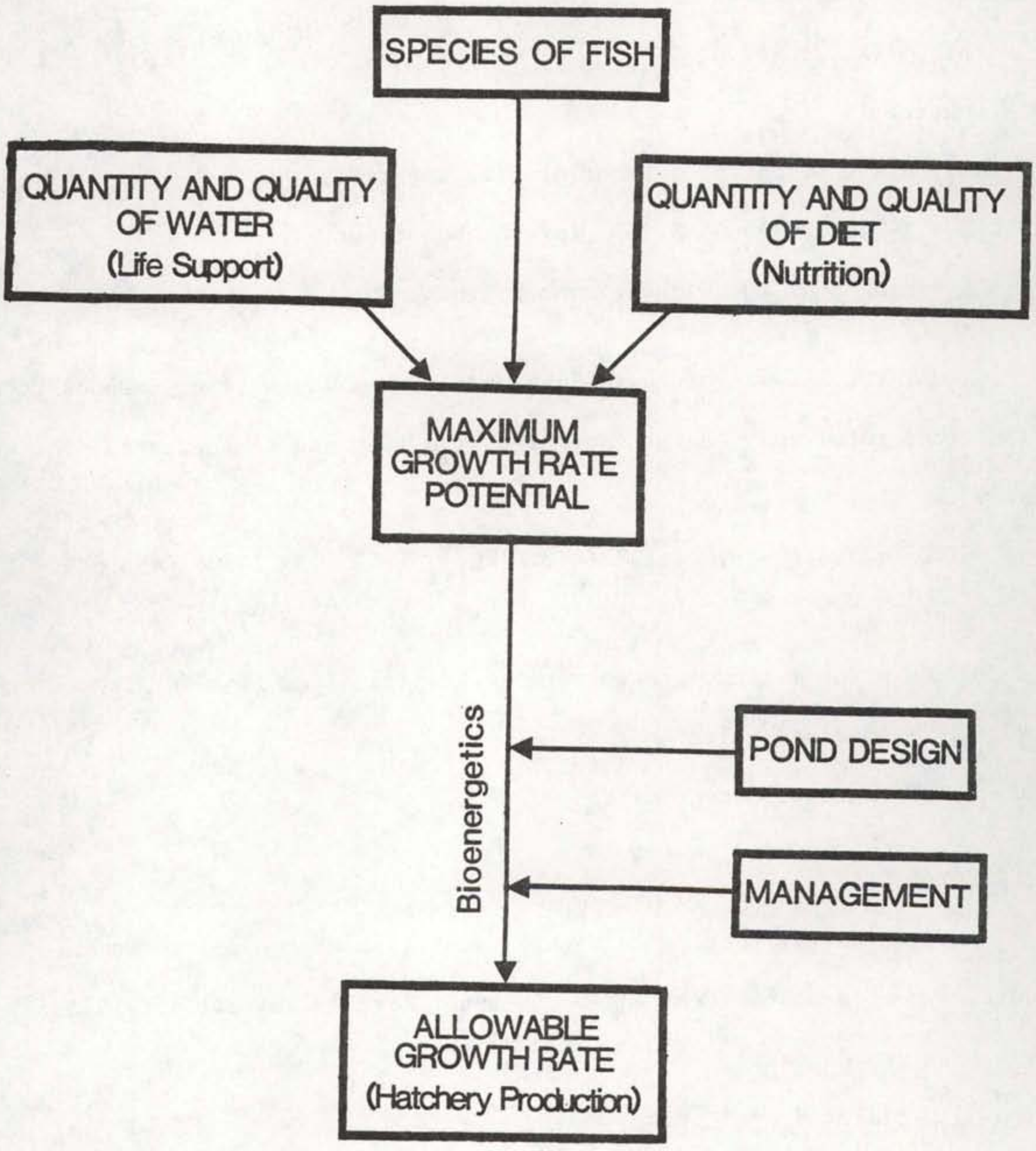

Figure 3. Relationships of major components defining allowable growth.

The K-factor which related fish length and fish weight is constant and is 4.055×10^{-4} for rainbow trout (U.S. Fish and Wildlife Service 1977).

Fish weight could be estimated from length by:

$$WT_i = (KL_i^3)\ 453.6 \qquad (3)$$

where:

WT_i = Wet weight of a trout at time i (grams)

K = K-factor, 4.055×10^{-4} for rainbow trout

L = Length of the fish at time i (inches)

Thus, the Allowable Growth Rate model for rainbow trout depends upon fish size, total body energy content of the fish and temperature. The model is:

$$GTEC_i = ABS\ (T-59)\ \{1.108\ (453.6\ KL_{i+1}^{\ 3})^{1.0622} - 1.108\ (453.6\ KL_i^{\ 3})^{1.0622}\} \qquad (4)$$

where:

$GTEC_i$ = The maximum growth rate of the ith sized fish (Kcals)

ABS = Absolute value

T = Temperature (degrees F)

B. METABOLISM

Theoretically, routine (= total) metabolism can be partioned into additive components (Warren and Davis 1968; Kerr 1971b; Elliott 1976b; Bond 1979) such that:

$$M_{rou} = HI + M_b + M_r + M_x \qquad (5)$$

where:

M_{rou} = Routine metabolic rate (Kcals/day)

HI = Heat Increment (= specific dynamic effect) (Kcals/day)

M_b = Basal metabolic rate (Kcals/day)

M_s = Swimming metabolic rate (Kcals/day)

Although specific components of total metabolism have been defined and quantified for homeotherms (Brody 1945; Maynard et al. 1975) and can be hypothesized for poikilotherms, such as fish, actual computation of these individual components is difficult. Fish are irrevocably oriented to their environment and therefore, the environmental changes altering metabolic processes can confound experiments designed specifically to quantify a single aspect of metabolism. In order to define basal (= minimum) energy requirements in a bioenergetics systems analysis, three assumptions about facility operations and fish metabolism were required:

1) Minimum metabolic rate occurs when trout are reared in water velocities of 2.4 cm/sec (0.08 fps). If the water velocity is less than 2.4 cm/s, then respiratory metabolism increases proportionally to the decrease in swimming metabolism. Therefore, water velocities in aquaculture systems which are less than or equal to 2.4 cm/sec results in minimum fish metabolic rates.
2) Respiratory metabolism in water velocities in excess of 2.4 cm/s is at a minimum and constant.
3) The facility environment is maintained as a "healthy" environment and environmental parameters which can affect the health of the fish are not operant.

Applying these assumptions a new term, Standard Metabolism, can be defined as: the minimum energy requirements necessary for a healthy trout to maintain itself at SET in adequately oxygenated (pO_2 > 90 mmHg) water with a velocity of 2.4 cm/s. Since respiratory metabolism energy is considered constant and part of standard metabolism, the relative effects of the environment, such as temperature and water velocity, can be determined by:

$$M_{rou} = HI + M_{st} + M_s \qquad (6)$$

1. Heat Increment:

Heat increment (= Specific Dynamic Effect) is defined as the amount of energy expended (i.e., heat produced) following food consumption when the animal is in a thermally neutral environment (Smith 1976). Heat increment (HI) results from the metabolic processes involved in the ingestion and processing of food and depends upon the diet composition. Typically, the HI is reported as a proportion of the total energy contained in the individual components of the diet.

The HI for fish is usually determined by the indirect method of oxygen consumption and applying oxycalorific coefficients. Recently, some investigators have questioned the accuracy of the extrapolation of oxycalorific coefficients to fish and other poikilothermous animals, since these coefficients were derived from homeothermic animals (mammals) (Smith 1976). To circumvent the shortcomings of this method, Smith (1976) developed a direct method, based on heat production, to measure fish metabolism, including HI. Results indicated that the HI for fish were far less than those recorded for homeotherms averaging 1.36% of ME for lipids, 3.5% of ME for carbohydrates, and 3.26% of ME for protein. Mathematically, the HI of a specific diet can be stated as:

$$HI = 0.035\ ME_c + 0.0136\ ME_L + 0.0326\ ME_p \qquad (7)$$

where:

HI = Heat Increment (Kcals/day)

ME_c = Metabolic energy of carbohydrates in the diet ingested (Kcals/day)

ME_L = Metabolic energy of lipids in the diet ingested (Kcals/day)

ME_p = Metabolic energy of proteins in the diet ingested (Kcals/day)

Subtraction of this HI from the metabolizable energy (ME) of a diet yields an estimate of the net energy of the diet.

2. Standard Metabolism:

The relationship between standard metabolic rate and fish size has been well documented by Brett (1965), Brett (1976b), Gerking (1955), Savitz (1969), Smith (1976) and becomes:

$$M_{st} = {}_{a}WT^{n} \qquad (8)$$

where:

M_{st} = Standard metabolic rate (Kcals/day)

a, n = coefficients, determined empirically.

The exponent, n, for fish generally ranges from 0.5 to 1.0 (Paloheimo and Dickie 1965; 1966; Brett 1976a). With the exception of those reported by Smith (1976), these metabolic relationships usually have been determined by indirect oxygen consumption methods.

Estimation of energy requirements for standard metabolism by trout in system environments can be obtained by coupling wet weight conversions with potential growth rates. This allows the determination of the size-related standard metabolic rate for trout. Estimates of size-related standard metabolic rates were fit to equation (8) and the relationship, which were highly significant ($P < 0.01$), is:

$$M_{sta} = 0.2599\ WT^{0.6311} \qquad (9)$$

where:

M_{sta} = Standard metabolic rate of allowable growth (Kcals/day)

WT = Fish weight (grams)

Equation (9) is only applicable to oxygen consumption rates when the feeding level is at allowable growth (Brett 1976b).

Klontz et al. (1978) measured the oxygen consumption rates of starved rainbow trout maintained in 59F (15C) water (= SET) and developed the model:

$$M_{stu} = 0.05600WT^{0.8423} \quad (10)$$

where:

M_{stu} = Standard metabolic rate of unfed fish (Kcals/day)

WT = Fish weight (grams)

Since the linear relationship exists between standard metabolic rates of fed and non-fed fish, the standard metabolic rate at any feeding rate between unfed and allowable (at SET) can be calculated by:

$$M_{st} = (R_f/R_{fa}) \{(0.2599WT^{0.6311} - 0.0560\ WR^{0.8423})\} + 0.056\ WT^{0.8423} \quad (11)$$

where:

R_f = Specific feeding rate (metabolizable Kcals)

R_{fa} = Feeding rate for allowable growth rate (metabolizable Kcals)

Temperature has a profound effect on the metabolic rate of fish. For every increase of temperature by 10C, the metabolic rate doubles. Therefore, if standard metabolic rate is known at SET (equations 10, 11), standard metabolism for trout at any temperature can be calculated by:

$$M_{st} = \exp\ (0.0693(T\text{-}SET)\ \left(\{ (R_f/R_{fa})\ (0.2599WT^{0.6311} - 0.0560WT^{0.8423})\} + 0.0560WT^{0.8423} \right) \quad (12)$$

where:

T = Water temperature (C)

SET = Standard Environment Temperature for the particular species of fish.

3. <u>Swimming Metabolism</u>:

The swimming metabolic energy requirements for trout vary according to fish size and velocity of the water (Brett 1965; Brett 1973; Brett and Glass 1973; Fry 1971; Kerr 1971b). Kerr (1971b) proposed a model for swimming metabolism for brook trout:

$$M_s = S(WT)\ (R_v)^2 \tag{13}$$

where:

M_s = Swimming metabolism (Kcals/day)

S = A constant relating swimming metabolism to fish weight and water velocity (= 0.0716×10^{-12})

WT = Fish weight (grams)

R_v = Water velocity (m/day)

4. Routine Metabolism:

The routine metabolic rate of fish in any aquaculture system is the sum of the component rates. Mathematically stated:

$$M_{rou} = M_{st} + M_s - HI \tag{14}$$

where:

M_{rou} = Routine metabolism (Kcals/day)

M_{st} = Standard metabolic rate (equation 12) (Kcals/day)

M_s = Swimming metabolic rate (equation 13) (Kcals/day)

HI = Heat Increment (equation 7) (Kcals/day)

Oxygen consumption models for aquaculture systems are based upon the relationship between routine metabolism and oxygen consumption by:

$$RO_i = KoM_{rou} \tag{15}$$

where:

RO_i = The rate of oxygen consumption by fish for a specific feeding rate i (= R_f) (mg oxygen/fish/day)

Ko = A constant relating oxygen consumption to routine metabolism (= oxycalorific coefficient)

M_{rou} = Routine metabolic rate of the fish for specified environmental conditions (temperature, water velocity, feeding rate)

Brett (1973) monitored oxygen consumption and energy expenditure (measured by calorie loss from the fish) of sockeye salmon exposed to various water velocities. He concluded that an oxycalorific equivalent of 4.8 Kcal/liter of oxygen (= 208.33 mg oxygen/Kcal) is an acceptable value for fish.

