The Relationship Between Monitoring and Modeling of Fish Populations

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15 The Relationship Between Monitoring and Modeling of Fish Populations

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Introduction

How one defines the relationship between population models and biological-monitoring programs depends on one's perspective. Some would define monitoring as collecting data for use in models. Others would define modeling as a method of manipulating and stretching the usefulness of field data. Models and monitoring programs cannot be separated; one complements the other.

Monitoring of fish populations involves measuring and recording the magnitude of biological variables over time. Types of variables measured depend on the model used, which in turn depends on the objectives of the monitoring program. In general, monitoring is conducted to detect changes in variables, and the model helps determine the significance of the changes.

The purpose of this paper is to discuss fish population models and their role in the biological monitoring of fisheries.

Definition of a Model

Models are defined as abstractions of reality. The form of abstraction can vary. Lackey, Powers, and Zuboy (1975) identified four categories of models: (1) verbal, such as a written description; (2) graphical, such as a picture or diagram; (3) physical, such as a miniature plastic replica; and (4) mathematical, such as a differential equation.

Many types of models can represent the same phenomenon. For example, Figures 15-1 and 15-2 are both graphical models of a stream trout fishery, and the following equation is a mathematical representation:

$$N_t = N_0 e^{-Z_t}$$

where:
N_t = number of trout in population at time t
N_0 = number of trout in population at $t = 0$
Z = instantaneous mortality rate
e = natural logarithm

