

A PERSONAL RETROSPECT OF THE HISTORY OF FISHERIES MODELLING

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Introduction

In this paper fisheries modelling is defined broadly as the application of mathematical techniques to quantify any aspect of the size or structure of a fish population or of the harvesting processes applied to it. It may include features of the individual fish (e.g. growth), or of their populations (e.g. natural or fishing mortality), or of the fishery (e.g. the fishing effort). Models may include both simple functional relationships (e.g. that between length and weight), and very complex ones (such as those describing the effects of the amount of fishing on the size and age-structure of a fish population, or the role of economic and social factors in determining the amount of fishing).

Modelling in this sense has long been recognised as an essential contribution to establishing a rational basis for the management of the fisheries.

A broad distinction can be made between use of models for *estimation*, in which estimated values of parameters or variables are obtained by analytical or numerical solution of implicit equations, and *simulation*, in which the behaviour of a variable, such as a fish population, is explored in its response to changes in external factors. Both models are widely used in fisheries studies.

This paper traces some of the main stages in the evolution of fisheries modelling, and examines some of the factors which have determined

the speed and direction of these developments. It draws attention to some of the principal advances in modelling techniques and their applications which seem to me to constitute landmarks in this development. In identifying particular landmarks I am presenting a personal reaction and not attempting in the limited time available to undertake a comprehensive review of the whole history of fisheries modelling.

An indication of the way in which the rate of activity in mathematical applications to fisheries has changed is given by Figure 1. This shows the number of publications in successive 5-year periods which are cited by three of the principal reviews of fisheries population dynamics (Beverton and Holt 1957; Ricker 1975; Megrey 1989).

Each series is truncated at the end by the date of the publication but they show some common fluctuations within the generally increasing overall trend. Particularly interesting are the checks during the two World Wars and the following bursts of activity. The latter were probably stimulated by the opportunities the wars provided for the study of the effects of major periods of almost complete cessation of fishing in many areas.

These wars have been fittingly described as the First and Second Great Fishing Experiments (Smith 1988).

After 1950, development in structure and use of models proceeded fairly continuously,

although the rate of progress varied from time to time and was influenced by changes in the opportunities for and demand for such studies and by the evolution of aids to calculation.

The following paragraphs describe some of the principal events in the main periods which can be identified in the development of fisheries modelling.

The beginnings

The present is an appropriate time to discuss the history of fisheries modelling since it is now about one hundred years since fisheries began to be considered in quantitative terms. In the later 1800s there was serious debate as to whether fishing could affect the size of fish stocks and as late as 1883 the eminent biologist T. H. Huxley could say "I believe ... that probably all the great fisheries are inexhaustible: that is to say nothing we do seriously affects the numbers of fish ... any attempt to regulate these fisheries seems ... to be useless." (Huxley 1884). Nevertheless realisation of the need to measure the size of fish stocks developed and soon Petersen (1896) estimated the size of a fish stock using a model which assumed that marked fish became randomly distributed in the population.

The first attempt to model the effect of catching on a fish population which recognised that natural and fishing mortality took place in parallel, was by Baranov (1918) who wrote the numerical yield equation which in modern notation is $C = NF(1 - \exp(-Z))/Z$, where C and N are the catch and population at the beginning of the season, and Z and F are the total and fishing instantaneous mortality rates.

Unfortunately his weight equation used unrealistic linear growth in length!

1890-1915

The creation of the International Council for the Exploration of the Sea in 1902, and the

immediate establishment of an Overfishing Committee marks the start of an organised attack on fisheries problems. The beginning of an age-structured approach can be seen in Hjort's (1914) suggestion that fisheries should try to follow the lines developed in human demography.

1916-1935

Although Baranov's use of exponential rates in building a yield equation in 1918 was generally overlooked, the growing interest in understanding what happens in exploited fish populations led to several other important developments. These culminated in 1937 in the world's first Overfishing Conference.

Hjort (1926) used the Pearl-Verhulst logistic equation to model the growth of whale populations.