Equation (15) becomes:

$$Ro_i = 208.33\ M_{rou} \qquad (16)$$

V. WATER IN AQUACULTURE SYSTEMS

A. OXYGEN

Low dissolved oxygen levels which have been shown to affect various species of fish in the following ways: reduce fish growth, decrease feed efficiency, alter feeding behavior, and decrease survival (Davis 1975). Even though these qualitative effects of dissolved oxygen in aquaculture systems have been documented, the lower limits of dissolved oxygen to avoid adverse conditions have not been adequately defined.

Many investigators have attempted to define the limiting levels of oxygen in the aquatic environment. Ellis et al. (1948) reported that a good mixed fish fauna exists only if the dissolved oxygen concentration is in excess of 5 mg/l. The key word in the foregoing recommendation is "exists" with no reference made to growth. Leitritz and Lewis (1976) stated that the lowest safe level of dissolved oxygen for trout is 5 mg/l but recommended that 7 mg/l dissolved oxygen would be a preferable minimum. Westers and Pratt (1977) and Westers (1979) recommend 5 mg/l as being the minimum dissolved oxygen content of water exiting hatchery ponds. Piper (1972) determined that when oxygen concentrations of water exiting experimental hatchery ponds averaged less than 5 mg/l growth of trout in the ponds was limited by oxygen. Wedemeyer and Wood (1974) recommended oxygen levels for salmon on the basis of water temperature because increases in water temperature require higher dissolved oxygen levels to meet the physiological needs of salmon.

Others have attempted to define oxygen levels using environmental partial pressures of oxygen. Jones et al. (1970), analyzed optimum oxygen transfer across the gill membranes, and determined that a pO_2 of 118 mmHg was necessary to maintain a proper gradient for oxygen uptake. Randall (1970) calculated that the external-internal dissolved oxygen gradient should be 20 mmHg pO_2. Cameron (1971) reported that rainbow trout blood remains nearly 100% saturated with oxygen until the pO_2 drops below 80 mmHg. Itazawa (1970) reported that rainbow trout blood remains saturated with oxygen until the pO_2 is less than 100 mmHg. Others have indicated equally as equivocal and seemingly contradictory data (Davis 1975). Nonetheless, oxygen requirements for aquaculture systems should be based upon the oxygen partial pressure. The reasons for the use of partial pressures are two fold; physical characteristics of oxygen in aquaculture systems, and the physiological requirements of fish (Downey and Klontz 1981).

B. TEMPERATURE

In aquaculture systems, water temperature directly affects the rates of system variables such as environmental partial pressure of oxygen, dissociation of ammonia, and the metabolic and growth rates of the fish. Through the direct effects, temperature indirectly affects virtually every other variable in the system, thus affecting the overall systems rate of operation.

Each species of fish (and sometimes strains within the same species) have preferred water temperatures at which growth and metabolism are optimal. This temperature has been designated as the Standard Environmental Temperature (SET) (Klontz et al. 1979).

The general relationship between growth rates of a specific sized fish and temperature is parabolic with the maximum growth occurring at the Standard Environmental Temperatures (Brett et al. 1969; Shelbourn et al. 1973; Elliott 1976a, b).

Several investigators attempted to model the effects of temperature on growth. Haskell (1959) noted that trout growth, for all intents and purposes, ceased at 38.6F (4C). From this concept, he defined the Temperature Unit (TU) for trout as the average daily water temperature of the system minus 38.6F. Thus, growth of fish at any water temperature could then be estimated by:

$$\Delta L_{30} = (TU_{\text{expected monthly}}/30)/TU_{\text{required for 1 inch growth}} \qquad (17)$$

C. CARRYING CAPACITIES

Physiological carrying capacities are indices based directly and indirectly upon the available oxygen of the system (Haskell 1955; Willoughby 1968; Elliott 1969; Westers 1970; Piper 1970; Liao 1971; Klontz et al. 1978) but also can consider metabolite concentrations (Westers and Pratt 1977). The available oxygen and metabolite concentrations are functions of pond design and therefore, physiological carrying capacities differ among pond designs.

A carrying capacity model of single-use noncirculating systems related to the available oxygen and oxygen uptake, is:

$$MPW_i = (AO/RO_i)\ (WT_i) \qquad (18)$$

where:

MPW_i = Maximum pond weight of fish (kg/pond).

AO = Available oxygen consumption (mg O_2/day) per fish with an average weight of i (equations 14 - 16)

WT = Fish weight i (kilograms).

In reuse systems, oxygen levels are reduced and metabolite concentrations are higher than those in single use ponds. The reduction in available oxygen in reuse noncirculating systems is the result of extraction of oxygen by fish in the previous pond system(s) and the fact that reaeration between ponds is seldom sufficient to obtain saturation (Haskell et al. 1960). Generally, carrying capacity models for noncirculating ponds, based on oxygen available, are determined by the Piper (1972) model.

Physiological carrying capacities of circulating ponds, based upon available oxygen, are superior than noncirculating ponds (Larmoyeux et al. 1973). This higher carrying capacity is attributed to increased aeration efficiency and to the relatively homogeneous (oxygen) environment of circulating ponds. The Piper (1972) model is applicable to estimating the physiological carrying capacities of circulating ponds.

D. OTHER ENVIRONMENTAL REQUIREMENTS

Other water quality variables, such as pH, alkalinity, water hardness can also affect metabolism and constrain growth if present in high or low concentration extremes. These variables increase metabolism by requiring the fish to expend more energy for ionic regulation in their body.

VI. POND DESIGN IN AQUACULTURE SYSTEM

A. WATER FLOW PATTERNS

Aquaculture ponds are classified into two types on the basis of water flow charcteristics: noncirculating and circulating. Noncirculating ponds, or raceways, are linear ponds in which water enters at one end of the pond and exits at the other. Water flow is laminar and there is relatively little mixing of incoming and existing water. Many width-length-depth ratios are used in raceway designs, buy hydraulically, and on the basis of productivity, ponds of 1:10:0.3 relative width:length:depth dimensions appear to be best (Burrows and Chenoweth 1970).

Raceway ponds are arranged as single systems or in series. In series (= linear reuse) systems, water exiting the upper pond is reused in succeeding ponds in the series before being discharged. Thus, water quality entering the reuse pond depends upon the quality of water exiting the previous pond.

Circulating ponds are rearing ponds in which the incoming water mixes with existing pond water, resulting in a homogeneous (or near homogeneous) water mass (Burrows and Chenoweth 1955; Burrows and Combs 1969; Burrows and Chenoweth 1970; Westers and Pratt 1977).

Some of the more common circulating pond designs are the Burrows pond, circular pond, modified Mayhall or Thayer-Ellis pond, Rathbun pond, and Foster-Lucas pond. Circulating water flows are also common in large dirt ponds (.3-10 acres) used in semi-intensive and extensive aquaculture, and in rectangular shaped ponds which deviate appreciably from the standard 1:10:0.3 dimensions.

The differences of water flow in circulating and non-circulating ponds provide different physical and psychological environments for fish. These differences are categorized into velocity, retention time, oxygenation.

B. WATER VELOCITY

Water velocity is important to the self-cleaning qualities of a pond. Burrows and Chenoweth (1970) state that a velocity of 6.1 cm/s (0.2 fps) is required along the center wall of a Burrows pond in order to maintain its self-cleaning properties. Jensen (1972) also stated that velocity is an important factor in determining whether fecal material will settle or remain suspended in raceways.

Pond water velocity also influences the metabolic rate and general condition of the fish. High velocities (9-12 cm/s) can increase the metabolic rate 2.3 times that of standard metabolism (Brett and Glass 1973). This increased metabolic rate produces high oxygen consumption by fish, increases ammonia production rates, and decreased dietary efficiency. These changes in metabolism coupled with other hydraulic characteristics (i.e., retention time) can cause reduced hatchery production. Average velocities in noncirculating ponds can be calculated by (Leitritz and Lewis 1976):

$$Rv = Rw/(Cd)(W)(D) \qquad (19)$$

where:

Rw = Water inflow (gpm; lpm).

Rv = Average water velocity (fps; cm/s)

Cd = Coefficient of drag (0.9 for concrete bottoms; 0.8 for dirt bottomed ponds).

W = Pond width.

D = Average pond depth.

Water velocity in circulating ponds must be determined empirically as there is currently no model available to take into account the wide varities of pond design and water inflow

C. OXYGENATION

Oxygen tensions in water entering single-use, non-circulating ponds is usually 95-100% saturated. As the incoming water progresses through the pond, oxygen levels in the water decrease reaching the lowest tensions at or before the outfall. This reduction, which is proportional to the amount and size of fish in the pond, can be so significant that water exiting a non-circulating pond has oxygen tensions which are at or near the incipient limiting oxygen levels.

In reuse non-circulating systems, ponds receive inflow water from the previous pond(s). Water generally flows out of the previous pond over a weir (damboards) and into the head end of the reuse pond. Oxygen tensions of the water entering the head of the reuse pond depends upon the oxygen tensions of the water exiting the previous pond, the height of the waterfall between the two ponds, and the oxygen saturation of the water. Efficiency of reoxygenation of water is higher in low oxygen waters than in water with high oxygen tension waters, and therefore, reaeration efficiency (on a percent basis) would be higher when the water exiting the previous pond is low in oxygen.

Reaeration of oxygen in the water is seldom complete and is related to the distance the water falls through the air (Haskell et al. 1960). Oxygen transfer across an air/water interface follows a simple first-order rate equation (McLean and Boreham 1980):

$$Ct = Cs - (Cs-Co)\ e\ (-k\ (\mathrm{sqrt}\ (2H/g))) \qquad (20)$$

where:

k = Aeration coefficient in 1.2572 (determined empirically)

Cs = Oxygen saturation (expressed as a percent)

Co = Oxygen concentration (in percent) at time 0

(= percent concentration of oxygen in the outfall of the previous pond)

Ct = Oxygen concentration (in percent) at time t

(= concentration of entering the head end of the reuse system)

e = 2.71828

H = Height that the water falls (feet or meters)

g = Gravitational acceleration coefficient (32 f/s^2 or 980 cm/s^2)

On the basis of available oxygen, the circular pond has a potential for greater oxygen concentrations and carrying capacity than non-circulating ponds (Larmoyeux and Piper 1973). This greater potential for circulating ponds is directly related to the oxygen concentrations of existing water in the pond. In non-circulating ponds, the oxygen content of the water constantly decreases towards the pond outfall. Although the overall average oxygen concentration in the pond is above minimum oxygen tensions, about 1/2 of the pond is less than this average concentration with a significant amount of the pond containing water which has oxygen tensions at or near minimum oxygen requirements of trout. However, circulating ponds have oxygen concentrations in the pond that are the same throughout (assuming completely homogeneous mixing) and these levels also are overall average tensions. Therefore, theoretically, the load in a circulating pond can be increased to the point where the average oxygen tension (which is also the content throughout the pond) are near minimum oxygen tensions without impairing growth. If pond loads in non-circulating ponds were increased in order to obtain average oxygen tensions near the minimum levels, oxygen tensions in about 1/2 of the pond would be below the minimum oxygen requirements for optimum growth and metabolism and, therefore, growth would decrease.

D. RETENTION TIME

Retention time is a measure denoting the length of time a substance, such as a metabolite or drug, remains in the system. Retention time, detention time, replacement time, filling time and water replacements per hour are interrelated hydraulic parameters. The retention time (= detention time) and replacement time of a pond are complementary statistics. Replacement time measures the rate of loss of a substance from a pond and, therefore, 99% replacement is equal to 1% retention. The term "replacements per hour" equals 60 over the 100% replacement time.

Calculation of retention time in non-circulating ponds generally have been estimated with models used to estimate filling time (Klontz 1979). This model is:

$$Rt = (V/Rw)\ (60) \qquad (21)$$

where:

Rt = Retention time (in minutes).

V = The volume of the pond (in cubic feet).

Rw = The water inflow into the pond (cubic feet/second).

Hydraulically, circulating ponds differ considerably from non-circulating ponds. The objective of circulating ponds in fish culture is to provide a homogeneous water mass (Westers and Pratt 1977). In a homogeneous system, the loss of a substance from the pond is directly related to the concentration of the substance in the pond. Loss of substances is by molecular displacement (rather than molecular replacement) in non-circulating ponds and is logarithmic:

$$Ct = CO\ e(-RwT/V) \tag{22}$$

where:

Ct = Concentration of substance in the pond at time t.

CO = Initial concentration of substance at time 0.

e = Base naturea logarithm, 2.71828.

Rw = Water inflow (cubicfeet/minute).

V = Volume of the pond (cubic feet).

T = Time in minutes.