Reviewers of this chapter: William C. Latta and James C. Schneider

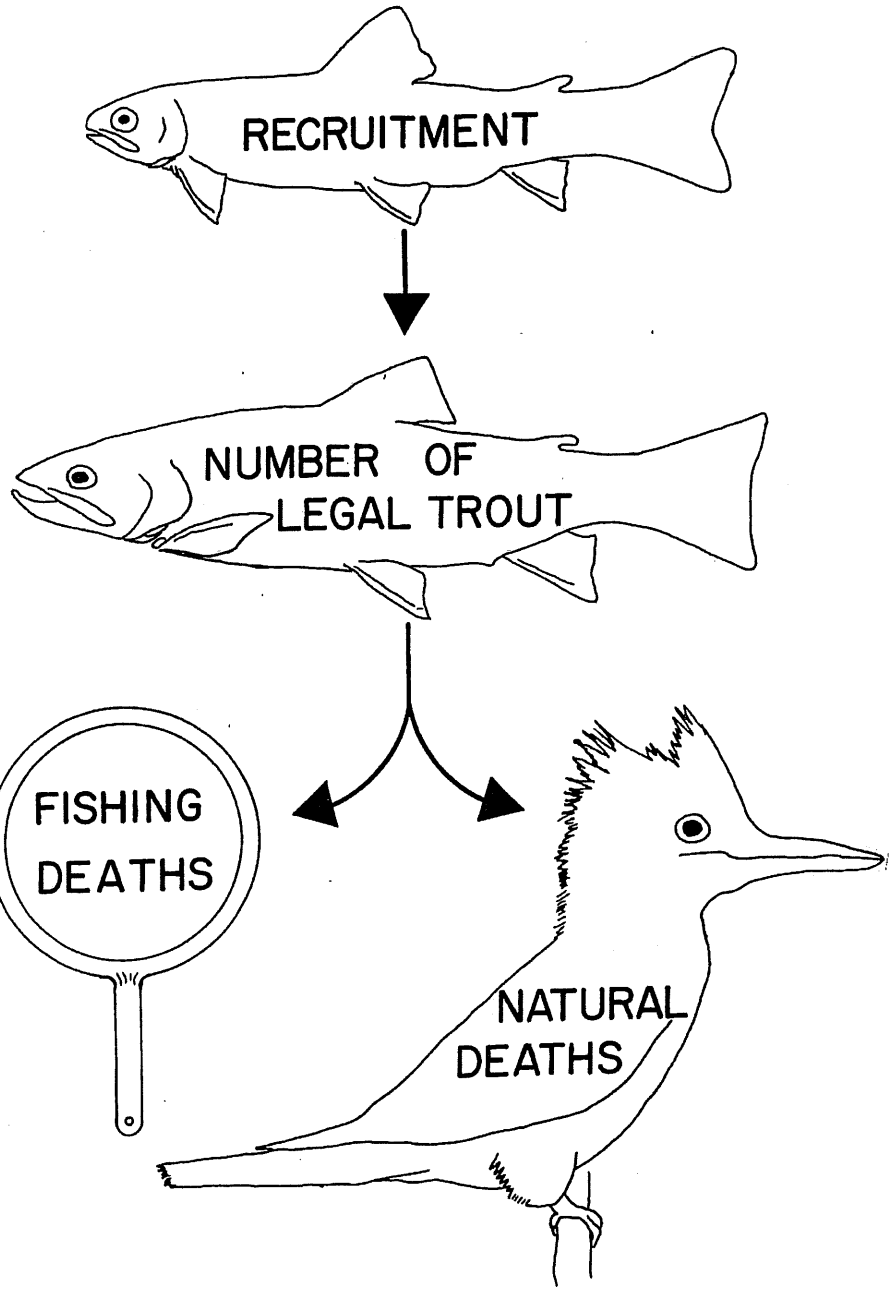
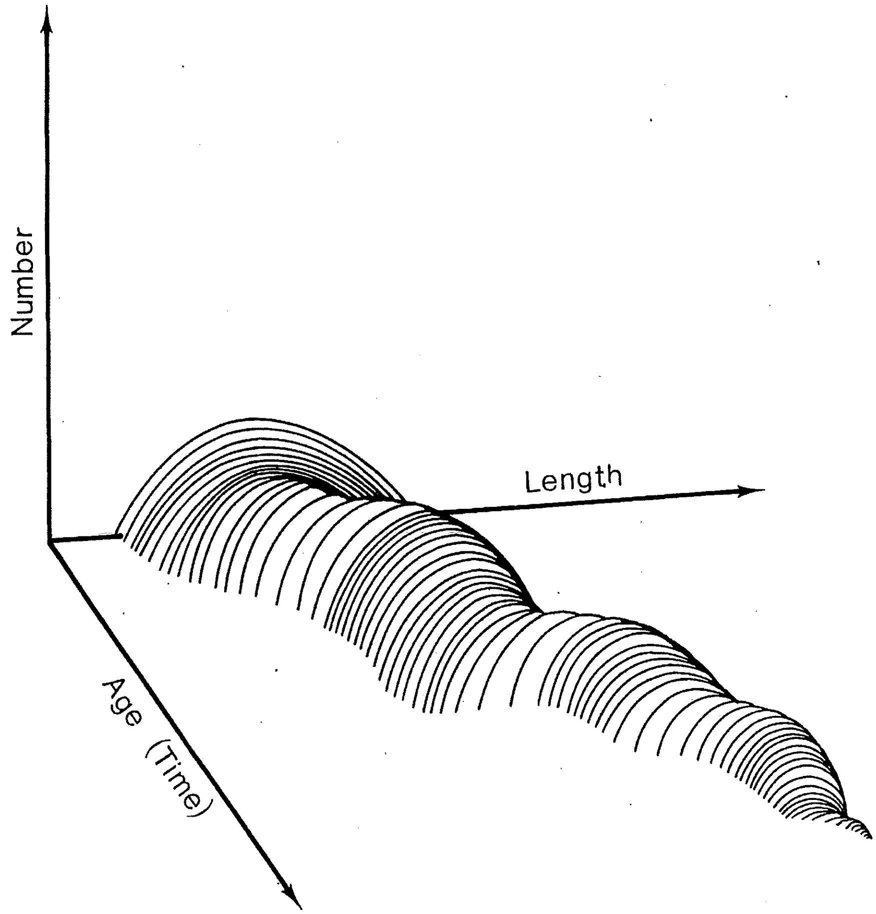


Figure 15-1. Graphical model (pictorial) of a stream-trout fishery.



