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# Aquaculture Systems Modeling: An Introduction with Emphasis on Warmwater Aquaculture

M.L. Cuenco



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## Foreword

Aquaculture has a long history, particularly in Asia, but a far weaker scientific base than agriculture. Research for the development of aquaculture to improve nutrition and livelihood in developing countries has a very short history: significant efforts started only about 20 years ago. Therefore, faced with a wide diversity of potential species to culture and culture systems, a need to find a sensible and profitable role for aquaculture in the overall context of food production and development, and a scarcity of clear guidelines from research, aquaculturists must use all possible devices to make the most of their databases and to frame and test new hypotheses.

Systems modeling is one such device (and a very powerful one) but it has seen little use so far in aquaculture research and development. Therefore ICLARM, supported by a Preparatory Assistance Grant from the United Nations Development Programme (UNDP), New York, commissioned this study to bring the advantages of systems modeling to the attention of aquaculturists and to provide a source of information on aquaculture modeling work to date. The study was undertaken parallel to a review of Research and Education for the Development of Integrated Crop-Livestock-Fish Farming Systems in the Tropics - published by ICLARM as a companion volume (Edwards et al. 1988).

The author of the present study, Dr. Michael L. Cuenco, is one of the pioneers of applying ecological modeling techniques to fishponds. His original manuscript was much debated during a peer review process. Practising or would-be modelers are still striving for consensus on the relative merits of different approaches. The resulting publication is therefore an *introduction* to the broad scope of modeling techniques, with pointers to other sources of detailed information and examples. ICLARM hopes that it will stimulate other aquaculturists to explore the potential of systems modeling. When faced with large datasets to interpret or with complex farming systems for which to frame new hypotheses for optimal management, they can also become pioneers in this field. To illustrate the application of systems modeling to a real world aquaculture system, Mr. Anne van Dam, an Associate Expert assigned to ICLARM by the Directorate General for International Cooperation of the Government of the Netherlands, has appended to Dr. Cuenco's study a detailed example of modeling approaches to integrated rice-fish culture.

ICLARM foresees a rapid increase in the application of systems modeling techniques in aquaculture research and wishes to thank UNDP for its farsighted support for this study and many colleagues around the world who helped to review this study.

ROGER S.V. PULLIN  
Director, Aquaculture Program  
ICLARM  
November 1989

# **Aquaculture Systems Modeling: An Introduction with Emphasis on Warmwater Aquaculture**

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## **Abstract**

An introduction to modeling is presented. The basic concepts of systems and models and various types of models and their use in research (e.g., to test hypotheses) and in management (e.g., to predict system behavior) are described. Models can integrate knowledge from several disciplines. Using computers, complex systems can be analyzed accurately in a short time. Models can provide a framework for coordinating technical, laboratory and field research. Guidelines for modeling aquaculture systems are presented: empirical models for the analysis of multivariate datasets; and theoretical models based on knowledge of the processes underlying a system. The steps in model development are discussed. Criteria for classifying and evaluating aquaculture models presented in the literature have been developed. Biological, engineering and economic aquaculture models are discussed and a broad review of their features is given.

## Introduction

Aquaculture, the farming and husbandry of aquatic organisms, is important in the food economy of many nations (Pillay 1979). Although much practical knowledge and experience have been accumulated (e.g., Ling 1977; Little and Muir 1987; Edwards et al. 1988), scientific research in aquaculture is relatively new and undeveloped (Shell 1983; Pullin and Neal 1984). With the exception of work on salmonids at the turn of the century, aquaculture research efforts have originated largely within the past fifteen years and have been small, diffuse and of limited success.

Despite some progress, there has been little concerted effort to integrate available knowledge into a consistent framework for describing and studying aquaculture systems. Lack of coordination has led to duplication of efforts, and to studies where important interactions were not considered or understood, and studies where important factors were not measured in a useful form or were not considered at all. As a result, aquaculture as currently practiced is very much an art. The pond as the basic production unit is a "black box" where inputs and outputs are known but little is known about the components and the mechanisms of the system itself.

A wide variety of aquaculture systems exists: ponds, cages, tanks, enclosures, rice fields, etc. These systems are difficult to study directly because of their size and complexity. A diversity of biota (fish, phytoplankton, zooplankton, benthos, macrophytes, insects, bacteria, etc.) dynamically coexist and interact in an aquatic environment characterized by many physico-chemical factors (temperature, dissolved gases, alkalinity, pH, etc.) that can vary not only in three dimensional space but also in time with daily and seasonal components (Boyd 1979).

Temporal fluctuations in water temperature, dissolved oxygen and pH are basically sinusoidal, whereas other factors, notably plankton density and composition are more difficult to characterize. Spatial variability with depth and area further complicates each system.

The air-water and sediment-water interfaces are sites of further dynamic and complex chemical reactions. Soil properties (pH, cation exchange capacity, base saturation, etc.) and processes (redox reactions, denitrification, organic matter decomposition, etc.), as well as weather variables (sunlight, precipitation, wind, etc.) and processes also influence the culture environment.

Human intervention through design and management practices (stock manipulation, feeding, manuring, fertilization, liming, aeration, water circulation, etc.) is superimposed upon this natural complexity. Although the use of experimental culture units reduces the size of the system for study, some factors influencing production cannot be controlled (Neal and Mock 1979). The effects of uncontrolled variables are mixed with the effects of experimental variables, complicating the interpretation of results.

Despite the absence of an adequate research base and the associated risk, aquaculturists have to make - and in fact do make - short-term as well as long-term decisions, based on present knowledge. Modeling is a powerful approach to problem solving. Models can become powerful tools in aquaculture research and management. The interactions that make understanding an aquaculture system difficult can be addressed by modeling. Modeling is an important component in efforts to promote the use of more quantitative methods in aquaculture research.



# What is Modeling?

## *Introduction*

Modeling means different things to different people - biologists, engineers, economists, chemists, physicists, statisticians, etc. Perceptions about modeling can be very different depending on the types of problems addressed and the kinds of tools commonly used (Starfield and Bleloch 1986). Problems that are well understood and with good supporting data are common in the engineering and physical sciences where models that address these problems are used routinely and with confidence because their effectiveness has been proven repeatedly.

Many biological problems have little supporting data and their understanding by biologists is limited. Models of biological systems are often speculative, lacking the respectability of models built for solving problems in the engineering and physical sciences field because they cannot be tested conclusively.

Ecological models (which include models of aquaculture systems) are built to explore the consequences of what is believed to be true. The modeler learns from these models by manipulating them, questioning their relevance and comparing their behavior with what is known about the system studied. This leads to new, improved versions of the model based on reevaluations of the modeler's perception of the system. The process of building a model, however speculative, improves the modeler's understanding of the real world and can facilitate finding and using data that were not considered relevant before.

Modeling has not been applied long enough in aquaculture to the point where an established methodology and standard terminology are used. The following sections provide a brief background of modeling with particular reference to its application in aquaculture.

## *Systems and Models*

A system is a set of components (elements or parts) that are linked, interdependent or work together to do a certain job or perform a certain function (Kitching 1983; Grant 1986). It is united by some form of regular interaction. Two components act as a system if the behavior of one is affected by the other.

A model is any representation, abstraction or working analogy of a system that includes only those attributes relevant to a particular problem, question or intended use (Spain 1982; Grant 1986; Starfield and Bleloch 1986). A particular group of components and their relationships are deliberately chosen to answer a particular question, illustrate a theory or describe a part of the natural world (Kitching 1983). A model represents an integrated body of plausible assumptions, theories and hypotheses about how a system works (Phillips et al. 1976).

Obviously, a model cannot have all the attributes of the system or it would not be a model - it would be the real system. Thus, a model will always involve varying degrees of simplification (Riggs 1963). Models never describe the real world exactly and often do not attempt to do so.

A model has inputs and outputs which are called the variables of the model. The model describes how the output variables change as the input variables are varied. A model also contains one or more parameters that mediate the relationship between the variables. A parameter is a constant that has to be estimated before the model can be used.

## Modeling

Modeling is an interdisciplinary approach to problem solving characterized by the construction, testing and use of models (Riggs 1963; Spain 1982; Grant 1986). It is a tool to specify, describe, organize and communicate knowledge about complex phenomena in precise, clear and concise form.

An important principle of modeling is that a mathematical equation serves as a model of a biological process (Spain 1982). A biological process may be described graphically. The graph expresses how a biological system performs under a given set of conditions. A graph can also describe the behavior of a mathematical equation relating an independent to a dependent variable. Thus, it is possible to find a mathematical equation that represents the biological system (Fig. 1).

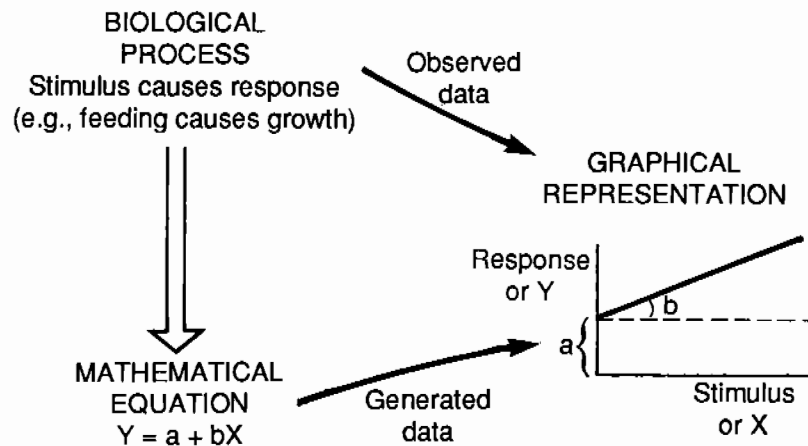


Fig. 1. As the same graph can represent data observed from a biological process and data generated by a mathematical equation, the equation can represent the process.

The process of finding an appropriate model involves an understanding of the functional relationships in the system. After examination of experimental data, a simple equation relating a dependent variable  $Y$  to an independent variable  $X$  can be formulated. Then, the parameters for the equation (the coefficients and exponents) can be estimated from experimental data, after which the model must be validated by comparing data generated by the model with data from the real system. Finally, the model can be used to make predictions about the behavior of the real system.

## Modeling Terminology

*Conceptual and mathematical models.* Using the broad definition of a model, it is evident that essentially all science deals with the formulation, examination and improvement of *conceptual models* of our universe (Spain 1982). The conceptual model is a picture of the real system based on available information and past experience.

Fundamental biological knowledge consists mainly of models. The double helix structure of DNA is a conceptual model based on the known properties of DNA. The typical representation of an animal or plant cell is a diagrammatic model based on a composite of many observations

on many kinds of cells using a variety of techniques. In ecology, the food chain and the food pyramid are important conceptual models that have been used to explain the flow of energy and cycling of materials in an ecosystem. Conceptual models can consist of a picture or diagram, or of a description in words (a "word model").

Conceptual models by themselves are generally lacking in precision and rigor (Spain 1982). A conceptual model needs to be translated into a form that is subject to precise description, evaluation and validation. This form of model is called a *mathematical model*. Such models may be as simple as a single equation relating one variable to another or may involve the interaction of many equations having several mutually dependent variables (Spain 1982). These equations are solved simultaneously for a set of variables at a given point in time (SAS/ETS 1984). Given the values for the input variables the model calculates values for the output variables.

*Empirical and theoretical models.* *Empirical* (also called *statistical* or *descriptive*) models are constructed by fitting one of several possible forms of equations to experimental data using statistical techniques. Empirical models merely describe the relationship between two or more variables as it was actually observed (Riggs 1963). Such models do not depend upon a theoretical understanding of the system (Spain 1982) and imply nothing about the underlying reason for the relationship. The system is treated as a "black box": inputs and outputs are known, but the underlying mechanisms are not (Piedrahita 1988). A particular data set can be described by an infinite number of empirical models. When no guidance is available from theory, the simplest equation which adequately fits the data should be chosen. Empirical models can contribute to biological theory since a model that summarizes an observed relationship may serve as the point of departure for the elaboration of a theory.

*Theoretical* (also called *mechanistic* or *explanatory*) models are based upon a theory or hypothesis about the nature of a system (Riggs 1963; Spain 1982). Whereas an empirical model can describe a particular data set faithfully enough, a well-founded theoretical model may describe all such sets of data and in addition explain why the observed relationships exist. Failure of a theoretical model to fit a wide range of experimental values can be turned to advantage if it suggests how the underlying theory can be improved.

Theoretical models play an essential part in the formulation and solution of biological problems that are too complex to solve nonmathematically. Because of their generality and power to aid in the development of basic knowledge, theoretical models have an elegance and intellectual appeal that is lacking in empirical models.

*Deterministic and stochastic models.* A *deterministic* model uses fixed values for model parameters and produces the same results given the same set of input variables (Spain 1982; Starfield and Bleloch 1986). In such models, the state of a given variable at any time is determined entirely by previous states of that variable and the other variables upon which it depends.

A *stochastic* (also called *probabilistic*) model uses random values for model parameters. Repeated calculations with the same input variables will therefore yield different output variables with every calculation. Probabilistic models are generally more complex than deterministic models because of the mathematics involved in formulating the random process.

A biological process may appear to be random because it is impossible to predict its behavior from the information currently available. As more is known about a system, a process previously thought of as random may turn out to be determined by biological factors.

*Static and dynamic models.* A *static* (also called *time-independent*) model does not change with time. A *dynamic* (or *time-dependent*) model changes as a function of time. Dynamic models can be discrete or continuous. In continuous dynamic models, time flows. These models are described by a system of differential equations (SAS/ETS 1984). The basic solution technique is to compute integrals across time. In discrete models, difference equations are analogues of differential equations (Table 1; Kitching 1983; SAS/ETS 1984). Whereas differential equations denote changes in time over an infinitesimal interval, difference equations represent changes over a finite interval (time jumps). A summation procedure replaces the integration used to solve differential equations.

Table 1. Continuous (differential) and discrete (difference) models of growth.  $W$  = weight;  $t$  = time;  $k$  = constant;  $W_1$  and  $W_2$  = values of  $W$  at times  $t_1$  and  $t_2$ , respectively;  $W_{\max}$  = maximum value of  $W$ ;  $dW/dt$  = derivative of  $W$  with respect to time  $t$  (after Kitching 1983).

Type	Differential form	Difference form
Linear	$dW/dt = k$	$(W_2 - W_1)/(t_2 - t_1) = k$
Exponential	$dW/dt = kW$	$(W_2 - W_1)/(t_2 - t_1) = kW_1$
Logistic	$dW/dt = kW(1 - W/W_{\max})$	$(W_2 - W_1)/(t_2 - t_1) = kW_1(1 - W_1/W_{\max})$

A discrete model is simpler in many ways and corresponds to the way data are usually collected in batches at regular intervals. Continuous models can be approximated, choosing a time interval small enough to capture the behavior of a system across time.

*Optimization models* are used to find the optimum value of a mathematical expression under a given set of constraints. These models descend straight from operations research (see below). An example of their use is in production planning, where price levels and technical limitations are constraints. A well-known form of optimization models is linear programming.

### *Variants of Modeling Depending on Application*

The modeling or systems approach has been called, depending on its application, operations research, systems engineering, systems analysis or systems ecology.

*Operations research.* A basic understanding of the modeling or systems approach can best be gained by a brief history (excerpted from Trefethen 1954) of one of its primary roots: operations research.

During World War II, many strategic and tactical problems associated with the Allied military effort were simply too complicated to expect adequate solutions from any one individual or even a single discipline. Thus, groups of scientists with diverse educational backgrounds were assembled as special units within the armed forces in Britain and later in the United States. Because of the pressure of wartime necessity and the synergism generated from the interactions of different disciplines and talented scientists, these special units were remarkably successful in improving the effectiveness of complex military operations. Typical projects were radar deployment policies, anti-aircraft fire control, fleet convoy sizing and detection of enemy submarines.

After the war some of these scientists returned to universities and concentrated their efforts on providing a sound foundation for the many techniques that had been hastily developed during the war, while others devoted their efforts to developing new techniques. Other scientists moved to various sectors of private enterprise where they adapted methods developed by others to the unique problems of particular industries. Petroleum companies were among the first to make regular use of linear programming (an operations research technique) on a large scale for production planning. Today, service organizations such as banks, hospitals, libraries and judicial systems use operations research in planning, policymaking and improving the effectiveness of their services.

The modern perception of operations research as a body of established techniques and models - that is a discipline in itself - is quite different from the original concept of operations research as an activity performed by interdisciplinary teams. It would be premature to exclude any of these interpretations.

*Systems engineering* is concerned with systems that are human-made, large and complex (Bode 1978). It is primarily a planning and design function whereas operations research concentrates on the analysis of how existing systems work.

*Systems analysis* is the study of how the parts of a system work together (White 1978). It is the orderly and logical organization of data and information into models followed by the rigorous testing and exploration of these models necessary for their validation and improvement (Jeffers 1978). The first systems analysis was accomplished by Sir Isaac Newton in his mathematical analysis of the solar system (White 1978). In his analysis, the sun, planets, moons and comets were the elements and the gravitational forces between these bodies were the

interactions between the elements. The analysis was based on Newton's three laws of motion and the law of universal gravitation. The mathematics involved geometry and calculus.

*Systems ecology* (or *ecological modeling*) is the application of systems analysis procedures to ecology (Walters 1971). It deals with existing natural systems, emphasizing the interactions between living and nonliving components. One of the goals is to evaluate the effects of human actions on the system in order to achieve certain objectives. Agriculture and aquaculture are good examples of fields where systems ecology can be applied.

### ***Constraints to Modeling Aquaculture Systems***

Building aquaculture models is not easy. Problems are often poorly defined, critical processes and mechanisms are little understood and data are often scant and difficult to obtain. Knowledge relevant to aquaculture is scattered and mostly qualitative. It is the modeler's challenge to gather relevant information and assemble it into a consistent and useful model.