Using logarithmic transformation this equation becomes:

$$\ln(Ct/Co) = -RwT/V \tag{23}$$

<u>or</u>

$$T = \ln(Ct/CO) \times -(V/RwT) \tag{24}$$

However, mixing does not always produce an "ideal" homogeneous system and incomplete mixing, which depends upon the amount of short circulating of new water, often occurs in circulating ponds (Burrows and Chenoweth 1955; Burrows and Combs 1968; Burrows and Chenoweth 1970). In circular ponds the amount of mixing is related to the inflow angle, which can be designated by an emperical mixing coefficient. The model is:

$$T = m\ln(Ct/CO) - (V/Rw) \tag{25}$$

The determination of a pond's retention time and the mixing coefficient can be estimated if three assumptions are assumed:

1. In any system, > 99% loss of a metabolite (< 1% retention) represents complete loss.
2. A completely homogeneous system has a mixing coefficient of 1 (i.e., equation 35 describes the retention time).

3. No mixing occurs in noncirculating systems and the retention time of the system is described by equation (22).

By setting equation (22) equal to equation (26), a mixing coefficient for a noncirculating (no mixing) system can be determined:

$$(V/Rw) = ((-\ln (Ct/CO)\ (V/Rw)/m) \qquad (26)$$

<u>or</u>

$$m = (-\ln (Ct/CO)) = 4.605 \text{ (Assumption 1)} \qquad (27)$$

By setting equation (25) equal to (26), a mixing coefficient for "ideal" homogeneous systems equals 1.0.

In a completely homogeneous water mass (m = 1), the distribution of a substance, such as ammonia, is uniform throughout the pond and the average concentration within the pond equals the concentration exiting the pond.

Noncirculating systems have a gradient of concentrations of a substance in the pond. The average concentration of the substance in the pond would be only 1/2 of the concentration entering the pond; this pond has a mixing coefficient of 4.605. Therefore, if the average concentration of ammonia in the pond is 1/2 of the ammonia concentration at the outfall, the mixing coefficient would be 4.605. If on the other hand the average concentration of ammonia in the pond equals the ammonia concentration at the outfall, the mixing coefficient would be 1. Mixing coefficients could then be determined by knowing the ratio of the average concentration to the outfall concentration. A mixing coefficient for incomplete mixing systems can be determined by:

$$m = -7.2\ (AC/OC) + 8.2 \qquad (28)$$

where:

m = Mixing coefficient 1.0 - 1.83

AC = Average concentration of ammonia in the pond.

OC = Outfall concentration of ammonia in the pond.

E. POPULATION DENSITY

In addition to the life support or physiological carrying capacity of a fish rearing unit, each species and perhaps strain of fish has its psychological limits to being crowded. If these limits are exceeded the growth rate potential of the system is reduced measurably.

Psychological carrying capacities are density indices which balance the fish, water, container, and management component interactions in order to satisfy the innate behavioral requirements of the fish. These indices are expressed in lbs/cuft/in, ($kg/m^3/cm$) of fish (Piper 1972; Klontz et al. 1978) and calculated by:

MDI = DI (volume) (fish length) (29)

where:

MDI = Maximum density index (lbs/pond; kg/pond).

DI = Density Index (lbs/cuft/in; $kg/m^3/cm$)

Fish Length = Size (inches; cm).

Density indices are not related to pond design and, therefore, can be used for any pond design.

VII. NUTRITION

The quality and quantity of food fed to fish in an aquaculture system is the main driving variable of the system. Virtually all the energy in intensive or semi-intensive aquaculture systems is derived from the ration presented. The amount and quality of food fed dictates the rate of growth and overall systems production.

Diet quality has a profound impact on dietary efficiency and fish health. Phillips and Brockway (1959) reported that the elaboration of one pound weight gain by brook trout (Salvelinus fontinalis) required more than twice the dietary protein in prepared diet (300 g) than in a natural diet (143 g). The differences in growth were attributed to the natural diet containing the essential dietary amino acids in their necessary proportions.

Excessive levels of dietary fat or carbohydrate alters the general state of fish health by causing fatty infiltration of the liver and excess glycogen reserves in the viscera, respectively. As a result of these findings, the general dietary composition of commercially prepared diets is 30-55% protein, 7-17% fat, and 9-23% carbohydrate (Halver 1972).

A. ENERGY CONTENT:

The dietary energy sources; i.e., protein, carbohydrate, and fat, and the feeding rate determine the total energy the system receives. The amount of energy consumed by fish, regardless of whether or not the energy can be utilized by the fish for growth or metabolish, is the Gross Energy (GE) of the diet. The GE of a diet is the sum of the three dietary energy components. Crude protein contains 5.65 Kcal/g, lipids contain 9.4 Kcal/g, and carbohydrates contain 4.16 Kcal/g (Phillips and Brockway 1959).

Although the gross energy content of a diet provides a general picture of its nutritive value, an estimate of the energy available for growth and metabolism is necessary for energetic studies of fish (Figure 4). The digestible energy (DE) and metabolizable energy (ME) of a diet depends upon the digestibility of each of the three individual energy components of the diet. In addition, the ME also reflects the energy lost due to nitrogenous excretory products of the fish.

1. Protein Energy

Digestibility and utilization of dietary protein by fish for growth and metabolism are not constant. Protein digestibility averages 90% (Phillips and Brockway 1959) but ranges from 82% (Klontz et al. 1978) to 92% (Windell et al. 1978). Recent evidence indicates that high feeding rates reduce nutrient digestibility, possibly due to the consumption of more food than required by the fish for growth and metabolism (Klontz et al. 1978; Focht 1981). The loss through excretion by uretelic animals was determined to be 1.3 kcal/g of protein consumed (Phillips and Brockway 1959). Although this value had been used for fish, recent evidence indicates that the excretory energy lost by teleost fish (which are ammonotelic) amounts to 0.95 Kcal/g of protein consumed rather than 1.3 Kcal/g (Elliott and Davison 1975).

Metabolizable energy of the protein component of the diet is determined by:

$$MEp = (5.65 - 0.95)\ Dp \qquad (30)$$

where:

MEp = Metabolizable energy derived from a gram of protein in the diet.

Dp = Digestibility of the protein in the diet.

5.65 = Kcals/g of protein gross energy.

0.95 = Kcals/g of protein lost in nitrogenous excretory wastes.

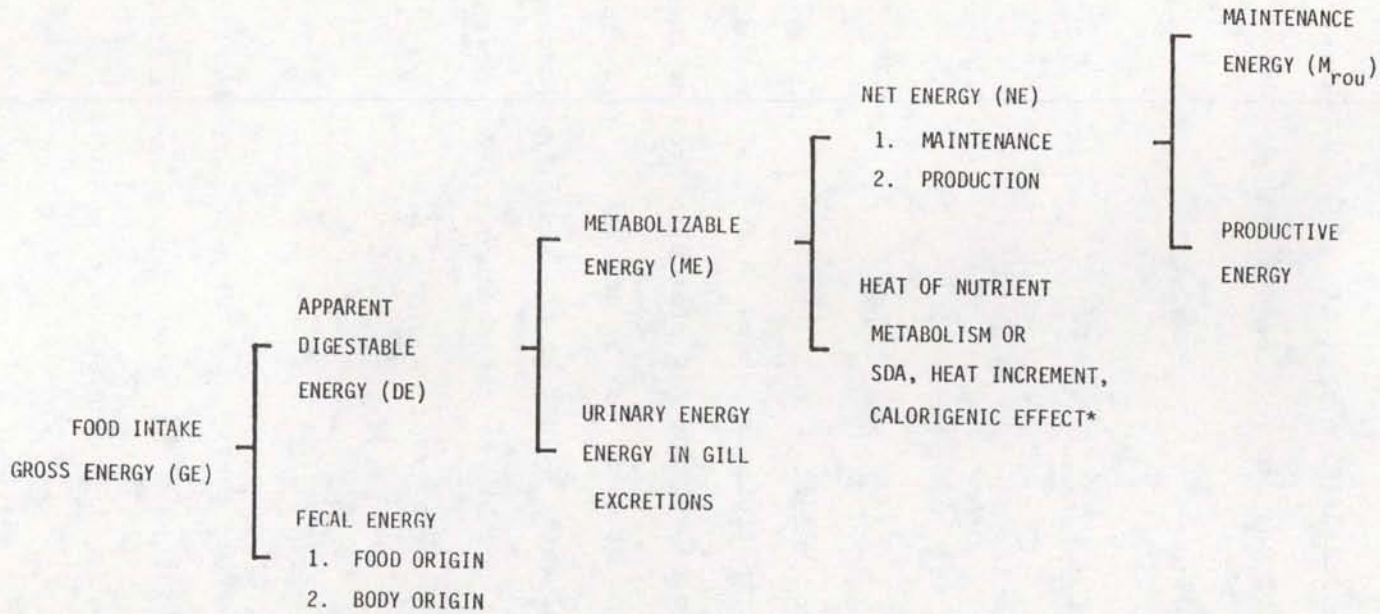

Figure 4. Energy flow in an aquaculture system (modified from Smith 1976).

2. Lipid Energy

Generally, 85% of fat contained in the diet is considered digestible by rainbow trout (Phillips and Brockway 1959), although digestibilities of 91% have been recorded (Klontz et al. 1978). The metabolizable energy of the fat content of the diet can be determined:

$$MEl = 9.4\ (Dl) \tag{31}$$

where:

MEl = Metabolizable energy of 1 gram of fat consumed.

Dl = Digestibility of fat in the diet.

9.4 = Kcals/g fat gross energy.

3. Carbohydrate Energy

Carbohydrate digestibility depends upon the types of carbohydrates in the diet; from a low of 40% for raw starch to greater than 90% for simple sugars. Phillips and Brockway (1959) determined an average carbohydrate digestibility of 40% while Klontz et al. (1978) recorded an average carbohydrate digestibility of 52% by rainbow trout. Calculation of metabolizable energy of the carbohydrate fraction of the diet is:

$$MEc = 4.15\ (Dc) \tag{32}$$

where:

MEc = Metabolizable energy of 1 gram of carbohydrate in the diet.

Dc = Digestibility of the carbohydrates in the diet.

4.15 = 4.15 Kcal/g of carbohydrate gross energy.

4. Total Energy

Total metabolizable energy of a diet can be obtained by:

$$MEt = (MEp\ (\%P) + MEl\ (\%L) + MEc\ (\%C)) \tag{33}$$

where:

MEt = Total metabolizable energy in the diet (Kcals/gram).

MEp = Metabolizable energy of protein (Equation 31).

%P = Percent protein composition of the specific diet (by proximate analysis).

MEf = Metabolizable energy of lipid (equation 32).

%L = Percent lipid composition of the specific diet (by proximate analysis).

MEc = Metabolizable energy of carbohydrates (equation 33).

%C = Percent carbohydrate composition of the specific diet (by proximate analysis).

B. WASTE PRODUCTS

1. Ammonia-Nitrogen:

Ammonia is a metabolic by-product resulting from protein anabolism and catabolism and is the main nitrogenous excretory product of teleost fish (Burrows 1964; Forster and Goldstein 1969). Ammonia is primarily excreted across the gills in exchange for sodium (Na^+). In aquatic systems, it dissociates into unionized and ionized forms. Although much of the ammonia in the aquatic environment is in the form of ionized ammonia, many studies have shown that the unionized fraction of ammonia is toxic to fish (Burrows 1964; Smith and Piper 1975; Larmoyeux and Piper 1973). High environmental concentrations of ammonia (NH_3) can cause gill hypertrophy or hyperplasia (Burrows 1964; Smith 1972), reduce fish growth (Brockway 1950; Burrows 1964; Larmoyeux and Piper 1973) or death (Smart 1976; 1978). Unionized ammonia (NH_3) limits in aquaculture systems have been set at a maximum of 0.0125 mg/l (Smith and Piper 1975). The dissociation of ammonia into ionized and unionized factions is described by:

NH_3 (unionized) + $H_2O \rightleftarrows NH_4^+ + OH^-$ (34)

Ammonia dissociation in water is pH and temperature dependent. Increases in temperature and/or pH decrease dissociation (shift the reaction to the left) (Trussell 1972). The model for ammonia dissociation is:

NH_3 (unionized) = (1/(10 exp (PKA-pH) +1) XTNH_3 (35)

where:

NH_3 (unionized) = unionized ammonia in the sample (mg/l).

PKA = 0.09018 + (2729.92/(C + 273.); where C is the temperature in centigrade.

pH = pH of the water.

TNH_3 = Total ammonia in the system (mg/l).

Maximum limits (= no-effect levels) of ammonia have been determined for continuous exposure to fish in the aquaculture systems, but the effects of exposure to varying concentrations of ammonia has received little attention (Smith and Piper 1975).

Burrows (1964) reported the differences in fish health as a result of varying the ammonia exposure pattern. These observations indicate that duration of exposure of ammonia to fish is at least as important as the ammonia concentration. Furthermore, a spiked (peaked) exposure of fish to high concentrations of unionized ammonia (total NH_3 0.7 ppm) did not adversely affect the health of the fish as much as continuous exposure to lower levels of unionized ammonia. The pattern of exposure of fish to unionized ammonia is directly related to the Total Ammonia Production (TAP) and its retention time in the rearing pond.