In 1931 Russell set out the basic equation underlying all fisheries production models $S_2 = S_1 + (A + G) - (M + C)$, where S_1 and S_2 are the weight of the stock at the beginning of seasons 1 and 2, and A , G , M , and C are the weights of recruits, addition by growth, natural deaths and the catch during year 1 respectively.

In 1933 Ottestad introduced the concept that it should be possible to identify an optimum catch level. This concept laid the basis for the idea of a maximum sustainable yield which dominated the development of fisheries management techniques for much of the next fifty years.

Age-structured population models first appeared in 1934 when Thompson and Bell attempted to construct such a model which included exponential growth and mortality rates.

1936-1943

As already noted the war prevented much work from being done during this period, particularly

in the European area. However in North America Rounsefell and Kelez (1938), working with salmon, made what was probably the first attempt to establish a function relating parent stock to the size of the next generation.

1944-1960

At this time calculation was still limited largely to manual methods using such means as tables of logarithms and mechanical rotary calculators, although the introduction of punched cards and the machines for manipulating them did substantially increase the ability to handle quite large amounts of data in simple ways.

In this situation the vigorous development of fisheries work that flowed from the general expansion of scientific activity in the post-war years coupled with the stimulus of the Second Great Fisheries Experiment brought about a great flowering in the mathematical theory of fisheries. Highlights of this period include the following:

Ricker(1944) correctly formulated the equations relating stock, catch and natural deaths for exponential rates.

Delury(1947) devised the method of estimating the initial size of a population from the relative decrease in an abundance index as catches are removed. Although originally applied to marking experiments this technique has since become the essential basis for a whole family of "stock reduction" methods.

Ricker(1954) introduced the stock-recruitment equations which became widely used.

Schaefer in 1954 introduced the surplus production model which did not require detailed data on growth rates and age structure, and enabled the sizes of populations to be estimated without breaking them up into age groups.

In 1957 Beverton and Holt put forward the detailed age-structured model which provided the means for the calculation of yields under a range of management parameters and which

formed the basis for so much stock assessment work over the next thirty years. In particular this model provided means of identifying the exploitation rate and minimum takeable size which would give the maximum weight of catch, assuming recruitment did not change.

Also in 1949 Fry described a form of virtual population analysis and laid the basis for one of the main techniques for building age-structured models based on actual data.

1961-1970

In the early part of this decade development of the theory of fish stock analysis seemed to slow down. This occurred as the methods which had evolved in the 1950s passed into common use. The chief limitation was often in the ability to handle the calculations. However, main-frame computers were gradually becoming freely available. The dominant feature of the decade then became the process of coming to grips with the opportunities provided by the speed and data-handling capabilities of the new machines.

The ability of computers to process long time-series and arrays of age- or length-distributions made cohort analyses, for example, relatively easy to handle.

Computers also facilitated the estimation of parameters and of population components by procedures involving solution of non-linear relations. Examples were the fitting of von Bertalanffy growth curves (e.g. Fabens 1965; Allen 1966), and stock reduction methods of population estimation(Allen 1969).

Stochastic modelling of populations subject to random environmental effects using Monte Carlo methods also became practicable (e.g. Tautz *et al.*(1969) working with Pacific salmon).

Tables of functions for use by those still calculating manually were also easily produced on computers (e.g. Gulland (1969) for yields based on the Beverton and Holt equations).

1971-1980

The increasing availability both of commercial packages, such as word processors and spreadsheets, and of general mathematical and statistical packages, made the large computers much more useful for the non-specialists.

The decade was also marked by the advent of portable electronic calculators, which soon became programmable. These greatly increased the ability of scientists to perform calculations of moderate complexity in real working time. It became less necessary to depend on tables of functions to perform routine calculations, although F.A.O. still continued to publish tables of the yield function as late as 1983 (Gulland 1983). They were perhaps particularly valuable in the ever-increasing activities of working groups.

