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Ray Hilborn*

Abstract

The parameters for a Ricker stock recruitment relationship can change due to a number of factors. Methods for distinguishing between habitat elimination, lowered brood success, and elimination of less productive substocks are discussed. Data for the Columbia River Fall Chinook, and Skeena River Sockeye are analyzed in light of these considerations. It is also shown that the expected changes in productivities are strongly affected by the correlation of productivities of the different substocks. The importance of the above factors are discussed in relation to proposed enhancement facilities.

Preface

At first glance it may be hard to understand how this paper fits into applied systems analysis. This paper is an offshoot of the salmon case study, but is being put out as a IIASA publication because many of the results and problems discussed in this problem are found in all fisheries, and in any renewable resource problem. It is written specifically for fisheries biologists and management agencies, but is not technical in nature. The problems are of a general nature, and are easily understood.

Introduction

Managers of Pacific salmon face many problems caused by the complexity of the resource they are managing. They face a dilemma because they know that the salmon populations have complex life histories and population dynamics, and yet they

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need simple models if they are to employ optimization. The result of this dilemma is that despite the great volume of complex models of salmon population dynamics (Larkin and Hourston [2], Larkin and McDonald [3]), current management is based upon a simple stock recruitment relationship (Ricker [6]). A stock recruitment relationship calculates the recruitment into the population as a function of population size. Most stock recruitment models do not take into account the existence of substocks, substock interactions, environmental variability, evolutionary change of the population due to exploitation, or a host of other possible factors.

The problem is not that the managers do not recognize the existence of these factors, but that the functional form of these relationships may be unknown, and there are no methodological tools to determine optimal harvest rates for the more complex models. The strategy that has been adopted, consciously or otherwise, for management of salmon on the west coast of Canada, is to use the simple stock recruitment models but also to be aware of the above factors and to take them into consideration whenever it is possible due to availability of data, or political and social opportunity. In response to this, the literature on salmon management has frequently pointed out the kinds of deviations expected from predictions based on simple stock recruitment relationships (see Ricker [7]). I wish to extend the currently used models to include substocks after the method of Paulik et al. [4] and then consider some of the consequences of current management practices based on this more complex model. I will then analyze the historical data for one major salmon system, the Skeena River Sockeye, and look for evidence of the predicted consequences.

The Stock Recruitment Model

The accepted model for salmon stock dynamics was first described by Ricker [6]:

$$R = Se^{\alpha(1-\frac{S}{B})} \qquad (1)$$

where

R = the total number of offspring that will return to spawn as adults (before harvest);

S = the total number of spawners;

α = a parameter of productivity;

B = the number of spawners at which the average number of returning fish per spawner is 1.

This model can be extended to consider a salmon population that consists of a number of separate substocks (Paulik et al. [4]) as follows:

$$R_i = S_i e^{\alpha_i (1-\frac{S_i}{B_i})} \qquad (2)$$

where all symbols are the same as in equation (1) except that they are separated by substocks (i). This model certainly has its shortcomings; although the stocks probably do not interact during their freshwater life, they probably do during the marine part of their life cycle, and yet the model clearly assumes no interaction between stocks. It has been shown that for any stock harvested singly, the optimal harvest rate is a function of the α value (Ricker [5]), and that for mixed stocks harvested jointly, the case I shall consider, it is a function of both the α and B values for all stocks in the fishery (Paulik et al. [4]).

Estimation of Stock Recruitment Parameters

Equation (1) can be rewritten, adding a stochastic element, as follows:

$$R = Se^{\alpha(1-\frac{S}{B})} e^{\varepsilon} \qquad (3)$$

where ε = a normally distributed random variable with a mean of zero. Converting this to a least squares fit model we get:

$$y = \ln(\frac{R}{S}) = \alpha + \frac{\alpha}{B}S + \varepsilon \qquad (4)$$

(see Dahlberg [1]). The variance of ε represents the uncertainty about the stock recruitment relationship. This estimation procedure requires a time series of spawning stock and resultant runs. The S values represent the spawning stock and the R values are the number of fish that returned from that brood year.

An alternate approach is to assume that B is a fixed value, and then to look at a frequency distribution of α values. This has been done by Walters [10] using the following relationship derived from equation (1). R and S have been scaled from zero to 1 by dividing by B :

$$\alpha = \frac{\ln(\frac{R}{S})}{1 - S} \quad . \qquad (5)$$

This model assumes that the factors influencing the limits of the stock are reasonably constant, and that most variation in the stock recruitment relationship is due to changes in α. This allows us to calculate an α value for each year and to plot a frequency distribution of annual productivities.

