DECISION THEORY AS A TOOL IN
SOCKEYE SALMON MANAGEMENT OF THE BABINE SYSTEM

by

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B.Sc., University of British Columbia, 1972

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THE REQUIREMENTS FOR THE DEGREE OF
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Interdisciplinary Studies
(Civil Engineering and Commerce)

We accept this thesis as conforming to the
required standard

THE UNIVERSITY OF BRITISH COLUMBIA

July, 1976

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Date August 1, 1976
A procedure for applying the concepts of Bayesian decision theory to salmon management is presented and illustrated with an application to the Babine system sockeye salmon fishery in British Columbia. The particular decision considered is the recommended escapement to aim for in a given year. The Babine fishery is described and the decision theory concepts are outlined. The procedure involves defining the relationship between the recommended spawning escapement and the number of adults returning in the cycle year in probabilistic terms; defining the utility, that is the relative desirability of various sizes of catch; and computing the total expected utility of both the catch in the current year and the spawning returns associated with alternative values of the recommended escapement. The escapement with the maximum expected utility should be chosen and recommended.
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The author is very grateful to his supervisor, Professor Samuel O. Russell, for his constant encouragement and available guidance in the development of this thesis. Special thanks are extended to members of the Pacific Biological Station, especially Mr. Howard Smith, Mr. Fred Withler, and Dr. Don Alderdice who supplied that data and reviewed the analysis. The author would also like to thank his colleague, Mr. Gunther Brox, for his comments and assistance; Mr. Richard Higgins and Mr. Robert H. Owen for assistance in developing the computer program; Mr. Richard Brun who prepared the drawings; and Miss Kathie Cook who typed this thesis.
CHAPTER 1

INTRODUCTION

Fishery management is difficult under almost any circumstances and particularly so in the case of sockeye salmon which spend part of their life cycle in fresh water and part in salt water. Some components of the sockeye salmon life cycle are relatively well understood while on others there is only sketchy information; for example, what happens to them in the ocean and what factors affect their survival there are almost completely unknown. Natural conditions such as river flows, water temperatures, sediment load vary from year to year and are very difficult to predict. Then there are social problems, etc. On top of this the whole field is so varied and complex it is not possible for one person to thoroughly understand all aspects of it. Consequently, the available knowledge and expertise is distributed among different experts who are expert on various components of the sockeye salmon life cycle.

Management decisions fall into two categories, those concerned with day to day operations and those concerned with long term effects, planning decisions which might be called enhancement decisions. The main operating decision is the target escapement, the number of sockeye salmon that should be allowed to escape for spawning purposes each year.

In this thesis a procedure is developed for making this operating decision; that is, for deciding on the optimal escapement in the light of all the available knowledge, using the sockeye salmon run of the Babine River and Lake system as an example. The procedure is based on the concepts of Bayesian decision theory, a set of concepts which allow
uncertainty and informed opinion to be taken into account in arriving at the optimal decision.

The sockeye salmon life cycle can be readily divided into five components or stages. In this thesis the relationship between the numbers at the beginning and at the end of each stage are defined in terms of probability bands, the widths of the bands reflecting the degree of uncertainty. The overall relationship between escapement and the size of the resulting return run is derived by converting the probability bands into probability matrices and multiplying the matrices together in order to obtain an overall probability matrix.

In order to evaluate possible target escapements using decision theory several chosen target escapements are selected and the total expected utility is calculated for each selection. The expected utility is the product of the probabilities of the various possible outcomes and the relative desirabilities of the outcomes expressed in utility units. The best decision is that for which the total expected utility is a maximum.

Enhancement decisions such as developing spawning channels, fishways, and incubation boxes could be evaluated in terms of their effect on the relationship that is affected by the specific enhancement project and from this the expected increase in production could be computed, using essentially the same procedure. The steps in this procedure are explained.

The Babine Lake and River System which provides the spawning grounds for 90% of the sockeye salmon of the Skeena River System is described in Chapter 2. In Chapter 3 Bayesian decision theory is explained while the five stages of the life cycle of the sockeye salmon
are outlined in Chapter 4. Utility and the computation to determine the optimal decision are described in Chapter 5 and a discussion of the procedure and the results are presented in Chapter 6.
CHAPTER 2

THE BABINE LAKE AND RIVER SYSTEM

The Babine Lake and River System which is located in central British Columbia east of Prince Rupert (Fig. 2.1), includes thirteen tributary streams as well as Babine Lake, Nilkitkwa Lake, and several smaller lakes. The system produces 90% of the sockeye salmon in the Skeena River and there are also pink, chum, coho, and chinook salmon runs.

Babine Lake drains by way of the Upper Babine River into Nilkitkwa Lake which in turn is drained by the Lower Babine River. A counting fence located on Lower Babine River has been operated since 1945. Counts of adults and smolts have been made each year since then, except for 1948 and 1964 when there were very high river flows (Fig. 2.2).

Johnson (1956-58, 1961, 1965) established that Babine Lake and Nilkitkwa Lake were underutilized as a nursery. Thus, the construction of the fishery channels was undertaken in order to increase the production of young fry. Spawning channels have been constructed at Fulton River and at Pinkut Creek as part of the 8 million dollar Babine Development Project (Jordan and Smith, 1972) (Figs. 2.3 and 2.4).