In human-made systems - buildings, factories, computers, automobiles, etc. - the level of complexity is necessarily commensurate with what humans can understand, design, build and operate. Humans specify the components and processes that they want to deal with. Natural systems were not designed and built by humans. Hence, the modeler is faced with the problem of discovering and understanding the processes, mechanisms and laws that operate in these natural systems. Living systems are highly complex, because biological variability is added to the physical and chemical processes that also operate in nonliving systems. Each individual organism has a unique genetic composition which derives from a random inheritance mechanism.

Problems can be classified according to which of the following three items are given and which one is to be found: excitation, system, response (Table 2; Karplus 1983). An analysis problem (i.e., a problem where excitation and system are given) generally has a unique solution: for a given excitation and system there is only one set of responses. In a synthesis problem however (i.e., a problem where only excitation and response are given) there is an infinite number of solutions: many different systems can have the same excitation and response pattern.

Table 2. Classification of problems according to which of the items Excitation (E), System (S) and Response (R) are given and which is to be found (after Karplus 1983).

Problem	Given	Find	Comments
Analysis	E,S	R	unique solution
Synthesis	E,R	S	no unique solution
Control	S,R	E	unique solution

Modeling is trying to characterize the system given the excitation and response (Karplus 1983). Modeling is therefore a synthesis problem with no unique solution and the number of mechanisms that are incorporated in the model determines the position of the model in the continuum from empirical "black box" models to theoretical "white box" models (Karplus 1983).

## Why Model Aquaculture Systems?

### *Research Applications: the Need to Understand Nature*

The primary benefit of modeling in research is to serve as a powerful tool for the formulation, examination and improvement of hypotheses and theories (Spain 1982). Science is primarily concerned with producing a conceptual model that accurately reflects the real system. From observation of the system, a tentative conceptual model is formed. This model usually suggests one or more experiments, the results of which support or refute the model. The model is then modified and improved. This sequence may be called the classical research loop (Fig. 2).

A mathematical model can be derived from statistical analysis of experimental data (empirical models) or from a formalization of the conceptual model in quantitative terms (theoretical models), or from both. The thinking involved in the formulation of the model results in an improved conceptual model which in turn will suggest further experimentation. Repeating this process results in further improvements in both conceptual and mathematical models.

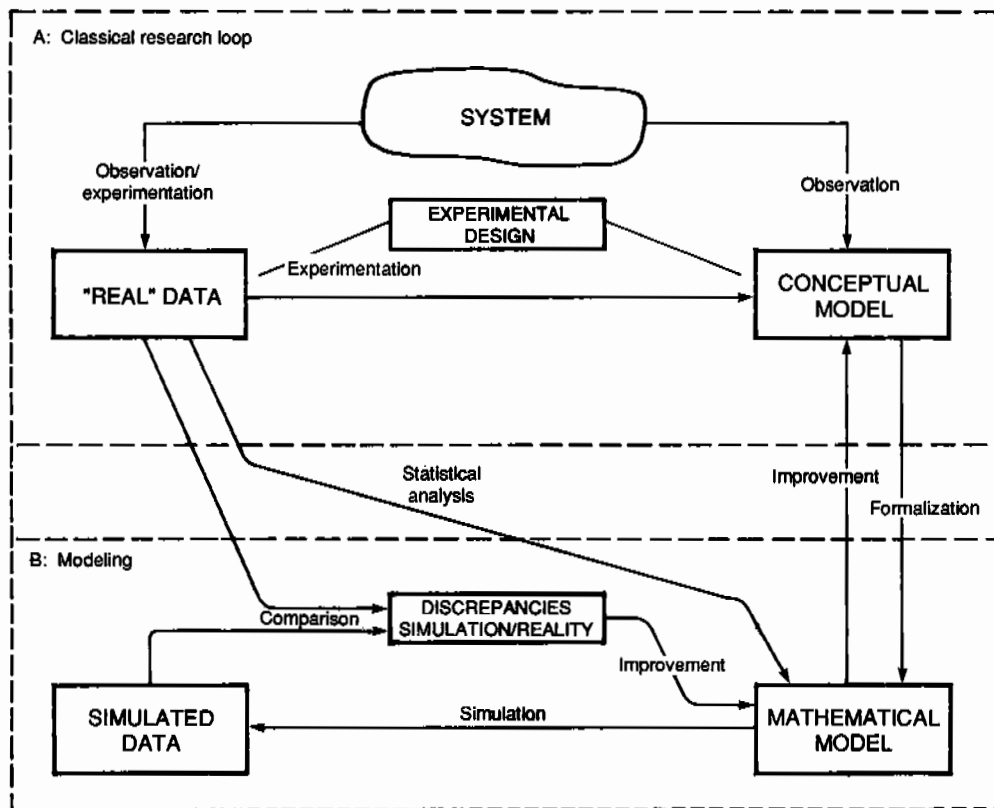


Fig. 2. The classical research loop and the modeling process. In the classical research loop, experimentation and observation lead to a conceptual model of the system that can be improved by more experimentation. With modeling, a mathematical model is constructed, either through statistical data analysis or formalization of the conceptual model. Simulation with the mathematical model results in simulated data that are compared with the "real" data. Discrepancies can point the way to improvement of the model and "what if" questions about the system can be answered.

The process of modeling expands the power of the classical research loop by using the mathematical model to generate data which can be compared to real data. Discrepancies between model output and real data may indicate errors in the assumptions used to formulate the mathematical model and consequently show flaws in the conceptual model. Small errors may lead to minor modifications of the parameters of the mathematical model, while large errors can require an entirely new conceptual model. In any case, new questions are raised and new experiments may be called for (see Fig. 2).

### ***Management Applications: the Need to Manage Nature***

After construction of a model, the modeler can make intelligent predictions about the consequences of various management strategies on the system. Simulation (using a theoretical model) is particularly valuable for complex systems which involve multiple nonlinear interactions of numerous variables in positive and negative feedback loops. In such systems, control measures may be counterintuitive and produce results that are opposite from what is expected.

Models may be developed to facilitate the day-to-day management of aquaculture operations, e.g., determining stocking and feeding rates, predicting dissolved oxygen levels and examining the effects of different management strategies (Piedrahita 1988). Decisionmaking involves an implicit, if not explicit use of models, since the decisionmakers invariably have a causal relationship in mind when they make a decision (Karplus 1983). On the other hand, models cannot replace decisionmakers and a model should never be used as a substitute for good judgement. Very often some other factors have to be considered along with the model results before committing to a course of action (Phillips et al. 1976). The subjective decisions and assumptions made during construction of the model are often not met fully in the particular problem to which the model is applied. The model is merely a tool: the modeler has to make the decisions.

Eventually, aquaculture models should be developed to the point where they become important tools in designing and managing aquaculture systems. Predicting the success or failure of the system under various conditions using a model of a proposed system is cheaper than building the system itself. Thus, costly trial and error methods can be avoided.

### ***Tool for Theoretical Analysis***

For practical or economic reasons, it is seldom feasible to experiment on certain aspects of large complex systems in their natural environment (Karplus 1983). Modeling provides a working tool to conduct numerous "what if" experiments quickly and can evaluate the consequences of various hypotheses or management strategies. By changing model parameters and variables the combined effects of many factors can be studied. This procedure is less costly than physical experimentation and can be used to focus our efforts on those critical questions that need to be verified through actual experiments. Chance elements can be included to evaluate results in a stochastic context. Real world processes that take months or years can be simulated by a computer in seconds or minutes.

### ***Integration of Knowledge***

Models serve as mechanisms to identify what is *not* known by organizing what *is* known within the framework of the models (Kitching 1983). Models are useful for extracting and synthesizing information from diverse disciplines into a consistent framework and for identifying research needs. Seemingly unrelated, fragmented and conflicting research results can be pulled together to form a concise and well-integrated whole.

Models also provide the framework to clarify ideas and concepts, organize thoughts and express insights. Complex problems are defined clearly and outlined for more detailed study by separating the important from the unimportant and eliminating less important factors. This helps focus on the critical aspects of a problem.

### ***Study of Interactions: Holistic Approach***

The study of a system is primarily a study of interactions between components because the interactions rather than the components by themselves determine the nature of a system. Studying, for example, the properties of hydrogen and oxygen will not predict the properties of the system that is made from these two elements: water. Likewise, studying the components of an aquaculture system independent of each other will not result in a good understanding of that system. Models facilitate the evaluation of complex interactions.

### ***Handling Complexity***

Many real world systems defy understanding because of their complexity. Modelers are forced to reduce their models to only the factors that are essential for solving a particular problem or answering a particular question. Information about a relatively small number of relevant variables is often sufficient basis for effective models because these key variables account for most of the phenomena to be explained (Odum 1971).

### ***Use of Mathematics and Computers: Quantification, Precision and Speed***

Modeling is an important step in accelerating the use of more quantitative and precise methods in aquaculture research. Mathematics provides models with a clear and precise language for describing and examining a system (Spain 1982; Karplus 1983). Computers can perform the many calculations necessary in modeling with accuracy and speed. Calculations that would take hours or days when done by hand can be done in seconds or minutes by a computer, leaving the modeler free to concentrate on evaluating the results, drawing conclusions and making decisions.

### ***Coordination of Theoretical, Laboratory and Field Research***

The construction of models demonstrates how knowledge from theoretical, laboratory and field studies can be put together into a consistent whole. Areas where our knowledge is sparse, non-existent or inconsistent are identified. Appropriate experiments can be implemented to elucidate these areas and result in more knowledge about the system. This knowledge leads to adjustments in the models and possibly a further round of experiments. Modeling and actual experimentation can and should complement and reinforce each other. The usefulness of models consists primarily in raising questions, not in answering them (Pielou 1977).

Models can be used to screen and design proposed experiments. As an extension of the scientific method, modeling is especially powerful for stating and testing complex hypotheses. Important variables and data are identified in modeling as well as the type of measurements required to predict system behavior. Thus, data collection (and associated costs) are limited to what is essential to solve a particular problem (Watt 1968).

Experimental data define the type of model and provide the data necessary to construct and calibrate the model. Experimental data can also act as a check of model validity and agreement with the real world.



## Guidelines for Modeling Aquaculture Systems

The objectives of the model determine the choice of model type. Two general types of models are distinguished here: empirical models and theoretical models.

### *Empirical Models*

Statistical models are the most widely used. They are useful when data have to be grouped and analyzed. Analysis of variance (ANOVA) and regression analysis are well-known examples, although many researchers applying these techniques may not realize that they are in fact going through a modeling exercise. A disadvantage of simple linear regression is that it does not consider more than two variables, whereas with ANOVA, treatment effects are often not detected because of large within-treatment variation and a too small number of replicates. Aquaculture data are usually multivariate: they consist of a set of variables that all belong to the same unit (e.g., fish stocking and harvest data, fertilizer inputs, water quality data; all from one pond).

Furthermore, experiments that were replicated in time are difficult to analyze with ANOVA because the circumstances change in time. Including environmental data as variables in the analysis can solve that problem and may even disclose some of the effects of the environmental factors. Similarly, farm data and results from on-farm research can be analyzed by including location-specific variables (e.g., soil type, climate) in the model.

Techniques of multivariate statistical analysis can handle the size and complexity of multivariate datasets. The statistical models are prescribed largely by the statistical theory, so that the modeler only has to feed the data into the model, check whether the basic assumptions of the model are not violated and interpret the model output.

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Data sets can be organized conveniently in a matrix form, with cases or experimental units (e.g., ponds, tanks, farms) as rows and variables (e.g., stocking density, growth rate, oxygen concentration) as columns (Table 3; Hopkins et al. 1988). Ideally, the dataset is complete, with a full set of data on the variables for every case, but incomplete cases can be added initially. Later, the final dataset for analysis can be extracted. All data should be checked for errors (Prein and Milstein 1988). Then some simple statistics like means, standard deviations, frequency

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Site	Day XX	Date		Time of day XXXX	Pond	Oxygen			Temperature			pH XX.X
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distributions and correlation coefficients can be calculated. If a computer with plotting facilities is available, variables can be plotted against each other or against time to detect patterns. The main condition for a meaningful analysis of the data is that there are enough cases (the more, the better) with variability in all variables, preferably with an even distribution over a range of values.

## Calculations

For actual statistical modeling, many methods exist (see Fig. 3). It may take a nonstatistician a lot of time to learn and master a complicated statistical technique, but a lot can be learned from colleagues' examples. Aquaculture researchers have used the following methods on their own data: multiple regression analysis (Hopkins and Cruz 1982; Pauly and Hopkins 1983; Prein 1985; Gonzal et al. 1987; van Dam, in press), path analysis (Prein 1985), principal component analysis (Milstein et al. 1985a, 1985b) and canonical correlation analysis (Milstein et al., 1988). Many textbooks on statistics also cover some parts of multivariate statistical techniques (Yamane 1973; Morrison 1976; Snedecor and Cochran 1980; Hair et al. 1987).

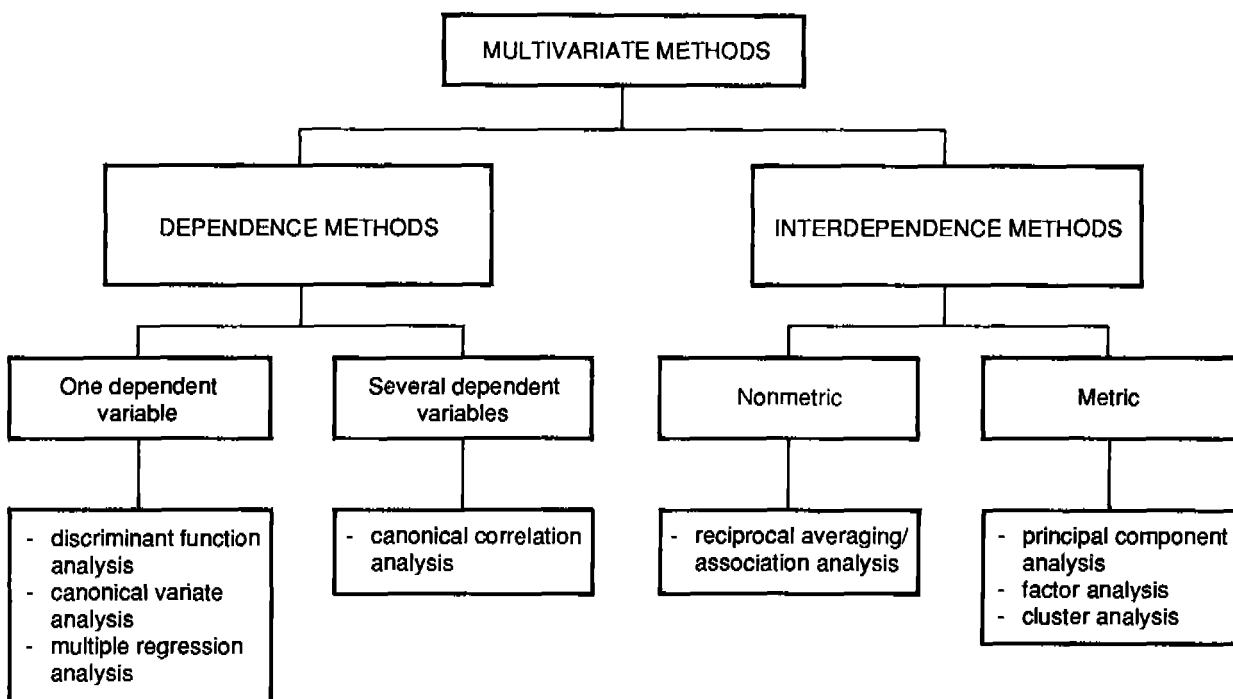


Fig. 3. Multivariate methods. For references with examples of multiple regression analysis, canonical correlation analysis and principal component analysis see text, p. 37 (adapted from Jeffers 1982 and Hair et al. 1987).

One approach to analyzing a large data set is to start working with an open mind, without any ideas about the outcome of the analysis. In the process of constructing the model, the trends and connections in the data emerge. Another approach is to formulate a hypothesis that states which variables are expected to appear in the model and what their role in the system is. The model can then be constructed using these variables and the resulting model parameters can be compared with the assumptions of the hypothesis.

Understanding and using statistical models require some effort initially, but the computations can in most cases be executed on microcomputers with readily available software. No computer programming skills are required. The basic assumptions underlying the statistical models sometimes limit the possibilities to analyze certain data: transformations have to be performed, or variables have to be excluded from analysis. After construction of the model, it should be checked routinely to see whether basic assumptions are violated. It is difficult for a nonstatistician to determine what is valid or invalid according to statistical laws. However, too much obedience in this respect may be in conflict with the goal of the modeling exercise: getting the most out of the data, based on stated assumptions and qualifications.

### *Theoretical Models*

Develop a frame of reference

Aquaculturists often strive for multiple and sometimes conflicting objectives. Increasing survival, growth, production and food conversion efficiency are important but so are reducing costs, maintaining water quality, avoiding disease outbreaks and minimizing economic risks. Economical control of the amount, quality and schedule of aquaculture production and optimizing the size of the entire farm and the individual pond unit are also important.

A common aquaculture objective is to maximize growth. However, this will not necessarily maximize production since favorable conditions for maximum growth (a low stocking density for example) may not correspond with the conditions for maximum production. Besides, the goal may be to maximize profits and not production as such. Similarly, increasing survival rate must be weighed against the additional costs incurred because it may be more economical to operate below 100% survival and still meet production goals. When optimizing the pond environment, a clear statement of what has to be optimized is necessary: maximum growth, maximum production, or maximum profit.

In economic analysis, the costs of providing and maintaining environmental factors at given levels to attain the production objectives have to be determined. For example, the cost of feeding at a certain level, or the costs of maintaining dissolved oxygen above a specified level or unionized ammonia below a specified level for appropriate periods.

