OPTIMAL MANAGEMENT OF THE
FRASER RIVER SOCKEYE SALMON

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ABSTRACT

The question to which this study is addressed is: can the Fraser River sockeye salmon fishery be managed in such a way as to maximize its present worth? A review of the existing biological and economics literature would suggest that such optimal management is indeed possible.

Putting numbers into the theoretical equations and solving for an optimal solution has been based on a three part approach. First, a Ricker form of recruitment function was used to model the basic interseasonal relationship between spawning escapement and subsequent future recruitment. Second, nonlinear production functions were used to model the harvesting process in a highly cyclical fishery spread out over a fairly extensive fishing gauntlet.

And third, it is assumed that the manager is faced with two inter-related problems which must be solved simultaneously: he must decide the optimal escapement which has future revenue consequences in terms of size of catch and future cost consequences in terms of size of the subsequent recruitment (the larger the recruitment, the lower the harvesting costs), and he must decide the least cost spatial combination of harvesting gear to take the specified catch.

The major finding of this study is that it is possible to
manage the Fraser River sockeye salmon fishery in an optimal manner and to do so would increase its present worth substantially. The use of cycle dummy variables to allow for the marked four year cycles in both recruitment and harvesting patterns plays a major role in improving parameter estimation. Nonlinear programming techniques can be developed to allow the simultaneous determination of the optimal intertemporal spawning escapement and the least cost spatial allocation of effort to harvest the optimal catch.

The original contribution of this dissertation lies in its use of deterministic models to empirically solve the problem of optimal management of a fishery.
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CHAPTER ONE: FISHERIES ECONOMICS AND THE FRASER RIVER SOCKEYE SALMON

I INTRODUCTION

This thesis is concerned with illustrating how best to manage the Fraser River sockeye salmon fishery. The study does not attempt to contribute to the theory of the optimal management of fishery stocks. As Peterson and Fisher (1977, p. 691) have pointed out, most of the theoretical models "cannot be used to manage actual natural resources, because their functional forms are too simple and their empirical content too low. With most fisheries, for instance, we do not know what the maximum sustainable yield is with any degree of accuracy, let alone the parameters of the growth and production functions. With expanded co-operation between natural scientists and economists, the empirical base might be developed to the point where the dynamic optimizing models could offer practical guidance to managers of fisheries."

The purpose of this thesis is to expand the "empirical base" for the Fraser River sockeye system and to show how these data can be used in a dynamic optimizing model to guide the managers of this salmon stock. The basis for this dynamic optimizing is the theoretical model developed by Clark and Munro (1975).

Optimal management has been the concern of resource economists ever since Hotelling's first attempts to grapple with the problem in 1931 (Hotelling, 1931). And it is only recently that economists have solved the problem on a theoretical level. Recent works in economic literature have reduced the theoretical complexities to the point where it is possible to start injecting empirical material to handle the practical problem of
optimal management. However, the task of transforming theory into empirically useful models is not simple and requires rather large amounts of information. For this reason the Fraser River sockeye salmon fishery was chosen for study as it has had a comprehensive data base for a long period of time.

(1) The Model

The need for management of the Fraser River sockeye arises from the international interception problem, the problem of spatial misallocation of harvesting effort on the fishing grounds and the problem of economic rent dissipation which results from the open access nature of the resource. The Fraser River sockeye fishery is a gauntlet type where the fish migrate through the Strait of Juan de Fuca and the Strait of Georgia and into the mouth of the Fraser River. During migration they pass through both U.S. and Canadian waters and are vulnerable to the fishing gear of fishermen from both countries. Since 1937 there has been an equal catch agreement between both countries regardless of harvesting costs. One of the problems addressed by this study is the measurement of the social costs imposed by such an agreement.

Because the sockeye are not equally dispersed throughout the gauntlet but swim through the gauntlet in one direction, gear harvesting earlier in the gauntlet can impose costs on gear harvesting later in the gauntlet by reducing the migration of sockeye. If the fish are easier to catch in the early part of the gauntlet, there is no problem. However, if harvesting is more efficient in later parts of the gauntlet, there is a social
cost involved in this spatial misallocation of harvesting effort. This study attempts to measure those social costs and to indicate how they could be reduced through spatial relocation of harvesting effort.

The common property problems associated with open access resources can best be summarized as an intertemporal misallocation of harvesting effort. Investment in future migrations of sockeye are made by abstaining from current harvesting. However, if a fisherman knows he cannot reap the full reward from his investment because of the open access nature of the fishery, he will not abstain from current fishing. The result is declining future migrations leading to smaller and smaller catches. Once again, this study attempts to measure the social costs which arise from such a common property problem and to indicate how they could be reduced by altering the intertemporal allocation of harvesting effort.

In order to manage the Fraser River sockeye fishery, a manager must work with a three part model. The first part is a biological system in which parent fish escaping from the nets of fishermen ascend the Fraser River system to spawn and die. The second part of the management model is an economic system in which fishermen have twelve weeks to harvest the fish migrating through the gauntlet. And the third part of the model is a management system which allocates harvesting effort so as to maximize the present value of the fishery through optimal intertemporal allocation of that harvesting effort, taking into account the social costs of international sharing of the catch and the costs of harvesting through least cost spatial
allocation of that harvesting effort.

(2) Making The Model Operational

To make this model operational requires a three stage process of obtaining data, estimating parameters and programming to achieve the optimal values. There are nearly two hundred thousand observations on the Fraser River sockeye fishery scattered in various journals and books in B.C. and Washington which means that data retrieval is a very involved task. Despite these data, many aspects of the management model had to be ignored because of the lack of observations. Furthermore, even where data did exist, some could not be used because of the need to make the model operational. That is, there are certain aspects of the problem over which a manager has little or no control and these must be excluded even though data exist to aid in devising solutions.

When sockeye escape from fishing gear they migrate up the Fraser River system until they reach their natal stream where they spawn, bury the fertilized eggs and die. The eggs hatch the following spring and the immature salmon swim to a lake where they spend a year preparing for the migration to ocean feeding grounds the following spring. They spend two winters in those ocean areas and return to spawn as mature, four year old sockeye by migrating through the fishing grounds.