Expected Changes in the Stock Recruitment Relationship

What kinds of factors can be expected to cause changes in the stock recruitment relationship? α represents the productivity of the stock at low levels when density dependent effects are of little importance. B represents the equilibrium unfished density of the stock. There are two major changes that obviously are occurring in salmon systems. Certain stocks are being eliminated due to overexploitation, and spawning habitats are being eliminated by logging operations, hydroelectric developments, landslides, etc. It is easily demonstrated that elimination of habitat will cause the estimated B value to decrease. If a regression of the form of equation (4) is done on data from a river system in which habitat was eliminated, and data was included from both before and after the elimination, both B and α would appear to go down. If only data from after the habitat elimination were used, then only B would appear to go down. If substocks are eliminated by overexploitation, then the estimated α value will go up because the less productive stocks will disappear, but the B value will go down because the density dependent effects will act at lower stock levels.

The changes described above are fairly easy to understand and are referred to in part in several papers (Ricker [7], for example). However, these expected changes make implicit assumptions about the correlation structure of the different substock parameters. If we use the notation of equation (4), the correlation structure mentioned in the previous sentence specifically refers to the correlation matrix of the ε values of the different substocks. I consider two substocks positively correlated if their ε values are positively correlated, and negatively correlated if their ε values are negatively correlated.

There are theoretical reasons to expect both possibilities. Arguments for positive correlation assume that there are environmental factors that would be similar for all substocks, so if it was a good year in the ocean for one substock it would be a good year in the ocean for all substocks. Arguments for negative correlation assume that the environmental factors affect stocks differently. A theoretical example might be that rainfall in northern British Columbia was negatively correlated to rainfall in southern British Columbia; if the main storm tracks run south then the southern spawning areas get high water flows, and the northern spawning areas get low flows. This could in turn cause the ε values of the northern and southern stocks to be negatively correlated. Many similar arguments can be made for several environmental variables that are known to affect salmon survival. The point is that stocks may be either positively or negatively correlated and, as I will demonstrate, the correlation structure makes a good deal of difference to what happens to the stock recruitment parameters when some stocks are eliminated by overexploitation.

Let us assume that we have two substocks, C and D. Assume further that C spawns in the south and D spawns in the north, and when the storm tracks run to the south, C has a better than average year, and when the storm tracks run to the north, D has a better than average year. Also assume that for some reason C has a higher productivity than D. This may be because the storm tracks run to the south more often than to the north, but it could also be because the fresh water habitat of C is generally better. Under low exploitation rates, the total stock, the sum of C and D, will be fairly consistent from year to year; when one stock has a good year, the other has a poor one and vice versa. If, however, the exploitation rates are increased to a point where stock D is seriously depleted, then when the storm tracks run to the north, and C has a bad year, there is no stock left to have a good year as it has been eliminated or severely reduced by overexploitation. These arguments suggest that it is possible that elimination of less productive stocks will not just reduce the estimated B value and increase the α parameter, but that the frequency distribution of the α parameter, as calculated from equation (5), will go from being somewhat normally distributed, to having a bimodality with an increased frequency of low α values. Combining low α values with reduced B values should lead to occasional years of very poor total runs. There are only two assumptions required to produce these conclusions, 1) the ε values of the substocks are negatively correlated, and 2) there are sufficient differences in productivity among the substocks such that the optimal exploitation rate, using current management models, will cause some of the less productive stocks to be severely reduced. I believe that most salmon biologists would agree that these assumptions are quite reasonable for a number of major salmon producing rivers.

Analysis of Some Historical Data

Described below are analyses of two sets of historical data. The first set of data is analyzed only for the changes in α and B. No consideration of the frequency distribution of

α is made because of the limited data. In the second set of data both the changes in α and B and the frequency distribution of α are considered.

Van Hyning [9] presented spawner and return data for Chinook salmon on the Columbia River from 1938 to 1959. He showed that the stock recruitment relationship had changed significantly during the twenty years. Figure 1 shows the regression lines for 1938 to 1946 and 1947 to 1959 from Van Hyning's data. The curves are the least squares fit from the regression in equation (3). Note that the estimated value of α corresponds to the y value ($\ln \frac{R}{S}$) when x is zero, and the estimated value of B corresponds to the x value when y is zero. The estimated values of α and B for 1938 to 1946 are 3.2 and 296,000 and for 1947 to 1959 are 2.0 and 236,000. The α values are significantly different at the .001 level but the B values are not significantly different at the .1 level. Van Hyning could offer no explanation for the changes in the stock recruitment relationship. No major dams were built around 1946, and there were no obvious changes in the fish habitat. Since the α values changed and the B values did not, it seems reasonable, from our previous consideration of expected change, to look for factors affecting the productivity of the existing stocks, and not the elimination of stocks due to overexploitation or stream blockage.