For this study the analysis of the Skeena River sockeye has been restricted to the Babine Lake and River System. The counting fence is considered the start of the system.

Since the construction of the spawning channels has been completed recently, it was decided to analyze two sets of data (ie. before the spawning channels were introduced and upon completion of the spawning
Fig. 2.1 SKEENA AND BABINE RIVER SYSTEM.
Fig. 2.2 LOCATION OF THE BABINE R. COUNTING FENCE.
LENGTH: 4900 FEET
WIDTH: 30 FEET
Q = 75 c.f.s., V = 1.8 FT./sec. AT d = 1.3 FT.
CAPACITY: 22,000 ADULTS
CHANNEL SLOPE = 0.0009

Fig. 2.3 SKETCH OF FULTON SPAWNING CHANNEL NO.1.
Fig 2.4 FULTON RIVER WITH INSET OF BABINE LAKE.
channels). The results in this thesis only pertain to the system before the spawning development was completed.

The total sockeye salmon production from the escapements for the years 1949 through to 1967 varied from 2,228,000 (1967) to 194,000 (1951). Table 2.1. A slide which blocked the river in 1951 accounts for the low escapement figure in that year. The total production figure for each escapement includes all the 3, 4, and 5 year old sockeye as outlined in Table 2.1. However, to simplify the analysis and presentation of results it has been assumed for the present study that all sockeye return after 4 years.
TABLE 2.1
Babine Lake Sockeye Production 1949 - 67
(All numbers in thousands)

<table>
<thead>
<tr>
<th>Year</th>
<th>Spawning Escapement</th>
<th>Adult Returns</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Recommended</td>
<td>Actual</td>
</tr>
<tr>
<td>1949</td>
<td>461</td>
<td>28</td>
</tr>
<tr>
<td>1950</td>
<td>364</td>
<td>28</td>
</tr>
<tr>
<td>1951</td>
<td>141</td>
<td>10</td>
</tr>
<tr>
<td>1952</td>
<td>349</td>
<td>31</td>
</tr>
<tr>
<td>1953</td>
<td>687</td>
<td>18</td>
</tr>
<tr>
<td>1954</td>
<td>494</td>
<td>50</td>
</tr>
<tr>
<td>1955</td>
<td>71</td>
<td>31</td>
</tr>
<tr>
<td>1956</td>
<td>355</td>
<td>32</td>
</tr>
<tr>
<td>1957</td>
<td>433</td>
<td>49</td>
</tr>
<tr>
<td>1958</td>
<td>812</td>
<td>28</td>
</tr>
<tr>
<td>1959</td>
<td>783</td>
<td>46</td>
</tr>
<tr>
<td>1960</td>
<td>263</td>
<td>173</td>
</tr>
<tr>
<td>1961</td>
<td>500</td>
<td>942</td>
</tr>
<tr>
<td>1962</td>
<td>548</td>
<td>64</td>
</tr>
<tr>
<td>1963</td>
<td>810</td>
<td>588</td>
</tr>
<tr>
<td>1964</td>
<td>630</td>
<td>828</td>
</tr>
<tr>
<td>1965</td>
<td>810</td>
<td>580</td>
</tr>
<tr>
<td>1966</td>
<td>650</td>
<td>389</td>
</tr>
<tr>
<td>1967</td>
<td>900</td>
<td>608</td>
</tr>
</tbody>
</table>
CHAPTER 3

USE OF DECISION THEORY

In decision making under uncertainty it is necessary to consider both the probabilities of the various possible outcomes and their relative desirabilities. Decision theory allows probabilities and outcomes to be considered separately and provides a method for combining the two. Bayesian decision theory allows the use of subjective probability estimates and hence, is most suitable when expert opinion is available. The concepts of decision theory are prescribed in numerous texts and papers (de Neufville and Stafford, 1972; Halter and Dean, 1973; Hershman, 1974) and are not repeated here.

In order to apply decision theory to sockeye salmon management of the Babine Lake and River System it is necessary to consider not only the current year's catch but also future catches from the allowable escapement. The following specific steps are involved.

1) Defining the probabilities of the size of runs of returning adults that could result from various allowable escapements in the current year.

2) Defining the relationship between the catch of returning adults in the current year and its utility.

3) Computing the discounted expected utility of various allowable escapements in the current year on the basis of numbers of adults returning in the next cycle. The discounted expected utility is the return of adult sockeye salmon that is realized four years into the future from the present escapement.
4) Defining the probabilities of various numbers of returning adults in the current years.

5) Computing the escapement with the maximum total expected utility.

The decision of recommending an escapement is primarily made as a result of assessing uncertainty adequately.

For the purpose of analysis, uncertainty is defined as uncertainty related to the returning sockeye salmon run, when a forecast is given and the return of sockeye salmon four years later from a given recommended escapement.

In the following section the procedure used to express the relationship between the escapement and the number of adults returning in the next cycle (step 1) in terms of a probability matrix is outlined.