The fishery manager can increase that migration either by enhancing the migration routes and spawning beds or by abstaining from fishing to allow a greater escapement of parents. Data on enhancement methods for the Fraser River...
sockeye do exist but are restricted in application and difficult to work with. Therefore, only escapement and catch data will be analysed. If we can assume that migration is the sum of escapement and catch, we can then attempt to estimate the parameters of the relationship between escapement and subsequent recruitment. Data also exist on the escapement of the eleven major races of Fraser River sockeye. However, as it is a very complex problem to model the race proportions in the subsequent recruitment, escapement and recruitment were analysed in aggregate form only. (This is not strictly correct: see Ricker, 1973b.)

Chapter Two of this study provides the parameter estimates for this biological relationship and is the basis of the biological part of the management model. Therefore, the first restrictive assumption is that the manager controls the biological system only to the extent that he controls the escapement of spawning parents.

Sockeye are harvested by four different gear types operating in seven fishing zones in the gauntlet. Data were not available for the processing industry (canning and freezing plants) but were available for catch and deliveries by gear type in each zone for the twelve week sockeye fishing season. Data also exist for the catch of four other species of salmon besides sockeye. If we can assume that deliveries can be transformed into harvesting effort, it is then possible to estimate the parameters of the relationship between catch and effort and the migration of sockeye calculated earlier. Chapter Three provides the parameter estimates for those harvesting production
functions and they form the basis of the economic part of the management model. The second restrictive assumption of the study is that the manager controls harvesting only to the extent that certain gear types are permitted to harvest sockeye in certain fishing zones for certain periods of time.

No attempt is made to account for the influence of the processing sector on the harvesting of sockeye, however, it can be assumed that competition amongst processors is adequate from an economic point of view. Despite increasing concentration over the last twenty-five years, Japanese, U.S. and Canadian investment in processing in both Washington and B.C. has turned the salmon fishing industry into an internationally financed industry operating in international trade markets. Fortunately, there is no need to include processors in the analysis if we can assume that fishermen are fairly mobile between processors. From discussions with processors, fishermen and officials in the departments of fisheries for both Washington and Canada, mobility of fishermen does not appear to be a problem. Processors engage in all types of non-price competition, particularly subsidized credit costs for purchase of boats and gear, to attract fishermen. The result is that most fishermen remain "loyal" during a single season but many switch loyalties between seasons.

Although biological data exist for the four species of salmon other than sockeye, the joint production nature of the harvesting production functions was ignored in parameter estimation because of the complexities of analysing a multi-species fishery. However, this joint production problem was
included in the management programming by using a system of capacity constraints to allow for the catch of salmon other than sockeye.

The transnational interception problem can be studied from the point of view of differing national tastes, social rates of discount and harvesting costs (Munro, 1979). Only limited data exist for gear type unit harvesting costs in Washington but adequate data do exist for B.C. Therefore, differences in costs of harvesting are restricted to production function effects. That is, it was assumed that gear type unit harvesting costs were the same for both countries but that gear efficiency was different as indicated by the parameter estimation for the harvesting production functions. Landed prices for sockeye were available for the two countries and price differentials were permitted at one point (Chapter Four) to affect harvesting proportions.

Although the data probably do exist to determine differences in consumer preferences and the social rates of discount, the exclusion of the processing sector and the difficulty in determining reaction functions in a bargaining model precluded work in these areas. Therefore, the third restrictive assumption of the study is that the manager is allowed to allocate country catch proportions only on the basis of differences in harvesting costs.

Programming to achieve the optimal values was divided into two parts. In the first part, landed prices and unit harvesting costs were obtained for each gear type operating in the seven major fishing zones; and, using historical values for migration,
catch and escapement, a profit maximizing routine was devised to permit relocation of harvesting gear in the gauntlet to take advantage of differences in levels of migration in each fishing zone, differences in gear type efficiency and differences in effort costs. Because harvesting production functions are nonlinear, more than one gear type could be chosen to harvest the sockeye catch. In fact, two gear types operating in four fishing zones proved to be far more profitable than the rest. These were chosen for subsequent programming work and their configuration of harvesting proportions was used as a basis for judging actual historical harvesting profits. The profit differential between the hypothetical configuration and the actual historical one indicated that social costs were incurred by an inappropriate spatial allocation of effort. The results are recorded in the last part of Chapter Three.

The second part of the programming for optimal values was designed to check both the least cost spatial location of gear and the intertemporal allocation of harvesting effort. That is, the program checks in two dimensions, the spatial and the intertemporal, to maximize profits over time. The basis of the intertemporal dimension is the Clark-Munro equilibrium equation which takes the rate of return on the fishery, allowing for the physical productivity of the sockeye themselves, the profits from catching sockeye and the cost reducing aspects of larger sockeye migrations, and sets this rate of return equal to the social rate of return.

The basis of the spatial dimension is the profit maximizing program used to choose the most profitable spatial configuration
of harvesting effort. This configuration is very sensitive to alterations in the relationship between catch and migrations, whereas the intertemporal allocation of harvesting effort is very sensitive to the profits from harvesting a specified catch. Therefore, the program must iterate between these two dimensions until profits are maximized for both simultaneously. Optimal equilibrium values are found for the catch, migration, escapement and gear type catch proportions by checking various combinations of catch and recruitment against various harvesting configurations to find the combination and configuration which maximizes the present value of the fishery. The results of the optimal value programming are given in Chapter Four.

In the intertemporal model there should be three capital stocks of interest: the stock of fish, the stock of vessels and the stock of capital equipment used in processing the catch. The lack of available data for the processing industry precludes any analysis of processing capital equipment. Data do exist for the stock of vessels but modeling requires a knowledge of capital malleability (Clark, Clarke and Munro, 1979) and the data do not exist for estimating this malleability parameter. Instead, it will be assumed that vessel capital is perfectly malleable. Extensive data do exist, however, for the stock of fish. For these reasons, it will be assumed that the stock of fish is the only capital stock in the model.
(3) Alternative Systems Of Management

To make the model operational a number of restrictive assumptions have been made. In particular, the study is restricted to a partial equilibrium approach. It will be assumed that: opportunity costs are constant; the harvest rate is equal to the consumption rate (Clark and Munro, 1975, p.95); the social rate of discount reflects perfectly the marginal product of capital plus percent capital gains and is, therefore, equal to the social time preference rate; systematic risk can be ignored; and that output from the sockeye fishery is too small to influence the overall price of salmon.