Because the same design cannot do the best job in all directions, it is necessary to define exactly what performance measures are important. To be economically viable, a "commercial" aquaculture enterprise (as opposed to subsistence) must produce a product at competitive cost and sell it at a reasonable profit. Although several combinations of inputs may produce the same amount of product, only a few of these combinations will be most efficient economically.

The economic objective of aquaculture production can be stated as: to minimize the total cost of producing a specified quantity of aquatic products of desired quality, at an accepted level of risk, by using the most economical combination of available technology and resources. This objective involves a choice among existing production systems or development of new ones based on present knowledge and available resources.

Three interrelated factors influence the choice of production technology: (1) the biological requirements of the fish; (2) the scale of operation; (3) the relative costs of available resources for production. For a given technology, decisions about site selection, facility design and production have to be made.

The site determines the ambient environmental conditions that are modified permanently by design and construction of the facility and temporarily by management operations (stocking, harvesting, feeding, etc.). Engineering an aquaculture system involves determining what the existing conditions are, what they should be during operation and finding an economical way of bringing them about.

## Define model objectives

The objectives of the modeling exercise have to be formulated before the actual modeling work begins. The objectives help specify the nature, content and structure of the model and guide the strategy for model construction. Conversely, the nature, content and structure of the model restrict the questions that it can address and its potential use. Thus, it is important to determine which questions are relevant in the aquaculture system under study.

*Focus/level of resolution.* A model must focus on the particular aspects of the system that contain the answers to the modeler's questions (Grant 1986). A focus that is too wide will not reveal important details of the system clearly whereas too narrow a focus may confine the model to an area that does not contain all the aspects of the system necessary to answer the questions. The modeler has to decide about (1) the components that are to be included in the model, and (2) the detail or emphasis that is ascribed to these components.

*Modular approach.* A large complex model is best constructed by decomposing it into logical and relatively simpler modules (Spain 1982; Grant 1986). Each module can be further subdivided into submodules of the next level of detail. The process is repeated until the desired level of detail is reached. Each module is individually built and tested before it is linked with other modules. Linked modules are integrated with other modules and tested until the complete model is assembled and tested. As an alternative to building one large model, time and effort could be more efficiently spent building a series of smaller models to address specific questions.

*Simplify the model.* As an abstraction of reality a model is not intended to capture every detail of the system. Some simplifying assumptions must therefore be made without losing the important mechanisms and essential features of the system (Riggs 1963; Levins 1966). Input variables that have a small influence on the output variable and those input variables which depend on other input variables are discarded. Factors that are similar to each other may be aggregated. Insufficient aggregation can lead to a model obscured by unnecessary and confusing details. With too much aggregation, important elements of dynamic behavior may be lost (Grant 1986). In aquaculture, the fish can be regarded at different levels of organization: cells, organs, organisms and populations.

## Assemble pertinent knowledge

A model must provide the required degree of correspondence with the real world in order to address the questions for which it was built (Grant 1986). Therefore, a model must be supported by data. It is usually helpful to build first a preliminary model of the system. An initial set of components and loosely defined structure are proposed. This model guides the assembly and assessment of what is known about the system in the process of developing a final model. A thorough knowledge of the system is required to develop a good model because the model cannot be any better than the knowledge that was used to develop it, i.e., "garbage in, garbage out".

## Determine the model components

To determine what to include or exclude from an aquaculture model, it is helpful to look at things from the position of the cultured organism. Fish depend upon their environment for the supply of resources (food, oxygen), for removal of metabolic wastes (ammonia, carbon dioxide, feces, urine) and for maintenance of conditions suitable for growth, survival and reproduction (temperature, pH, salinity, etc.).

It is useful to make the distinction between state variables, rate variables, driving variables and parameters. State variables are the quantities in the model that determine the state of the model at any point in time. Rate variables represent the flow of materials from or to state

variables. Driving variables (or auxiliary variables) and parameters are not affected by the system: parameters are given constants and driving variables can be changed by the modeler to simulate certain conditions (e.g., a feeding regime or a climate).

Classifying environmental factors according to their action on any biological function and not merely by type grouping is useful in the understanding of biological systems (Brett 1979). The following scheme was used to develop a fish bioenergetics growth model (Cuenco 1982; Fig. 4):

*Controlling factors* govern the rates of biological reactions and operate at all nonlethal levels of the factor concerned. A distinction can be made between external and internal controlling factors. Examples are temperature, which sets the pace of all metabolic processes in fishes; and body size, which scales the metabolic rate to the size of the fish, respectively.

*Limiting factors* restrict the supply of food and oxygen to the fish or the removal of its metabolic wastes. They become operational at specific levels. Unionized ammonia and carbon dioxide may restrict the removal of these metabolic wastes.

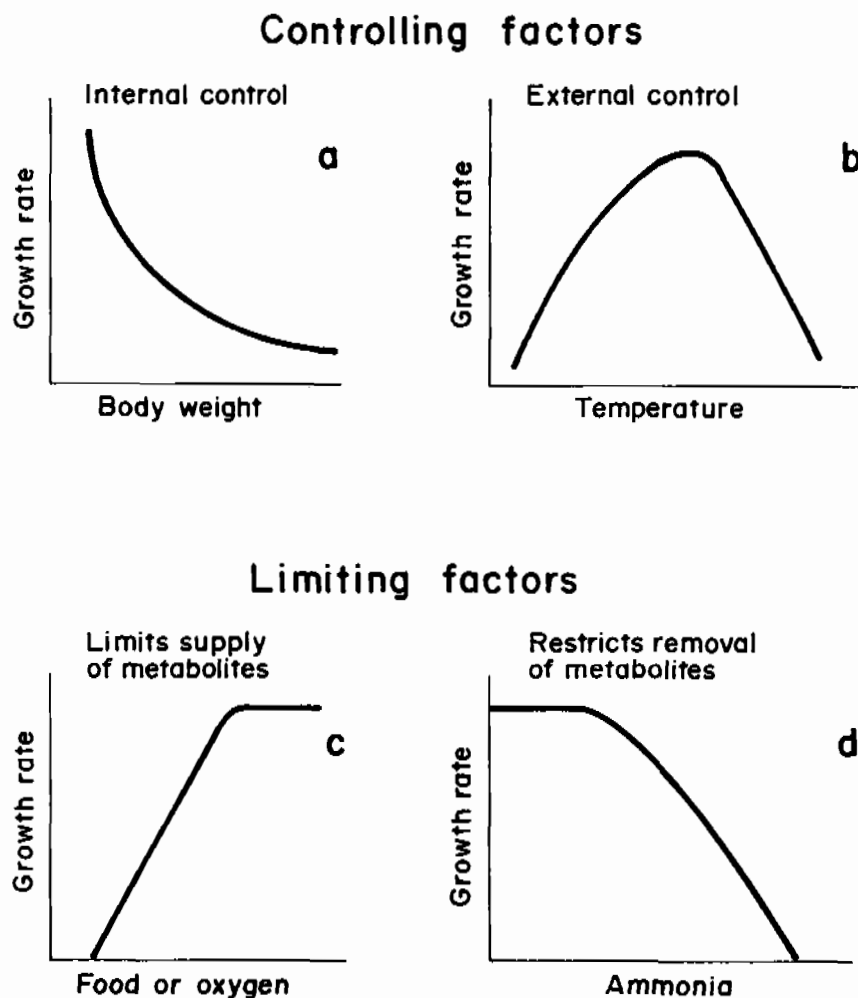


Fig. 4. Controlling factors (a, b) influence a variable (growth rate) throughout their range. Limiting factors (c, d) work only at certain levels.

Specify relationships between components

When the components of the model are identified their relationships to each other have to be determined. These relationships can be expressed initially as a written statement or a graph (a conceptual model) and eventually as a mathematical equation (the mathematical model).

One example of visualizing a conceptual model is the symbol and arrow diagram (Riggs 1963, Fig. 5). In this scheme, each variable is represented by its usual symbol. Arrows show the direction of influence and point from the independent variable towards the dependent variable. A solid arrow indicates that the dependent variable changes in the same direction as the independent variable, whereas a broken arrow expresses an inverse relationship between the dependent and the independent variable. Based on the symbol and arrow diagram the functional relations between the variables are developed into equations.

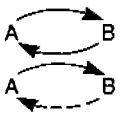
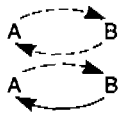
Symbol and arrow diagram		Comments
A	B	No relation between A and B.
A $\longrightarrow$ B A $\dashrightarrow$ B	A $\longleftarrow$ B A $\dashleftarrow$ B	One independent equation exists with one variable unequivocally dependent and the other independent.  Either $A = f(B)$ or $B = g(A)$ .  Example: Growth = f (Temp.) but Temp $\neq$ g (Growth).
A $\longleftrightarrow$ B	A $\longleftrightarrow$ B	One independent equation exists with no exclusive distinction of one variable as dependent and the other as independent.  $A = f(B)$ and $B = f(A)$ .  The two equations are rearrangements of the same equation.  Example: Equilibrium concentrations of hydrogen ions $[H^+]$ and hydroxyl ions $[OH^-]$ in aqueous solution.  $[H^+][OH^-] = kw$  $[H^+] = kw/[OH^-]$ Increase $[OH^-]$ by adding NaOH.  $[OH^-] = kw/[H^+]$ Increase $[H^+]$ by adding HCl.
		Two independent equations exist.  $A = f(B)$ and $B = g(A)$ .  Example: Feedback relationship Growth = f (Weight) and Weight = g (Growth).

Fig. 5. Symbol and arrow diagram. A and B are any two variables without any *a priori* implication that one is an independent variable and the other is a dependent variable.

The concepts of state- and rate-driving variables can be visualized easily using Forrester's (1961 in Jeffers 1982 or de Wit and Goudriaan 1978) relational diagram for industrial dynamics. Translation of the diagram into mathematical equations follows naturally because the state variables are calculated from integration of the rate variables over time (see Fig. 6). Other ways of visualizing conceptual models (Jeffers 1982) can suit a modeler's personal preference.

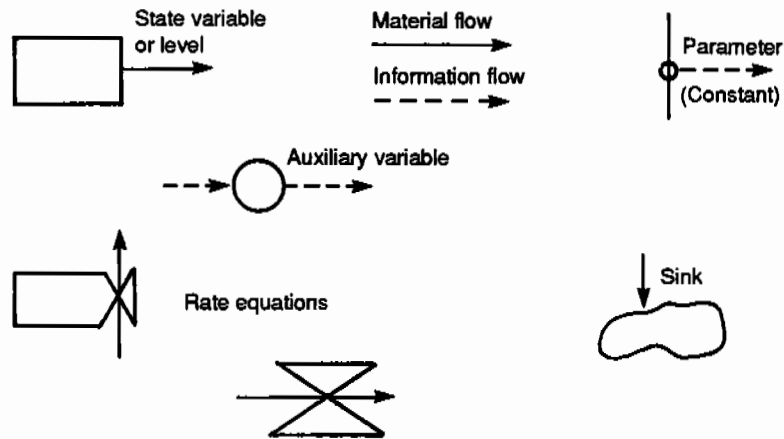


Fig. 6. Forrester's symbols for presentation of system-interrelationships (after Forrester 1961).

For translation of the conceptual model into mathematical equations, the relation of each input variable to the output variable is defined. Riggs (1963) gives a summary of all possible relationships between two variables (Fig. 7). Table 4 shows several mathematical forms that are used commonly to model biological phenomena (Spain 1982; see also Gold 1977).

Next, the combined effects of two input variables on the output variable have to be determined. Limiting factors like food and oxygen can be combined by using the minimum function. Cumulative factors like natural food and added feed can be combined simply by adding them together. Compensatory factors are combined by computing their average effect. Control factors like body weight and water temperature are combined by multiplying their effects. This process of combining the factors is continued until all the components of the model have been included.

Table 4. Standard forms of equations used in modeling.  $y$  = dependent variable;  $x$  = independent variable;  $e$  = base of the natural logarithm;  $A, B, n$  = parameters of the equation (after Spain 1982).

1.	Straight line	$y = Ax + B$
2.	Exponential	$y = Ae^{nx}$
3.	Power function	$y = Ax^n$
4.	Hyperbola	$y = Ax/(B+x)$
5.	Exponential saturation	$y = A(1 - e^{-nx})$
6.	Sigmoid	$y = A/(1 + Bx^n)$
7.	Exponential sigmoid	$y = A/(1 + Be^{nx})$
8.	Modified inverse	$y = A/(B+x)$
9.	Modified power function	$y = Ax^n + B$
10.	Maxima function	$y = Axe^{-nx}$

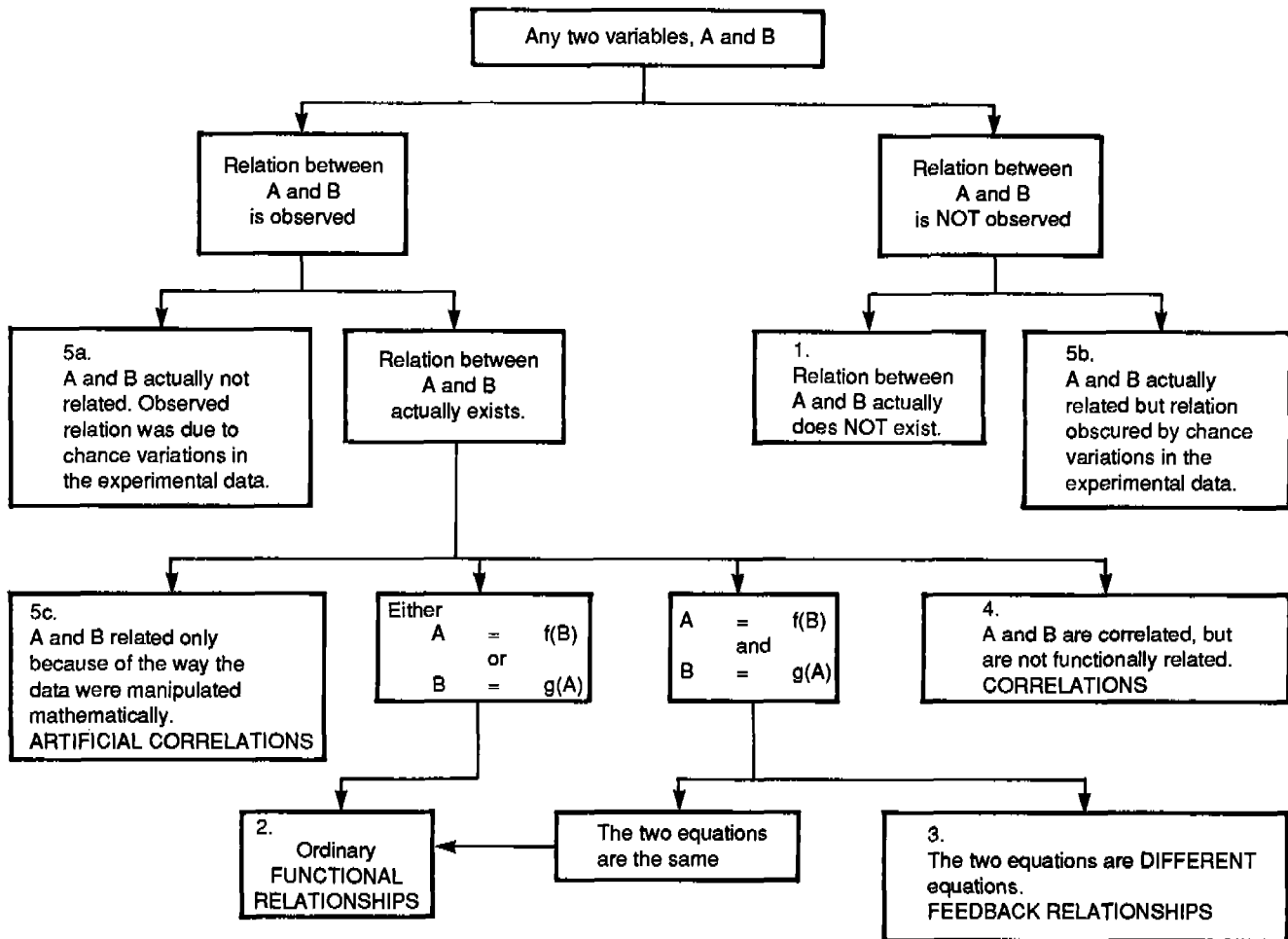


Fig. 7. Relationships between any two variables (after Riggs 1963).

### Estimate parameters/calibrate the model

After deriving the model equations, appropriate values for the parameters - the coefficients and exponents in the equations - have to be found. The conditions under which these parameters are estimated define the particular aquaculture system to which the model may be applied.

Ideally, parameters that refer to measurable traits of the fish or its environment should be used instead of arbitrary constants (Cuenco 1982). Since the forms of the mathematical equations dictate the parameters required, it is important to use equations that not only adequately represent the biological relationships, but provide biologically meaningful parameters as well.

### Test and validate the model

*Internal consistency.* Model testing should be conducted as an integral part of the process of model construction. As the model is being built, each component is tested separately, and again after integration with other components. This process is continued until the entire model is tested and verified.



Every variable in the model should be defined precisely and clearly, dimensionally correct and consistently used. Symbols representing variables should be chosen with three considerations in mind: ease of recognition, brevity, and conformity with established use (Riggs 1963).

*External consistency.* The model can be tested by letting each appropriate variable approach its specified limits and checking if the simulation results make sense. Artificial data can be created and used to test the behavior of the model.

Validation is the process of testing how much confidence can be placed on the model results as applicable to the real system. Given proper inputs, a valid model produces results that are consistent with reality and meaningful when properly interpreted. It is not difficult to build a model that mimics the effect of each factor independent of the other factors. The main difficulty lies in linking and structuring the components of the model together in such a way as to capture all relevant interactions. It is in this phase that data are usually absent and models fail to simulate known interactions. The model can be validated by comparing simulated results with experimental data or historical values from the real system and computing statistics of fit. Discrepancies between model output and reality can serve as a guide to improving the model.