**Relationship Between Escapement and Number of Adults Returning in the Next Cycle—Fig. 3.1**

The relationship between the target escapement and the number of adults returning in the next cycle is derived by obtaining information on various components of the salmon life cycle and combining these into an overall relationship.

Steps in the cycle were defined as:

1) Recommended escapement, the number of sockeye salmon that the Management Committee would like to see enter the Babine System - the basic decision to be made.

2) Actual escapement, the number of spawning salmon that pass the counting fence.

3) Egg deposition in the system - in channels, rivers, and also
FIG. 3.1 RELATIONSHIP BETWEEN RECOMMENDED ESCAPEMENT AND NO. OF RETURNING ADULTS.
the eggs deposited by lake spawners.

4) Number of fry, the young fingerlings that hatch and enter the Babine and Nilkitkwa Lakes.

5) Number of smolts, the young salmon that pass the counting fence on their way to sea.

6) Number of returning adults, the adults that return at the end of the cycle. Some are caught and some return to spawn.

The development of the component relationships between the above steps which are defined as probability bands, is discussed in Chapter 4. The other steps outlined above are described in subsequent chapters.
### TABLE 3.1

Babine System Sockeye Salmon Fishery, Probability

Relationship Between Chosen Escapement and Number of Returning Adults

<table>
<thead>
<tr>
<th>Chosen Escapement in thousands</th>
<th>400</th>
<th>450</th>
<th>500</th>
<th>550</th>
<th>600</th>
<th>650</th>
<th>700</th>
<th>750</th>
<th>800</th>
<th>850</th>
<th>900</th>
<th>950</th>
</tr>
</thead>
<tbody>
<tr>
<td>Returning Adults in thousands</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>0.070</td>
<td>0.027</td>
<td>0.009</td>
<td>0.003</td>
<td>0.001</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>150 - 450</td>
<td>0.082</td>
<td>0.038</td>
<td>0.018</td>
<td>0.009</td>
<td>0.005</td>
<td>0.003</td>
<td>0.002</td>
<td>0.001</td>
<td>0.001</td>
<td>-</td>
<td>-</td>
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<td>450 - 750</td>
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<td>0.299</td>
<td>0.229</td>
<td>0.160</td>
<td>0.106</td>
<td>0.068</td>
<td>0.044</td>
<td>0.029</td>
<td>0.021</td>
<td>0.016</td>
<td>0.013</td>
<td>0.010</td>
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<tr>
<td>750 - 1050</td>
<td>0.352</td>
<td>0.330</td>
<td>0.274</td>
<td>0.214</td>
<td>0.163</td>
<td>0.123</td>
<td>0.095</td>
<td>0.075</td>
<td>0.063</td>
<td>0.055</td>
<td>0.048</td>
<td>0.044</td>
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<tr>
<td>1050 - 1350</td>
<td>0.074</td>
<td>0.131</td>
<td>0.184</td>
<td>0.218</td>
<td>0.231</td>
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<td>0.239</td>
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<td>0.219</td>
<td>0.210</td>
<td>0.202</td>
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<tr>
<td>1650 - 1950</td>
<td>0.018</td>
<td>0.039</td>
<td>0.066</td>
<td>0.095</td>
<td>0.123</td>
<td>0.146</td>
<td>0.165</td>
<td>0.177</td>
<td>0.185</td>
<td>0.189</td>
<td>0.193</td>
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<td>1950 - 2250</td>
<td>0.002</td>
<td>0.009</td>
<td>0.022</td>
<td>0.042</td>
<td>0.068</td>
<td>0.095</td>
<td>0.120</td>
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<td>0.154</td>
<td>0.164</td>
<td>0.172</td>
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<td>0.052</td>
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<td>0.006</td>
<td>0.012</td>
<td>0.020</td>
<td>0.028</td>
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<td>0.044</td>
<td>0.050</td>
<td>0.055</td>
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<td>0.002</td>
<td>0.004</td>
<td>0.007</td>
<td>0.011</td>
<td>0.016</td>
<td>0.020</td>
<td>0.024</td>
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<td>-</td>
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<td>0.001</td>
<td>0.003</td>
<td>0.005</td>
<td>0.007</td>
<td>0.009</td>
<td>0.011</td>
<td>0.012</td>
<td>0.014</td>
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<td>3750 - 4050</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>0.001</td>
<td>0.002</td>
<td>0.002</td>
<td>0.003</td>
<td>0.004</td>
<td>0.004</td>
<td>0.005</td>
<td>-</td>
</tr>
<tr>
<td>4050</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
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</tbody>
</table>
CHAPTER 4

COMPONENT RELATIONSHIPS OF THE SOCKEYE SALMON LIFE CYCLE

Introduction

Component relationships between steps in the cycle are described in this chapter together with the factors considered in their derivation. Each of the component relationships is expressed in the form of a probability band rather than a unique curve, the width of the band reflecting the extent of uncertainty and unknowns in the relationship. The derived relationships were all reviewed by experts - personnel from the Pacific Biological Station, Nanaimo (Smith, Alderdice, and Withler personal communication), and they agreed that the curves appeared satisfactory in light of their knowledge, experience, and judgment.