To avoid second-best problems which can arise from monopoly power, management will be vested in an international agency and it will be assumed that artificial scarcities cannot take place. Even if output constraints were permitted and pricing rules devised to attain second-best (Allingham and Archibald, 1973), it is not clear that these would be valid in an intertemporal framework. That is, there are other sectors of the economy which may be at first best static optimum and yet not at first best intertemporal optimum (see the public sector example in Arrow and Kurz, 1970). The complexities involved in calculating time paths for the pricing rules to reach some kind of second best intertemporal optimum would be formidable. For these reasons, this study will assume that the rest of the economy is at first best intertemporal optimum.

Within the sockeye fishery, only an economic profit derived from the inherent nature of the problem will be permitted. And the rent derived therefrom will be assumed dispersed in lump sum
form so as to create no allocative distortions.

Most of these assumptions are made because the data do not exist to allow the model to be generalized or because inclusion of some of these factors would complicate an already complex model. That is, the model includes only those factors which can be quantified and which are essential to optimal management of the Fraser River sockeye fishery. The data retrieval, parameter estimation and optimal value programming even for these most essential biological and economic factors have been very involved.

Comparison of the model used in this study with alternative models indicates which essential parts of the model must be retained to give some indication of optimal management. For many years the Fraser River sockeye fishery has been managed according to biological criteria and certain economic criteria. Great progress has been made in increasing the sockeye-run potential and in preventing economic demise through overfishing and destroying the stock of sockeye. But very little has been written about the economics or about fishermen and their returns. Harvesting effort has been regulated to facilitate control of sockeye escapement and to prevent uneconomic overfishing; and some attempt has been made by respective governments to stop the steady increase in harvesting effort capacity. The economic distress caused by this increase in harvesting capacity has resulted in both B.C. and Washington imposing license limitation schemes. A management model must, therefore, include economic factors if it is to be expected to lead to optimal exploitation of the resource.
A management model with a biological element and effort limitation could lead to static profit maximization. That is, harvesting gear could be allocated to certain areas of the gauntlet in restricted numbers so as to take the specified catch in the least cost manner. This would, in fact, maximize profits each season. The results would appear to be superior to a management model based on biology alone. However, the capital theoretic problem involved in the decision to invest in future migrations has still been ignored.

In the early history of fishery management there was a tendency to emphasize the harvesting on a sustained basis of the largest catch that the biological system could bear. This is usually at some intermediate size of stock in terms of migrating parents. If too few adults escape, subsequent migrations and catches will be smaller. It is equally true that if too many adults escape, subsequent migrations and catches will also be smaller because of the destruction of spawning beds by large numbers of spawning parents.

However, harvesting the largest catch is unlikely to be the most profitable way of harvesting. It is true that profits are influenced by the total revenue derived from selling the catch. But profits are also influenced by the costs of taking that catch. Harvesting production functions indicate that the larger the catch, the more effort required to land that catch unless there is some offset by increased migrations of sockeye which makes it easier to catch them. It is highly unlikely that the largest sustainable catch is associated with the largest sustainable migration.
Static profit maximization is not good enough: there must be intertemporal profit maximization in order to maximize the present value of the fishery. The model developed in this study includes all these essential features: the biological system, the least cost harvesting system and the intertemporal view of harvesting in which the rate of return on the fishery is equated with the social rate of return. Despite the many considerations which have been ignored, these three essential parts of the model can give some indication of the optimal management of the Fraser River sockeye fishery. Once the data become available, a more general model can include some of these considerations and will probably give superior results.

(4) Survey Of The Thesis

Part II of this chapter reviews the jurisdictional limits to the management of the Fraser River sockeye salmon fishery. Included is a history of management practices in the past. Part III of this chapter reviews the biology of the Fraser River sockeye and discusses the compilation of biological data and the essential elements of parameter estimation for the biological relationships. Part IV surveys the economic theory of fisheries management and discusses the main features of the Clark-Munro equilibrium equation. Included in this part is a discussion of the harvesting model and the management model.

In Chapter Two a biological model is developed which relates the escapement of sockeye from fishermen's nets to the return migration (called recruitment) four years later. In Chapter Three a harvesting model is developed which will tell us
the costs involved in taking a specific catch given a certain run or recruitment. Chapter Four takes the recruitment model and the harvesting costs model and combines them into a management model. In it, the manager decides both how to harvest a given run of sockeye at least cost, and how to obtain a division of that run into catch and escapement so as to get a subsequent catch and escapement which will maximize the present value of the fishery.

With the data presently available it will be possible to develop the recruitment model and the harvesting model for the Fraser sockeye. Using the prices and costs which are also available, it will then be possible to estimate the optimal stock level and the optimal amount of effort needed to harvest from that stock. The results permit comparison of the actual management experience over the period 1951 to 1975 with a hypothetical situation in which a sole owner had been charged with the task of maximizing the present value of the fishery. The results can be used to test different managerial systems and this has been done at different points in the study.

II MANAGEMENT OF THE FRASER RIVER SOCKEYE

There are a number of jurisdictional limits on the management of the Fraser River sockeye because of the transnational nature of the fishing gauntlet. These limits place certain constraints on the management model and it is useful to have some idea of the historical experience of sockeye management within these limits.
Historically the Fraser River sockeye salmon have been managed through a transnational commission operating through the relevant legal administration in each jurisdiction. And, although the commission is charged only with the biological, not the economic, management of the fishery, many of its efforts have been directed toward preventing the economic catastrophe which can result from the common property problem. Despite the very serious nature of this problem, management has been constrained by the structure of the fishing industry and the economic rationalization programs instituted recently.

From 1900 to 1913 catches were very large but steadily declining as catching efficiency and profits drove fishermen to exploit the resource more heavily. In 1913 there was a serious slide in the Fraser River Canyon which, together with the heavy exploitation, reduced the Fraser River sockeye to a less significant fishery. Pressure from processors and fishermen culminated in the signing of a treaty convention in 1930 which included provisions for an equal division of the sockeye catch and enhancement programs to restore yields to previous levels. However, this treaty was not ratified until 1937 because of the political nature of the interception problem. Prior to that date, the Canadian Department of Fisheries had jurisdiction over Canadian territorial waters and the State of Washington Department of Fisheries had jurisdiction over U.S. waters.

The Sockeye Salmon Fisheries Convention

"applies to the territorial waters and high seas westward of Canada and the United States from a line between Bonilla Point, Vancouver Island, and Tatoosh Island, Washington. It includes all such waters between 48 and 49 degrees north latitude, excepting Barkley Sound and Nitinat Lake. Eastward of this line,"
it includes the Strait of Juan de Fuca, the Strait of Georgia as far as Lasqueti Island -- excepting Howe Sound and the waters east of Whidbey Island -- and the Fraser River and its tributaries.