Other environmental variables altering susceptibility of fish to the effects of unionized ammonia are high carbon dioxide concentrations (Lloyd and Herbert, 1960) and low dissolved oxygen tensions (Merkens and Downing 1957; Downing and Merkens 1960). Both observations support the hypothesis that many environmental constraints affect growth and metabolism by altering oxygen uptake rates of the fish.

Previous models of Total Ammonia Production (TAP) by trout (Liao 1971; Willoughby et al. 1972; Speece 1973; Meade 1974; Paulson 1980) were developed from Haskell's supposition: "The amount of metabolic products generated is proportional to the amount of food fed." (Haskell 1959). These models linearly relate the TAP to the amount of food fed.

TAP by fish can be partitioned into two recognizable fractions; endogenous ammonia production (EAP) and exogenous ammonia production (EXAP). Endogenous ammonia excreted by fish is a waste product generated as a result of normal cellular catabolism. Exogenous ammonia excreted by fish is a waste product formed due to the breakdown of absorbed dietary nitrogen (protein) compounds which are not synthesized into body protein (Maynard et al. 1975).

Rates of endogenous ammonia production have been determined by measuring the amount of ammonia excreted by fish fed a diet of nitrogen-free, calorically adequate diet (Gerking 1955; Savitz 1969) or by starved fish (Brett and Zala 1975). Ammonia generated as a result of the consumption of protein-nitrogen (EXAP) was calculated by subtracting ammonia generated by fish receiving a nitrogen diet.

A systems model for TAP includes the components of the TAP, EAP, and EXAP, and the effects of systems variables, such as water temperature, fish size, and diet (Downey 1982).

a) Endogenous Ammonia Production:

A model proposed by Gerkins (1955) which was based upon homeothermous animal excretion models (Brody 1945), related EAP (mg/fish/day) to fish weight.

$$EAP = aWTn \qquad (36)$$

where:

a and n are constants determined empirically.

Experimental data indicated that (a) and (n) were 0.937 and 0.5394, respectively.

Equation 36 becomes:

$$EAP = 0.937\ (WT)\ 0.5394 \qquad (37)$$

Savitz (1969) demonstrated a temperature effect on EAP. The estimated weight slope coefficient (n) was considerably higher (0.93-0.99) than that estimated by Gerking (0.5394). He hypothesized that the variability may have been due to nutritional and/or thermal history of the fish and individual differences in activity (metabolism) during the experiments.

Brett and Zala (1975) recorded the highest EAP rates ever reported for fish. These high rates were attributed to species variation and high water velocity (10-12 cm/s) in the experimental ponds, which resulted in metabolic rates 2.3 times that of standard (= unfed) metabolism.

In this study, the model of EAP rates by trout in aquaculture systems is:

$$EAP = .1761\ (WT)\ 1.0457 \qquad (38)$$

Water temperature influences EAP rates indirectly by altering the metabolic rate of the fish. Paulson (1980) determined that ammonia excretion increased by 3.75% and 8.39% for rainbow trout and brook trout, respectively, for each degree centrigrade increase in water temperature. Generally, metabolic rates of fish double for every 10 C increase in temperature which is a 7.18% increase for each degree centrigrade increase.

b) Exogeneous Ammonia Production:

The production of exogeneous ammonia (EXAP), on the other hand, is proportional to the amount of food fed (I) (Brett and Zala 1975) and to the digestible protein content of the diet (Pc). Mathematically stated:

$$EXAPd = Ek\ (MPc)\ (I) \quad (39)$$

where:

EXAPd = The daily (24-hour) exogenous ammonia production.

Ek = A constant relating protein and food fed to ammonia production. (determined empirically).

MPc = Metabolizable protein content of the diet (g/kg).

I = Food intake (kg wet weight).

The amount of protein content of one kilogram of the diet can be determined by:

$$MPc = (\%P) \times (Dp) \times (1000 g/kg) \quad (40)$$

where:

%P = Percent protein of the diet (determined by proximate analysis).

Dp = Average protein digestibility.

Substitution of equation (40) into equation (39) yields:

$$EXAPd = Ek\ (\%P)\ (Dp)\ (1000)\ (I) \quad (41)$$

The constant, Ek, was determined empirically for rainbow trout from experimentally collected data. The EXAPd model is:

$$EXAPd = 51.928\ (\%P)\ (Dp)\ (1000)\ (I) \quad (42)$$

Since EXAPd rates are independent of the fish metabolic rate (Brett and Zala 1975), temperature does not affect EXAP. However, other systems variables, such as feeding rate, which can alter digestibility, can indirectly affect EXAPd.

The rate of total ammonia production during a 24-hour period is not constant, but demonstrates a predictably daily (24-hour) cycle (Brett and Zala 1975; Nightingale 1974; Hartman 1978; Paulson 1980). After feeding, ammonia production increases sharply until the maximum production occurs 4-6 hours after feeding. Rates decreased exponentially after peak production, returning to baseline levels. Brett and Zala (1975) noted that the baseline production during the night was the same as the endogenous ammonia excretion rates of the fish. In addition, the amount of ammonia being excreted in excess of the baseline rate was due entirely to EXAP production. Therefore, the expoential decrease in total ammonia production was due solely to fluctuations in EXAP. The model of hourly EXAP production is:

$$EXAPir = 0.085 (\exp (-0.130 (H-5))) (EXAPd) \qquad (43)$$

where:

EXAPir = Exogenous ammonia production by rainbow trout during the ith hour.

H = The number of hours post feeding.

EXAPd = Daily exogenous ammonia production by the trout (equation 41).

Since EXAP is a function of food fed, different feeding frequencies result in different hourly EXAP rates under similar conditions. Increasing the feeding frequency from one time (1 X) to three times (3 X) per day tends to result in "leveling" off the of the EXAP response. Analysis of feeding frequency effects on hourly EXAPh production requires two assumptions be made:

1) Daily (24-hour) EXAPd is not significantly affected by feeding frequency.
2) Hourly EXAP (EXAPh) for one feeding follows the "typical" response curve with the only difference being a magnitude change proportional to the digestible protein consumed.

The exogenous ammonia production for each feeding in feeding frequencies greater than 1 X per day could be represented by a series of curves in which each curve is described by equation (43). EXAPh is determined for more than one feeding frequency be summing the contribution of each feeding. Mathematically stated:

$$EXAPh = EE\ EXAPih \qquad (44)$$

where:

EXAPih = The EXAP produced for the ith feeding (ith curve) during the h hour.

2. Feces:

Fecal products excreted by fish are largely a composite of waste products from two sources; undigested feed residues and metabolic waste products In aquaculture systems the undigested feed residue contributing to the feces is directly related to the quantity (= feeding rate) and quality of the diet. Metabolic waste products, on the other hand, are end-products of fish metabolism. Both components must be considered singly or collectively when analyzing total feces production (TFP).

Analysis of TFP has been estimated by a model developed from empirical observations (Willoughby et al. 1972; Liao and Mayo 1974) or in laboratory digestibility studies (Phillips and Brockway 1959; Klontz et al. 1978). In these digestibility studies, the apparent digestibility (which differs from the actual digestibility) of various feed components is determined by calculating the difference in total component concentration (determined by proximate analysis) in the diet and the feces. This method of assessing apparent digestibility provides an estimate of the composite fecal production, which includes both the endogenous and exogenous components of the fecal material (Downey 1982).

Digestibility coefficients developed by these methods in the laboratory can be utilized in the analysis of fecal production of fish. With the bioenergetics systems approach, effects of feed composition are incorporated into the prediction of TFP. Since TFP is the difference between gross energy and digestible energy of the diet, TFP can be expressed as:

$$TFP = I - (Dp)(P) + (Dl)(L) + (Dc)(C) + (0.1)(ASH) \qquad (45)$$

<u>or</u>:

$$TFP = (1-Dp)(P) + (1-Dl)(L) + (1-Dc)(C) + FIBER + (0.9)(ASH) \times I \qquad (46)$$

where:

TFP = Total Fecal Production (dry weight) of the system on a daily basis.

I = Total food fed (grams).

Dp = Protein digestibility (90%).

P = Protein content in one kilogram of the diet (grams).

Dl = Lipid digestibility (85%).

L = Lipid content in one kilogram of the diet (grams).

Dc = Carbohydrate digestibility (40%).

C = Carbohydrate content in one kilogram of the diet (grams).

FIBER = Fiber content in one kilogram of the diet (grams).

ASH = Ash content in one kilogram of the diet (grams).

(assuming 10% of the minerals utilized for growth).

TFP can be converted to wet weight, assuming a 30% water content, and expressed as:

$$TFPw = TFP/0.70 \qquad (47)$$

This theoretical model, which directly relates TFP to the amount of food fed, quality of the diet, diet component digestibility and indirectly to feed efficiency and feeding rate, was compared to other predictive models. The TFP estimates generated by the theoretical proposed model were within 20% of the empirical models developed by Speece and Klontz et al.

3. Carbon Dioxide Production:

Carbon dioxide in aquaculture systems is a direct result of fish metabolism. High levels of CO_2 in the system can alter the hemoglobin oxygen affinity (Bohr effect) and carrying capacity of the blood (Root effect) and correspondingly reduce oxygen uptake resulting in reduced system productivity. High carbon dioxide levels can also affect the toxicity of ammonia in aquaculture systems by altering the system's pH (Lloyd and Herbert 1960).

The rate of CO_2 production by fish can be related to the amount of oxygen consumed by the respiratory quotient (RQ) defined as (Gorden et al. 1972):

$$RQ = VCO_2/VO_2 \qquad (48)$$

where:

VCO_2 = The volume of carbon dioxide expired.

VO_2 = The volume of oxygen consumed.

The amount of CO_2 expired (mg/fish/day) is:

$$CO_2 = RQ\ (44/32)\, R_{ot} \qquad (49)$$

Rot = Total oxygen consumption (mg/fish/day)

44/32 = Molecular weight correction for converting from volumetric to a weight measure.

The respiratory quotient depends upon the composition of the materials metabolized by the fish. The RQ has a value of 1.0 for carbohydrates, 0.8 for proteins, and 0.71 for fats (Gordon et al. 1972). Average RQ values for salmonids have ranged from 0.8 (Brett 1973) to 0.9 (Kutty 1968; Brett and Groves 1980).

The quantitative effects of CO_2 on the pH of the water can be described by (McLean 1979):

$$pH = -\log\ (1.136 \times K1 \times CO_2/A) \qquad (50)$$

where:

pH = The pH of the water.

CO_2 = The carbon dioxide concentration of the water (mg/l).

A = The bicarbonate alkalinity (mg/l as $CaCO_3$).

K1 = First ionization constant of H_2CO_3 at 10C (=3.436 X 10^{-7}) (Strumm and Morgan 1970).

C. FEEDING RATES

Feeding rates (i.e., amount of food fed per time) are a means by which growth rates of fish and systems productivity can be modified to meet specific management needs. If system productivity falls behind projected rates, management can increase feeding rates (if feeding rates are below allowable) to increase productivity. A reduction in feeding rates reduces productivity and can bring a system which is ahead of projected productivity back on schedule.

Feeding rates for fish in aquaculture systems have received considerable attention (Schaeperclaus 1933; Deuel et al. 1952; Phillips and Brockway 1959; Freeman et al. 1967; Phillips 1972: Klontz et al. 1979).

Development of feeding rate calculations should incorporate the energy gain of the fish, and routine metabolic rates of the fish. The amount of food fed during a specified period must contain enough metabolizable energy to satisfy all of these energy requirements of the fish for growth and metabolism. Mathematically stated:

$$TEd = GBEC + Mrou \qquad (51)$$

where:

TEd = Total energy requirements for feed (Kcals/day).

GBEC = Energy required for a specific growth (Kcals/day)

Mrou = Routine Metabolic rate (Kcals/day)

The feeding rate for the diet can be calculated by:

$$Rf = TEd/(MEt) \qquad (52)$$

where:

Rf = feeding rate (grams/day).

Met = Metabolizable Energy of the diet (Kcals/gram)

Wet weight feed conversions, which are the wet weight of food fed divided by the wet weight growth can be calculated by:

$$CONV = Rf/WTGAIN \tag{53}$$

where:

Rf = Feeding rate (grams/day)

WTGAIN = Wet weight gain of fish per day (grams/day).

VIII. PRODUCTION FORECASTING COMPUTER MODEL

The forecasting model, written in IBM WATFIV fortran, requires 520K of storage and takes approximately 7.5 seconds of CPU time to execute completely on a 4341 IBM Central Processor. There are three purposes of the model:

1. To provide a growth forecast, based on allowable growth for a specified product and systems configuration.
2. To provide information on pond hydraulics, diet composition, and average water quality of the system.
3. To provide information on the pond space requirements for rearing the product.