Relationship Between the Chosen Escapement and the Actual Escapement

Fig. 4.1

The actual escapement is generally not the same as the recommended escapement. There are several reasons for this but the main one is that control of the fishery is rather tenuous since it has to be conducted at "arms length". If fish traps were built across the Skeena River, then it would be a relatively straightforward procedure to ensure that the actual escapement was the same as that decided upon.

However, as it is, control is obtained by adjusting the allowable fishing times. There is no direct relationship between fishing times and escapement so the decisions have to be based on forecasts, which themselves might not be very accurate, and experience built up over the years.
RELATIONSHIP BETWEEN RECOMMENDED AND ACTUAL ESCAPEMENT.

FIG. 4.1
The effectiveness of the fishing fleet varies from year to year depending on factors such as the degree to which the fishing time coincides with the peak of the salmon run. There is also the Indian Fishery in which the catch also varies from year to year.

In addition, there are subtle long term effects which are not fully understood, as is evidenced by the fact that the level of recent yields (1968-71) of the Skeena River fishery are about 45% as large as those of the system's best 4-year period, 1908-1911 (Ricker and Smith, 1975).

The relationship between the chosen escapement and the actual escapement on the Babine Lake and River System is given in Fig. 4.1 in the form of a probability band. This was obtained from a comparison of the escapement objectives and an estimated actual escapement during a number of years from 1963 to 1974 (Skeena River Management Committee Annual Reports, 1963-74).

Relationship Between the Actual Escapement and the Potential Egg Deposition-Fig. 4.2

The potential egg deposition is defined as the number of eggs that enter the Babine Lake and River System. It is necessary to characterize the actual escapement in order to determine the number of eggs that will enter Babine Lake and River System in terms of the sex ratio, the size and age of the females, and the mixture of the stocks.

The number of eggs entering the system depends not only on the number of fish, but also on the sex ratio of the returning sockeye salmon. The sex ratio is important in considering the eventual survival of the eggs as well as the number of eggs that are brought into the system. If
RELATIONSHIP BETWEEN ACTUAL ESCAPEMENT AND POTENTIAL EGG DEPOSITION.

FIG. 4.2
there is a large female to male ratio, there may not be adequate space in the tributaries and spawning channels for the female sockeye salmon or else there may not be enough males to fertilize the eggs.

The sockeye salmon entering the Babine Lake and River System are those that escape the combined Indian and commercial fishery. The fishery selects fish from the returning run on the basis of size and, in turn, on the basis of sex (Jordan and Smith, Fig. 471972). Since the potential reproductive capacity, which is based on the number of eggs carried by the female sockeye salmon, is a function of size and, in turn, equivalent ocean age, the number of eggs deposited in the gravel is greatly influenced by the ratio of 4 and 5 years old females in the escapement. The mean age of the sockeye salmon, for the total escapement has declined (Ricker, 1972, 1975) while the sex ratio does not appear to have varied significantly relative to other escapement years. This may account for the fact that the number of eggs which are carried by the female sockeye salmon for the years 1967-1971 is low relative to the number of eggs carried by female sockeye salmon from other years. There are several possible reasons for the occurrence of a shift in the sockeye salmon mean age such as an inherent shift in the genetic makeup of the sockeye salmon stocks, the fishing gear used, and the approved fishing schedule. Ricker (1972) has shown that there has been a gradual increase in the portion of jacks relative to other age classes of sockeye salmon stocks, where the jack portion of a stock has been initially considered moderate. Jack sockeye salmon are excluded from the escapement figures used in the analysis for the Babine-Nilkitkwa lakes system as they are considered immature sockeye.

There are at least 10 stocks of sockeye salmon associated with the
Babine Lake and River System (Ricker, 1972). Each stock differs in mean size and mean age, thus the number of eggs carried by the sockeye female of each stock varies and as a result the mixture of the stocks which return to the spawning channels and tributaries is a factor in determining the number of eggs that enter the system.

The probability band which defines the relationship between the actual escapement and the potential egg deposition was arrived at by first, plotting the total escapement of large sockeye against the number of eggs (potential egg deposition) brought into the system (Skeena River data, 1946-1971, supplied by the Biological Station, Nanaimo). The upper and lower limits of the data which formed the probability band were extended to include variation that might occur as a result of extraordinary events such as a high male to female ratio.

**The Relationship Between the Potential Egg Deposition and the Number of Fry**

Not all eggs that enter the Babine Lake and River System, the potential egg deposition, are deposited in the gravel. The number of eggs that are deposited in the spawning channels and tributaries depends on social behaviour of the salmon in the spawning channels and tributaries, the number of spawning sockeye salmon in the spawning channels and tributaries, and the time of arrival of the sockeye salmon at the spawning grounds.

The effect of social behaviour on the egg deposition cannot be entirely isolated from the factor of density. A. Tautz (1974) has observed that in high density situations in the Fulton channels females are forced into the pools where they wait for an opportunity to move into the
RELATIONSHIP BETWEEN POTENTIAL EGG DEPOSITION AND NO. OF FRY.