Regulations enacted by the International Pacific Salmon Fisheries Commission are enforced within the territories of each nation solely by the government of that nation. The Commission has no power to authorize any type of fishing gear contrary to laws of the State of Washington or the Dominion of Canada.

The Convention required research for eight years before power to regulate the catch was given to the Commission. During this time studies were made of the salmon runs and of the river, and obstructions to the migration of salmon were removed. In addition, the Commission collected detailed and excellent statistics of the total sockeye runs. Regulation of the Fraser River and Puget Sound sockeye fisheries was undertaken for the first time by the Commission in 1946.

The responsibilities of the Commission were enlarged to include pink salmon stocks of the Fraser River by an amendment which was signed on 28, December, 1956.

Essentially the Commission has the responsibility to decide on the required escapement and the permissable catch from each run of pink and sockeye salmon and to recommend regulations to the Government of Canada and to the State of Washington which will allow an even division of the catch between the fishermen of Canada and the United States." (Royce-Bevan, 1963, pp.6-8)

The first attempt at regulation of fishing effort was made by the IPSFC in 1946. Their techniques were refined so that by 1951, mesh size, length of nets, area closures by gear type and weekly limits on days of fishing had settled into a consistent pattern. The IPSFC also worked on enhancement through removal of obstructions and the construction of fish ladders. After the removal of the Hell's Gate obstruction, recruitment to the fishery increased significantly. This led to increasing investment in gear and vessels to enhance catching ability during permitted times and in open areas. The ratio of capital
investment to catch rose rapidly (McMyan, 1965, p.152) leading to increasingly restrictive measures on the part of the IPSFC: "the effect of increasing units of gear, greater gear efficiency, and expanded fishing area in convention waters has been largely offset by reduced fishing time" (IPSFC, 1961, p.16).

The result of most of these regulations designed to prevent disastrous overfishing has been to create distortions in the structure of the sockeye fishing industry. The intra-seasonal closed periods are normally too short and irregular to permit fishermen to look for alternative employment during the fishing season. Increased gear efficiency and availability of gear has led to increased congestion and gear interference. And the bunching of deliveries because of the severe curtailment of permissible fishing days (as few as two per week in some areas) has led to more packers and collector boats, more overtime hours in shore-based plants, greater investment in plant capacity and fish storage facilities (Sinclair, 1960, p.135). The reason for these distortions arises from the legal constraints on the IPSFC attempts to limit effort. Support and reinforcement of these IPSFC measures by the respective governments has been reluctant and inadequate.

Turning to the Canadian administration of salmon fishing, it is important to note that the federal government has jurisdiction over the salmon until they are actually landed. The legislative jurisdiction over seacoast and inland fisheries is vested in the federal government under Section 92 of the BNA Act, but under the same section the provinces get property
rights over anything taken or caught in those waters. As a result of Privy Council decisions in 1898, 1913 and 1920, the federal government handed over the administration of non-tidal sport and commercial fisheries to the provincial government in B.C. but retained the sole right to enact any provincial legislation which affects them. The federal government retained all rights to marine and anadromous species.

One of the major sources of cost to fisheries in B.C. is the confusion over jurisdictions and the pre-emptive rights of the federal government in fisheries affairs through different pieces of federal legislation covering fisheries, navigation, and transboundary interests. For projects affecting fisheries there is seldom a co-ordinated joint impact study which means that priorities are based on chronology rather than on efficiency. The federal government deals with fishing while the provincial government deals with landed fish.

Despite these jurisdictional problems and because of protection and enhancement, the value of the salmon catch has risen, investment in gear and vessels has increased and technical change has been rapid. And yet the incomes of salmon fishermen have not kept pace even though a strong union acts as a unit in bargaining with processors to set prices (see Campbell, 1969 and Canada, 1971). It appears that total costs had been pushed to an equilibrium with total revenues. To counteract this, in the B.C. fishery, the federal government, using its powers under the Fisheries Act, instituted a rationalization policy in 1968. For similar reasons the State of Washington enacted a rationalization policy in 1974.
From a study of the historical record it appears that the U.S. and Canada have had some type of catch agreement since 1937. The U.S. has attempted to maintain a proprietary interest in Fraser River sockeye salmon by participating in abstention through the IPSFC and by helping to finance enhancement programs on the Fraser. This has led to an equal sharing of the sockeye catch but neither party has been interested in maximizing the resource royalty potential from the fishery. The institutional arrangements have probably worked well in terms of minimizing transaction, agreement and compliance costs (and the economic costs associated with destructive overfishing). However, they appear to have failed in terms of minimizing user and abstention costs.

The management model developed in this study will be constrained by a number of these considerations. The major reason is the lack of data which could have been used as a guide when releasing such constraints. It will be assumed that management will remain in the hands of the IPSFC because of the transnational nature of the interception problem and because of the very capable management of the IPSFC given the highly restrictive legal constraints in the existing convention. Therefore, the terms of reference of the IPSFC will be assumed to be broadened to include economic management as well.

The IPSFC could take the whole sockeye catch with a few, well placed traps in the mouth of the Fraser River (Crutchfield and Pontecorvo, 1969). However, only limited data exist for traps. For sockeye catches taken by traps since 1951, data do exist for the traps in Sooke Harbour but only for seven years.
It is also unlikely that either government would wish to reduce employment in the fishing industry by introducing such a harvesting system. For these reasons, the IPSFC will be constrained to using the usual gear types, although they will be able to assign or exclude certain gear types from certain fishing zones.

The use of fish finding equipment and monofilament nets (which cannot be seen by sockeye) must also be excluded for the same reasons. There does not appear to be any data available for changes in gear type productivity associated with these innovations but one can presume that productivity increases were considerable given the speed with which this gear was banned by both governments. The employment-reducing effects will be assumed to be not politically feasible given the transnational background to the catching agreement.

It will be assumed that the IPSFC is restricted to managing in the physical areas delineated above and to a twelve week period including July, August and September (two weeks earlier in the first part of the gauntlet and two weeks later in the last part). These spatial and temporal limits would encompass ninety-five percent of the sockeye catch. This harvesting of sockeye can have a serious impact on stocks of the other four species of salmon. This is particularly true for the run of pink salmon which occurs every other year only but takes place at the same time as the sockeye run. However, the IPSFC currently has jurisdiction over the pink salmon escapement; and this jurisdiction is assumed to include harvesting.