To meet these specified goals, the following assumptions are made:

1. Maximum growth rates for trout stated by Klontz et al. (1979) hold true for all systems.
2. A management strategy which loads ponds to reach maximum carrying capacities at the end of a growth period is assumed when calculating water quality parameters.
3. Management strategies which maintain fish densities below carrying capacity during the growth period are employed and that constraints to growth, such as DO < 90 mmHg and $NH_3 > 0.0125$ mg/l, are never operational.
4. The average diet quality for specific diets is constant.
5. Only one pond type (single use, multiple use raceway and circular ponds) are used for each product definition and water inflow per pond is constant throughout product rearing.
6. A linear relationship exists between any two specified water temperatures.
7. The circular pond mixing coefficient and water velocity is 1.83 and 0.5 fps, respectively.
8. The digestibilities for nutritional components are: Protein-90%; Lipids-85%; Carbohydrates-40%.

A. MODEL DESCRIPTION

The actual computer model consists of two programs. The first program, which consists of 228 statements, is an EXEC, a special program in IBM interactive systems, which attaches data files and calls the FORTRAN program, PRELIM, for execution. In the EXEC program, the user has the opportunity to obtain a manual at his/her terminal describing the program, and provides the name(s) of the data file(s) to be used in the program.

PRELIM has approximately 1525 statements organized in a main program and 25 subroutines (Figure 5). The main program contains many of the input read statements which request information on the product definition and systems description. The program can handle 15 product definitions simultaneously, each with 40 growth periods (15-day periods) per product definition. When all input information is acquired, specific subroutines depending upon the stated product definition are called.

Subroutine ERROR checks the input data to insure the data entered are reasonable. If inputed data are unreasonable; i.e., a 13 is entered for month, this subroutine alerts the user that the data has been improperly entered. Program control is then returned to the main program and the user is asked to reenter the product definition(s).

Subroutine WATERT requests information on the water temperature profile, water pH, and facility elevation. The subroutine then calculates the water temperature for each day of the year by linearly interpolating values from the input temperature data.

Subroutine CALCGR is called by the main program when the user specifies the fish will arrive (or hatch) on the facility. The Allowable Growth Rates (AGR) of the fish for the particular system is calculated and compared to the required growth rate (end size minus beginning size). A performance factor is calculated (= required/allowable) and allowable growth rate is adjusted

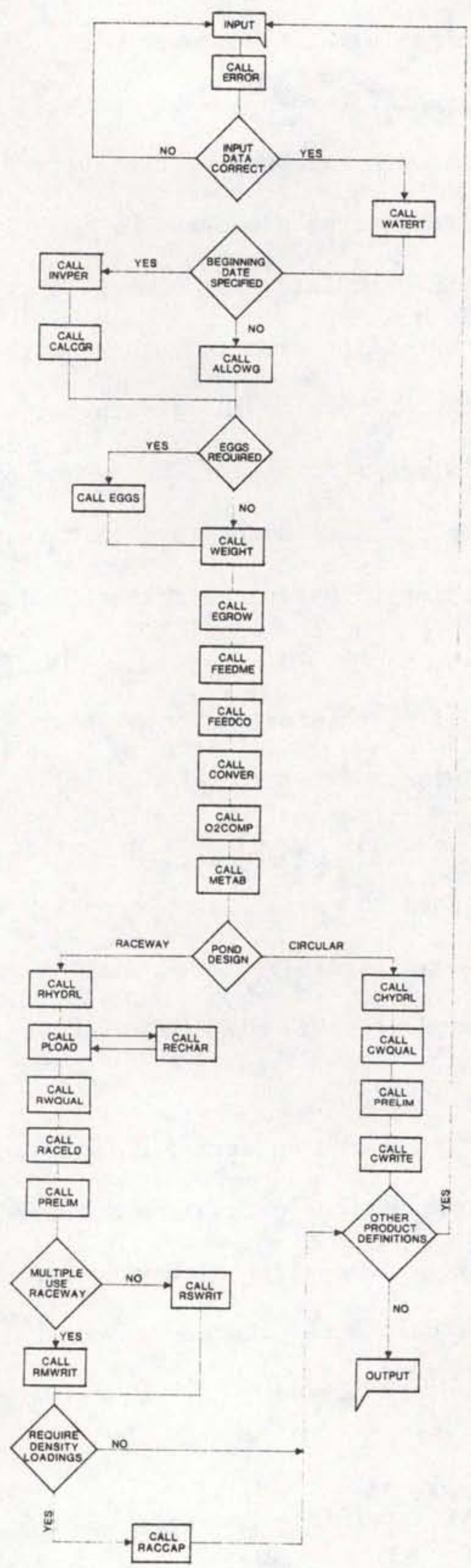

Figure 5. Flow diagram of the production forecasting mode, PRELIM.

by this factor. If the performance factor is greater than one, the product definition cannot be met within the constraints of the system. If the required growth is greater than allowable growth, the computer prints a message stating the growth rate and productivity are not within the means of the system and then terminates execution.

Subroutine INVPER calculates the number of growth or inventory periods and the approximate dates for each inventory period in the growth forecast.

Subroutine ALLOWG calculates the growth rates for each inventory period when the beginning is not specified. The number of inventory periods and the inventory period date are also determined in this subroutine. Growth rates are determined according to water temperature and are considered to be allowable for the system.

Subroutine WEIGHT calculates the total poundage and total number of fish at each inventory period.

Subroutine FEEDME reads the diet file containing proximate analysis information and calculates the metabolizable energy and net energy of each pellet size. Average wastage (%), based upon nutritional components (protein, lipids, fiber, carbohydrates) is also calculated. This subroutine calls another subroutine, FEEDCO.

Subroutine FEEDCO creates an array, COLLAT, which contains the variables which correspond to the various diet sizes required for each fish size, collates the diet size, and quality with specific inventory periods.

Subroutine EGROW calculates the energy content contained in the body of one fish at each inventory period. It then calculates the growth of fish in terms of energy.

Subroutine CONVER determines the total energy requirements of an individual fish for each inventory period. Feed conversions (wet weight) and feed requirements for the entire product are also calculated.

Subroutine O2COMP reads in data files containing the saturation values of oxygen (mg/l) and minimum oxygen levels (mg/l) for various temperatures and elevations. Carrying capacities based on available oxygen and calculated oxygen consumption per pond for each inventory period are also calculated.

Subroutine METAB computes the daily amount of total ammonia and feces produced per fish.

If the fish are to be raised in raceways, subroutine RHYDRL is called from the main program. Subroutine RHYDRL calculates the hydraulic components, volume, retention time, and water velocity of a raceway pond.

Subroutine CHYDRL calculates the hydraulic components, volume, retention time, and water velocity if circular ponds are used to raise the trout.

Subroutine PCCAP calculates the maximum density index of the pond. This subroutine also compares the maximum density carrying capacity to the oxygen carrying capacity and stores the lesser of the two as a value of another variable. If the system is a multiple-use raceway, this subroutine calls subroutine RECHAR in order to determine carrying capacities in reuse ponds. Subroutine RECHAR determines the recharge of oxygen occurring in the reuse ponds of the raceway system.

Subroutine RWQUAL computes the unionized ammonia concentration in a raceway pond generated by a full pond of fish (determined from the lesser of the two carrying capacities of PCCAP). If this concentration exceeds 0.0125 mg/l in the pond (or reuse pond) new maximum carrying capacities are determined. Once maximum poundage is calculated, average water quality, unionized ammonia concentration, average fecal solids concentration, and starting and ending densities, based on maximum carrying capacities, are also recorded.

Subroutine RACELD calculates the total pounds of fish, total pond and water flow requirements for each inventory period.

Subroutine CWQUAL determines the carrying capacity of circular ponds. It determines which carrying capacity, density or oxygen, is lower and then uses these densities to calculate average unionized ammonia concentrations in the pond. If the average unionized ammonia concentration exceeds 0.0125 mg/l, the maximum poundage is reduced to produce an average concentration of 0.0125 mg/l. Average fecal solids concentrations are then calculated.

Subroutine PRELIM contains the "write" statements for the preliminary growth program.

Subroutine RSWRIT writes the summary of the pond, diet, and water quality characteristics for a single-use raceway system.

Subroutine RACCAP writes the beginning and ending fish densities for a completely loaded raceway. This output has to be specifically requested.

Subroutine CWRITE writes the summary of the pond, diet, and water quality characteristics for a circular pond system.

B. MODEL OUTPUT

The production forecasting model generates depending on pond design, several sets of summary statistics tables (Tables 1 - 3).

The first set of tables printed by the program is a preliminary production forecast. The number of eggs needed for the product definition (if the fish are reared from eggs) and the days required for egg incubation are presented. The incubation times are based on temperature units and data defined by Leitritz and Lewis (1976).

The main table of the preliminary forecast consists of nine columns of information. The inventory period column contains approximate dates of pond inventory. The density capacity and oxygen capacity columns provide a maximum poundage of fish, according to fish size and pond design, permitted in the pond without exceeding pond capacities. The fish size, number of fish,

Table 1. An example of the input required and summary tables for single use raceway ponds generated by the PRELIM computer program.

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THE PRELIMINARY PROGRAM IS A LONG RANGE FORCASTING MODEL.  IT IS
DESIGNED TO ALLOW THE USER TO PROGRAM THE FACILITY'S PRODUCTION
BY PROVIDING QUANTITIVE INFORMATION ON GROWTH RATES, FEED SCHEDULES,
WATER AND POND REQUIREMENTS AND SUGGESTED LOADING AND SPLITTING
DENSITIES. DETAILS OF THE PROGRAM'S OPERATION AND THE GENERAL USE OF
COMPUTERS FOR GROWTH FORCASTING ARE EXPLAINED IN TWO MANUALS PRINTED
AT THE UNIVERSITY OF IDAHO ("USING THE PRELIMINARY GROWTH PROGRAM",
BY PHILIP C. DOWNEY AND GEORGE W. KLONTZ, AND "USING THE CMS INTERACTIVE
COMPUTER SYSTEM FOR GROWTH PROGRAMMING", BY PHILIP C. DOWNEY AND GEORGE
W. KLONTZ.  WOULD YOU LIKE A COPY OF EITHER THE CMS MANUAL (ENTER CMS),
OR THE PRELIMINARY GROWTH PROGRAM (ENTER PRE) OR BOTH MANUALS (ENTER
BOTH)?  IF NOT ENTER NO.
no


THE PRELIMINARY PROGRAM REQUIRES THE USER TO INPUT INFORMATION IN
ORDER TO OPERATE THE PROGRAM AND CALCULATE THE FACILITY'S POTENTIAL.
PROVIDING THIS INFORMATION TO THE COMPUTER CAN BE ACCOMPLISHED  BY
ENTERING THE DATA IN AN INTERACTIVE MODE OR BY PROVIDING THE COMPUTER
WITH DATA FILES CONTAINING THE INPUT DATA.

DO YOU WANT TO INPUT THE DATA IN THE INTERACTIVE MODE (ENTER INTER)
OR USING DATA FILES (ENTER DATA)?
inter
EACH TIME INFORMATION IS NECESSARY THE COMPUTER WILL PRINT A MESSAGE
EXPLAINING WHAT TYPE(S) OF INFORMATION ARE REQUIRED. UPON COMPLETION
OF THE COMPUTER MESSAGE YOU WILL INPUT THE DESIRED INFORMATION.


WHAT BRAND OF FEED WILL BE FED?

    OREGON MOIST PELLET (ENTER OMP)
    SILVERCUP           (ENTER SIL)
    MOORE-CLARK         (ENTER MC)
  * A SPECIFIC DIET     (ENTER NAME)

*NOTE:
 THE USER OF THIS PROGRAM MAY SPECIFY A SPECIFIC DIET HE/SHE WISHES
  TO USE.  THE DIET INFORMATION MUST BE STORED IN A DATA FILE AND GIVEN
  A NAME (ANY 8 CHARACTER NAME), AND FOLLOW A SPECIFIC FORMAT. IF YOU
  LIKE TO USE A SPECIFIC DIET FOR PRODUCTION, CONSULT THE USER'S MANUAL
  FOR INSTRUCTIONS ON FORMING THE DIET DATA FILE.
sil
```

Table 1. (continued).

```
EXECUTION BEGINS...
 HOW MANY DIFFERENT PRODUCT DEFINITIONS DOES THE FACILITY HAVE
?
1
 ENTER THE PRODUCT DEFINITIONS, ONE DEFINITION PER LINE-AFTER EACH QUESTION MARK.


 A COMPLETE PRODUCT DEFINITION CONSISTS OF:

 (1) THE SPECIES OF FISH (CODE IS 1--RAINBOW TROUT)
 (2) THE MONTH, DAY AND YEAR THE PRODUCT IS TO BE READY (I.E.,4,15,0).
 (3) THE SIZE OF THE FISH ON THE DAY THEY ARE TO BE READY FOR MARKET OR STOCKING;
     ENTER BOTH THE NUMBER PER POUND AND THE TOTAL LENGTH IN INCHES
 (4) THE SIZE(IN INCHES)AND THE DATE AT THE BEGINNING OF THE GROWTH PROGRAM;
       A) IF THEY ARE TO BE EGGS AT THE BEGINNING ,ENTER O FOR SIZE.
       B) IF THE SIZE OF THE FISH (EGGS,1",2",ECT.) ARE AVAILABLE YEAR ROUND,
          YOU CAN ENTER 0 AND THE COMPUTER WILL CALCULATE THE DATE WHEN EGGS
          SHOULD BE OBTAINED.
 (5)  ENTER THE MAXIMUM DENSITY INDEX.