FIG. 4.3
gravel beds. In some cases the females do not reach the gravel beds. Thus, egg deposition does not occur and the eggs that were retained in their bodies decompose with the fish tissue. In a preliminary study, Ginetz (Fig. 12, 1972) has shown that if spawning area available to each female in Fulton channel No. 1 is less than 1.0 sq.yd., but greater than 0.82 sq.yd., the percentage of unspawned females is 3% to 4%; whereas, in the Fulton channel No. 2, if the area available per female is less than 1.0 sq.yd. but greater than 0.52 sq.yd. the percentage of unspawned females is 5.5% to 6.5%. Simultaneous studies were not conducted in the river. Overcrowding in the spawning channels is not entirely due to high density. Sockeye salmon spawn in waves and as a result, mechanical action by spawners plays a role in the disruption of eggs previously deposited (Ginetz, 1972). If several waves of sockeye salmon spawn in the channels some of the eggs will be removed from the gravel.

A large number of eggs that enter the Babine Lake and River System are not deposited in the gravel due to the fact that many adult sockeye salmon do not reach the spawning grounds. They may be lost as a food source to hawks, bears, and eagles, deprived of sufficient water supplies, or confronted with log and rock obstructions. Even if the eggs are deposited in the gravel, they may not survive. The survival of the eggs in the gravel of the spawning channels, rivers, and streams depends on the rate of siltation, flow fluctuations, predation, disease, water temperature, and the quality of the water supply.

Siltation of the spawning grounds is likely to lead to reduced gravel permeability and subsequent embryonic mortality from insufficient oxygen. The siltation rate will vary from year to year depending on the water runoff and activities such as logging and mining which can dislodge
a great deal of sediment.

Fluctuating flows in the streams and rivers result in extensive movements of the river beds and can lead to a lack of water during the period when the eggs are developing into alevins and in turn, fry. Although an even flow is desirable during the incubation period, fluctuating flows result in a natural cleaning process.

In studies conducted by Ginetz (1972) in Fulton channels, predation of the eggs by macroinvertebrates, such as stonefly nymph (Allopeda sp., Acroneuria pacifica) was not considered to be a major source of embryonic mortality of sockeye eggs. It is also possible that mortality of the eggs is due to fungal and viral infections.

Mortality of the eggs can be greatly influenced by the high levels of several water quality parameters such as NH₄, NO₂, NO₃, CO₂, Temp, and O₂ that may interfere with permeability or else reach toxic levels inside the eggs.

Some of the mortality factors seems to be accentuated in the channels of the Babine Lake and River System. The Pinkut Creek channel system is exposed to the freezing winds in the winter and as a result anchor ice forms. The gravel is scoured and a high winter mortality of alevins occurs. Wickett (1974) points out that the phenomena occur only under clear skies. It has been suggested that the planting of Black Spruce would alleviate the problem and also reduce the influence of the light during the summer. The potential for algal blooms is present and it is possible that toxic biproducts produced by the algae will affect the survival of a portion of the alevins and the eggs particularly if the algal blooms occur in early May. Ginetz (1972) predicts that mortality will rise if algae growth and siltation continue unchecked in the Fulton
The probability band which defines the relationship between the potential egg deposition and the number of fry was arrived at by first, plotting the potential egg deposition, the number of eggs brought into the system, against the estimated number of fry, fingerlings that enter the lakes system for the years 1955-1961 (Johnson, 1955-61). This information supplied by the Pacific Biological Station acted as a basis for the construction of a probability band. The Skeena River System has spawning channels at Pinkut Creek and Fulton River which were not present when the population studies were undertaken. Subsequent studies lead to an approximate survival figure of 40% for the eggs in the channels. For the purpose of analyzing a second set of data, it is assumed that 20% of the eggs that enter the system enter the spawning grounds.

Relationship Between the Number of Fry and the Number of Smolts-Fig. 4.4

The fry emerge from the rivers, streams, and spawning channels and enter Babine and Nilkitkwa Lakes in the spring. They remain in the lakes for approximately one year before migrating as smolts to the sea by the Skeena River. Once in the lakes, the survival rate of the fry depends on physical and biological factors such as water temperature differences, availability of food, and intensity of the pressure from predators such as Rainbow trout, Dolly Varden, and lake trout.

The fry are exposed to a different thermal environment when they emerge from the tributaries and spawning channels. If there is a large difference in the temperature between the rivers and the lake water, it is likely mortality will be high. Brett (1952) demonstrated that the young sockeye (4.7 months of age) acclimated to 5°C could not tolerate long
Relationship between No. of Fry and No. of Smolts.

FIG. 4.4
exposure (four days) to 0°C. His work outlined the thermal tolerance of young sockeye salmon in relation to different acclimation temperatures (Brett, Fig. 22, 1952).

Babine Lake is considered to have an abundant supply of food in the form of zooplankton biomass. Johnson (1956, 1958, and 1961) measured the standing crop of zooplankton (mg dry weight/m^3) in the 0-5 m depth interval in order to estimate food abundance. He found that the mean concentration of zooplankton varied from 8-100 mg/m^3 from mid-June to mid-October for seven defined basins in Nilkitkwa and Babine Lakes. His studies implied that the main basin on Babine Lake (which accounts for 88% of the total surface area) was underutilized as a lake nursery for sockeye. This information provided one of the main reasons for construction of the spawning channels at Fulton River and Pinkut Creek.