Area and time closures, the methods used for controlling
escapements in the past, will only apply to areas which are not least cost in terms of harvesting. That is, certain gear types operating in certain fishing zones will be excluded during the sockeye-run because they are not economic and interfere with migrations of sockeye to other zones and more productive gear. The most efficient gear types will be assigned to the most efficient areas for the whole season but in restricted numbers. Gear types will no longer be restricted to two or three days a week but will be able to fish for seven days a week if they wish.

The release of this major time constraint will allow the present fleet to be able to harvest the larger catches proposed by the optimal values derived from the management programming. However, this may entail severe limits on hours per day to prevent decimation of milling stocks and, to avoid inter-gear interference, purse seines will continue to be restricted to daytime operations and gillnets to nighttime operations. A second major change is that the IPSFC will no longer manage by permitting others to fish. Instead, it will be assumed that the IPSFC itself harvests the specified catch by hiring vessels and assigning them to the appropriate areas.

To avoid over-investment in boat capital and the subsequent problems associated with the irreversible nature of such an investment, it will be assumed that the IPSFC simply hires units of effort (fishermen plus gear and boat) to take the specified catch in the specified areas. Only least cost gear and vessels will be used and the rest will be offered lump sum compensation for their capital loss.
Finally, given constant opportunity costs, it will be assumed that the most rapid approach to the equilibrium biomass level is optimal. This will, of course, only occur once in the life of the fishery. Given the past success of the IPSFC in controlling catch (despite severe constraints on its ability to limit effort), it will be assumed that this task will be made easier by the IPSFC harvesting for itself only. Therefore, if a larger escapement is optimal, the IPSFC will simply reduce the catch. If a smaller escapement is optimal, the IPSFC will simply increase the catch. The former entails a sacrifice while the latter results in greater profit. But these would be once-and-for-all as subsequent catches would always be the same after the initial year of adjustment.

III THE BIOLOGY OF THE FRASER RIVER SOCKEYE

The first part of the management model must provide a link between escapement of spawning parents and the subsequent return migration four years later. This link is often referred to as the recruitment relationship because of the "recruitment" of migrating sockeye to the fishery. As there are five species of salmon available to the nets of fishermen in the fishery through which the Fraser River sockeye salmon migrate on their way to their spawning grounds, this is a multi-species fishery. The sockeye fishing season lasts for a twelve week period every summer during which time sockeye is the dominant species both in terms of weight and in terms of value per pound. For this reason and because of the complexities involved in modeling a multi-species fishery which includes the other four species of salmon,
it was decided that a recruitment model would be developed for sockeye only.

Map (1-1) illustrates the extent of the sockeye spawning in the forty-four creeks and streams of the Fraser River watershed. As soon as the spawn hatch, they migrate to eleven fresh water lake systems connected with those creeks and streams. They spend two winters in those lakes and streams and then migrate to the ocean when the melt-water has swollen the Fraser River. They migrate to the oceanic feeding grounds which are rich in zooplankton and spend two winters in that environment. The next spring, the four year old sockeye migrate back to spawn in their natal streams.

The recruitment model gives us some idea of the return on the "in-kind" form of investment produced by abstaining from fishing in any period. The model indicates that if escapement is either too small or too large, subsequent recruitment will be small. That is, the largest recruitments arise from intermediate escapements. The work in this study supports previous studies which have found that recruitment is very sensitive to differences in average weight of sockeye, the race of sockeye, and the year class of sockeye. The cycle year class of sockeye itself appears to influence average weight, fertility, survivability and growth in a highly significant manner.

There has been extensive research both by biologists working for the IPSFC and by other biologists into the nature of the sockeye salmon stock. These studies were of great assistance in compiling the data and formulating the basic model. No attempt was made to improve on the biological nature of the
DISTRIBUTION OF SOCKEYE SALMON SPAWNING GROUNDS IN THE FRASER RIVER WATERSHED
recruitment relationship. However, every attempt was made to ensure good parameter estimates as the recruitment relationship is of fundamental importance in the management model.

Because of the four year lag between escapement and subsequent recruitment, there are four distinct year class cycles in the annual migrations. In estimating the parameters for the sockeye recruitment function, the major innovation was the inclusion of a four year cycle through the use of slope dummy variables which led to a significant improvement in fit. It should be made clear that biologists have worked with cycles for some time but there do not appear to be any studies which have incorporated cycle effects through the use of cycle dummies.

Disaggregating the escapement data according to the eleven freshwater lakes (to give race of sockeye) led to a further significant improvement in fit. The IPSFC uses time of entry models to facilitate control of escapement by race and it would be very feasible to use these parameter estimates for the management model. To include race escapement improves the parameter estimates for recruitment in aggregate form. However, to determine race proportion of the subsequent recruitment and the influence of gear type catch on recruitment to subsequent fishing zones would require intra-seasonal analysis and complicate an already complex model. For this reason the recruitment model developed in this study distinguishes between the recruitment/escapement relationship on a year class basis but not according to race.
The second part of the management model involves the harvesting of the sockeye as they migrate through the fishing gauntlet. What is of primary interest in the harvesting model is the amount of gear type effort required to land a specified catch of sockeye in different fishing zones in the gauntlet. As one would expect, the larger the migration of sockeye, the less effort required to take that catch. Taking into account the size of migration, the efficiency of various gear types and the costs associated with gear type effort, the manager must choose the least cost method of harvesting.

Once this spatial location problem has been solved, one must then consider the intertemporal nature of the fishery. A survey of the literature indicates that, given certain assumptions, the capital theoretic problem can be solved by setting the rate of return on the fishery equal to the social rate of return. This fishery rate of return must take into account the physical productivity of the stock of fish itself and the impact on harvesting profits of different combinations of catch and recruitment. Once equilibrium is achieved, the present value of the fishery is maximized.

Therefore, the management model consists of a recruitment function which provides the link between escapement and subsequent recruitment and a harvesting cost function which indicates the costs of harvesting a specified catch given a certain level of recruitment. These components are combined into a management program which varies the spatial location of the harvesting gear and the intertemporal flow of effort, catch and
recruitment until the fishery rate of return equals the social rate of return.