After construction and validation, the model should be documented. Documentation should include the assumptions that were made building the model, the intended uses of the model, the output produced by the model and its interpretation, and the data required for using the model.

#### Use the model - simulation and forecasting

Use of the model strongly depends on the objective with which it was built. For research applications, the process of building the model, the research gaps uncovered and the conclusions about the modeled processes are often its only use, although some models can be used for predictive purposes. Management models can be used to evaluate management strategies under different environmental or economic conditions. Users must consider the limitations of the model. A model should not be used with input variables that are beyond the range with which the model was developed.

To use the model, values for the input and control variables are supplied and the model calculates the output variables using the estimated parameter values (SAS/ETS 1984). To forecast the future, future values for input and control variables can be assumed. Certain conditions can be simulated by changing the values of control variables or input data.

## Guidelines for Modeling Aquaculture Systems

The objectives of the model determine the choice of model type. Two general types of models are distinguished here: empirical models and theoretical models.

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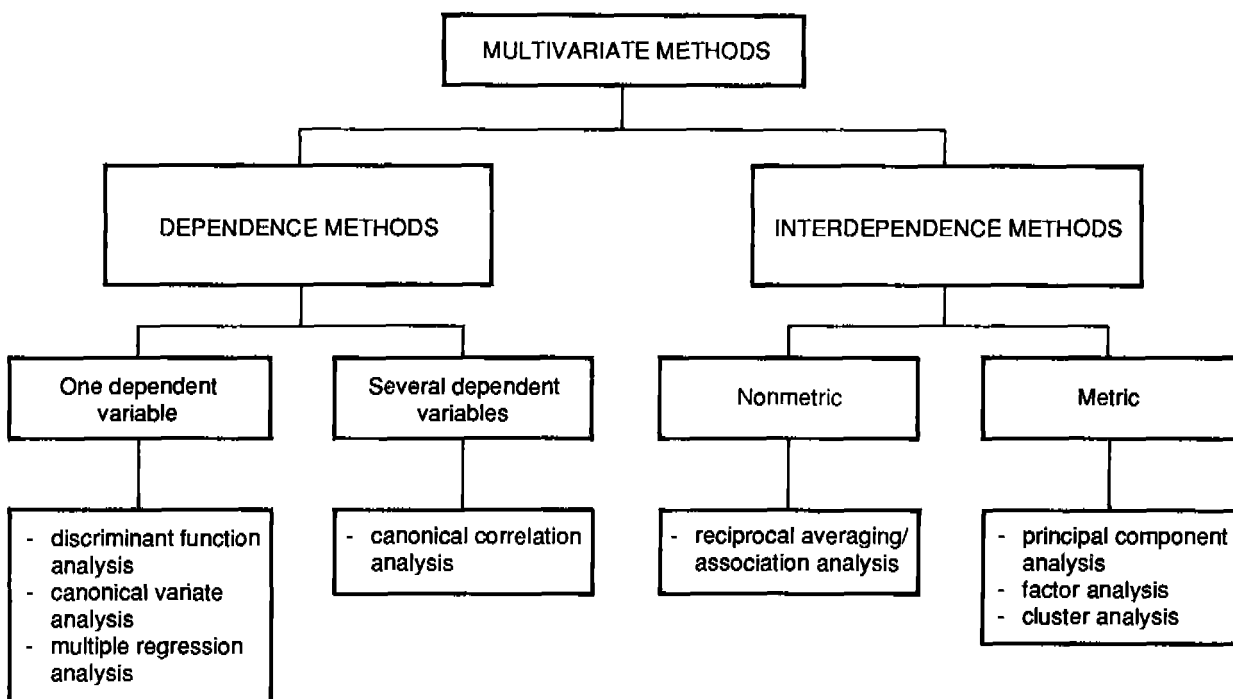


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*Controlling factors* govern the rates of biological reactions and operate at all nonlethal levels of the factor concerned. A distinction can be made between external and internal controlling factors. Examples are temperature, which sets the pace of all metabolic processes in fishes; and body size, which scales the metabolic rate to the size of the fish, respectively.

*Limiting factors* restrict the supply of food and oxygen to the fish or the removal of its metabolic wastes. They become operational at specific levels. Unionized ammonia and carbon dioxide may restrict the removal of these metabolic wastes.

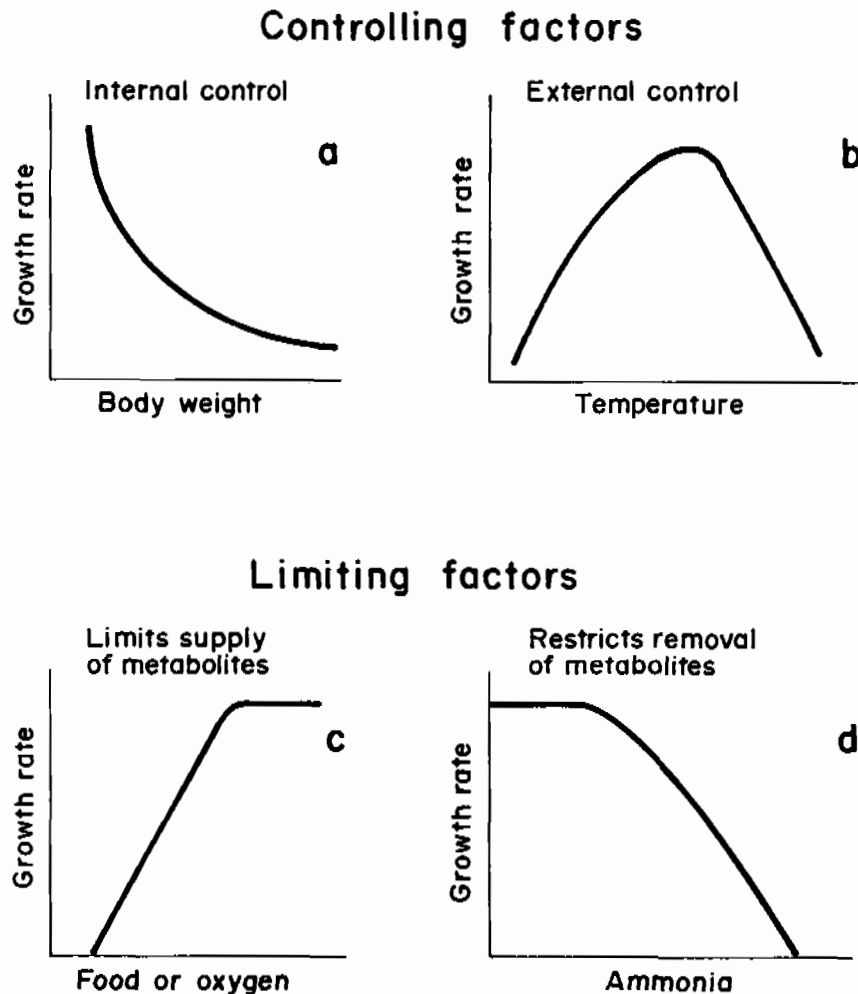


Fig. 4. Controlling factors (a, b) influence a variable (growth rate) throughout their range. Limiting factors (c, d) work only at certain levels.

## Specify relationships between components

When the components of the model are identified their relationships to each other have to be determined. These relationships can be expressed initially as a written statement or a graph (a conceptual model) and eventually as a mathematical equation (the mathematical model).

One example of visualizing a conceptual model is the symbol and arrow diagram (Riggs 1963, Fig. 5). In this scheme, each variable is represented by its usual symbol. Arrows show the direction of influence and point from the independent variable towards the dependent variable. A solid arrow indicates that the dependent variable changes in the same direction as the independent variable, whereas a broken arrow expresses an inverse relationship between the dependent and the independent variable. Based on the symbol and arrow diagram the functional relations between the variables are developed into equations.

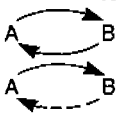
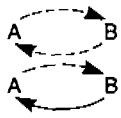
Symbol and arrow diagram		Comments
A	B	No relation between A and B.
A $\longrightarrow$ B A $\dashrightarrow$ B	A $\longleftarrow$ B A $\dashleftarrow$ B	One independent equation exists with one variable unequivocally dependent and the other independent.  Either $A = f(B)$ or $B = g(A)$ .  Example: Growth = f (Temp.) but Temp $\neq$ g (Growth).
A $\longleftrightarrow$ B	A $\longleftrightarrow$ B	One independent equation exists with no exclusive distinction of one variable as dependent and the other as independent.  $A = f(B)$ and $B = f(A)$ .  The two equations are rearrangements of the same equation.  Example: Equilibrium concentrations of hydrogen ions $[H^+]$ and hydroxyl ions $[OH^-]$ in aqueous solution.  $[H^+][OH^-] = kw$  $[H^+] = kw/[OH^-]$ Increase $[OH^-]$ by adding NaOH.  $[OH^-] = kw/[H^+]$ Increase $[H^+]$ by adding HCl.
		Two independent equations exist.  $A = f(B)$ and $B = g(A)$ .  Example: Feedback relationship Growth = f (Weight) and Weight = g (Growth).

Fig. 5. Symbol and arrow diagram. A and B are any two variables without any *a priori* implication that one is an independent variable and the other is a dependent variable.

The concepts of state- and rate-driving variables can be visualized easily using Forrester's (1961 in Jeffers 1982 or de Wit and Goudriaan 1978) relational diagram for industrial dynamics. Translation of the diagram into mathematical equations follows naturally because the state variables are calculated from integration of the rate variables over time (see Fig. 6). Other ways of visualizing conceptual models (Jeffers 1982) can suit a modeler's personal preference.

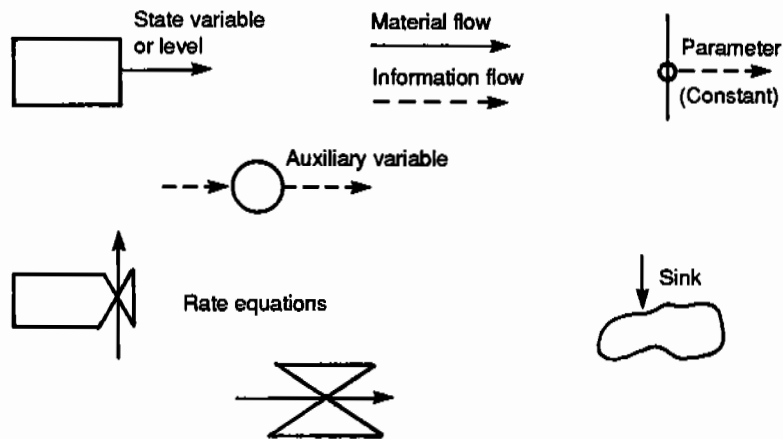


Fig. 6. Forrester's symbols for presentation of system-interrelationships (after Forrester 1961).

For translation of the conceptual model into mathematical equations, the relation of each input variable to the output variable is defined. Riggs (1963) gives a summary of all possible relationships between two variables (Fig. 7). Table 4 shows several mathematical forms that are used commonly to model biological phenomena (Spain 1982; see also Gold 1977).

Next, the combined effects of two input variables on the output variable have to be determined. Limiting factors like food and oxygen can be combined by using the minimum function. Cumulative factors like natural food and added feed can be combined simply by adding them together. Compensatory factors are combined by computing their average effect. Control factors like body weight and water temperature are combined by multiplying their effects. This process of combining the factors is continued until all the components of the model have been included.

Table 4. Standard forms of equations used in modeling.  $y$  = dependent variable;  $x$  = independent variable;  $e$  = base of the natural logarithm;  $A, B, n$  = parameters of the equation (after Spain 1982).

1.	Straight line	$y = Ax + B$
2.	Exponential	$y = Ae^{nx}$
3.	Power function	$y = Ax^n$
4.	Hyperbola	$y = Ax/(B+x)$
5.	Exponential saturation	$y = A/(1-e^{nx})$
6.	Sigmoid	$y = A/(1+Bx^n)$
7.	Exponential sigmoid	$y = A/(1+Be^{nx})$
8.	Modified inverse	$y = A/(B+x)$
9.	Modified power function	$y = Ax^n + B$
10.	Maxima function	$y = Axe^{nx}$



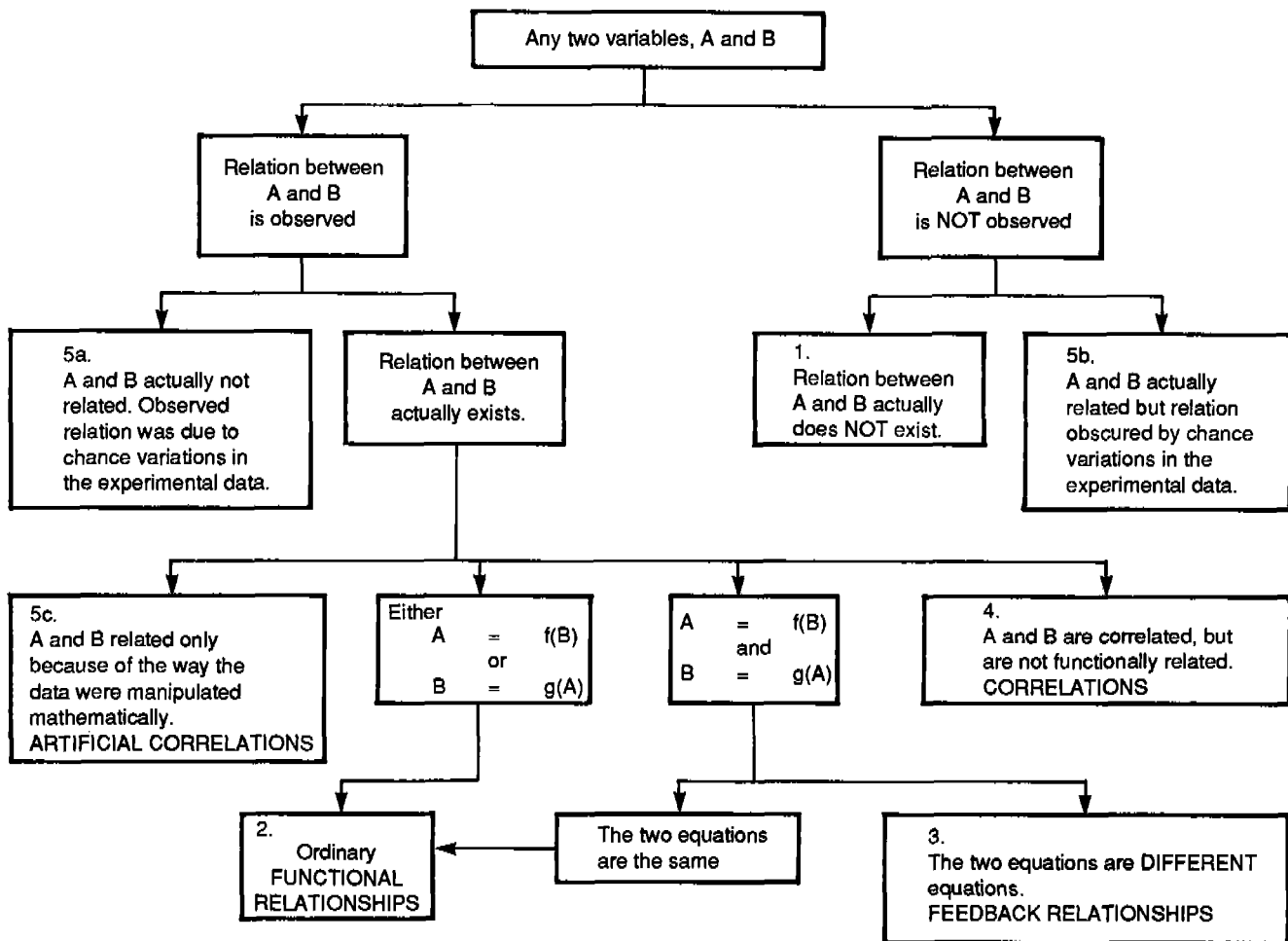


Fig. 7. Relationships between any two variables (after Riggs 1963).

### Estimate parameters/calibrate the model

After deriving the model equations, appropriate values for the parameters - the coefficients and exponents in the equations - have to be found. The conditions under which these parameters are estimated define the particular aquaculture system to which the model may be applied.

Ideally, parameters that refer to measurable traits of the fish or its environment should be used instead of arbitrary constants (Cuenco 1982). Since the forms of the mathematical equations dictate the parameters required, it is important to use equations that not only adequately represent the biological relationships, but provide biologically meaningful parameters as well.

### Test and validate the model

*Internal consistency.* Model testing should be conducted as an integral part of the process of model construction. As the model is being built, each component is tested separately, and again after integration with other components. This process is continued until the entire model is tested and verified.

Every variable in the model should be defined precisely and clearly, dimensionally correct and consistently used. Symbols representing variables should be chosen with three considerations in mind: ease of recognition, brevity, and conformity with established use (Riggs 1963).

*External consistency.* The model can be tested by letting each appropriate variable approach its specified limits and checking if the simulation results make sense. Artificial data can be created and used to test the behavior of the model.

Validation is the process of testing how much confidence can be placed on the model results as applicable to the real system. Given proper inputs, a valid model produces results that are consistent with reality and meaningful when properly interpreted. It is not difficult to build a model that mimics the effect of each factor independent of the other factors. The main difficulty lies in linking and structuring the components of the model together in such a way as to capture all relevant interactions. It is in this phase that data are usually absent and models fail to simulate known interactions. The model can be validated by comparing simulated results with experimental data or historical values from the real system and computing statistics of fit. Discrepancies between model output and reality can serve as a guide to improving the model.