Skeena River Data

Estimates of escapement and resultant run on the Skeena River are available for brood years 1908 to 1952 from Shepard and Withler [8]. They separate resultant runs by age of return, although for the early years of the fishery the techniques determining age composition in the spawning stock are quite crude and the data are less reliable than more recent ones. Data for brood years 1957 to 1965 were obtained from the files of the Canadian Department of Fisheries (Mike Staley, personal communication). To determine what changes in productivity have occurred since the commercial fishery started, we have separated the data into two periods, pre-1920 and post-1920. The commercial fishery was established in 1877 (Shepard and Withler, [8] and by 1908, the year the first data are available, the exploitation rate had already reached 55%. These thirty years of the fishery before the data became available represent between six and eight generations and it is likely that most of the stocks with very low productivities had been eliminated by 1908. However, significant changes did occur between the pre-1920 and the post-1920 productivity parameter estimates. The pre-1920 estimates are $\alpha = 1.1$ and $B = 2.7$ million. The post-1920 estimates are $\alpha = 1.5$ and $B = 1.4$ million. It is clear that some stocks were still being eliminated. However, the increase in α was not very large, and it may be that some of the stocks

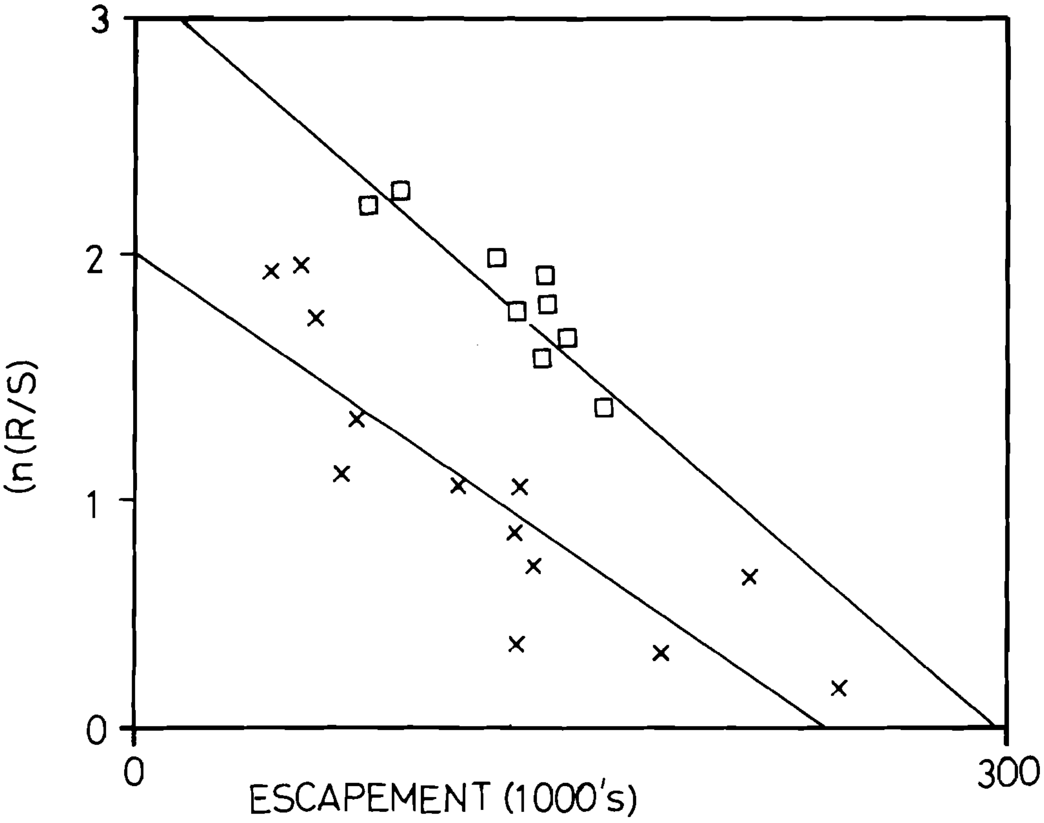

Figure 1. The stock recruitment data for Columbia River Fall Chinook Salmon. The natural logarithm of the resultant run divided by the spawning stock is plotted against the spawning stock. Squares represent brood years 1938-1946, and x's represent brood years 1947-1959.

were eliminated for reasons other than overexploitation. Figure 2 presents the distribution of net productivity for the Skeena River brood years 1921 to 1965. This plot is analogous to that presented by Walters [10], except that he did not separate the returning fish into brood years. No statistical tests have been performed on this distribution, but it is clear that it does not display the bimodality predicted for situations where the values of ε are negatively correlated. Unfortunately, data are not available on spawners and result runs by substock, so Figure 2 is our only clue to the correlation structure of the ε values. From these admittedly meagre data, we must conclude that there is no evidence of negative correlation of the ε values. However without stock recruitment data for substocks, our chance of detecting negative correlations in ε is probably very small.