(1) The Harvesting Model

Given the recruitment or size of run and the escapement required to achieve that level of recruitment, the manager must decide which method of harvesting the catch is least cost. The higher the catch, the higher the costs in terms of harvesting effort. But the larger the recruitment, the lower the costs, because of greater availability of sockeye to the nets (see Bradley, 1970). That is, the same gear may have the same technical efficiency in different fishing areas but if the fish are more concentrated in one area, it is easier to take the specified catch with a minimum of effort. But, even if the concentration or "availability" of the fish is great, there is a second question, whether they are "catchable". A given recruitment availability or concentration of fish swimming very deeply and out of the reach of the fishermens' nets is far less "catchable" than if swimming near the surface.

Recruitment availability is dependent on the recruitment/escapement model which is under the control of the manager. However, the model suggests that catchability is dependent on year class cycle, over which the manager has no control. For this reason, the harvesting model is different for each of the four year class cycles.

The migration route of the sockeye is illustrated in Map (1-2). After spending time in ocean feeding grounds, four year old sockeye migrate toward the Fraser River by passing through
READ CAREFULLY

1. PIN UP IN WHEELHOUSE.
2. WHEN DELIVERING YOUR CATCH, GIVE TALLY MAN THE MAP NUMBER OR NUMBERS SHOWING THE AREA IN WHICH YOUR FISH WERE CAUGHT.
3. ACCURATE CATCH REPORTS WILL HELP PRESERVE YOUR FISHERIES.
4. FOR COMPLETE DETAILS, CONSULT BRITISH COLUMBIA FISHERIES REGULATIONS.

DEPARTMENT OF THE ENVIRONMENT
FISHERIES SERVICE

STATISTICAL MAP
SHOWING AREAS OF CATCH FOR
BRITISH COLUMBIA WATERS
(SOUTHERN HALF)
the southern half of area 24 and through areas 23 and 21. They migrate along the north side of the Strait of Juan de Fuca through areas 20 and the southern half of 19. They then enter U.S. waters and migrate through the San Juan Islands and past Point Roberts into the mouth of the Fraser River. Migrating sockeye in the Fraser River after Mission are only vulnerable to native Indians who fish for their own consumption according to treaty rights.

Ninety percent of the migrating sockeye pass through the fishing gauntlet in about six weeks with the peak of the run usually about the second week of August. The sockeye arrive in area 24 by the middle of June and have all passed Mission by the middle of October.

Sixteen gear type fishing areas can be distinguished in this fishing gauntlet. Trolls, gillnets, reefnets and purse seines in these areas account for ninety-five percent of the sockeye catch. However, gillnets and purse seines in only six of these areas account for ninety percent of the total sockeye catch. The harvesting model developed in this study is based on these six gear type areas only and assumes that costs of harvesting for these areas are dependent on size of catch (direct relationship) and availability of recruitment (modified by catchability) to that fishing area (inverse relationship). Catchability by gear type is assumed to vary on a year cycle basis for each gear type area.

The analysis of the optimal spatial distribution of effort in a gauntlet type of fishery such as this one, is fairly straightforward. The salmon follow customary routes and are
catchable in predictable ways by the sixteen different gear type harvesting areas. Common property causes a problem because fishermen will tend to move out to earlier positions in the gauntlet to overcome the crowding and congestion of gear in later areas (see Bradley, 1970). This can result in quite severe reductions in recruitment availability in other areas where gear may be more efficient.

Furthermore, inter-gear interference between purse-seines and gillnets can have a serious impact on availability to a later area where gear efficiency may be higher. The IPSFC regulations confining purse seines to daytime operations and gillnets to nighttime operations should eliminate this last problem.

The spatial allocation problem can be handled, using non-linear mathematical programming, to permit many different harvesting configurations to be tried. Only in this way can the complex interactions between gear efficiency, recruitment availability and biomass catchability be resolved to give the least cost harvesting areas.

The production function for each gear type area is sensitive to changes in catchability between seasons and also to changes in recruitment availability for any given season. Thus recruitment can be permitted to flow through to any single area for each year of the four year cycle without being reduced by fishing in areas earlier in the gauntlet. The gear type areas with the most efficient gear and the greatest catchability of that given recruitment will harvest the specified catch at least cost.
With more recruitment flowing through to certain zones and larger catches to be taken by certain gear types operating in those zones, it is clear that more effort will be needed than the historical levels of effort. This should not lead to serious complications such as congestion because the number of days of fishing per week is no longer restricted. That is, most gear type areas have historically been reduced to an average of three fishing days per week, whereas the management model used in this study can allow fishing seven days per week. In fact, only five days per week should be sufficient as the maximum increase in any gear type effort appears to be about thirty percent. Note that this change in number of days per week will not affect costs as unit opportunity costs are assumed to be constant. However, because of the possible decimation of a milling stock, if the numbers of days per week is increased, there may be a need to restrict the hours of fishing per day.

The first step in developing the harvesting model is to estimate the parameters of the production functions for the sixteen gear type areas. Effort is adjusted for technical change over the period under study. Gear type areas within each fishing zone are all assumed to experience the same availability of sockeye. However, each subsequent zone in the gauntlet experiences a reduction in the migration available by the amount of fishing by gear type areas in the previous zone. There are no data on these reduced availabilities; however, we know the actual migrations from the work with the recruitment function and we know the gear type area catches and effort from published reports. Therefore, it is a simple matter to calculate reduced
migration to subsequent zones.

Because no data were available to aid in estimating the catchability parameter, the estimation process itself was used to derive estimates by putting recruitment availability in dummy cycle form. That is, actual catches were regressed on effort adjusted for technical change and on recruitment adjusted for availability in each zone in four year cycle dummy form. This meant that the exponent on recruitment availability could be different for each of the four year classes. Allowing for varying catchability is a well established practise in biological studies. However, there do not appear to be any studies which incorporate fluctuations in catchability by using cycle dummies. These led to a significant improvement in fit.

The second step in developing the harvesting model was to convert the production functions into cost functions given available cost data. Using the actual historical averages for catch and recruitment, a nonlinear cost minimization program was then employed to achieve least cost harvesting. Profit calculations using these least cost harvesting spatial configurations were then compared with calculated profits for the actual historical harvesting experience. The results indicated that significant gains could be made by relocating gear type effort in the gauntlet.