Although the abundance in total quantity may be more than adequate to meet the needs of the young sockeye, the standing crop of zooplankton will vary with the time of year. In the spring, before the lake warms up, productivity will be low so that when the fry first enter the lake, food may be scarce and competition for it intense. Bilton and Robins (1971) found from controlled experiments that young sockeye salmon deprived of food for a period of 20 weeks did not suffer a high rate of mortality (1 out of 79 fish). They also found that the fish were capable of enduring a longer period of starvation (30.5 weeks) but with an increased mortality rate (8 out of 54 fish). However, the young sockeye salmon utilize energy due to the fact that they are continually being subjected to stresses such as attacks from predators, temperature fluctuations, and competition with rivals for food. The lack of food can contribute to mortality of the young sockeye by depriving them of energy
required to sustain life in the natural environment.

McCart (1966) found that seven species of fish were preying on the sockeye fry: rainbow trout, cutthroat trout, coho salmon, Dolly Varden, lake trout, lake whitefish, and burbot. The rate of mortality was high (6.7 fish per predator stomach) in the Upper Babine River, a river which joins Nilkitkwa and Babine Lakes while the rate of mortality was low (0.4 fish per predator stomach) in Babine Lake. The high rate of predation appears to be due to the greater availability of fry on the Upper Babine River.

The size of the sockeye fry population is not stable. One year a large number of fry enter the lake and the next year a small number of fry enter the lake; for example, in 1958, $189 \times 10^6$ fry entered the lake and in 1959, $95 \times 10^6$ fry emerged from the streams and spawning channels. The result is that there is a continually fluctuating population of predators and prey.

In Babine and Nilkitkwa Lakes fish are not the only predators of the sockeye fry. The Bonaparte gull and the American merganser were seen on the Upper Babine River. Although an accurate assessment was not made, the birds appeared to be feeding on the sockeye fry (Allan, 1953-54).

There is evidence which indicates that the predator population size may vary relative to the fry population size although there is a time lag involved. Ward and Larkin (1964) found that the condition of the rainbow trout in the western region of Shuswap Lake was relatively poor when the juvenile sockeye were scarce. The substandard condition of the trout presumably would result in an increased mortality rate and a
reduction in the number of rainbow trout predators. The following year the young sockeye salmon would not be as susceptible to attacks from the rainbow trout so, in that year, the number of sockeye will be high relative to the number of rainbow trout. The few rainbow trout that remained would have ample prey so that they would be expected to multiply into a large predator population which would result in a reduced number of juvenile sockeye salmon, thus completing the cycle.

Babine and Nilkitkwa Lakes support a number of smaller landlocked sockeye known as kokanee. There is no morphological criteria that could be used to distinguish sockeye progeny from andronomous parentage and sockeye fry of kokanee parentage (Johnson, 1958). However, the eggs are smaller and the kokanee fry were found to be smaller when they emerged in the spring (Johnson, 1958). Estimates were established during the period August 21-25, 1957, which indicated that 26% or 22.3 million progeny of kokanee while 61.3 million or 74% of the progeny were andronomous sockeye. It is assumed that some of the fry of the non-andronomous fish may go to sea and so contribute to andronomous return of the adults (Johnson, 1958). It is also possible that the kokanee were progeny of the andronomous sockeye. Thus, it is difficult to establish an accurate figure for non-andronomous sockeye.

The probability band which defines the relationship between the number of fry (fingerling) and smolts was based on the estimated number of fingerlings in the lake for the years 1956-1961 (data obtained from Pacific Biological Station) and the resulting number of smolts leaving the lake for those years.
The young sockeye or smolts migrate from the Babine Lake and River System by way of the Skeena River to the sea. Once they emerge from the lake, the survival rate of the smolts depends on physical and biological factors such as the size of the smolts, the size of the smolt population, the ocean nursery conditions upon arrival, the prey density in the Skeena River and in the ocean (Ricker, 1968), and the loss of adults due to the harvesting methods employed. After one or more years of ocean life the sockeye return as adults to either spawn or be caught. The Skeena River sockeye usually mature at either 4 or 5 years of age, though the sockeye populations generally include some 3 year olds or "jacks". The jack sockeye salmon are predominantly males. For the purpose of analysis, the smolts are not classed as adults until they begin to migrate from the ocean to the spawning channels and tributaries of the Babine and Nilkitkwa Lakes.

The size of the smolts that leave Babine Lake and River System may be a factor that results in either increased or decreased mortality. Ricker (1969) points out that predators or parasites may kill more of a group of small fish than of large, and as an example Parker (1971) demonstrated that juvenile coho salmon is a predator of juvenile pink salmon until the juvenile pink salmon reach a certain size. He found the growth rate of coho salmon to be .7%/day while the pink salmon had a growth rate of 1.4%/day. Thus, the survival of the pink salmon increases as they "outgrow" their suitability as prey for the juvenile coho salmon. However, there is also a possibility that the larger smolts are the prey for larger predators that would ignore the smaller smolts.

The size of the smolt population that leave the lakes is a factor
RELATIONSHIP BETWEEN NO. OF SMOLTS AND NO. OF ADULTS.