Discussion

It may seem circular to argue that from the distribution of net productivities there is no evidence of negative correlation between the ε values, when the reason we were worried about the possibility of negative correlation is that it would cause bimodality of the net productivity curve. The importance of this analysis lies in considering enhancement of current stocks. If the enhanced stocks are more productive than the current stocks, which is the usual case with salmon enhancement, then the optimum exploitation rate would increase. Economic considerations, along with the regulation of the treaties with Japan, suggest that there would be strong pressure to increase the harvest rate to near its optimum. Because of the possibility of another increase in exploitation rates and subsequent elimination of more stocks, we must be very concerned about increasing the frequency of low values in the course of enhancement programs.

The purpose of this paper is primarily to pose the problem, and demonstrate how current management models are ignoring a potential problem. The data analysis is a first cut at seeing if the problem exists. The management agencies should certainly look closely for evidence of negative correlation of different stocks, both from a priori considerations of known biological relationships, and from data analysis. The current status of data on substocks is so dismal that money should certainly be invested in collating existing data to provide some time series of spawners and resultant recruits by substocks. These data should then be published in a form that makes them accessible to the general scientific public. The time lags in collecting new data on substocks are so severe that they would probably be of little use for at least twenty years. Specifically, I suggest that the dangers of increasing exploitation rates as enhanced stocks start to become important could be much more severe than currently expected.

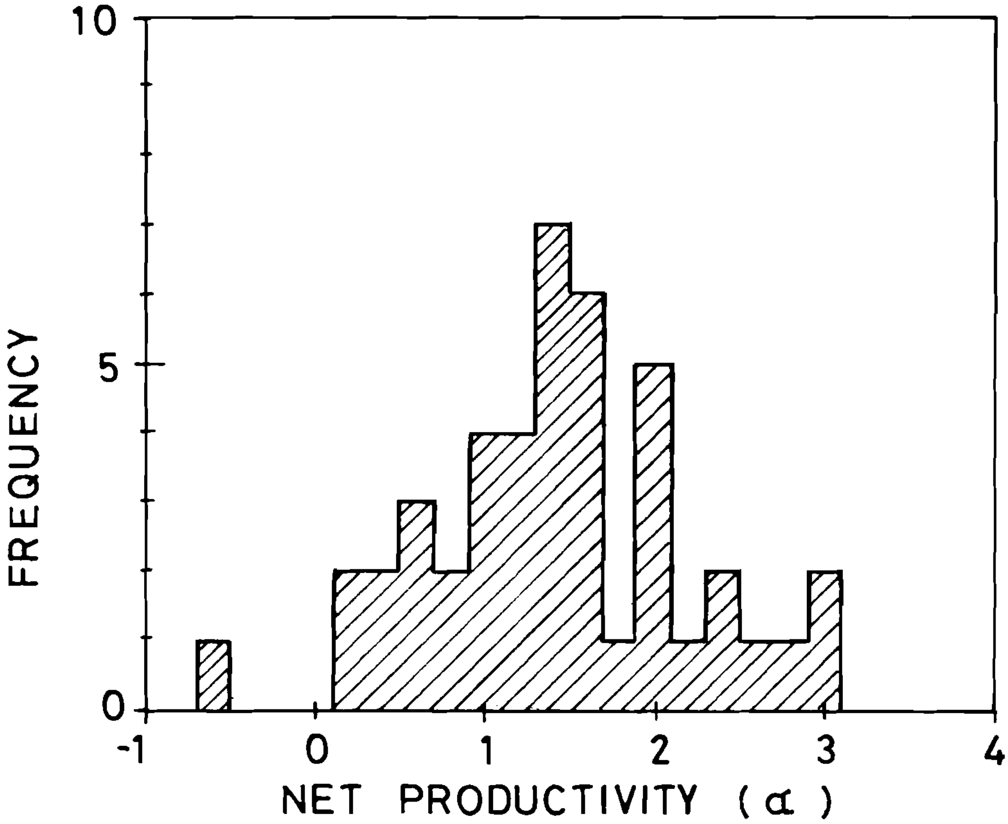

Figure 2. Distribution of net productivity for the Skeena River, brood years 1921 to 1965.

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