As the various reactions to catch, recruitment availability and biomass catchability are different for each of the gear type areas for each of the four cycle years, the optimal harvesting configuration in terms of catch proportions amongst the gear type areas will be different for each of the four cycle years.
The parameter estimates for the production functions indicated increasing returns to scale for the six major gear type areas for each of the four cycle years. Although the scale does not change proportionately for each input in each cycle year, the change in recruitment availability from one cycle year to another is so large that the cycle influenced catchability exponents (recruitment elasticities) signal quite large shifts in harvesting effort from one fishing zone to another and from one gear type to another.

The profit improvements resulting from these differing harvesting configurations arise only from inter-seasonal changes in configuration. No attempt was made to alter configurations on an intra-seasonal basis. A full intra-seasonal harvesting model would involve the analysis of thousands of daily records for all gear type areas in the gauntlet. And it is not clear that the resulting spatial, cost minimizing program would be significantly different from the one based on the assumption of one least cost spatial configuration for each of the four cycle years. Loose (1977) gives an analysis of the significant profit improvements that can be realized through cost minimizing intra-seasonal harvesting patterns in a gauntlet type of fishery. However, in this study it will be assumed that the least cost harvesting configuration for any particular year of the four year cycle remains the same for the whole fishing season during that cycle year but will be different for each of the four cycle years.
(2) Optimal Fisheries Management

The purpose of the following survey is to highlight the theoretical considerations involved in managing a fisheries resource in an optimal manner. The word optimal implies maximizing the feasible present value of the resource taking into account the best relationship between catch, escapement and subsequent recruitment in terms of the biological model and in terms of the costs and revenues involved in taking that catch. The variable under control of the manager is assumed to be the effort involved in landing the catch; and the manager must allocate this effort in the least cost spatial configuration and in an optimal manner over time. The final influences on the optimizing process are the types of effort control used and the management regime itself.

The most important development in fisheries economics has been the recent work on the capital theoretic problem encountered when working with stocks of fish. Resolution of this problem, however, has depended on the correct analysis of the economic exploitation of a fishery. Although Gordon's (1954) analysis was static rather than intertemporal, it must be singled out as one of the most important early works because of the isolation and clarification of four issues which are relevant to this thesis.

Gordon's first point was that because fisheries are exploited for economic reasons and not biological, the concept of net economic yield must have precedence over the biological concept of maximum sustainable yield.

Gordon's second point was that the equilibrium solution is
a composite of biological and economic factors. This "bionomic" solution involves some type of biological function to determine population size (the recruitment function), the introduction of a harvesting production function with inputs of the fish stock and fishing effort, and the conversion of the latter into a cost function. The comparison of the price of fish and the cost of landing them determines the feasibility of fishing. The interaction of effort (and its cost) with the population dynamics of harvesting (and its subsequent revenue) simultaneously determines both the biological and the economic equilibrium.

Gordon's third point was that the capital component (stock of fish) of the production process and not the law of diminishing returns is responsible for the diminishing rate of catch. That is, the effect of harvesting is to reduce the fish population thereby reducing the availability of the stock.

Gordon's fourth point was that most fisheries are common property. And this open access to a common fish stock reduces and dissipates the economic profit or rent. If this open access externality can be internalized somehow, the maximized net economic yield which is derived from exploitation of the fishery results in an economic profit. This economic rent arises from the bounty of nature and not from an artificial scarcity.

Scott (1955a) was the first to point out that Gordon had missed the essential intertemporal nature of the investment problem. A fundamental analysis of capital theoretic problems in an intertemporal setting reveals two parts to the problem of investment: an "inventory" handling aspect and a "re-stocking"
aspect.

Ignoring the congestion and crowding problems that arise with open access, Scott (1955a) recognized that in the short run a monopoly regime and a competitive regime would handle the inventory in much the same way. Both would "mine" to the point where short run marginal cost equals price. Only in the long run would the behaviour of the monopolist be significantly different; it would pay the monopolist to invest "in-kind" by abstaining from fishing. The reason is the user cost encountered by using some of your capital today rather than leaving it for tomorrow. That is, by landing an extra fish today you not only reduce the stock available for tomorrow but you also reduce the potential growth of that future stock.

A fishery manager is concerned with maximizing profit over time and not just at a point in time. Therefore, the management objective becomes the maximization of total discounted net revenue derived from exploiting the resource.

This dynamic optimization, or control, problem requires the manager to take explicit account of time, the capital stock (or state variable) and the effort (or control) variable. Profit over time is determined by revenue which consists of price per pound (assumed constant) times the catch and also by costs which are derived from the per unit costs (assumed constant) times the amount of effort required to land the catch. The catch itself is determined by the biological recruitment function and its intrinsic productivity in terms of escapement, recruitment and catch. And finally, recruitment itself affects the costs of harvesting by reducing the amount of effort needed to take the
catch. Therefore, revenue can be raised by increasing catch but with the penalty of reduced recruitment to sustain that catch. Or costs can be reduced by increasing recruitment but with the penalty of reduced catch to allow for that larger recruitment.

If certain assumptions are made, the solution to a dynamic problem of this sort can be simplified. By assuming prices and costs are constant over time, we can eliminate the explicit role of time. If we put the analysis in discounted present value terms, time is still implicit but the model is autonomous (Arrow and Kurz, 1970, pp. 50-51). This stationarity assumption together with a further assumption of concavity in all functions and a linear harvesting function permits the derivation of an interior solution.

The control problem then becomes one of maximizing an objective functional of the form:

$$PV = \int_{t_0}^{t} \exp(-st) (p-c(x(t)))h(t)\,dt$$

where $PV$ = present value  
$s$ = social rate of discount  
$p$ = constant price of the resource  
$c$ = costs which are linear in harvesting  
$x(t)$ = biomass at time $t$ (state variable)  
$h(t)$ = harvest rate (control variable)

This is the present value of net economic profit over all time periods (starting from the initial period): that is, the present value of current profits plus the imputed value, at the shadow price, of the current rate of investment in restocking (see Neher, 1974b, p. 40). Using the maximum principle this can be seen more clearly by forming the Hamiltonian:

$$H = \exp(-st) \{(p-c(x))h(t) + k(t)(F(x)-h(t))\}$$

where $k(t)$ = costate variable (shadow price)  
$F(x) = dx/dt$, the natural rate of increase of the
stock (recruitment function)

Note that the approach follows the Lagrangian technique in which net profit is maximized subject to a recruitment/harvesting constraint with its attached shadow price.