FIG 4.5
in determining the adult population return. A high density of smolts at the mouth of the Skeena River, which is likely to develop as a result of the smolts leaving Babine and Nilkitkwa Lakes at the same time, may attract large numbers of predators such as the coho salmon. The density of smolts would not be high at the mouth of the Skeena River if the smolts arrive at intervals. However, the mortality rate could be similar. This time the number of smolts would be supporting the resident predation population which may have the ability to crop the prey population at a constant rate. It is possible that smolts depend on a high dispersion rate in order to avoid the predators at the mouth of the Skeena River.

The survival of the young smolts is thought to be dependent largely on the distance that the smolts have to travel from the lakes to the feeding grounds which may be located several miles off the mouth of the river. A high concentration of zooplankton (mg dry weight/m³) which is the source of food for the young smolts is associated with a high level of primary productivity. In the case of the Fraser River estuary, the maximum level of primary production is located several miles offshore and is dependent on such factors as the increased availability of light due to decreased sedimentation, mixing processes with distance, and a time factor which allows the cells of the phytoplankton to increase exponentially as the water moves away from the river mouth (Parsons et al, 1969). If the smolts have to swim a long distance to the feeding grounds and they are a suitable size as prey for such predators as coho salmon, then they are susceptible to increased attacks and mortality will increase.

There are difficulties in studying the subject of predator-prey relationships in the ocean because of the interrelations that are likely
to exist between the predator populations and the prey populations. Predator density may or may not be related to the emergence of the smolt population. There may be certain times of the year where other prey are in short supply and thus, for certain periods the smolts are the most available source of food for a host of predators. Certain species of fish, such as coho salmon, may act as predators for a certain period of the smolt life cycle, but not after the smolts reach a certain size. These predators could reduce the smolt population substantially at that stage in the life cycle of the sockeye salmon; however, they would not be a factor contributing to mortality at a later stage in the life cycle of the sockeye salmon.

There may be a high mortality factor attached to the harvesting method employed. Adult sockeye salmon that become entangled with the fishing nets and drop out before the net is taken in are not counted as returning adults in the analysis. These fish are part of the mortality figure, presumably they die prematurely as a result of damage sustained. The information supplied by the Pacific Biological Station, Nanaimo, covered the years 1949 to 1972. The basic relationship between smolts and adult returns is presented in the form of a probability band which is based on counts of the smolts and adult returns.

Combining the Component Relationships

The component relationships were each transformed into probability matrices on the assumption that a "skew normal" probability distribution could be fitted to the upper and lower probability limits with the limits being two standard deviations from the mode. A "skew normal" distribution is simply a composite of two halves of the two different normal dis-
tributions adjusted to meet in the center and maintain the area under the curve equal to 1.0. Another distribution could have been used. Neverthe­less, a skew normal had been used elsewhere (Hershman, 1974) and a computer program for the conversion was available. Once the component relationships had been converted to probability matrices they were combined by multiplying the matrices together to obtain one overall probability matrix (Table 3.1). This has been converted back to a probability band, as shown in Fig. 3.1, and records of actual escapements (Jordan and Smith, 1972) with corresponding numbers of returning adults have been plotted for comparison.
CHAPTER 5

UTILITY

Introduction

It can be shown (de Neufville and Stafford, 1972) that to be consistent, a decision maker must choose the course of action with the maximum expected utility. The expected utility

$$E(U) = P_i(U_i)$$

where $P_i$ = probability of outcome i, and

$$U_i = \text{utility (relative desirability) of outcome i.}$$

The utilities of particular outcomes in a specific situation are obtained by first assigning arbitrary numbers to the best and worst outcomes under consideration (generally 100 and 0 or 1 and 0). Next, for an intermediate outcome the decision maker is asked, "what chance of obtaining the best outcome (with the complementary chance of obtaining the worst) is equivalent to obtaining this particular outcome for certain?" Chances are expressed as a percentage if using the scale 0 to 100, or as a fraction if using 0 to 1. The answer gives its utility.

Utility of the Current Year's Catch

Developing a utility curve for the Babine system sockeye salmon catch involves subjective judgment on the part of the Skeena River Management Committee, the body responsible for management of the fishery. The Skeena River Management Committee would have to take into account not only the economic advantage of a large sockeye catch, but also the disadvantage of possibly interfering with the management of other species
such as chinook and steelhead, the needs of the Indian fishery, and the need to maintain the run. Fig. 5.1 shows the curve used in the present study. It is believed to be reasonably representative and adequate for purposes of illustration.

The "worst" normal case was assumed to be a catch of 400,000 (utility value 0, Fig. 5.1). Below that a curve goes sharply negative reflecting the fact that at lower figures there would be severe social problems, it could be difficult to control fishing and the whole run could be endangered. A catch of 3.5 million is assumed to be the "best" (utility value of 100, Fig. 5.1). Returns are excellent and processing facilities are not overloaded. Higher catches mean higher returns, but also more overloading of processing facilities and the interference in the management of other species. Above a catch of 3.5 million the utility decreases to reflect the increasing negative effects of greatest numbers. As an example of the meaning of utility, a decision maker would be reasonably satisfied with a catch of 1.7 million (50 utility points) and would consider this as equivalent to a 50-50 chance of having a catch of 400,000 (0 utility points which would be considered as highly unsatisfactory) or a catch of 3.5 million (100 utility points which would be considered to be excellent).