After construction and validation, the model should be documented. Documentation should include the assumptions that were made building the model, the intended uses of the model, the output produced by the model and its interpretation, and the data required for using the model.

#### Use the model - simulation and forecasting

Use of the model strongly depends on the objective with which it was built. For research applications, the process of building the model, the research gaps uncovered and the conclusions about the modeled processes are often its only use, although some models can be used for predictive purposes. Management models can be used to evaluate management strategies under different environmental or economic conditions. Users must consider the limitations of the model. A model should not be used with input variables that are beyond the range with which the model was developed.

To use the model, values for the input and control variables are supplied and the model calculates the output variables using the estimated parameter values (SAS/ETS 1984). To forecast the future, future values for input and control variables can be assumed. Certain conditions can be simulated by changing the values of control variables or input data.

## Past Uses of Aquaculture Systems Modeling

Modeling aquaculture systems is relatively new and is not yet practiced extensively. It has not matured to the point where a common, consistent terminology and a well defined methodology are in use. Approaches to aquaculture modeling reflect adaptation of modeling developed for and used in other disciplines.

### *Criteria for Evaluation*

In order to review some existing aquaculture models, criteria for describing and evaluating them were developed (see Tables 5-9). These criteria covered the utility of the models (intended use, applicability and relevance to aquaculture), the realism and the modeling aspects (number and type of parameters, general type of model).

### *Functional Scheme for Classifying Aquaculture Models*

The following scheme has been used as a context for classifying aquaculture models (Cuenco 1982; Allen et al. 1984):

*Biological models* are concerned with the responses (growth, survival, reproduction) and interactions (eating, breathing, excretion) of the cultured fish and its environment.

- choice of species: the biological requirements of the species have to be matched to its proposed environment as defined by site selection and facility design. Although finfish represent the principal commodity group cultured in the world (FAO 1989), most existing aquaculture models deal with crustaceans. This reflects the fact that modeling has been developed and mostly used in western developed countries where modelers applied the technique to the species most relevant or economically viable.
- seed or fingerling production: this phase may include reproduction in captivity and hatchery operations to raise the larvae/fry (e.g., common carp) or may consist of capturing the larvae/fry and raising them to fingerlings in nursery ponds (e.g., milkfish).
- growout to market size: the aquaculture production phase most commonly modeled is the growout from fry or fingerling to market-size fish. A problem with unwanted reproduction may occur with species that reach sexual maturity when smaller than market size (e.g., tilapias).

*Engineering models* are concerned with designing, managing and controlling the environment of the fish. These models use biological models to determine which type of environment is required. None of the models reviewed here deal specifically with site selection. Some of the models deal with a few aspects of facility design while the rest focus on production operations.

- site selection: the site must correspond with the biological requirements of the fish and the proposed culture technology. Aspects to be considered in selecting a site are: climate, water sources (surface or ground water), water quality and quantity, and soil conditions (suitability for building ponds and fertility).

- facility design and construction: the site determines the ambient environment which is modified permanently by the design and construction of the production units (ponds, cages, raceways).

- operation and management: from a practical viewpoint, a distinction should be made between biological factors that are controlled by the aquaculturist and those that are not. Research and experience show that fish production can be increased by: (1) optimum stocking and cropping schemes to control the biomass and individual size of the fish; (2) fertilizing or manuring to increase *in situ* production of natural foods; (3) providing artificial feeds; (4) water exchange or aeration to increase, or water mixing to conserve dissolved oxygen; (5) water exchange or treatment to remove metabolic wastes from the culture environment; (6) maintaining optimum water temperatures through site selection, facility design and other means.

*Economic models* are concerned with the economic feasibility of aquaculture enterprises: the costs associated with providing and maintaining the culture environment and the revenues from expected production. These models tie together the biological and engineering models and use them to define the production function as a basis for economic analysis.

### *Growth Models (Table 5)*

Growth in fish is governed by a variety of environmental factors (Brett 1979) including temperature (Brett et al. 1969; Elliot 1976), oxygen concentration (Stewart et al. 1967; Doudoroff and Shumway 1970), unionized ammonia (Colt and Tchobanoglous 1978), food availability (Brett 1971), salinity (De Silva and Perera 1976; Peters 1971) and photoperiod (Gross et al. 1965). In addition, fish growth is influenced by one or more internal factors including body size (Brett 1979) and genotype (Hickling 1962). The combined effect of all or a number of these factors can range from complete growth inhibition to maximum growth.

Most growth studies have been done under laboratory conditions using fixed/narrow ranges of factors that influence growth. Such studies apply directly to growth in highly controlled culture environments. Ponds show wide fluctuations in water temperature, dissolved oxygen and ammonia, both within and between days. To model growth under pond conditions, the effects of these diurnal and seasonal fluctuations must be determined. These experiments are much more complicated and difficult to conduct. An alternative approach is to design and conduct "comparison" experiments to determine whether and how results obtained with fixed ranges of growth factors can be applied under conditions where these factors fluctuate. Studies in this area are scarce and need to be emphasized (Cuenco 1982). The effects of environmental factors on fish growth are discussed here under pond ecosystems models.

If possible, the parameters used in fish growth equations should refer to measurable traits of the fish or its environment. It is then possible to apply the same model to different species or genotypes by changing the parameters. A parameter could, for example, represent the feeding habits or food processing apparatus of the fish. Predominantly herbivorous fish have a lower assimilation efficiency (about 57%) than carnivorous fish (about 73%). Pandian and Marian (1985) showed that the nitrogen content of food is positively correlated with absorption efficiency. Although at a disadvantage in terms of food assimilation efficiency, herbivorous fish are compensated by a generally greater abundance of food since they feed lower on the food chain.

Table 5. Fish growth models.

	1	2	3	4	5	6	7	8	MODELS									16	17
									9	10	11	12	13	14	15				
<b>CATEGORIES</b>																			
Intended use	R	R	R	M	R	M	R	R	R	R	R	R	R	R	R	R	R		
System		L	H	H	P/L	H		P	P	P	P		H	H		P	R/L		
Relevance		G	H	H	G	H		G	G	G	G		G	H	G	G	G		
Organism	F	F	F	F	F	F	F	S	F	S	S	F	L	F		F	F		
# parameters				15	17	15		11	3						13				
Type																	E		
Growth equation	B	B	B	B	B	F	V	V	V	V	V	W	W	W		V	T		
<b>VARIABLES</b>																			
Age							X	X	X										
Body size	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		
Stock biomass																			
Stock number					X	X					X								
Amount of food				X	X	X									X		X		
Feeding frequency																	X		
Food quality					X									X			X		
Water temperature	X	X	X	X	X	X	X		X	X	X		X	X	X	X	X		
Dissolved oxygen					X		X			X	X				X	X			
Ammonia					X														
Salinity										X	X								
Water exchange											X								
Space													X			X			

1. Paloheimo and Dickie (1965; 1966a; 1966b) 2. Elliott (1976) 3. Jorgensen (1976) 4. Fromm and Rasmussen (1979) 5. Cuenco (1982); Cuenco et al. (1985a, 1985b, 1985c); Masser (1986) 6. Bergman et al. (1972); Stauffer (1973); Corey et al. (1983) 7. Ursin (1967) 8. Adams (1978); Adams et al. (1980) 9. Ekstrom (1979) 10. Hanson (1979); Griffin et al. (1981) 11. Parfy et al. (1983); Griffin et al. (1984) 12. Parker and Larkin (1959) 13. Botsford et al. (1975) 14. Zweifel and Lasker (1976) 15. Yamaguchi (1981) 16. Pauly and Hopkins (1983); Prein (1985) 17. Machiels and Henken (1986).

Intended use : R = research  
M = management  
System : F = flow-through system  
P = pond  
R = recirculating system  
H = hatchery  
L = laboratory  
Relevance : G = growout  
H = hatchery or fingerling production  
D = design or site selection  
Organism : F = finfish  
S = shrimp  
L = lobster

Type : E = empirical  
T = theoretical  
Growth equation : B = bioenergetic  
F = based on relation between growth and food consumption  
V = based on von Bertalanffy growth equation  
W = based on power function of weight  
C = based on biochemistry  
Variables : X = indicates that variable was included in the model

Assimilation efficiency and stomach evacuation rate are also related to feeding habits (Fänge and Grove 1979). The stomach capacity and the length of the gastrointestinal tract, both expressed per unit body size are probably related to the exponent of the power function commonly used to relate food consumption to body weight (Cuenco 1982). Meaningful parameters could be identified by studying respiratory exchange in fishes, especially those factors governing the uptake of oxygen from the water and the excretion of ammonia and carbon dioxide. The exponent of the power function relating respiration to body weight measures the ability of the fish to take up oxygen and is related to the gill surface area, expressed per unit body weight, which in turn is related to the average maximum size of the fish (Pauly 1981, 1982).

Growth models can be classified according to their basic derivation. *Bioenergetic models* are based on the bioenergetic growth equation:

$$\text{Food} = \text{Growth} + \text{Wastes} + \text{Respiration}$$

Fish gain matter and energy solely from their food. For a given time period, the energy of the food consumed must equal the sum of the change in body energy (growth), the energy lost in waste products and the energy used for activities and metabolism (respiration) (Fig. 8; Warren and Davis 1967). Factors influencing growth act not directly on growth, but through the

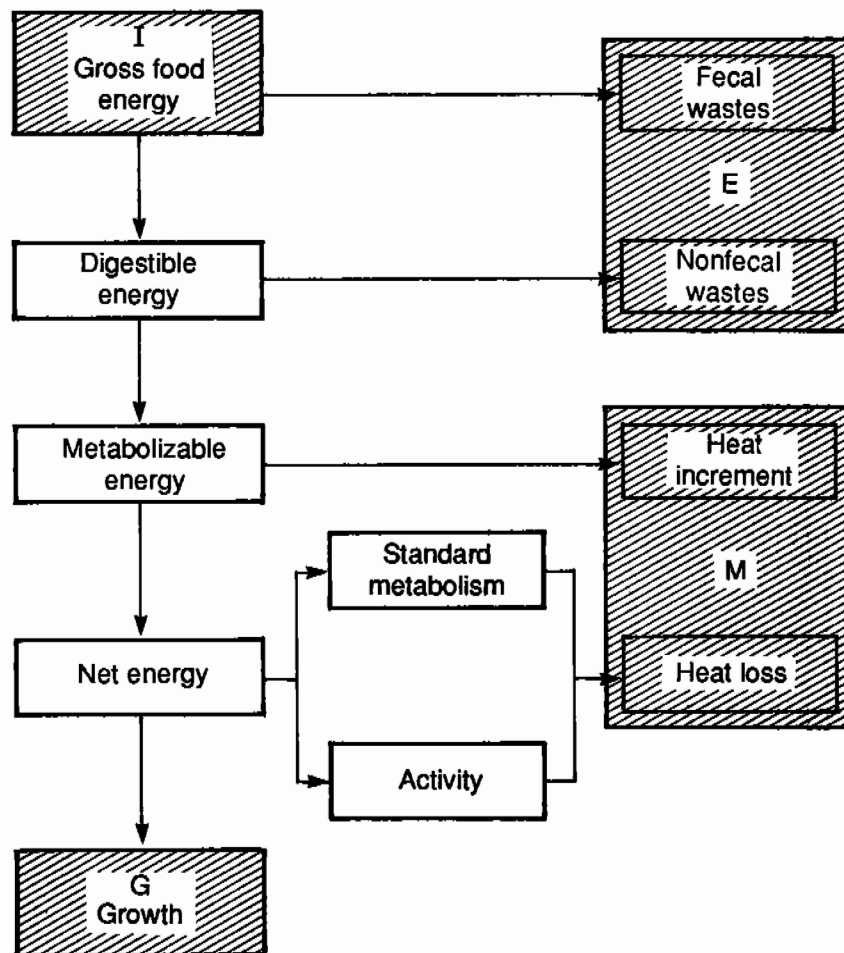


Fig. 8. The bioenergetic model of fish growth. The sum of the energy in biomass increase (growth G), the energy in the waste materials (E) and the energy used for metabolism and activity (M) equals the gross food energy (I).

mechanisms of energy supply and demand (Brett and Groves 1979). Bioenergetic models provide a sound basis for aquaculture models, because all major components are included: food consumption (often the most important cost item), excretion (excretion products pollute the environment, affecting growth), respiration (dissolved oxygen is a major limiting factor) and growth itself.

Other models are based on von Bertalanffy's growth equation:

$$\text{Growth} = \text{anabolism} - \text{catabolism}$$

or, mathematically:

$$dw/dt = Hw^d - kw^m \text{ (Pauly 1981)}$$

where  $dw/dt$  is the growth rate,  $w$  is fish weight and  $H$  and  $k$  are coefficients of anabolism and catabolism, respectively. Although originally von Bertalanffy thought that the exponents  $d$  and  $m$  were constants ( $2/3$  and  $1$ , respectively), Pauly (1981) provided evidence that these exponents vary among species.

Machiels and Henken (1986) presented a growth model based on the biochemistry of fish growth. Another group of models is based on the relation between growth and food consumption (Stauffer 1973).

### ***Pond Ecosystem Models (Table 6)***

Pond ecosystem models attempt to incorporate the many components and processes relevant to the pond environment. These include the biotic components (cultured organisms, phytoplankton, zooplankton, benthic organisms, bacteria-detritus complex), the abiotic components (water characteristics, such as pH, alkalinity, carbon dioxide, temperature, dissolved oxygen, ammonia-ammonium, nitrite, nitrate, phosphorous, organic matter; soil type; climatic factors such as solar radiation, wind, evaporation and precipitation) and management factors.

The core of a pond model is usually some type of growth model (as discussed in the previous section). Linked to this are the environmental factors that are considered important or of interest for the particular problem under study, and the management factors (especially inputs like feeds and fertilizers). The environmental and management factors that are usually incorporated in pond models are discussed here briefly.

Dissolved oxygen (DO) is required by the fish for its metabolism. Fish growth rate increases with rising oxygen concentration up to a maximum where oxygen is not limiting anymore and growth rate is independent of the oxygen concentration.

Unionized ammonia ( $\text{NH}_3$ ) is a by-product of metabolism and can be regarded as a limiting factor restricting the removal of a metabolite and consequently decreasing growth (Cuenco 1982). Unionized ammonia is in equilibrium with the ammonium ion ( $\text{NH}_4^+$ ). High temperatures and high pH cause the equilibrium to shift towards  $\text{NH}_3$ , which is very toxic to fish.

The pH of the water in freshwater tropical fishponds shows a diurnal rhythm which is caused by the production and consumption of carbon dioxide. During the daytime, carbon dioxide is taken up by the phytoplankton causing an increase in pH. At night, photosynthesis stops while respiration continues to produce carbon dioxide, causing the pH to decrease. The pH level affects the ammonia equilibrium.

Growth, like other physiological processes, is regulated by body temperature which is equal to the ambient water temperature in fish. Relative growth rate increases with rising temperature, reaches a peak at the optimum temperature for growth and falls steeply above the optimum temperature (Brett and Groves 1979).

Salinity affects growth as well. Fishes regulate the internal osmotic pressure of their body fluids to a salinity of about 10 ppt (Holmes and Donaldson 1969). To counteract loss of ions and

Table 6. Pond ecosystem models.

	1	2	3	4	5
<b>CATEGORIES</b>					
Intended use	R	R	R	R	R
Relevance	G	G	G	G	G
Organism	S	S	F	F	
# parameters		17	22	112	29
Type	T	T	T	T	T
<b>VARIABLES</b>					
<b>(biota)</b>					
Nekton	X	X	X	X	
Phytoplankton	X	X	X	X	X
Zooplankton	X	X	X	X	
Benthos		X		X	
Bacteria	X			X	X
Detritus	X	X	X	X	X
<b>(environment)</b>					
Water temperature	X			X	
Dissolved oxygen	X		X	X	X
Salinity					
pH	X		X		
Carbon dioxide	X		X		X
Alkalinity	X		X		X
Hardness					
Ammonia	X		X		X
Nitrate	X		X	X	X
Phosphorus	X		X	X	X

1. Farnsworth (1979)

2. Ma (1979)

3. Piedrahita et al. (1983); Piedrahita (1984)

4. Svirizhev et al. (1984)

5. Fritz et al. (1979)

Intended use	:	R	=	research
		M	=	management
Relevance	:	G	=	growout
		H	=	hatchery or fingerling production
		D	=	design or site selection
Organism	:	F	=	finfish
		S	=	shrimp
		L	=	lobster
Type	:	E	=	empirical
		T	=	theoretical
Variables	:	X	=	indicates that variable was included in the model

body flooding in freshwater environments, fishes excrete a highly dilute urine with small loss of salts which are replaced through the diet.

Of the management factors, pond fertilization (Swingle and Smith 1939; Hopher 1962) and feeding (Shell 1968; Swingle 1968) are traditional methods of increasing fish production in ponds. The distinction between fertilization and feeding is arbitrary because uneaten feeds add fertility to ponds (Boyd 1979) and some organic fertilizers may be eaten directly by the fish (Spataru 1976). In pond culture, overfeeding must be avoided because it is a waste of high quality, expensive feed and may have adverse effects on water quality.

Frequent applications of small manure doses give higher fish yields than applying large amounts a few times during the growing season. Kelly (1957) applied 4.2 t/ha/day of manure at monthly intervals resulting in tilapia yields of 2.6 kg/ha/day. Ledgerwood et al. (1977) applied 34 kg/ha/day of manure at daily intervals (which amounted to 25% of the amount used by Kelly) leading to tilapia yields of 6.8 kg/ha/day.



Other management factors are stocking density and harvesting. The ideal stocking density is the maximum density that results in production of desirable-sized fish in a reasonable period of time (Swingle 1968). The maximum number of fish that can be stocked depends on the maximum biomass the pond can support (i.e., the carrying capacity) and the average size of the fish. As fish size increases during the culture period, the initial biomass may be far below the carrying capacity of the pond. With a model, it is possible to investigate the possibility of stocking more fish of different sizes with regular harvesting during the culture period to regulate the biomass.