   AN EXAMPLE OF HOW TO ENTER THE DATA.


    THE PRODUCT DEFINITION IS:

 1000000 RAINBOW TROUT 1.4 PER POUND (SIZE=12 INCHES) ARE NEEDED ON APRIL 1.
 THEY WILL BE RAISED FROM EGGS WHICH CAN BE OBTAINED THROUGHOUT THE YEAR.
 MAXIMUM DENSITIES ARE NOT TO EXCEED 0.5 LBS/CUFT/INCH.

    THE ENTRY WOULD APPEAR AS:

 1,4,1,0,1.4,12,1000000,0,0,0,.5


?
1,4,1,0,1.4,12,1000000,0,0,0,.5
```

Table 1. (continued).

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 WHAT TYPE OF POND WILL BE USED TO REAR THIS PRODUCT DEFINITION?
 ENTER 1 FOR RACEWAY PONDS AND 2 FOR CIRCULATING PONDS.
?
1
 ENTER THE AMOUNT OF WATER (IN CFS) ENTERING EACH RACEWAY, AND THE WATER USE;
 (THE CODE FOR WATER USAGE IS: 1 FOR SINGLE USE,2 FOR 1 REUSE,3 FOR 2 REUSES.)
?
2.1,1
 ENTER THE AVERAGE LENGTH, WIDTH, AND DEPTH OF A SINGLE POND IN THE
 RACEWAY SYSTEM.
?
100,10,3
 WHAT IS THE WATER PH, ALKALINITY AND THE ELEVATION OF THE STATION ?
?
7.6,190,1000
 HOW MANY DIFFERENT WATER TEMPERATURE VALUES ARE RECORDED AND WHAT IS THE MEASUREMENT SCALE
(ENTER 1 FOR FAHRENHEIT OR  0 FOR CENTIGRADE)
?
2,1
 ENTER THE MONTH AND DAY THE TEMPERATURE WAS RECORDED,
 AND THE WATER TEMPERATURE SCALE (0 FOR CENTIGRADE, 1 FOR FEHRENHEIT).
?
1,1,54
?
6,1,59
```

Table 1.(continued).

** PRODUCT DEFINITION 1 **

*** PRELIMINARY PROGRAM FOR RAINBOW TROUT ***

THE EGGS SHOULD BE OBTAINED ON APRIL 22 AND WILL
REQUIRE 40 DAYS TO REACH 1.90 ON JUNE 01 .

INVENTORY PERIOD		DENSITY CAPACITY (LBS/POND)	OXYGEN CAPACITY (LBS/POND)	FISH SIZE (IN INCHES)	NUMBER OF FISH	NUMBER PER LB	TOTAL LBS OF FISH	FEED CONVERSION	TOTAL LBS FEED FED PER INVENTORY	FEED SIZE
JUNE	01	2852.0	1032.6	1.90	1093935.	351.955	3108.16	1.317	5628.77	32 FRY COARSE
JUNE	15	3811.1	1455.9	2.54	1089035.	147.504	7383.10	1.458	10005.66	33 FINE CRUMBLES
JULY	01	4751.9	1907.3	3.17	1084158.	76.093	14247.88	1.446	14369.04	34 COARSE CRUMBL
JULY	15	5676.8	2375.4	3.78	1079302.	44.631	24182.75	1.488	19864.37	3/32" PELLET
AUGUST	01	6582.3	2876.2	4.39	1074468.	28.629	37530.36	1.477	25293.85	3/32" PELLET
AUGUST	15	7471.9	3385.3	4.98	1069654.	19.573	54649.73	1.476	31097.64	1/8" PELLET
SEPTEMBER	01	8342.1	4027.3	5.56	1064864.	14.064	75713.44	1.506	36433.54	1/8" PELLET
SEPTEMBER	15	9163.5	4570.8	6.11	1060094.	10.611	99903.94	1.505	42268.54	1/8" PELLET
OCTOBER	01	9967.4	5148.3	6.64	1055346.	8.245	127994.94	1.539	47275.52	5/32" PELLET
OCTOBER	15	10724.4	5710.7	7.15	1050619.	6.620	158714.94	1.540	52760.11	5/32" PELLET
NOVEMBER	01	11463.5	6319.4	7.64	1045914.	5.420	192976.81	1.576	57038.66	3/16" PELLET
NOVEMBER	15	12157.8	7063.9	8.11	1041229.	4.543	229171.87	1.576	61982.56	3/16" PELLET
DECEMBER	01	12835.9	7698.1	8.56	1036566.	3.861	268489.44	1.571	66716.06	3/16" PELLET
DECEMBER	15	13499.9	8326.7	9.00	1031922.	3.319	310950.00	1.621	69967.56	3/16" PELLET
JANUARY	1	14118.6	8994.2	9.41	1027301.	2.901	354102.75	1.561	75526.69	3/16" PELLET
JANUARY	15	14756.5	9146.4	9.84	1022699.	2.541	402487.31	1.605	83182.50	3/16" PELLET
FEBRUARY	01	15387.5	9213.7	10.26	1018119.	2.241	454318.69	1.616	93170.62	3/16" PELLET
FEBRUARY	15	16036.8	9121.9	10.69	1013558.	1.980	511987.50	1.673	101636.75	1/4" PELLET
MARCH	01	16672.6	9221.9	11.12	1009019.	1.762	572748.37	1.678	112601.56	1/4" PELLET
MARCH	15	17325.7	9318.3	11.55	1004499.	1.570	639852.56	1.678	124897.75	1/4" PELLET
APRIL	01	18000.0	9348.6	12.00	1000000.	1.400	714285.87	0.0	0.0	---------

Table 1. (continued).

*** SUMMARY OF SINGLE USE RACEWAY COMPONENTS ***

POND HYDRAULICS

POND-SINGLE USE RACEWAY

INFLOW- 2.1 CFS

POND DIMENSIONS

POND LENGTH-100.0 FEET
POND WIDTH- 10.0 FEET
POND DEPTH- 3.00 FEET
VOLUME- 3000.0 CUFT.

MEAN RETENTION TIME 23.8 MINUTES

AVERAGE WATER VELOCITY-0.0778 FPS

DIET COMPOSITION

FEED SIZE	PROTEIN (%)	LIPID (%)	CHO (%)	METABOLIZABLE ENERGY (KCAL/LB)
STARTER	54.4	15.8	10.7	1697.2
#1 FRY FINE	52.2	13.1	10.7	1557.1
#2 FRY COARSE	52.2	13.1	10.7	1557.1
#3 FINE CRUMBLES	48.3	9.3	18.3	1401.9
#4 COARSE CRUMBL	48.3	9.3	18.3	1401.9
3/32" PELLET	44.6	9.4	21.6	1359.5
1/8" PELLET	44.6	9.4	21.6	1359.5
5/32" PELLET	44.6	9.4	21.6	1359.5
3/16" PELLET	44.6	9.4	21.6	1359.5
1/4" PELLET	44.6	9.4	21.6	1359.5

Table 1. (continued).

WATER QUALITY PER POND SYSTEM

WATER PH= 7.6
ALKALINITY=190.0

INVENTORY PERIOD		FISH DENSITIES (LBS)	WATER TEMPERATURE (F)	INFLOW OXYGEN (PPM)	OUTFALL OXYGEN (PPM)	DAILY AMMONIA PRODUCTION (MG/FISH/DAY)	AVERAGE UNIONIZED AMMONIA CONCENTRATION (PPM)	DAILY FECES PRODUCTION (MG/FISH/DAY)	AVERAGE FECAL CONCENTRATION (PPM)
JUNE	01	1032.6	59.0	10.3	5.9	3.14164	0.002385	28.94041	2.044818
JUNE	15	1455.9	58.7	10.3	5.9	5.82851	0.002579	64.67914	2.799239
JULY	01	1907.3	58.3	10.3	5.9	9.14380	0.002692	98.45935	2.777985
JULY	15	2375.4	58.0	10.3	5.9	12.64402	0.002682	163.41197	3.368002
AUGUST	01	2876.2	57.6	10.3	5.9	17.16086	0.002781	214.65712	3.436338
AUGUST	15	3385.3	57.2	10.3	5.9	22.36272	0.002877	270.73145	3.498427
SEPTEMBER	01	4027.3	56.9	10.5	6.0	27.87006	0.003014	325.36816	3.582793
SEPTEMBER	15	4570.8	56.5	10.5	6.0	33.98338	0.003104	384.15332	3.622224
OCTOBER	01	5148.3	56.1	10.5	6.0	40.20023	0.003163	438.12695	3.6615583
OCTOBER	15	5710.7	55.8	10.5	6.0	46.96262	0.003246	495.77832	3.643508
NOVEMBER	01	6319.4	55.4	10.5	6.0	53.56314	0.003299	544.80176	3.627625
NOVEMBER	15	7063.9	55.1	10.8	6.2	60.75105	0.003458	598.99243	3.737373
DECEMBER	01	7698.1	54.7	10.8	6.2	68.22371	0.003539	651.83203	3.766201
DECEMBER	15	8326.7	54.4	10.8	6.2	75.35713	0.003585	693.60254	3.726077
JANUARY	1	8994.2	54.0	10.8	6.2	83.77879	0.003700	753.00073	3.819813
JANUARY	15	9146.4	54.5	10.8	6.2	94.39813	0.003787	836.77808	3.780689
FEBRUARY	01	9213.7	55.0	10.8	6.2	106.88470	0.003902	942.50659	3.783305
FEBRUARY	15	9121.9	55.5	10.5	6.0	119.39996	0.003887	1030.5088	3.644929
MARCH	01	9221.9	56.0	10.5	6.0	133.81546	0.003997	1176.0471	3.651708
MARCH	15	9318.3	56.4	10.5	6.0	149.96117	0.004113	1332.1179	3.665835
APRIL	01	9348.6	57.0	10.5	6.0	74.30809	0.001867	1332.1179	3.279742

Table 1. (continued).

MANAGEMENT COMPONENT

INVENTORY PERIOD		TOTAL PONDS REQUIRED	WATER REQUIREMENTS (IN CFS)
JUNE	01	6	12.60
JUNE	15	8	16.80
JULY	01	11	23.10
JULY	15	14	29.40
AUGUST	01	17	35.70
AUGUST	15	19	39.90
SEPTEMBER	01	22	46.20
SEPTEMBER	15	25	52.50
OCTOBER	01	28	58.80
OCTOBER	15	31	65.10
NOVEMBER	01	33	69.30
NOVEMBER	15	35	73.50
DECEMBER	01	38	79.80
DECEMBER	15	40	84.00
JANUARY	1	45	94.50
JANUARY	15	50	105.00
FEBRUARY	01	57	119.70
FEBRUARY	15	63	132.30
MARCH	01	69	144.90
MARCH	15	77	161.70

Table 2. An example of the summary tables generated by the PRELIM computer model for multiple use raceways.

*** PRELIMINARY PROGRAM FOR RAINBOW TROUT ***

THE EGGS SHOULD BE OBTAINED ON SEPTEMBER 03 AND WILL
REQUIRE 42 DAYS TO REACH 1.89 ON OCTOBER 15 .

INVENTORY PERIOD		DENSITY CAPACITY (LBS/POND)	OXYGEN CAPACITY (LBS/POND)	FISH SIZE (IN INCHES)	NUMBER OF FISH	NUMBER PER LB	TOTAL LBS OF FISH	FEED CONVERSION	TOTAL LBS FEED FED PER INVENTENTORY	FEED SIZE
OCTOBER	15	2265.5	1090.2	1.89	112314.	364.087	308.48	1.383	512.64	FRY COARSE
NOVEMBER	01	2951.7	1506.8	2.46	111811.	164.621	679.20	1.636	935.54	GROWER CRUM
NOVEMBER	15	3623.6	1939.2	3.02	111310.	88.976	1251.00	1.633	1306.35	COARSE CRUM
DECEMBER	01	4279.2	2399.7	3.57	110811.	54.027	2051.05	1.466	1544.08	3/32" PELLET
DECEMBER	15	4920.6	2872.7	4.10	110315.	35.535	3104.37	1.467	1932.44	3/32" PELLET
JANUARY	1	5544.6	3461.7	4.62	109821.	24.837	4421.62	1.404	2358.68	4/32" PELLET
JANUARY	15	6182.2	3811.4	5.15	109329.	17.917	6101.85	1.402	2962.39	4/32" PELLET
FEBRUARY	01	6836.5	4040.1	5.70	108839.	13.250	8214.27	1.627	4052.21	5/32" PELLET
FEBRUARY	15	7478.6	4355.2	6.23	108352.	10.121	10705.20	1.631	4902.83	5/32" PELLET
MARCH	01	8134.0	4665.0	6.78	107867.	7.867	13711.41	1.680	5762.39	5/32" PELLET
MARCH	15	8775.7	4952.3	7.31	107383.	6.264	17142.17	1.680	6804.95	5/32" PELLET
APRIL	01	9432.7	5084.3	7.86	106902.	5.044	21192.37	1.739	7844.29	5/32" PELLET
APRIL	15	10074.4	5337.4	8.40	106424.	4.141	25702.77	1.742	9079.51	5/32" PELLET
MAY	01	10729.9	5566.6	8.94	105947.	3.427	30914.35	1.817	10223.74	5/32" PELLET
MAY	15	11361.9	5868.3	9.47	105472.	2.886	36540.93	1.818	11480.70	5/32" PELLET
JUNE	01	12000.0	6154.8	10.00	105000.	2.450	42857.13	0.0	0.0	------------

Table 2. (continued).