The expected utility of the current year's catch, $E(C)$, at the time the decision is being made is:

$$E(C) = \xi U(R_i - E)P_i$$

where $R_i =$ Number of returning adults,

$E =$ Escapement,

$(R_i - E) =$ Catch,

$R_i =$ Probability that there are $R_i$ returning adults (obtained from forecast), and
UTILITY CURVE FOR CATCH.

FIG 5.1
\( U(R_i - E) = \text{Utility of catch } (R_i - E) \) (obtained from Fig. 5.1).

**Expected Utility of the Escapement**

The matrix relating escapement to numbers of returning adults (Table 3.1) gives the probabilities of various numbers of returning adults in the next cycle resulting from a recommended escapement in the current year. The expected utility of the escapement, thus, is:

\[
E(e) = \varepsilon U(R_{ie} - F) \cdot P_{ie}
\]

where \( F \) = average escapement,

\( R_{ie} \) = number of returning adults in cycle year,

\( (R_{ie} - F) \) = catch in cycle year, and

\( P_{ie} \) = probability that there will be \( R_{ie} \) returning adults if escapement in current year is \( e \).

In the above, the average escapement \( F \) is used to simplify the computations. In the study, \( F \) was taken as equal to 620,000, the average escapement during the period from 1957 to 1967.

The future catch is assumed to be realized in 4 years time. Thus, it seems proper to discount the future catch. For the present purposes the rate has been taken as 10\% per year which probably errors on the high side.

**The Total Expected Utility of the Current Year's Run**

The total expected utility of the current year's run, including both the catch and the escapement, thus, is:

\[
E(C) + \frac{E(e)}{(1.1)^4}, \text{ which is equal to }
\]

\[
\varepsilon U(R_i - E)P_{ie} + \varepsilon U(R_{ie} - F) \cdot P_{ie} \frac{1}{(1.1)^4}
\]
Computing the Recommended Escapement with the Maximum Total Expected Utility

A forecast is made of the number of returning adults in the current year and with the utility curve for the catch (Fig. 5.1) and a matrix relating numbers of adults returning in the cycle year to the recommended escapement in the current year, it is then possible to compute the total expected utility for a range of possible escapements. A forecast was simply assumed to be normally distributed with a mean of 1,400,000 and a standard deviation of 500,000. This was derived from the actual numbers recorded during the period from 1957 to 1967 and this is roughly what one would assume if there were no forecasts and had to rely on records. The relationship between the expected utility and the calculated escapement is shown in Fig. 5.2. The optimal escapement in this case is 720,000 but any value between 650,000 and 800,000 would be quite acceptable.
TOTAL EXPECTED UTILITY ASSOCIATED WITH ESCAPEMENT DECISION.

FIG 5.2
CHAPTER 6

DISCUSSION

The example given above is intended to illustrate a procedure and approach rather than to document an actual working example. This approach could be used to make a decision provided all of the factors in the analysis were examined carefully and agreed with those responsible for the decision. For example, great care would be necessary in establishing the utility curve; the fact that some sockeye return after 3, 4, and 5 years would have to be taken into account. The discount value of future returns would need to be examined as would the skew normal distribution. These factors could be dealt with. The concepts have been used elsewhere (Caselton and Russell, 1976) and it would be quite possible to extend the analysis to find the present value of a future salmon run.

With the procedure outlined for handling separate components of the salmon life cycle, it should be possible to compute an expected value for any proposed change affecting any of the component relationships (Brox, 1976). This could be a useful tool in evaluating enhancement decision possibilities that otherwise are difficult to compare. For example, in order to increase the adult return of sockeye salmon, should the decision maker construct spawning channels or fertilize the lake?

It has been suggested by Mr. Howard Smith of the Pacific Biological Station that the final probability matrix developed could act as a forecast table for the fishing industry. A long range forecast would be particularly useful for the fish processing plants that order cans and equipment well in advance of the fishing season.
The procedure brings an objective approach to the area of resource management. The procedure does encourage direct debate on controversial points yet it reduces the possibility of arguments at cross purposes. Thus, wiser decisions and a general increase in understanding should prevail.
CHAPTER 7

FUTURE DEVELOPMENT

This thesis deals with operational decision-making, namely the escapement to aim for in the current year. It is meant for use in real time using forecast information about the current year's run and the utility or value of the catch in the current year.

The technique could be used to evaluate possible enhancement projects. The basic procedure of examining various stages of the salmon life cycle tends itself to assess the effects of changes in one or more stages of the cycle on the total run. Information on the immediate effects of changes such as increasing spawning channels, would come from present available information and from past research and experience. Information need not be precise to be usable, but the procedure permits the use of all available information. It could be extended to assess the value of additional information and hence could be a valuable aid in assigning research priorities.

The technique could also be used for assessing alternate management strategies. For example, it could be possible to evaluate different methods of harvesting such as the use of traps as opposed to utilizing a fishing fleet, in terms of potential benefits versus social consequences.
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