### ***Production Models***

Aquaculture production is predicated on the survival and growth of the cultured organisms. Thus, production is easily modeled as the sum of the weights of each surviving fish or the product of the average weight of the fish and the number of fish. Production is measured as total weight or biomass of the fish.

The size distribution of the fish at harvest is important to determine the number of fish that reach market size. Morita (1977) developed a statistical regression model of total prawn production in ponds as a function of survival, stocking size, stocking density, length of the culture period and amount of feed.

### ***Survival Models***

Most survival models merely assume an expected value for survival at the end of the culture period based on past experience. A linear or curvilinear equation is then fitted to the value to determine survival at any time during culture. Polovina and Brown (1978) developed a survival model for shrimps in ponds as a curvilinear function of size and pond biomass and three parameters. In the model of Huang et al. (1976), shrimp survival was an exponential function of size and sex. Griffin et al. (1984) constructed a model where shrimp survival was a linear function of the day of the year, based on historical records that showed survival to be about 60% of the number stocked. Morita (1977) developed a statistical regression model with dissolved oxygen, pH, stocking density and length of the culture period as independent variables explaining shrimp survival.

### ***Bioeconomic Models (Table 7)***

Bioeconomic models are used to study the economic feasibility of aquaculture. To accomplish this, economic analysis is dependent on biological and engineering models of the aquaculture enterprise. Costs are assigned to all inputs while prices are assigned to all outputs or products. From these basic elements various types of economic analysis are conducted. An example is the linear programming study of integrated rice-poultry-fish culture in Malaysia by Syed (1985), which shows how a bioeconomic model can be used to evaluate a production system under "real-life" economic conditions. This can be very useful when different culture systems have to be compared and for policy planning purposes.

Some models concentrate on certain aspects of aquaculture production systems. These models can in a later phase be incorporated into larger, more comprehensive models like pond ecosystem models or bioeconomic models. Examples of models of subsystems are dissolved oxygen models, ammonia models, temperature models and salinity models.

Table 7. Bioeconomic models.

	1	2	3	4	5	6	7	8
<b>CATEGORIES</b>								
Intended use	R	R	R	R	R	R	R	R
System	H	H	P	P	P	P	P	P
Relevance	G	G	G	G	G	G	G	G
Organism	L	L	S	F	S	S	S	S
# parameters	17	22	11					
Random mechanism	D	D	D	D	P	D	D	P
<b>VARIABLES</b>								
<b>(output)</b>								
Revenues			X	X	X	X	X	X
Costs	X	X	X	X	X	X	X	X
Budgets			X	X				
Cash flow			X	X				
Financial ratios			X	X		X	X	
Production	X	X	X	X	X	X	X	X
Survival						X	X	
<b>(input)</b>								
<b>Feeding</b>								
Water temperature	X	X		X	X		X	X
Dissolved oxygen					X		X	
Ammonia								
Salinity					X		X	
Age			X					
Stock number			X			X	X	
Stock size dist.	X	X				X		
Stocking date					X	X	X	X
Harvest date						X	X	X
Multiple crops						X		
<b>Aeration</b>								
Water exchange	X	X			X		X	
<b>Fertilization</b>								
Farm size		X		X				
Pond size	X			X				
Air temperature		X			X			

1. Botsford et al. (1975) 2. Allen and Johnston (1976) 3. Adams (1978); Adams et al. (1980) 4. Ekstrom (1979) 5. Hanson (1979); Griffin et al. (1981) 6. Pardy et al. (1983) 7. Griffin et al. (1984) 8. Sadch et al. (1986)

Intended use : R = research  
M = management  
System : F = flow-through system  
P = pond  
R = recirculating system  
H = hatchery  
L = laboratory  
Relevance : G = growout  
H = hatchery or fingerling production  
D = design or site selection  
Organism : F = finfish  
S = shrimp  
L = lobster  
Random mechanism : D = deterministic  
P = probabilistic  
Variables : X = indicates that variable was included in the model

*Dissolved Oxygen Models (Table 8)*

Two basic types of these models occur: theoretical models, based on mass balance (Fig. 9) and empirical models, based on regression analysis of historical data.

Dissolved oxygen fluctuates on a daily and seasonal basis. Models generally include only one of these two aspects: short-term or diurnal and long-term or seasonal fluctuation.

Dissolved oxygen generally increases during the daytime due to photosynthesis and declines during the nighttime due to the absence of photosynthesis and continuing respiration. Models can break down the diurnal fluctuation into two: the nighttime decrease and the daytime increase.

Table 8. Dissolved oxygen models.

	MODELS					
	1	2	3	4	5	6
<b>CATEGORIES</b>						
Intended use	R	R	R	R	R	R
System	P	P	P	P	P	P
Relevance	G	G	G	G	G	G
# parameters	39	27		21	21	
Type	T	T	E	E	E	E
<b>VARIABLES</b>						
<b>(endogenous)</b>						
Temporal flux	D	S	D	D	D	D
Diurnal phase	N,D		N	N	N	D
<b>(control)</b>						
Mech. aeration			X			
Water exchange		X				
Water mixing						
Feeding	X					
Manuring					X	
<b>(processes)</b>						
Photosynthesis	X	X				X
Air diffusion	X	X		X	X	
Plankton resp.	X	X	X	X	X	
Fish respiration	X	X	X	X	X	
Sediment demand	X			X	X	
<b>(environmental)</b>						
Sunlight	X	X				X
Cloud cover	X					X
Wind	X	X				
Temperature	X			X	X	

1. Meyer (1980); Meyer and Brune (1982); Meyer et al. (1983) 2. Cassinelli et al. (1978); Hanson (1979); Griffin et al. (1984) 3. Busch et al. (1977) 4. Boyd et al. (1978) 5. Romaine et al. (1978) 6. Romaine and Boyd (1979)

- Intended use : R = research
- M = management
- System : F = flow-through system
- P = pond
- R = recirculating system
- H = hatchery
- L = laboratory
- Relevance : G = growout
- H = hatchery or fingerling production
- D = design or site selection
- Type : E = empirical
- T = theoretical
- Diurnal phase : N = night
- D = day
- Temporal flux : D = diurnal
- S = seasonal
- Variables : X = indicates that variable was included in the model

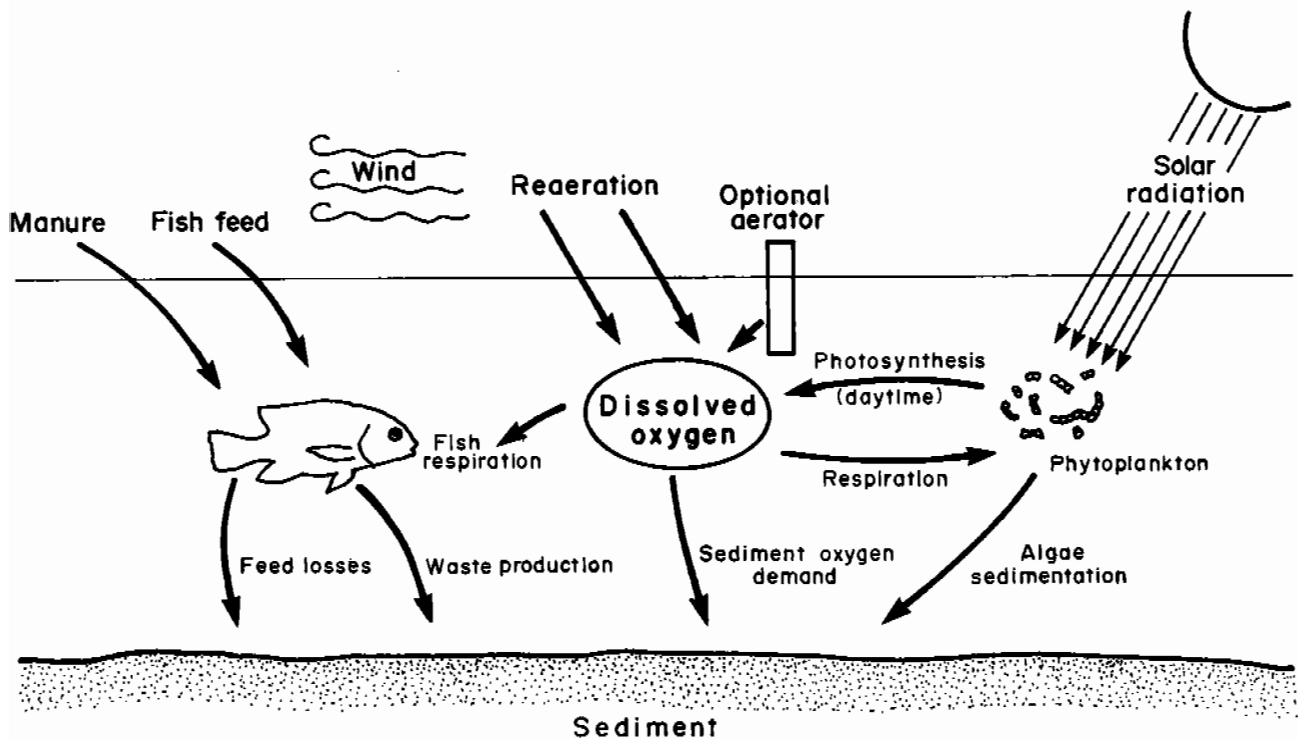


Fig. 9. A conceptual model of pond dissolved oxygen based on mass balance (after Meyer and Brune 1982).

There are two basic ways of controlling dissolved oxygen in the culture environment. One way is to increase the supply of oxygen into the pond, which can be done by mechanical aeration, exchange with oxygen-rich water, and water mixing to conserve photosynthetically produced oxygen. The other way is to decrease the removal of oxygen from the pond by preventing excessive feeding and manuring.

The processes that add oxygen to the pond are: (1) photosynthesis by phytoplankton, the major source of oxygen; (2) oxygen diffusion from the air governed by the difference in oxygen concentration between the pond water and the air and the wind speed. Photosynthesis can be estimated indirectly via chlorophyll *a* concentration, Secchi disk visibility and chemical oxygen demand. Photosynthesis is governed by the amount of sunlight, cloud cover and water temperature.

The processes that consume oxygen from the pond are respiration by plankton, fish and other biota and mud. Plankton respiration can also be assessed indirectly via Secchi disk visibility and chemical oxygen demand.

The amount of oxygen that the water will hold is determined by the temperature and the salinity of the water.

### ***Ammonia Models***

A conceptual model of ammonia transformation processes in fishponds is shown in Fig. 10 (Shilo and Rimon 1982; van Rijn et al. 1984). Both the diurnal and the seasonal fluctuations of ammonia in the pond were considered. Fish feed and added manures are the major sources of nitrogen in fishponds. The major sinks for ammonia are the photo-oxidation of algae and bacteria and bacterial nitrification of ammonia to nitrate.

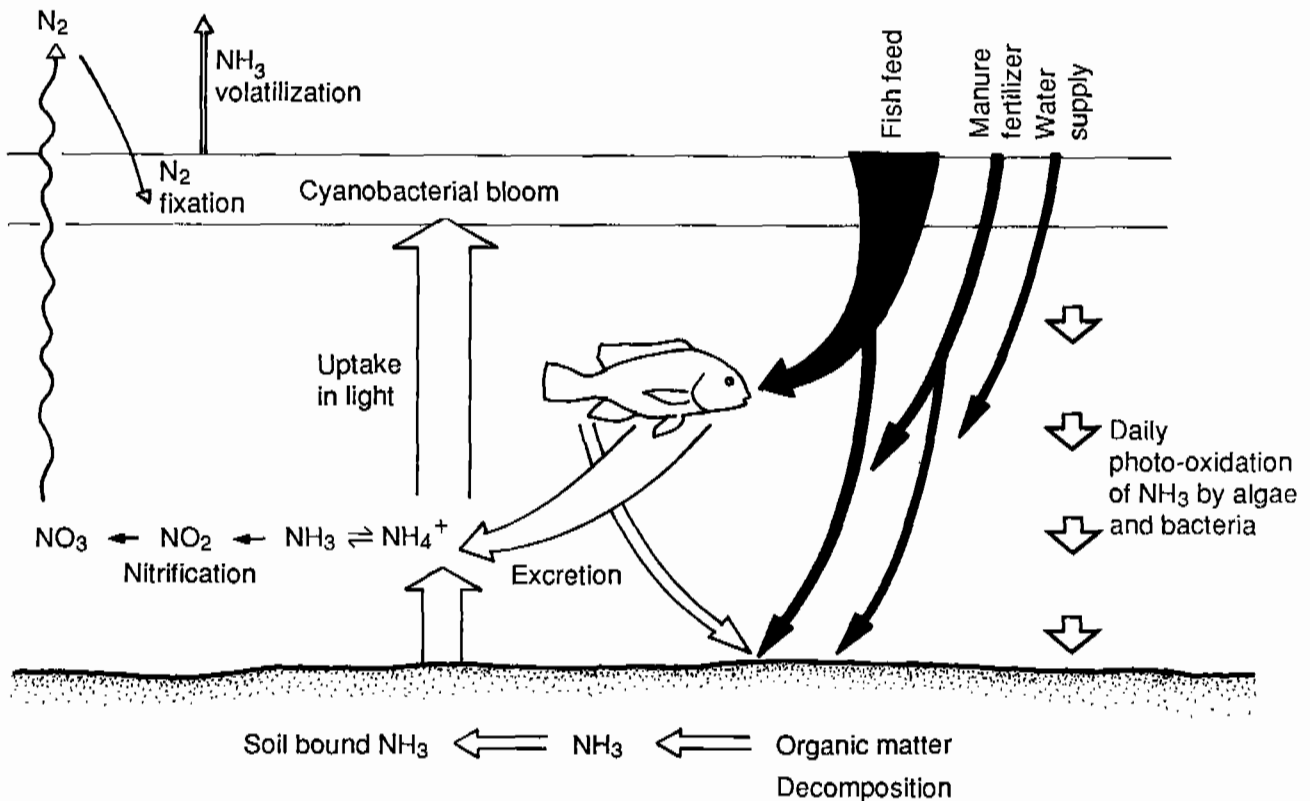


Fig. 10. A conceptual model of ammonia in a fishpond, based on nitrogen transformation processes (after Shilo and Rimon 1982).

Ammonia is produced by bacterial decomposition of organic matter (uneaten feeds, manures, feces) and ammonia excretion by the fish. Ammonia is removed from the water through uptake by algae and bacteria. The pond sediment acts as a storage medium for ammonia. However, ammonia may also be released from the sediment into the water column.

The level of unionized ammonia in the pond water increases with pH and temperature. The toxicity of ammonia increases at low dissolved oxygen concentrations. Periodic drying of ponds, an established practice for many aquaculturists, was found to remove ammonia from the ponds and renew the ability of the pond to reach high levels of production.

### **Water Temperature Models (Table 9)**

Water temperature models may be (1) theoretical (based on heat energy balance, see Fig. 11) or (2) empirical (based on historical air or water temperature records and regression analysis). Temperature varies temporally with diurnal and seasonal components. This temporal variability approximates a sine or cosine curve. To control water temperature in ponds several strategies can be followed. Proper selection of the site is the most obvious one and sets the ambient temperature range. Pond depth can also be designed to stabilize water temperature fluctuations compared to air temperature fluctuations. Mixing of two or more sources of water of different temperatures is another technique. Circulation of water in the pond is important to prevent temperature gradients and reduce spatial variability.

Table 9. Models of pond water temperature.

	MODELS			
	1	2	3	4
<b>CATEGORIES</b>				
Intended use	R	R	R	R
System	P	P	P	P
Relevance	G	D	G	G
# parameters			4	4
Type	E	E	T	T
<b>VARIABLES</b>				
(endogenous)				
Temporal flux	D	S	S	S
(control)				
Water exchange	X	X		
Water mixing				
(processes)				
Solar radiation	X	X		
Convection	X	X		
Evaporation	X	X		
Precipitation				
Seepage				
(environmental)				
Sunlight	X	X		
Cloud cover				
Air temperature	X	X	X	
Wind speed	X	X		
Humidity	X	X		
Water temperature				X
Day of year			X	X

1. Krant et al. (1982); Krant et al. (1985) 2. Klemetson and Rogers (1985) 3. Cuenco (1982) 4. Hanson (1979); Griffin et al. (1984)

Intended use : R = research  
M = management  
System : F = flow-through system  
P = pond  
R = recirculating system  
H = hatchery  
L = laboratory  
Relevance : G = growout  
H = hatchery or fingerling production  
D = design or site selection  
Type : E = empirical  
T = theoretical  
Temporal flux : D = diurnal  
S = seasonal  
Variables : X = indicates that variable was included in the model

Processes affecting water temperature in the pond are: (1) the amount of solar radiation falling on the pond surface, which depends on the radiation for the particular time of the year and the amount of cloud cover; (2) convective heat transfer, that may add or remove heat from the pond depending on the difference between air and water temperature and the wind speed; (3) evaporative heat loss, which depends on wind speed, water temperature and relative humidity; (4) precipitation and runoff, that usually decrease the pond temperature as rainfall is colder than the pond water; (5) seepage/infiltration, but these can be considered negligible for ponds with appropriate soils for water retention.