SUMMARY OF MULTIPLE USE RACEWAY COMPONENTS

POND HYDRAULICS

POND—MULTIPLE USE RACEWAY

INFLOW- 2.1 CFS

POND DIMENSIONS

POND LENGTH-100.0 FEET
POND WIDTH- 10.0 FEET
POND DEPTH- 3.00 FEET
VOLUME- 3000.0 CUFT.

MEAN RETENTION TIME 23.8 MINUTES

AVERAGE WATER VELOCITY-0.0778 FPS

DIET COMPOSITION

FEED SIZE	PROTEIN (%)	LIPID (%)	CHO (%)	METABOLIZABLE ENERGY (KCAL/LB)
CHINOOK MASH	53.1	11.8	10.7	1527.3
FRY FINE	46.6	12.5	15.5	1464.1
FRY COARSE	46.6	12.5	15.5	1464.1
GROWER CRUMBLE	43.2	7.2	18.4	1228.7
COARSE CRUMBLE	43.2	7.2	18.4	1228.7
3/32" PELLET	39.8	11.9	21.6	1358.0
4/32" PELLET	45.6	9.5	20.2	1371.7
5/32" PELLET	37.3	9.3	22.1	1219.5
3/16" PELLET	37.3	9.3	22.1	1219.5
1/4" PELLET	45.8	8.4	21.1	1342.5

Table 2. (continued).

WATER QUALITY PER POND SYSTEM

WATER PH= 7.5
ALKALINITY=150.0

INVENTORY PERIOD	POND REUSE	FISH DENSITIES (LBS)	WATER TEMPERATURE (F)	INFLOW OXYGEN (PPM)	OUTFALL OXYGEN (PPM)	DAILY AMMONIA PRODUCTION (MG/FISH/DAY)	AVERAGE UNIONIZED AMMONIA CONCENTRATION (PPM)	DAILY FECES PRODUCTION (MG/FISH/DAY)	AVERAGE FECAL CONCENTRATION (PPM)
OCTOBER 15	0	1090.2	57.0	10.1	6.0	2.6046	0.001584	34.9754	0.763677
	1	457.6		7.8	6.0		0.000664		1.132352
	2	457.6		7.8	6.0		0.0		0.0
OUTFALL AVERAGE		0.0					0.002247		1.895028
NOVEMBER 01	0	1506.8	56.6	10.1	6.0	4.8763	0.001818	69.1900	1.503974
	1	632.5		7.8	6.0		0.000763		1.399457
	2	632.5		7.8	6.0		0.000763		1.399457
OUTFALL AVERAGE		1264.0					0.003344		4.302888
NOVEMBER 15	0	1939.2	56.2	10.1	6.0	7.3990	0.001890	101.8794	2.204622
	1	814.0		7.8	6.0		0.000792		1.432734
	2	814.0		7.8	6.0		0.000792		1.432734
OUTFALL AVERAGE		1626.0					0.003475		5.070091
DECEMBER 01	0	2399.7	55.8	10.1	6.0	8.9031	0.001679	144.1580	3.105538
	1	1007.3		7.8	6.0		0.000704		1.524719
	2	1007.3		7.8	6.0		0.000704		1.523719
OUTFALL AVERAGE		2014.0					0.003088		6.154977
DECEMBER 15	0	2872.7	55.4	10.1	6.0	11.9055	0.001740	185.9077	3.689429
	1	1205.8		7.8	6.0		0.000730		1.547601
	2	1205.8		7.8	6.0		0.000730		1.547601
OUTFALL AVERAGE		2410.0					0.003201		6.784631
JANUARY 1	0	3461.7	55.0	10.4	6.2	17.0272	0.002057	197.9249	3.308335
	1	1453.1		7.9	6.2		0.000864		1.388620
	2	1453.1		7.9	6.2		0.000864		1.388620
OUTFALL AVERAGE		2906.0					0.003785		6.085576

Table 2. (continued).

JANUARY	15	0	3811.4	55.3	10.4	6.2	22.1952	0.002162	252.3626	3.350367
		1	1599.8		7.9	6.2		0.000907		1.405600
		2	1599.8		7.9	6.2		0.000907		1.405600
OUTFALL AVERAGE			3198.0					0.003976		6.161566
FEBRUARY	01	0	4040.1	55.8	10.1	6.0	26.4962	0.002060	433.2178	4.508469
		1	1695.8		7.8	6.0		0.000864		1.891503
		2	1695.8		7.8	6.0		0.000864		1.881503
OUTFALL AVERAGE			3390.0					0.003788		8.291475
FEBRUARY	15	0	4355.2	56.1	10.1	6.0	33.1644	0.002155	530.5967	4.547051
		1	1828.1		7.8	6.0		0.000904		1.908518
		2	1828.1		7.8	6.0		0.000904		1.908518
OUTFALL AVERAGE			3656.0					0.003963		8.364087
MARCH	01	0	4665.0	56.5	10.1	6.0	40.5997	0.002229	633.3560	4.518703
		1	1958.1		7.8	6.0		0.000935		1.896616
		2	1958.1		7.8	6.0		0.000935		1.896616
OUTFALL AVERAGE			3916.0					0.004100		8.311934
MARCH	15	0	4952.3	56.8	10.1	6.0	49.3499	0.002324	755.2798	4.555154
		1	2078.7		7.8	6.0		0.000975		1.911343
		2	2078.7		7.8	6.0		0.000975		1.911343
OUTFALL AVERAGE			4156.0					0.004274		8.377839
APRIL	01	0	5084.3	57.2	9.9	5.9	58.9984	0.002338	882.6404	4.400823
		1	2134.1		7.6	5.9		0.000981		1.847141
		2	2134.1		7.6	5.9		0.000981		1.847141
OUTFALL AVERAGE			4268.0					0.004301		8.095105
APRIL	15	0	5337.4	57.6	9.9	5.9	70.0844	0.002429	1030.5088	4.427429
		1	2240.4		7.6	5.9		0.001019		1.858111
		2	2240.4		7.6	5.9		0.001019		1.858111
OUTFALL AVERAGE			4480.0					0.004468		8.143652

Table 2. (continued).

MAY	01	0	5566.6	58.0	9.9	5.9	81.8338	0.002490	1176.0471	4.361670
		1	2336.6		7.6	5.9		0.001045		1.830373
		2	2336.6		7.6	5.9		0.001045		1.830373
OUTFALL AVERAGE			4672.0					0.004579		8.022415
MAY	15	0	5868.3	58.2	9.9	5.9	94.5578	0.002571	1332.1179	4.386629
		1	2463.2		7.6	5.9		0.001079		1.841113
		2	2463.2		7.6	5.9		0.001079		1.841113
OUTFALL AVERAGE			4926.0					0.004728		8.068855
JUNE	01	0	6154.8	58.3	9.9	5.9	100.1888	0.002444	1332.1179	3.905168
		1	2583.5		7.6	5.9		0.001025		1.638879
		2	2583.5		7.6	5.9		0.001025		1.638879
OUTFALL AVERAGE			5166.0					0.004495		7.182925

MANAGEMENT COMPONENT

INVENTORY PERIOD		TOTAL PONDS REQUIRED	MAXIMUM WATER REQUIREMENTS (IN CFS)	TOTAL NO OF RACEWAYS	MINIMUM TOTAL WATER REQUIRED (IN CFS)
OCTOBER	15	1	2.10	1	2.10
NOVEMBER	01	1	2.10	1	2.10
NOVEMBER	15	1	2.10	1	2.10
DECEMBER	01	2	4.20	1	2.10
DECEMBER	15	2	4.20	1	2.10
JANUARY	1	2	4.20	1	2.10
JANUARY	15	3	6.30	2	4.20
FEBRUARY	01	3	6.30	2	4.20
FEBRUARY	15	3	6.30	2	4.20
MARCH	01	4	8.40	2	4.20
MARCH	15	5	10.50	3	6.30
APRIL	01	5	10.50	3	6.30
APRIL	15	6	12.60	4	8.40
MAY	01	7	14.70	4	8.40
MAY	15	7	14.70	4	8.40

```
WOULD YOU LIKE STARTING AND ENDING DENSITIES FOR THE     RACEWAY SYSTEM ?
yes
```

Table 2. (continued).

*** STARTING ENDING DENSITIES FOR EACH DECK IN A COMPLETELY LOADED RACEWAY ***

INVENTORY PERIOD		UPPER DECK STARTING-ENDING LBS	MID DECK STARTING-ENDING LBS	LOWER DECK STARTING-ENDING LBS	TOTAL LBS IN RACEWAY LBS
OCTOBER	15	308.48- 679.20	287.04- 632.00	287.04- 632.00	882.57- 1943.20
NOVEMBER	01	679.20- 1251.00	441.40- 813.00	441.40- 813.00	1561.99- 2877.00
NOVEMBER	15	1251.00- 2051.05	614.20- 1007.00	614.20- 1007.00	2479.41- 4065.05
DECEMBER	01	1897.97- 2872.68	796.14- 1205.00	796.14- 1205.00	3490.25- 5282.68
DECEMBER	15	2430.43- 3461.72	1020.14- 1453.00	1020.14- 1453.00	4470.70- 6367.71
JANUARY	1	2761.84- 3811.35	1158.69- 1599.00	1158.69- 1599.00	5079.23- 7009.35
JANUARY	15	3001.13- 4040.10	1259.11- 1695.00	1259.11- 1695.00	5519.34- 7430.90
FEBRUARY	01	3341.83- 4355.22	1402.65- 1828.00	1402.65- 1828.00	6147.13- 8011.22
FEBRUARY	15	3642.17- 4664.95	1528.71- 1958.00	1528.71- 1958.00	6699.59- 8580.95
MARCH	01	3961.19- 4952.34	1662.12- 2078.00	1662.12- 2078.00	7285.42- 9108.34
MARCH	15	4112.58- 5084.27	1726.16- 2134.00	1726.16- 2134.00	7564.89- 9352.27
APRIL	01	4400.75- 5337.37	1846.92- 2240.00	1846.92- 2240.00	8094.59- 9817.37
APRIL	15	4628.13- 5566.55	1942.19- 2336.00	1942.19- 2336.00	8512.52-10238.55
MAY	01	4964.73- 5868.34	2083.75- 2463.00	2083.75- 2463.00	9132.22-10794.34
MAY	15	5247.75- 6154.84	2202.32- 2583.00	2202.32- 2583.00	9652.39-11320.84

Table 3 An example of the summary tables generated by the PRELIM computer model for circular ponds.

** PRODUCT DEFINITION 1 **

*** PRELIMINARY PROGRAM FOR RAINBOW TROUT ***

THE EGGS SHOULD BE OBTAINED ON JULY 06 AND WILL
REQUIRE 40 DAYS TO REACH 1.70 ON AUGUST 15 .

INVENTORY PERIOD	DENSITY CAPACITY (LBS/POND)	OXYGEN CAPACITY (LBS/POND)	FISH SIZE (IN INCHES)	NUMBER OF FISH	NUMBER PER LB	TOTAL LBS OF FISH	FEED CONVERSION	TOTAL LBS FEED FED PER INVENTORY	FEED SIZE
AUGUST 15	1491.9	340.0	1.70	106965.	502.759	212.76	1.597	519.03	3/64" PELLET
SEPTEMBER 01	2035.3	488.7	2.31	106486.	198.017	537.76	1.651	895.86	3/32" PELLET
SEPTEMBER 15	2572.1	643.4	2.92	106009.	98.110	1080.52	1.593	1282.61	1/8" PELLET
OCTOBER 01	3101.5	805.9	3.52	105535.	55.962	1885.82	1.585	1758.68	1/8" PELLET
OCTOBER 15	3624.2	972.9	4.12	105062.	35.071	2995.69	1.583	2289.50	5/32" PELLET
NOVEMBER 01	4139.0	1177.1	4.70	104591.	23.545	4442.16	1.575	2862.75	5/32" PELLET
NOVEMBER 15	4647.2	1359.5	5.28	104123.	16.634	6259.50	1.574	3479.82	5/32" PELLET
DECEMBER 01	5148.0	1550.4	5.85	103657.	12.237	8470.55	1.610	4055.20	5/32" PELLET
DECEMBER 15	5623.1	1737.0	6.39	103192.	9.390	10989.72	1.610	4688.97	5/32" PELLET
JANUARY 1	6090.6	1934.5	6.92	102730.	7.389	13902.35	1.618	5301.81	5/32" PELLET
JANUARY 15	6545.5	2061.6	7.44	102270.	5.953	17178.70	1.618	6162.81	5/32" PELLET
FEBRUARY 01	7007.9	2180.3	7.96	101812.	4.851	20987.84	1.670	6988.90	5/32" PELLET
FEBRUARY 15	7456.8	2298.2	8.47	101356.	4.026	25172.30	1.673	7961.94	5/32" PELLET
MARCH 01	7911.7	2414.7	8.99	100902.	3.371	29930.50	1.726	8850.89	5/32" PELLET
MARCH 15	8352.3	2462.7	9.49	100450.	2.865	35057.82	1.727	9942.97	5/32" PELLET
APRIL 01	8799.8	2558.7	10.00	100000.	2.450	40816.31	0.0	0.0	------------

Table 3 (continued).