Specialised fisheries packages began to appear. These linked together a number of estimating procedures, and, in some cases, produced an assessment of the state of a fish stock and even management recommendations from standardised input data. The Elefan series of packages later produced by Pauly and co-workers provide a well-known example (e.g. Pauly and David 1981).

Age-structured models, commonly derived from the original cohort analysis and virtual population analysis (V P A) techniques, continued to evolve. For example, Pope(1971) introduced the approximation which for a long time was widely used in these analyses. However, the age-composition data used for these models were often not easily available. Towards the end of the period, models, such as the delay-difference constructions of Deriso(1980), began to appear which produced successive estimates of population numbers or weight without requiring a full age breakdown. Much effort was also directed to developing techniques which could provide measures of the error structure of the population estimates.

The increasing realisation of the uncertainties in parameter estimates, and of environmen-

tal variability, stimulated widespread criticism of maximum sustainable yield (MSY) as a basis for management (Larkin 1977). The debate was however to some extent a semantic one and, as Gulland(1978) pointed out, when MSY population level is replaced with optimal sustainable population (OSP) in legal documents "the outside observer can obtain some amusement in noting that by the time the definitions are pursued through the various sections OSP starts to bear surprising resemblance to that population which will produce the maximum sustainable yield".

1981-present

Use of large computers in fisheries work has continued to expand but in this decade the outstanding advance in facilities has been the appearance of the personal computer on the desk, and now in the briefcase, of almost every fisheries biologist. Use of personal computers in fisheries has been reviewed by Walters(1989) who has suggested that their use would be roughly for

word processing	50%
data storage and retrieval	30%
statistical analysis	10%
simulation and gaming	5%
advanced technology	5%

A number of important developments in models and in the associated computer programmes can be identified during this period.

Progress in age-structured models has been comprehensively reviewed by Megrey (1989). An important tendency has been to replace the deterministic calculation of values of mortality rates and catchability coefficients at each age in each year by stochastic estimation of vectors of catchability by age and of fully-recruited fishing mortality rate by year (e.g. CAGEAN(Deriso *et al.* 1985). These methods have obvious advantages particularly in error estimation, but they may mask historical changes in catchability particularly in its distribution over age.

Length-based models

The difficulties in obtaining satisfactory age-structure data, due both to the uncertainties of the age-determination techniques and to the time-consuming nature of the work, led to the formulation of models using only data on length distribution (e.g. Schnute 1987). However, these methods still need information on growth and natural mortality rates from some external source. They have been reviewed by Rosenberg and Beddington (1988).

Fishery system models

The traditional fisheries models have centred on the fish population and treated the effort used to catch the fish as an input from external sources, and the catch as the principal output. It is now becoming widely realised that such a model is only a small component at the centre of a large and complex web. Other components include, for example;

- the influence of environmental factors on the fish;

- the economic output from the fishery, both as contributing to the development of the industry itself, and as a contributor to the national economy;

- the factors, economic, political and social which determine government policies in the regulation of fisheries;

- the structure and behaviour of the industry both in determining capital investment and in controlling the operations and movements of fishing vessels.

Some modelling is now being undertaken in all these areas although such work has generally had a very short history compared to biological modelling. Like the biological work the models are limited to only small compartments of the total system. In particular the fish popula-

tion models included as necessary contributors within models of other segments seem usually to be distinctly simplistic. Rodrigues(1990) contains a number of studies of various components of the fishing industry and their internal and external regulatory mechanisms.

Management Applications

Models have also become more closely directed towards the development of specific management advice in a number of ways. In these applications the models are generally used in simulation mode and run dynamically to explore their behaviour under a range of external influences, including exploitation.

One such application is risk analysis which uses information derived from models, such as the error structure of population estimates and the variability of recruitment, to assess the likelihood that specified levels of fishing pressure will bring about particular consequences, such as the collapse of the fishery within a given period(Sainsbury 1991; Francis 1992).

Population models have also been applied in analyses of the possible benefits of "adaptive management", the rationale of which has been defined as "to consider fishing as an experiment and to use the results of experimentation to increase long-term yield or return from the fishery" (Walters 1986). Practical application of this approach is rarely possible for political or economic reasons but one of the few fisheries in which its use is being explored is the trawl fishery on the Australian Northwest Shelf (Sainsbury 1991).