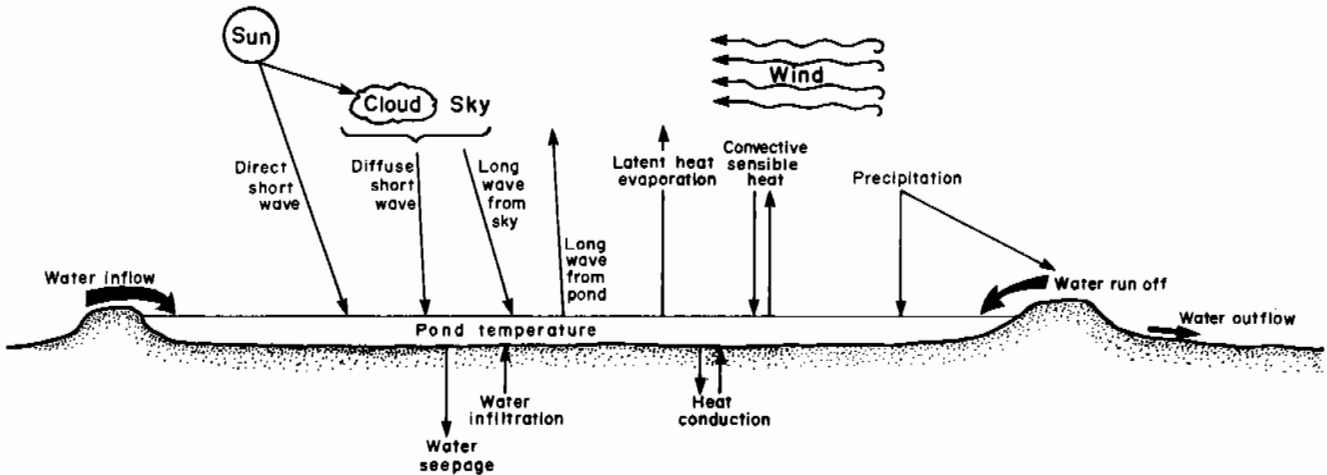


Fig. 11. A conceptual model of pond water temperature based on heat energy principles.

### Salinity Model

Salinity is important in brackishwater and marine aquaculture. Krant et al. (1982) developed a mathematical model of pond salinity based on mass balance, that considered evaporation, precipitation and water exchange. Seepage was considered negligible.

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# **Appendix: An Example of the Potential Application of Modeling in Aquaculture: Production of the Nile tilapia, *Oreochromis niloticus* in Rice Fields\***

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## **Abstract**

The use of modeling techniques to analyze aquaculture systems is demonstrated with examples of two modeling approaches to the production of Nile tilapia (*Oreochromis niloticus*) in rice fields.

The first approach is empirical and uses the multiple linear regression technique to analyze accumulated data from previous experiments. Model results showed the effects of several inputs (fingerlings, fertilizers, pesticides) on fish yield and growth rates.

The second approach is theoretical. A conceptual model, based on available information about the processes underlying tilapia production in rice fields, is constructed and visualized using relational diagrams. Translation of the diagrams into mathematical equations is demonstrated and possibilities for theoretical evaluation of management options are indicated.

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## Introduction

Fish production in rice-based farming systems is now increasing after a decline of the practice during the 1960s and 1970s. In China, Indonesia and Thailand the number of farmers and the culture area have increased during the last five years (Lightfoot et al., in press).

In the Philippines, fish production from rice fields is still largely experimental. The culture system aims at producing consumption-sized Nile tilapia, *Oreochromis niloticus* (a well-accepted freshwater species in the Philippines) in concurrent culture with lowland irrigated rice (*Oryza sativa*). Fingerlings are stocked between one and two weeks after the transplanting of the rice seedlings and harvested one week before the rice harvest. With a modern rice variety like IR64, this results in a fish culture period of about 70 days. The water depth is maintained at between 5 and 15 cm during that period. A shallow trench fish refuge (40-50 cm deep, 1 m wide) is constructed during land preparation for periods of low water level. Apart from this, rice culture is practiced as usual, although the application of pesticides needs special attention to prevent fish poisoning (some formulations are avoided and spraying is done cautiously).

Although trials with this system have been conducted since 1974, only a few farmers in the Philippines have adopted the practice. Apart from important socioeconomic constraints, the main technical/biological problems are: (1) slow growth rate of the tilapias in the rice field, resulting in a need for stocking large fingerlings to obtain market-sized fish; and (2) great variation in fish survival, often resulting in low fish yields. In on-station trials at the Freshwater Aquaculture Center (FAC) of Central Luzon State University (CLSU), tilapia survival varied between 25 and 100%. In order to reach an average size of 50 g at rice harvest, the stocking weight of the fish had to be 20-25 g.

Possible explanations for the slow growth and poor survival are: (1) inadequate food for the tilapia in the rice field; (2) adverse environmental conditions (e.g., high afternoon temperatures, low early morning dissolved oxygen, low water levels); (3) adverse effects of pesticides.

Investigating the validity of these explanations could be done by designing and implementing experiments with different kinds and dosages of fertilizers, different kinds of supplemental feeds, with intensive water quality monitoring, and with different kinds, dosages and application methods of pesticides. Some of such experiments have been carried out at the FAC, but each can focus on only a few factors influencing fish production. For instance, an experiment on the effect of fertilization will use only one kind of pest management. Numerous experiments would be required to investigate all important factors and their interactions, demanding a lot of research time, facilities and money.

In this paper, two modeling approaches to this problem are discussed. The first approach is empirical and uses a statistical model to analyze data from previous experiments with the objective of extracting as much information from the available data as possible without doing new experiments. The model reveals the most important factors affecting fish production in this system. Future experiments could focus on these factors, thus making the use of expensive research resources more effective.

The second approach is theoretical. For this, the processes underlying tilapia growth in a rice field have to be identified. Information from previous experiments and from the literature in all related disciplines (e.g., rice agronomy, aquaculture, freshwater ecology, soil science) is used for the construction of a conceptual model, which can be translated into mathematical equations. Simulation of tilapia production with the mathematical model under a wide range of management conditions will improve the understanding of tilapia growth and point the way to the most promising strategies for improving tilapia production. Again, this can lead to a more efficient way of doing experiments.

## First Approach: Multiple Linear Regression Analysis of Data from Previous Experiments

*Method.* Fifty experiments on integrated rice-fish culture were done at the FAC between 1974 and 1983. Fifteen of these were selected for statistical analysis (van Dam, in press). Although the 15 experiments focused on different factors influencing fish production, they had a lot in common: they all dealt with concurrent culture of Nile tilapia and rice and a complete set of information on the inputs used in the experiments was available. An attempt was made to relate the outputs of the system (tilapia yield, growth rate and survival; rice yield) to the inputs (fertilizers, fingerlings, pesticides). Added to this was information about the climatic conditions during the experiments as these might have effected fish and rice production. Instead of evaluating one experiment at a time, input and output of all 15 experiments were integrated into one model for every output variable.

Multiple linear regression was used to analyze the data. The model is:

$$Y = a + b_1X_1 + b_2X_2 + \dots + b_kX_k + \epsilon$$

with

Y	:	dependent variable (in this case the output variables)
$X_{1..k}$	:	independent or explanatory variables (in this case the inputs)
a	:	constant
$b_{1..k}$	:	partial regression coefficients
$\epsilon$	:	residual

With data for Y and the Xs, estimations for a and the bs can be calculated and interpreted. An important coefficient is the coefficient of multiple determination ( $R^2$ ), which indicates the amount of variation in the dependent variable (Y) that is explained by the independent variables (Xs). For example, if  $R^2 = 0.60$ , 40 % of the variation in Y is unexplained. Detailed discussions of the technique can be found elsewhere (Yamane 1973; Snedecor and Cochran 1980).

*Results.* Appendix Table 1 gives a summary of the results. Independent variables were included in a model only when their b was significant at least at  $\alpha = 5\%$ . From the model equations some inferences about tilapia growth can be made. Nitrogen application had a positive effect on fish production, but phosphorous had a strong negative effect. No explanation for this

Appendix Table 1. Three multiple regression models for gross Nile tilapia (*Oreochromis niloticus*) yield in kg/ha (GY), tilapia recovery percentage (REC) and tilapia growth rate in g/day (GR). All models were significant at the 0.1% level and all regression coefficients (b's) were significant at least at  $\alpha = 5\%$  (after van Dam, in press). Independent variables: PER = length of the culture period (days); SD = stocking density (fish/ha); SS = stocking size (g); N = basal nitrogen application (kg/ha); P = basal phosphorous application (kg/ha); I = no. of insecticide sprays; H = yes/no herbicide application; T = air temperature ( $^{\circ}$ C).  $R^2$  is the coefficient of multiple determination. Standard errors of the coefficients are in brackets.

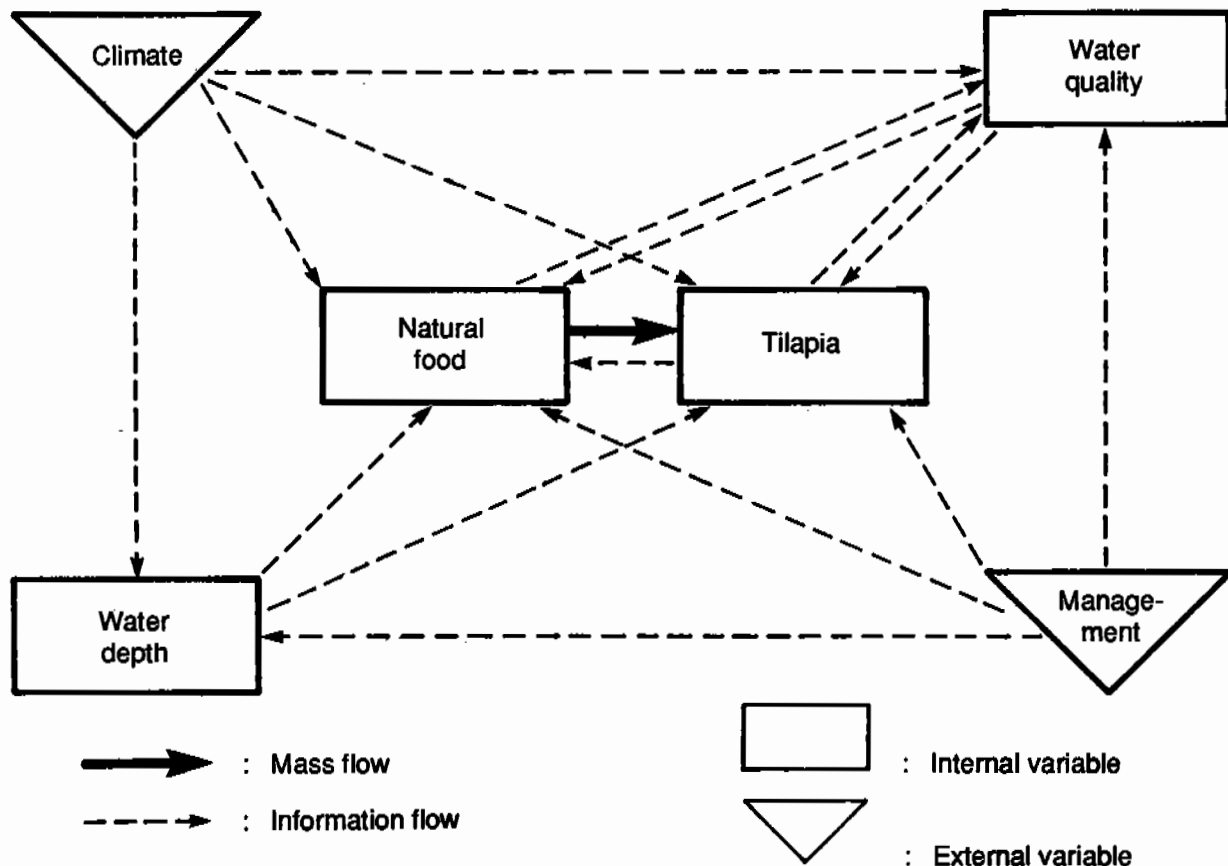
GY =	-1022.83	+	1.57*PER	+	0.012*SD	+	3.78*SS	+	1.74*N	-	2.05*P	-	10.03*I	+	26.97*T
			(0.225)		(0.002)		(0.432)		(0.283)		(0.318)		(4.15)		(3.21)
( $R^2 =$	0.657)														
REC =	-174.75	+	0.393*PER	-	0.0043*SD	+	0.894*SS	+	0.749*N	-	0.586*P	-	19.68*H	+	5.79*T
			(0.112)		(0.000821)		(0.202)		(0.130)		(0.133)		(5.98)		(1.39)
( $R^2 =$	0.447)														
GR =	0.389			-	0.0037*SS	+	0.0019*N	-	0.0020*P	-	0.0535*H	-	0.0413*I		
					(0.0010)		(0.00062)		(0.00065)		(0.0251)		(0.0082)		
( $R^2 =$	0.335)														

was conceived and this might be an interesting subject for further research. Another interesting result was that insecticide applications seemed to affect fish growth rate but not fish recovery (the variable for insecticide applications may not be significant in the recovery model), which is an indication of indirect effects of insecticides on the fish (e.g., by affecting fish food organisms), rather than a direct effect on fish survival. It can also be seen that the  $R^2$  of some models is low, indicating that a lot of information on the processes involved is still missing.

The models are purely descriptive. They were not validated with independently derived data and therefore cannot be used for predictive purposes. The power of the models is that they integrate and summarize the available information on the subject of tilapia growth in rice fields which leads to new ideas and hypotheses. Analysis of separate experiments could not cover the whole array of variables involved.

### Second Approach: Dynamic Simulation of the Rice Field Ecosystem

*Model objectives.* A comprehensive theoretical model of tilapia production in rice fields involves a large number of processes. A rough conceptual model is presented in Appendix Fig. 1. Tilapia biomass is based on the production of natural food in the rice field. The conversion of natural food biomass into tilapia biomass is indicated by the solid arrow. Tilapia biomass in its turn influences the natural food (e.g., grazing affects food density, tilapia excreta provide nutrients).



Appendix Fig. 1. Rough conceptual model of tilapia production in rice fields. Natural food is converted into tilapia biomass. This process is controlled by climate, water depth, water quality and management variables (see also Appendix Table 2).

A number of variables affect this process. In this first diagram, they are grouped into four categories: climate, water quality, water depth and management. Triangles in the diagram indicate external variables, uninfluenced by the other variables in the model (which is illustrated by the fact that all arrows point away from the triangles).

All triangles and boxes in the model represent a number of variables that have to be specified in a more detailed version of the model. Appendix Table 2 lists the possible variables. It can be seen that the number of variables in a comprehensive model is very big, which easily confuses the modeler and may distract attention from the original modeling objective. It is better to reduce the scope of the model to include only the part of the system that is relevant to the modeling objective. Later on, other parts can be modeled and united into a more comprehensive model.

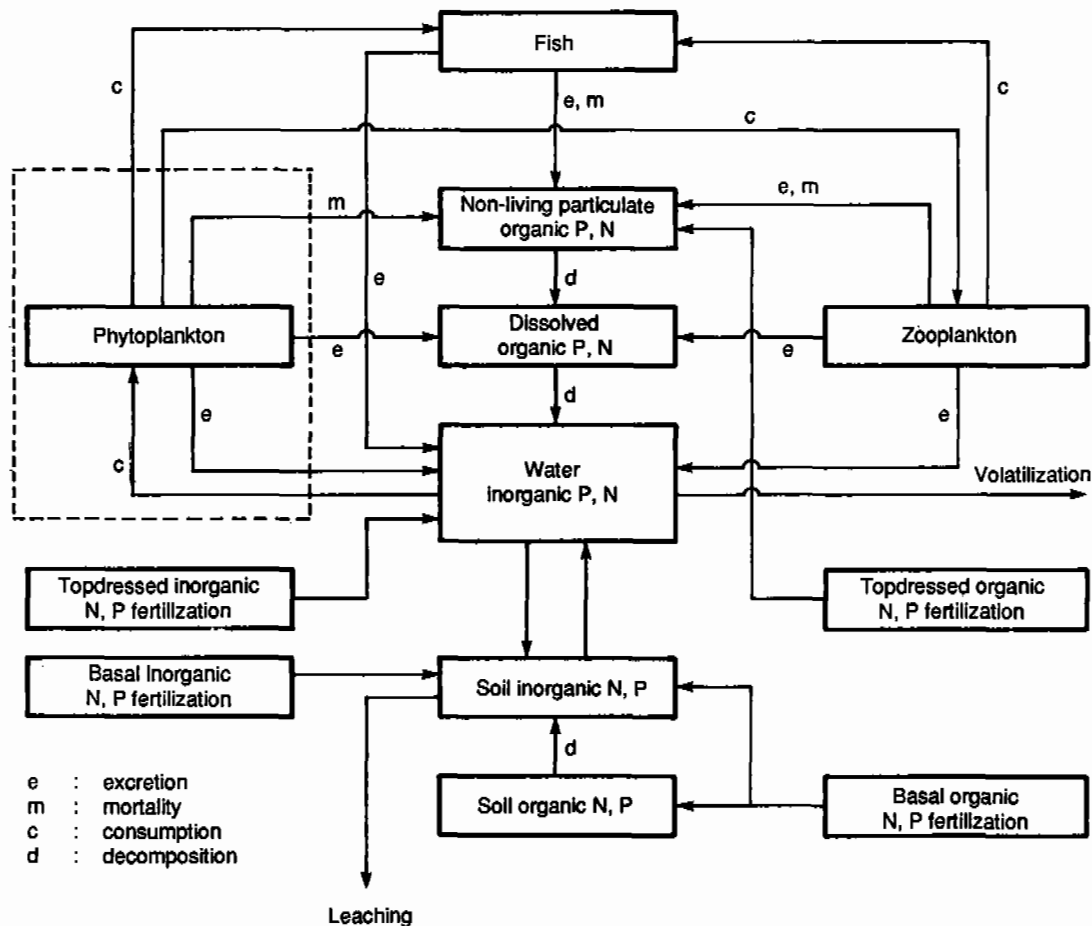
Appendix Table 2. Possible variables for a comprehensive theoretical model of a rice-based fish culture system (see Appendix Fig. 1).