Source: Clark, R.D., Jr.; G.R. Alexander; and H. Gowing. 1979a. Mathematical Description of Trout Stream Fisheries. Michigan Department of Natural Resources, Fish Research Report 1869.

Figure 15-2. Graphical model (diagrammatic) of changes in number and length of a trout cohort over time.

We will direct our comments toward population models of the mathematical type.

Potential Benefits of Population Models

Many benefits have been attributed to the application of systems analysis, mathematics, and computer science to fisheries-management problems

(Paulik 1972a, 1972b; Saila 1972; Saila and Hess 1975; Titlow and Lackey 1972; Lackey 1975a, 1975b; Lackey, Powers, and Zuboy 1975; Jester et al. 1977; Lackey and Hubert 1978). We will concentrate on two of the most important benefits that can be obtained from using population models in biological monitoring: organization and prediction.

Organization

Use of a model is one of the fundamental concepts in the design of scientific experiments or monitoring programs. Models are recommended to aid in the design of simple analysis of variance (ANOVA) experiments (Hicks 1964); and as experiments become more complex, models become more important. They encourage formal quantitative definition of experimental objectives; they require definition of the major components of the experimental system; and they require definition of the relationships between the major components.

The main reason for advance planning of a monitoring program is to determine how the objectives of the program can be achieved with minimum cost. If a fishery is the object of the monitoring program, then a fish-population model can be just as useful in the design of the program as a statistical model is in the design of an ANOVA experiment. The type of model used defines the data requirements of the program, and thus saves money and other resources by reducing wasted data-collecting and analysis effort.

Models can be useful as vehicles for interpreting data that have been collected. Mortality, growth, and recruitment data are the standard types of information needed for fisheries monitoring and assessment work. Each type can be useful by itself, but population models enhance interpretation of the data by organizing it into a framework for analysis. Models link these vital population statistics to the human benefits that can be derived from a fishery.

Prediction

The major objective of many biological-monitoring programs is to provide quantitative information on which to base management decisions, but the information is of little value unless it is interpreted properly and unless the effects of various management alternatives can be predicted with acceptable levels of confidence. Fish-population models can be helpful in prediction; a population model can be used to predict results of applying various management alternatives to regulate or enhance the fishery.

A population model can help predict the significance of events, such as temperature variations, entrainment of larvae, or environmental pollution, especially if the effects of these events can be described in terms of mortality, growth, or recruitment. For example, Prentice and Dean (1977) presented data from six southern reservoirs which showed that the hatching rate of walleye eggs was related to water temperature at time of fertilization. Clark and Prentice (1978) added the average mid-January water temperatures (which affect the development of eggs in the ovaries) for these reservoirs to these data (table 15-1) and calculated three linear-regression equations for predicting hatching rates: (1) hatching rate versus fertilization temperature ($R^2 = 0.46$); (2) hatching rate versus mid-January temperature ($R^2 = 0.25$); and (3) hatching rate versus fertilization temperature and mid-January temperature ($R^2 = 0.68$). The best equation was the one using both temperatures:

$$H = 1.5119 - (0.067)T' - (0.045)T''$$

where H = hatching rate
T' = water temperature at fertilization
T'' = average mid-January water temperature

Mean hatching rates reported by Prentice and Dean (1977) were in good agreement to those predicted by regression equation (table 15-1).

The regression equation is a model in itself and may be useful for assess-

Table 15-1
Actual Hatching Rates of Walleye Eggs Fertilized at Various Water Temperatures Compared to Hatching Rates Predicted by Multiple-Linear-Regression Model

Reservoir and State	*Temperature (°C)* Fertilization	*Temperature (°C)* Average mid-January	*Hatching Rates* Actual	*Hatching Rates* Predicted
Meredith, Tx.	9.2	3.0	0.765	0.758
	14.4	3.0	0.558	0.408
Ft. Phantom Hill, Tx.	11.5	5.8	0.744	0.477
Ute, N.M.	11.5	3.0[b]	0.610	0.603
	15.0	3.0[b]	0.217	0.133
O. C. Fisher, Tx.	7.2	8.4[c]	0.564	0.649
	13.0	8.4[c]	0.276	0.133
Canyon, Tx.	7.2	10.7	0.439	0.545
	15.0	10.7	0.026	0.021
Twin Buttes, Tx.	12.2	8.4	0.363	0.313

[a]Regression model uses fertilization temperature and mid-January temperature in home reservoir as independent variables.