Population models can be embedded within a game type structure to demonstrate the results of various management strategies. These programmes can be used both for research purposes and for educating managers and operators in the fishing industry (e.g. Prince *et al.* 1991).

What of the future?

Up to the present modelling seems to have gone through two main stages. Until about 1960 emphasis was necessarily on the development of a sufficient body of theory on which to base models of fish populations and the effects of exploitation. Progress was thus *theory-limited*. Since then the basic theory has changed little and computers have progressively provided the power to handle the data and make the calculations; progress has been *calculation-limited*. It is impossible to foretell what expansion of computing power will appear in the coming years but it seems certain that it will more than keep pace with the demands of progress in models. I believe that the greatest problem which will face fisheries modellers will be to obtain the ever-increasing amounts and kinds of data which they will need to run their models in the real world. Progress will thus be *data-limited*. I suggest therefore that a major direction of advance will be in the building of larger data-collecting systems; these will often be automated. They will frequently be remote reading and capable of producing data which can be fed directly into the computer models. We are already seeing such procedures in, for example, remote monitoring of vessel operations and in the collection of environmental data. Other possible extensions are in fish identification and size-measurement by sonic means.

In the models themselves we are likely to see, in one direction, an expansion in the construction of complex models embodying larger parts of the overall system. In another, it seems likely that there will be moves towards the use of models in which functions, such as growth curves, are replaced by arrays of observed values.

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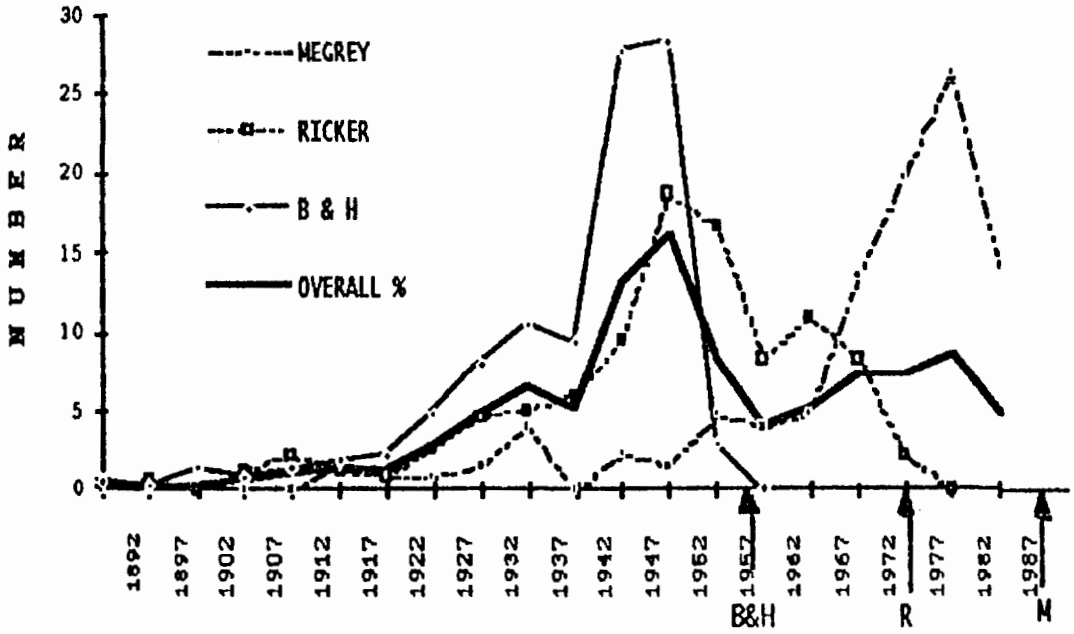


Figure 1. The number of publications included in each 5-year period from 1890 to the present in the reference lists of Beverton and Holt (1957), Ricker (1975) and Megrey (1989); and the average percentage.