Group	Variables
Climate	air temperature, wind speed, evaporation, daily sunshine duration, rainfall, radiation
Water depth	seepage, percolation, drainage, irrigation, evapotranspiration, rainfall
Water quality	temperature, dissolved oxygen, pH, total ammonia, unionized ammonia, nitrite, nitrate, particulate organic nitrogen, dissolved organic nitrogen, orthophosphate, dissolved organic phosphorus, particulate organic phosphorus, carbon dioxide, alkalinity, hardness
Management	irrigation pattern, fertilization (kind, rate and method), feeding (kind, rate and method), fish stocking size and density, pest management, rice variety, planting method
Natural food	benthic organisms (insect larvae, worms, molluscs), phytoplankton (several species), zooplankton (several species), insects, macrophytes development and mortality characteristics of each food type; size distribution
Tilapia	number, average size, size distribution, mortality, feeding behavior, sex ratio, number of fingerlings, age/size at maturity

In the introduction to this case study, three possible explanations for low tilapia production in rice fields were given. Here, the focus will be on the possibility that the natural food in the rice field environment is not suitable for adult Nile tilapia, at least not for free-breeding, mixed sex populations. Nile tilapia is generally considered to be a microphagous omnivore relying heavily on filter feeding with preferences for phytoplankton and other microorganisms (Bowen 1982; Colman and Edwards 1987). It seems reasonable to assume that the natural fish food in rice fields, given their shallow water depth, is dominated by benthic organisms. This would make the rice field environment more suitable for bottom feeders like the common carp (*Cyprinus carpio*). These assumptions are supported by the fact that successful rice-fish systems in Indonesia produce mainly common carp (Lightfoot et al., in press).

Improving tilapia production in rice fields should thus focus on enhancing the production of suitable natural food organisms for tilapia. The model presented here will deal with phytoplankton in particular. The objectives of the model are: (1) to investigate whether the environmental conditions in rice fields are suitable for phytoplankton production; (2) to formulate strategies for improvement of phytoplankton productivity in rice fields.

*Conceptual model.* The development of phytoplankton biomass is governed by five processes: photosynthesis, grazing, excretion, respiration and mortality. Appendix Fig. 2 presents a diagram (modified from Rose et al. 1988) showing the mass flow of nutrients, phytoplankton, zooplankton and fish. Only nitrogen and phosphorous are included in the diagram as they are assumed to be the limiting nutrients in the system (this may be not realistic as carbon could also be important). Nitrogen and phosphorous enter the system mainly by way of fertilizer applications, if one ignores nitrogen fixation by rice field biota. Incorporation of fertilizers in the soil during land preparation adds the nutrients to the pool of soil nutrients



Appendix Fig. 2. Mass flow diagram of nutrients and biota in a rice-fish system. The phytoplankton part (indicated by dotted line) is detailed further in Appendix Fig. 3. For explanation, see text (modified from Rose et al. 1988).

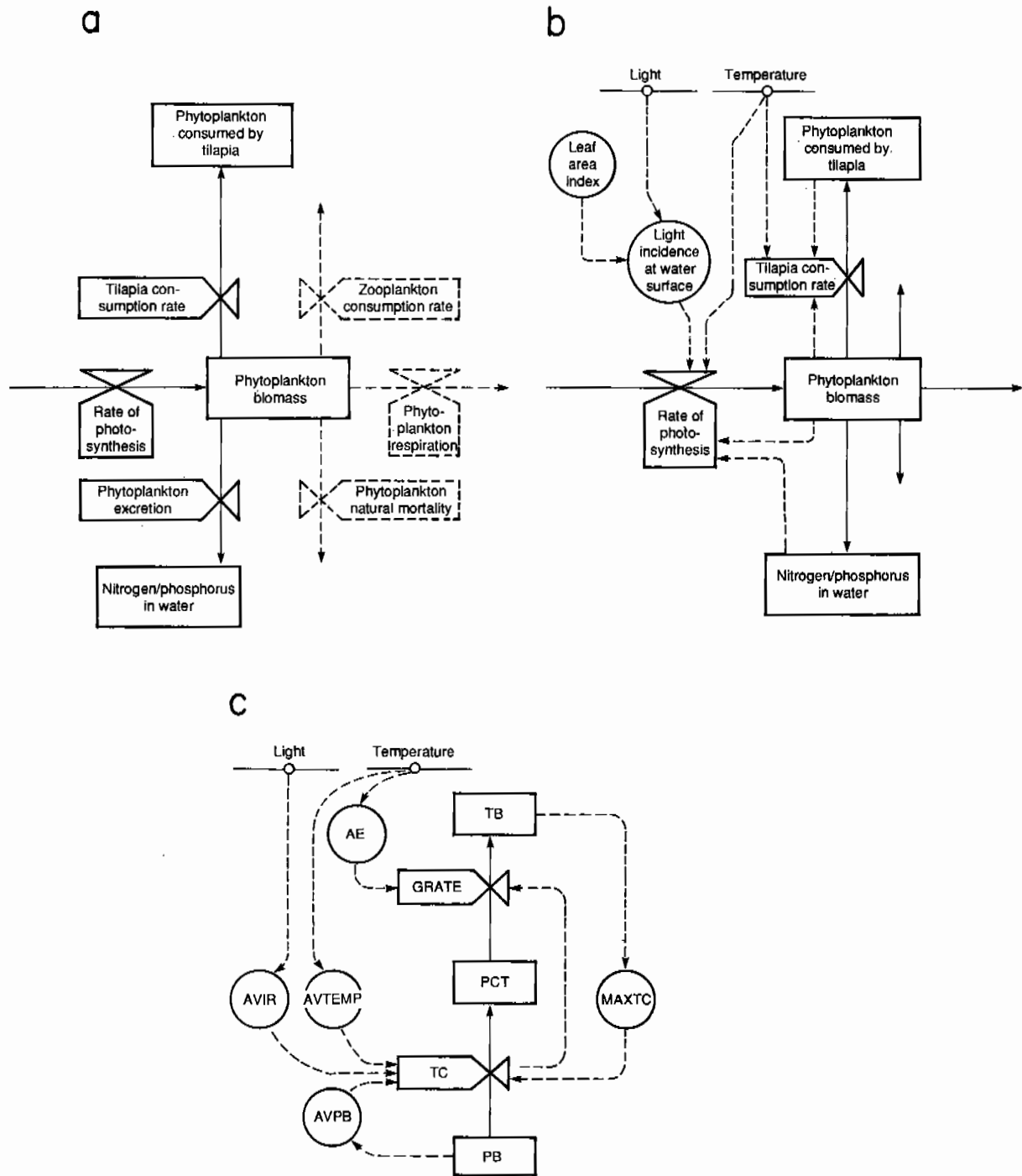
(organic or inorganic) and top dressing leads to increased concentrations of nutrients in the water. The processes of nutrient loading from the soil and absorption by the soil are included in the model. Inorganic nutrients may be lost by leaching from the soil or volatilization from the water. Of course, a lot of nutrients are absorbed by the rice crop.

In the water, particulate organic matter is decomposed into dissolved organic and inorganic forms. Phytoplankton utilizes the inorganic nutrients for its development. Phytoplankton is consumed by fish and zooplankton. All organisms contribute to the inorganic and organic nutrient pools by excretion, respiration and mortality.

This mass flow model is still not detailed enough for the next modelling step: translation into mathematical equations. To demonstrate the technique, the phytoplankton part of Appendix Fig. 2 is now considered in detail. The processes affecting the biomass of phytoplankton are: (1) photosynthesis; (2) consumption by fish; (3) consumption by zooplankton; (4) excretion; (5) respiration; and (6) natural mortality. These processes are all rate variables: they express the change in phytoplankton biomass with time. Photosynthesis is the only positive rate, contributing to development, while all other rates are negative. The sum of the rates is equal to the actual change in phytoplankton biomass.

Appendix Fig. 3a is a more detailed diagram using Forrester's (1961) symbols. Note the distinction between the *rate* variables (processes) and *state* variables (biomasses). This diagram still lacks the relationships between the variables and the effects of external factors. For the photosynthetic rate and the rate of phytoplankton consumption by the fish, these relationships are now discussed.





Appendix Fig. 3. Development of relational diagram for a dynamic theoretical model of tilapia production in rice fields. Fig. a: detail of phytoplankton-related state- and rate-variables using Forrester's (1961) notation; Fig. b: as fig. a, with auxiliary variables. Dotted arrows indicate the flow of information; Fig. c: Conversion of phytoplankton into tilapia biomass. Diagram contains all auxiliary variables from mathematical equations (see text).

The rate of photosynthesis is dependent on the concentration of inorganic nutrients, the irradiance, phytoplankton biomass and temperature. These relationships are indicated in Appendix Fig. 3b with dotted arrows. The nutrient with the lowest concentration with respect to what is required will limit the photosynthetic rate. Light incidence can be calculated from irradiance or sunshine data and the Leaf Area Index of the rice crop. As the rice canopy grows, less light will penetrate to the water surface. In the water, light is extinguished because of water depth and turbidity. Phytoplankton has an optimum temperature for growth, below and above which growth rate declines.

The consumption rate of phytoplankton by fish is a function of the species and size of the fish (preference for certain types and sizes of food organisms), the concentration of phytoplankton (below a certain density the feeding stops; with increasing phytoplankton density, the fish ingests more phytoplankton per unit time until the maximum consumption is reached), the light intensity (*O. niloticus* has a diurnal feeding rhythm) and temperature (see Appendix Fig. 3b).

Similarly, diagrams can be constructed for all rate and state variables. Note that the mass flow diagram in Appendix Fig. 2 contains only state variables. Some of these have to be split when a more detailed diagram is drawn (nitrogen and phosphorous have to be separated; "inorganic" nutrients can be subdivided into, e.g., ammonia, nitrite, nitrate, etc.).

**Mathematical model and parametrization.** The next step is the translation of the conceptual model into mathematical equations. One possibility is to express rate variables as the product of a maximum rate and a number of limiting factors. For the consumption of phytoplankton by the fish, this works as follows.

Suppose the maximum consumption rate of phytoplankton by fish is the auxiliary variable MAXTC (in g dry weight phytoplankton per day). Then the actual consumption rate TC (same units) can be expressed as:

$$TC = MAXTC \cdot AVIR \cdot AVTEMP \cdot AVPB$$

where:

- AVIR : an auxiliary variable that regulates feeding activity dependent on the dark/light cycle. AVIR=0 during darkness and AVIR=1 during the daytime;
- AVTEMP : an auxiliary variable relating feeding activity to temperature. At the optimum temperature for feeding, TC = MAXTC and AVTEMP = 1. Below and above this temperature, AVTEMP < 1;
- AVPB : an auxiliary variable relating feeding activity to phytoplankton density. AVPB=0 below the density at which fish feeding ceases.

MAXTC is dependent on fish size. Multiplying the consumption rate (TC) with the assimilation efficiency (AE) gives the rate of tilapia biomass increase (GRATE):

$$GRATE = AE \cdot TC$$

Integration of this rate over time gives the state variable for tilapia biomass (TB):

$$TB = \int_{t_1}^{t_2} GRATE \cdot dt$$

These auxiliary variables can be entered into the diagram resulting in Appendix Fig. 3c.

Because many rate equations in dynamic models cannot be integrated analytically, numerical integration methods are applied to calculate the values of integrals. The values of the state variables are calculated at any point in time from the rate variables. For the starting point  $t_0$ , initial values for all state variables are fed into the model. Starting from  $t_0$ , the state variables

change according to their rates. At  $t_1 = t_0 + \text{DEL T}$ , new values for the state variables are calculated as:

$$S(t_1) = S(t_0) + (\Delta S/\Delta t) \cdot \text{DEL T}$$

where:  $S(t)$  = state variables at  $t$ ; DELT = time step between two calculations; and  $\Delta S/\Delta t$  = rate of change in  $S$ .

The values at  $t_1$  serve as the basis for the calculations at  $t_2 = t_1 + \text{DEL T}$ . During DELT, the rates are assumed to be constant whereas in continuous simulation (and in reality, of course) the rates change continuously. Numerical integration can therefore lead to under- or overestimation of the state variables if the time step or the method of integration are wrongly chosen (de Wit and Goudriaan 1978).

After translation of all relationships into mathematics, parameter values and relationships for auxiliary variables are defined. Information can be obtained from the literature and from experimental data. Parameters and auxiliary variables that are biologically interpretable should give no problems in this respect. In the example above, AVIR, AVTEMP and AVPB are biologically meaningful and values for them can be found (see e.g., Caulton 1982).

*Application of the model.* After proper validation and testing of the model, the model can calculate the effects of all kinds of management strategies on phytoplankton production (refer back to Appendix Fig. 2), like:

- the effects of different kinds of fertilizers on plankton production (e.g., inorganic fertilizers vs. organic fertilizers);
- the effects of different methods of applying fertilizers (e.g., soil incorporation during land preparation vs. broadcasting);
- the effect of different rice varieties with different LAI characteristics;
- the effect of different planting methods (e.g., border method of rice planting which may allow more light to penetrate into the water);
- the effect of fish size, as this may affect the consumption rates (MAXTC) and assimilation efficiency (AE).

The model could be used to investigate the often observed phenomenon that rice yields in rice-fish systems are higher than in comparable rice monoculture. Nitrogen losses in rice-fish fields may be smaller because fish eat phytoplankton, causing pH fluctuations to be less extreme and therefore reducing ammonia volatilization.

The model could be refined and extended. Phytoplankton and zooplankton may be split into several different genera or even species groups. Characteristics of many species, like temperature and light optima and nutrient limitations, are known from ecological studies. It is possible that the solution to some of the tilapia production problems in rice fields can be found from recognizing that certain plankton species are favored by the rice environment and others are inhibited. Rice fields may be distinctly different from fishponds in this respect because of their low, strongly fluctuating water levels. This instability may interrupt phytoplankton development in the water column.

An interesting possibility is the modeling of nitrogen fixation by blue-green algae or by *Azolla* sp. With the model, estimations could be made of the potential reduction in fertilizer use when nitrogen-binding organisms are included in the system. Management options to maximize utilization of biological  $N_2$ -fixation could be evaluated (Grant et al. 1986).

Another refinement would be the inclusion of bacteria in the model. The absence of bacteria from the current model is not very realistic, especially now that detritus with associated bacteria is considered a major nutrient source for Nile tilapia (Pullin 1987). In addition, benthic organisms could be included to compare the nutrient dynamics when a fish species with a completely different feeding behavior (like common carp, *Cyprinus carpio*) is introduced.

The role of weeds could be investigated with the model. Weed growth can absorb considerable amounts of nutrients from the soil, leading to reductions in rice yield. How do weeds compete with phytoplankton for nutrients? Likewise, epiphyton should be considered as it may be an important component in the nutrient cycle.

Other water quality parameters could be included in the model. Dissolved oxygen levels in the water can be calculated at any point in time from the difference between oxygen production by phytoplankton and macrophytes and diffusion through the water surface on the one hand, and oxygen consumption by heterotrophic respiration on the other hand.

It is not clear whether enough suitable experimental data about the ecology of rice-fish systems are available to parametrize and validate the kind of model proposed. As most researchers working on the rice environment are specialized in a specific discipline, it would require an interdisciplinary effort to compile the information available to date. In this sense, a theoretical model provides an excellent conceptual framework for the synthesis of available knowledge. Interesting conceptual models of the rice ecosystem are given by Roger (1989).

Theoretical models of agriculture systems are, compared to aquaculture models, relatively well developed. Numerous aspects of cropping systems, such as water use, soil processes, micrometeorology, pest management and crop production have been modelled successfully (de Wit and Goudriaan 1978; van Keulen and Wolf 1986; Penning de Vries et al. 1988) which contributed tremendously to better understanding and management. Aquaculture systems modeling should benefit from that experience, both in terms of theory development and modeling techniques.

The sequence of steps in this example is described in more detail in a number of modeling studies. For examples of theoretical aquaculture system models see: Cuenco et al. (1985a, 1985b, 1985c); Piedrahita et al. (1983); Piedrahita et al. (1984); Svirezhev et al. (1984); Piedrahita (1986, 1988); Machiels and Henken (1986; 1987); Machiels and van Dam (1987); Machiels (1987). More general models of freshwater ecosystems are described in, e.g., LeCren and Lowe-McConnell (1980).

## Conclusions

The advantage of theoretical models over statistical models is their stronger ability to analyze the processes underlying the system. Where statistical models merely show to what extent variables co-vary (which confirms or refutes the modeler's hypothesis, but proves nothing about the underlying processes), theoretical models allow the modeler to simulate the processes according to a hypothesis, compare simulated data with real data, review both hypothesis and model, and try again.

The structure of the theoretical model is determined by the modeler. Information from the literature, the objective of the model and the modeler's views determine the model structure. This is a fundamental difference with statistical models. However, the freedom of the modeler to decide about model structure can be both a blessing and a burden. If well developed ideas about the structure of the system and the underlying mechanisms exist, the modeler may feel confident enough to start constructing a theoretical model. On the other hand, if the information about a system consists of a lot of unstructured data, the rigor of a statistical model may be a better option and theoretical modeling can be considered later.

The predictive power of theoretical models is generally stronger than that of statistical models. The latter may not be extrapolated beyond the range of data that they were constructed with, whereas theoretical models can be defined and used for a wide range of environments, provided that the models are validated for these ranges before use. For example, the multiple regression models in this paper describe a rice-fish system with *O. niloticus* as the fish species and with only inorganic fertilization, in a Philippine environment. The applicability of this to Indonesian rice-fish systems with *C. carpio* is negligible, whereas the theoretical model can be adjusted relatively easily because the ecological processes underlying that model are basically identical for the two locations.

A final advantage of theoretical models is the possibility to model the time aspect of processes (so-called dynamic modeling). As time is important in most farming systems, most theoretical aquaculture models will be of the dynamic type.

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