[b]Actual mid-January temperature unavailable. Assumed to have same temperature as Meredith Reservoir.

[c]Assumed to have the same winter temperature as Twin Buttes Reservoir because of the close proximity of the two impoundments.

ing temperature-related impacts on walleye fisheries. However, a greater understanding of the significance of warm water temperatures on walleye populations can be obtained when the equation is incorporated into a population model. This was accomplished in a model called WALLEYE which was used to help identify the reservoirs in Texas that were suitable for walleye introductions (Prentice and Clark 1978).

Models in Common Use

Most population models currently used by management agencies address a single species of interest. Multispecies population models and broad-based ecosystem models have been developed (Ivlev 1961; Riffenburgh 1969; Regier and Henderson 1973; Kitchell et al. 1974; Lackey, Powers, and Zuboy 1975; Parrish 1975; Patten 1975; May et al. 1979); but these are relatively new and complex tools that require a large data base and therefore have not yet been used extensively to solve fisheries management problems. The two major types of population models that have long histories of use in fisheries management are surplus-production models (Graham 1935; Schaefer 1954) and dynamic-pool models (Thompson and Bell 1934; Ricker 1944; Beverton and Holt 1957). Both types of models are used primarily to estimate the yield in weight of fish that can be expected from different rates of fishing. Both assume that equilibrium conditions exist in the fishery.

Surplus-Production Models

When detailed data for growth, mortality, and recruitment are not available, a surplus-production model is usually applied to evaluate a fishery. In general, this model relates yield directly to stock abundance. A series of catch-and-effort data is all that is needed.

The mathematical form of the surplus-production model was given by Schaefer (1954) as:

$$\frac{dP}{dt} = kP\,(P\infty - P) - qfP$$

where
P = population biomass
$P\infty$ = maximum biomass population can attain
k = population-growth coefficient
q = catchability coefficient
f = fishing effort

When a steady state is assumed, then

$$\frac{dP}{dt} = 0$$

which means that population biomass can be calculated as

$$P = P\infty - \frac{qf}{k}$$

and yield (Y) as

$$Y = qfP$$

or

$$Y = qf(P\infty - \frac{qf}{k})$$

More complete discussions of the surplus-yield model can be found in tests by Gulland (1974); Everhart, Eipper, and Youngs (1975); Cushing (1975); Ricker (1975); and Lackey and Hubert (1978); and in papers by Sillman (1971) and Jensen (1972, 1973). Also, Pella and Tomlinson (1969) and Fox (1970) presented improved versions of the model that seem to work better for some fisheries. General reviews of the methods for applying the model were given by Gulland (1969) and Ricker (1975).

Dynamic-Pool Model

The biological aspects of a fishery are described in greater detail in a dynamic-pool model. In general, this model describes the fish population in terms of growth, mortality, and recruitment. Mathematically, this task is fairly complicated; but biologically, the approach is intuitive.

Baranov (1918) gave one of the earliest descriptions of a dynamic-pool model, but this model is most often associated with the works of Ricker (1944, 1945) and Beverton and Holt (1957). The general form of the model is:

$$\frac{dY}{dt} = F \cdot W(t) \cdot N(t)$$

where: Y = yield in weight

F = fishing-mortality coefficient

$W(t)$ = mean weight of an individual at time t

$N(t)$ = number of fish at time t

Various mathematical functions can be used to describe $W(t)$ and $N(t)$. Ricker's method was to assume exponential growth and mortality.

$$W_t = W_0 e^{-Gt}$$
$$N_t = N_0 e^{-Zt}$$

where G and Z are the instantaneous growth and mortality rates, respectively. Ricker divided the life cycle into a series of time intervals, within which the assumption of exponential growth and mortality was nearly correct. Total yield was then calculated by summing over the intervals.