*** SUMMARY OF CIRCULAR POND COMPONENTS ***

POND HYDRAULICS

POND-CIRCULAR

INFLOW- 0.75 CFS

MIXING COEFFICIENT-1.83

POND DIMENSIONS
POND DIAMETER- 40.0 FEET
POND DEPTH- 1.8 FEET
VOLUME- 2200.0 CUFT.

MEAN RETENTION TIME 89.5 MINUTES

AVERAGE WATER VELOCITY-0.5000 FPS

DIET COMPOSITION

FEED SIZE	PROTEIN (%)	LIPID (%)	CHO (%)	METABOLIZABLE ENERGY (KCAL/LB)
FRY START	38.3	12.6	10.3	1269.3
FRY MEAL	35.0	13.0	12.0	1233.3
1/32" PELLET	38.6	12.1	10.4	1257.7
3/64" PELLET	39.4	12.0	11.1	1274.7
1/16" PELLET	39.0	12.1	9.7	1260.0
3/32" PELLET	36.3	12.5	9.8	1223.5
1/8" PELLET	36.7	13.4	9.8	1263.8
5/32" PELLET	36.7	13.4	9.8	1263.8

Table 3 (continued).

WATER QUALITY PER POND SYSTEM

WATER PH= 7.3
ALKALINITY=190.0

INVENTORY PERIOD	FISH DENSITIES (LBS)	WATER TEMPERATURE (F)	INFLOW OXYGEN (PPM)	DAILY AMMONIA PRODUCTION (MG/FISH/DAY)	AVERAGE UNIONIZED AMMONIA CONCENTRATION (PPM)	DAILY FECES PRODUCTION (MG/FISH/DAY)	AVERAGE FECAL CONCENTRATION (PPM)
AUGUST 15	1491.9	58.3	10.3	2.1754	0.010943	25.3729	24.3038
SEPTEMBER 01	2035.3	58.0	10.3	3.9766	0.010625	45.3484	23.3397
SEPTEMBER 15	2572.1	57.8	10.3	6.3615	0.010541	70.9403	22.8611
OCTOBER 01	3101.5	57.5	10.3	9.4320	0.010631	101.6138	22.5223
OCTOBER 15	3624.2	57.3	10.3	13.1400	0.010742	136.7503	22.1968
NOVEMBER 01	4139.0	57.0	10.5	17.4596	0.010815	175.4787	21.8385
NOVEMBER 15	4647.2	56.8	10.5	22.4503	0.010925	217.9942	21.5202
DECEMBER 01	5148.0	56.5	10.5	27.8079	0.010907	259.9197	20.9103
DECEMBER 15	5623.1	56.3	10.5	33.7789	0.010997	305.3408	20.5884
JANUARY 1	6090.6	56.0	10.5	40.1715	0.011017	350.5940	20.1500
JANUARY 15	6545.5	56.2	10.5	48.1993	0.011558	411.5977	20.4821
FEBRUARY 01	7007.9	56.5	10.5	56.8665	0.012039	473.1492	20.5407
FEBRUARY 15	7401.6	56.7	10.5	66.6954	0.012500	543.8691	20.6989
MARCH 01	7582.1	57.0	10.5	77.0059	0.012500	612.1882	19.9829
MARCH 15	7664.2	57.2	10.3	88.7604	0.012500	693.1016	19.4369
APRIL 01	8799.8	57.5	10.3	41.3896	0.005791	734.3451	20.1325

Table 3 (continued).

MANAGEMENT COMPONENT

INVENTORY PERIOD		TOTAL PONDS REQUIRED	WATER REQUIREMENTS (IN CFS)
AUGUST	15	1	0.75
SEPTEMBER	01	1	0.75
SEPTEMBER	15	1	0.75
OCTOBER	01	2	1.50
OCTOBER	15	2	1.50
NOVEMBER	01	2	1.50
NOVEMBER	15	2	1.50
DECEMBER	01	3	2.25
DECEMBER	15	3	2.25
JANUARY	1	3	2.25
JANUARY	15	4	3.00
FEBRUARY	01	4	3.00
FEBRUARY	15	5	3.75
MARCH	01	5	3.75
MARCH	15	5	3.75

total pounds of fish, and number per pound, all which reflect summary statistics at the beginning of the period, are presented for each inventory period. The total pounds of food fed provides an estimate of food required during the inventory period to obtain the desired fish size (predicted size at the beginning of the next period) and growth rates. The feed size column presents the size of feed based on manufacturer's recommendations fed to the lot of fish for each inventory.

The second set of tables generated by the program is a summary of the pond system components. It contains summary information on pond hydraulics, diet composition, water quality and management of the system.

The pond hydraulics consists of water flow per pond, pond dimensions, mean retention time, and water velocity. The diet composition records the average dietary percent of protein, lipid, and carbohydrates and the calculated metabolizable energy of the specified diet.

In the pond water quality summary, the pH and alkalinity are recorded. In addition, water temperature, oxygen saturations, minimum oxygen levels (pO_2 > 90 mmHg), ammonia and feces production, and average concentrations are presented.

The management component of the system consists of the pond water and water requirements for single-pass and reuse systems. Since there are many ways in which ponds in linear reuse systems can (and are) utilized, knowing the minimum and maximum water requirements can be an aid to forecasting any particular management strategy. Therefore, the management component of multiple pond raceway systems contains minimum and maximum water and space requirements for the product definition.

The third set of tables provides starting and ending densities of an individual completely stocked raceway. The tables are created at the request of the user and are currently available for raceway systems only. They contain estimates based on growth rate and fish mortality of the maximum starting and ending densities of a completely loaded raceway for each inventory period. The pond loadings are based upon the assumption that at the end of the inventory period the poundage in the pond will equal the carrying capacity of the pond system (calculated according to the lowest estimated carrying capacity). The maximum poundages at the beginning (and ending) of the inventory period provide the user with a relative measure for determining the water and space requirements for the particular loading densities employed at the facility.

C. MODEL VALIDATION

Testing of the conceptual model was accomplished by comparison of predicted results with independent data collected from Washington Department of Game Trout Hatchery, Spokane. Feeding rates, diet quality, and pond densities were established by hatchery personnel and were consistent with management objectives.

Two components, Allowable Growth Rate (AGR) and ammonia production-pond concentrations, were chosen for validation since they represent two major components of the conceptual model.

1. Allowable Growth Rates:

The prediction of AGR and fish size of rainbow trout reared in circular ponds were calculated on a weekly basis, with input data of feeding rate, diet quality and fish size. Predicted fish size and pond weight at the end of the 8-week period averaged 6.9% less than actual size and pond weight while predicted AGR averaged 25.4% less than actual. None of these results were significant (P = 0.05) primarily due to the large sampling error associated with measuring fish size and growth. Although none of the differences between actual and predicted size or growth were significant, the model consistently underestimated fish size and growth during each inventory period.

A sensitivity analysis of AGR predictability to systems variables, indicated that AGR is most sensitive to temperature estimation, secondarily, to estimation of feed proportion, and least sensitive to swimming energy requirements.

2. Ammonia Production and Concentration:

Ammonia production by rainbow trout was compared to predicted estimates using the mathematical models generated in this study. The predicted and actual values of this parameter deviated by an overall average of 22.1% (12.1-25.6%). Even though there was a large variation between predicted and actual concentrations, there was no apparent bias in the model. It underestimated actual concentrations in two trials and overestimated actual concentrations in three trials.

Prediction of ammonia concentrations in circular ponds requires the coupling of pond retention time with Total Ammonia Production (TAP). This model, with a mixing coefficient of 1.83 predicted ammonia concentrations in circular ponds that were significantly less (58.8-81.3%) than actual concentrations.

A sensitivity analysis was conducted on the predictive model, and the results indicated that the mixing coefficient is an important variable in determining pond concentrations. If a mixing coefficient of 1.00 (a completely homogeneous model) is used in the model, the resultant predictive capabilities are significantly improved with predictive values averaging 7.2% more than in actual concentrations. It is apparent that the generalized homogeneous net balance rate model is applicable to metabolite concentrations in incomplete mixing systems. However, further parameterization of the mixing coefficients for these systems is required to refine metabolite concentrations in circulating ponds.

D. MODEL APPLICATION

The computer model is flexible and can be used to enhance management, design, and evaluation decisions for aquaculture systems operations. Some of these applications are:

1. Provide a long-range production forecasting information for more effective management of aquaculture systems. The output of this program provides a long-range production forecasting model which can be used to meet market demands and increase productivity through effective planning.
2. Test alternate strategies to determine the least cost processes for rearing fish. Alternate strategies can be evaluated with the computer model by changing input variables; i.e., diet, water flows, and weir heights, and obtaining the output requirements of growth rates, feed requirements, pond requirements, and water requirements. By assigning actual costs and profits to these components, an economic analysis of the management strategies can be accomplished.
3. An aid in designing new facilities and/or renovating existing facilities. The use of the model for designing hatcheries is an

extension of the model usage for evaluating management strategies. In addition to varying input variables mentioned above, the design engineer can also alter pond design to observe how growth rates, feed requirements, pond requirements and water requirements change. Again, by assigning costs to the individual factors, an economic analysis of alternate pond designs can be accomplished.

4. Assessment of hatchery effluents and water treatment facility requirements necessary for meeting present and future EPA regulations. One of the outputs of the program is the prediction of waste production and concentration. This information, coupled with performance efficiencies of waste treatment facilities such as settling ponds and biofilters, can be used to determine the waste treatment facilities required at present or proposed facilities to meet water quality standards.

5. A teaching tool for training fish culturists at the middle and upper managerial levels. The model can be used as a teaching tool by providing a mechanism for managers to immediately evaluate a proposed management solution to an aquaculture systems problem. An added benefit of using this model is that the application of the solution (a management strategy) does not result in the large scale involvement of fish if a wrong solution is chosen. Therefore, one can learn valuable lessons without risking fish and money.

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AND

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SELECTED WATER RESOURCES ABSTRACT Input Transaction Form	1. *Report No.*	2.	3. *Accession No.*

4. *Title* An Applied Couples Simulation-Optimization Model of Water Use Efficiency in Intensive Fish Culture Systems	5. *Report Date* March 1982 6. 8. *Performing Organization Report No.*
7. *Author(s)* George W. Klontz	10. *Project No.* A-063-IDA
9. *Organization* Idaho Water and Energy Resources Research Institute	11. *Contract/Grant No.* 14-34-0001-0114
12. *Sponsoring Organization* OWRT	13. *Type of Report and Period Covered.* Completion

15. *Supplementary Notes*

16. *Abstract* An aquaculture system consists of a number of biotic and abiotic factors which act alone and/or interactively in defining systems behavior and impacting the available growth rate (AGR) of the fish. The bioenergetics approach, as presented, provides the necessary common denominator linking the quantitative effects of the biotic and abiotic dependencies of systems operation.

Computer implementation of the mathematical models of quantitative relationships in aquaculture systems is a dynamic process which provides a conceptual framework for understanding systems behavior. These models can provide useful information on variable significance to systems functioning, thereby directing research resources into areas which will most benefit further understanding of the system. Furthermore, as aquaculture systems research progresses, the composite model can be modified to incorporate new technology. Modelling therefore is a cyclic process, a means for understanding the system, evaluating the system, and using the model to incorporate the new technology.

The conceptual framework of the model presented is not only applicable to rainbow trout, but is an acceptable conceptual model for all aquaculture systems. Reparameterization of specific components results in valid models for other species.

This computer implemented mathematical model has addressed one of the significant limitations of aquaculture systems management; namely, production forecasting, by providing a method of using current technology for the predictions of allowable growth rates and systems production forecasting. The use of the model in aquaculture operations would serve as a valuable aid to production forecasting, resulting in more efficient and profitable aquaculture systems operation.

17a. *Descriptors*

instream flows, salmonids, rainbow trout, oxygen concentrations

17c. *COWRR Field & Group*
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