Beverton and Holt used time periods corresponding to age groups, and used the von Bertalanffy equation to describe growth. More detailed descriptions of these models can be found in the texts mentioned previously for the surplus-production model.

Recruitment is considered constant in most assessments, and yield is calculated on a per-recruit basis. However, dynamic-pool models with self-regenerating properties have been developed (Ricker 1954; Beverton and Holt 1957). Walters (1969) presented an age-specific version of the model that allows the user to specify any stock-recruitment function that describes the fishery being analyzed.

Both the Beverton and Holt dynamic-pool model and the surplus-production model were developed for commercial-fisheries assessments, but the dynamic-pool model can be adapted for evaluating recreational fisheries also. Ricker's model was originally applied to evaluate minimum size limits for a bluegill population (Ricker 1945), and his model has been used extensively to evaluate minimum size limits for recreational species in Michigan (northern pike - Latta 1972; bluegill - Schneider 1973; largemouth bass-Latta 1974; smallmouth bass - Latta 1975; and walleyes - Schneider 1978).

Clark, Alexander, and Gowing (1979a) developed a dynamic-pool model specifically for recreational fisheries and applied it to brook and brown trout fisheries in Michigan (Clark, Alexander, and Gowing 1979b). The most significant features of this model were its description of the size structure of the population and catch, its direct method of addressing hooking mortality, and its calculation of the catch-and-release frequency of sublegal fish. The model also allowed evaluation of many of the unusual length-limit regulations (for example, an inverted length limit where only fish smaller than the given limit are harvested) that have been proposed to improve the quality of recreational fisheries. This was accomplished by dividing a cohort, N, into two groups: sublegal fish, I, which were subject to natural and hooking mortality; and legal fish, L, which were subject to natural and fishing mortality. Thus,

$$N_{t+1} = L_t e^{-M-H} + L_t e^{-M-F}$$

where:
M = instantaneous natural mortality rate
F = instantaneous fishing mortality rate
H = instantaneous hooking mortality rate

The two groups I_t and L_t were defined by the size limits and the length-frequency distribution of N at time t. That is,

$$I_t = N_t g_t (X')$$
$$L_t = N_t[1 - g_t(X'')]$$

where $g_t(X)$ is the cumulative length-frequency distribution at time t, and X'' is a minimum size limit. The length-frequency distribution can be imitated by any probability-density function that fits the empirical data (for example, log-normal, beta, Weibull, and so on). The parameters of the length-frequency distribution must be recalculated for each time period t to reflect the growth in length of the cohort.

Because of its explicit expression of the biological components of a fishery, the dynamic-pool model can be adapted to solve many fisheries-modeling problems. For example, any environmental impact described in terms of growth, mortality, or recruitment can be evaluated with a dynamic-pool model. Thus, the dynamic-pool model is probably the most powerful tool in common use for modeling fish populations.

One of the problems with the dynamic-pool model, relating directly to monitoring programs, is its detailed data requirements. The data needed are often difficult to collect and almost always expensive. However, fisheries-monitoring programs designed around a dynamic-pool model are well equipped to detect problems occurring in the fishery.

Challenges for the Future

One of the major challenges of the future is to design programs for monitoring fish populations so that stated objectives can be met. This must begin with the development of realistic objectives, a task that is often more difficult than expected. There are many constraints limiting the success of monitoring programs; some objectives, no matter how noble, may be unattainable. Questions that must be considered include: (1) What models apply to the problem? (2) How costly are measurements? (3) How accurate are measurements? (4) How large a difference is to be detected in variables measured? (5) What risk of being incorrect will be tolerated? and (6) How much money is available for the program? These are essentially the same questions that must be addressed when designing any scientific experiment. It should be noted that when these questions are appropriately answered, the usual result is the adoption of the simplest model that can meet the objective. In this way, management becomes more efficient.

The final challenge is to improve the precision of fisheries data by developing new tools and techniques of data collection. Large variances are associated with most biological field data, and even when population models are theoretically perfect, large variances on model parameters and input serve as constraints that limit the usefulness of models as predictive tools.

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