Following Neher's routine, the first step is to maximize this Hamiltonian for all possible values of the state and costate variables during the time period. The maximum principle shows that this is accomplished when the Hamiltonian is maximized with respect to the control. Before this can be accomplished, however, a prior minimum cost programming problem must be solved (Clark, 1976, p.239). Once this is done, "c" can be assumed to be the minimum cost form of harvesting.

If we assume that the Hamiltonian is linear in production, the maximum principle will be unsuccessful in solving for the optimal state and costate values by setting the partial derivatives of the Hamiltonian with respect to the control equal to zero. The reason is that the partial will not contain any form of the control variable.

Instead, the generalized Pontryagin version which permits discontinuities in the constraints is used. That is, the control is either on or off and operates along a boundary at some point in time; called a switching function, it is set equal to zero. We can then derive an "upper semi-continuous correspondence" (Neher, 1974b, pp.40-41) for the state and costate variables; and the control is either switched on or off until an interior solution is found.

The decline of the "present value shadow price" must equal the state variable's contribution to the Hamiltonian if the
second condition is to be fulfilled (Neher, 1974b, pp.40-41). Neher calls this the zero net profit condition because it requires that the state variable be applied to the point where the value of the marginal product of the fish stock plus its capital gains equals marginal net cost of an uncaught fish. The last is just the foregone market rate of return on that uncaught fish less the value of its own growth rate of return. That is, the value of the marginal product of the fish stock plus the capital gains (given by the equation of motion for the shadow price) equals the financial cost of an uncaught fish minus the value of appreciation at the biological own rate of interest (Neher, 1974b, p.41). If this time derivative of the shadow price is equal to zero, as it will be at the singularity, then there are no capital gains or losses in the implicit cost of the fish stock (Quirk and Smith, 1970, pp.12-13).

The final condition the solution must fulfill if it is to be optimal, is that the fish stock obey the biotechnical constraints (Neher, 1974b, pp.41-42) given by \( F(x) \) in expression (1-2). This condition is fulfilled when the partial derivative of the Hamiltonian with respect to the shadow price is equal to the natural rate of increase of the stock \( (F(x)) \). Neher calls this the resource constraint condition for obvious reasons.

The solution will be stationary if the time derivative of the switching function is equal to zero (Clark and Munro, 1975, p.104); we have an interior solution when the switching function is equal to zero; and we can use the calculus of variations Euler equation which is none other than the time derivative of the switching function (because of the autonomous nature of the
model). Following Clark and Munro (1975, p.95) this leads to an equation for the singular solution:

\[(1-3) \left(1/s\right) \left(\frac{d}{dx} \left(\frac{p-c(x)}{F(x)}\right)\right) = -\frac{p-c(x)}{s}\]

where \(x\) = singular or equilibrium solution

As Clark and Munro (1975, p.96) explain, the l.h.s. "can be interpreted as an expression of marginal user cost, in that it shows the present cost of capturing the marginal increment of fish, a cost that has to be weighed against the marginal gain from current capture."

Simplifying equation (1-3) leads to

\[(1-3') F'(x) - \left(c'(x) \frac{F(x)}{(p-c(x))}\right) = s\]

Again, Clark and Munro (1975, p.96) explain that the l.h.s. "is the 'own rate of interest' (which) consists of two components: \(F'(x)\), the instantaneous marginal physical product of capital, and \(-\left(c'(x) \frac{F(x)}{(p-c(x))}\right)\), the marginal stock effect." The first indicates the foregone gain in future growth by harvesting an extra fish today and the latter indicates the increased future costs of harvesting you are imposing on yourself by harvesting an extra fish today, making future stock more dispersed and thus, more difficult to catch than today (both through reduced stock and through reduced growth in the stock).

In summary, the method for obtaining an optimal equilibrium solution depends on generating a singular solution which is then made specific through substitution of parameters from the recruitment and harvesting cost functions. This solution is then solved for the optimal escapement given the social rate of discount. It should be noted, however, that this approach
bypasses a number of the complications found in a more general model (see Clark, 1976b, pp.88-108).

There are three problems associated with the derivation of the equilibrium equation in expression (1-3) which preclude its use in this study. First, equilibrium equation (1-3) is a continuous time model which assumes that "the response of the population to external forces such as harvesting is instantaneous" (Clark, 1976b, p.210) and yet sockeye salmon are only harvested for one twelve week period in their four year life cycle. The model for sockeye salmon is a discrete time model and depends on the inter-relationships amongst escapement (parent fish left over from harvesting), the subsequent recruitment four years later and the catch (the difference between recruitment and escapement). Recruitment four years hence is a function of escapement today which, in turn, is a function of the recruitment (derived from escapement four years previously) minus the current catch.

The second problem is that the equilibrium equation in expression (1-3) is derived for a linear harvesting function, whereas the harvesting production functions used in this study are nonlinear.

Allowing for a nonlinear harvesting function and the discrete nature of the recruitment function, Clark (1976b, pp.250-253) has developed an alternative equilibrium equation of the form:

\[(1-4) \ G(x) \left( \frac{P(R) + P(C)}{P(C)} \right) = (1+s)^5\]

where \(x\) = optimal escapement
\(G(x)\) = derivative of recruitment function with respect to \(x\)
\(P(R)\) = derivative of profit with respect to
This is the equilibrium equation used in this study to solve for optimal escapement, recruitment and catch (the derivation of (1-4) is given in the Appendix attached to this chapter). As with expression (1-3*), the l.h.s. is the fishery rate of interest consisting of the marginal physical product of capital, \( G(x) \), and the marginal stock effect, \( \frac{(P(R) + P(C))}{P(C)} \). Because of the discrete nature of the profit function, and the impact on costs and profits of the interrelationship amongst escapement, recruitment and catch, the derivative with respect to optimal escapement is indirectly obtained through observing the impact of changes in catch and recruitment (given that optimal escapement) on profits. Clark (1976b, pp.243-253) explains how the discrete version in expression (1-4) can be converted into the continuous version in expression (1-3*). Given a linear cost function.

The third problem with the derivation of both equilibrium equation (1-3) and (1-4) is the assumption that a prior minimum cost programming problem has been solved to achieve the minimum cost form of harvesting. This may be possible with a linear harvesting function as assumed for (1-3) but is not possible with nonlinear harvesting production functions as assumed in (1-4). The reason is that the equilibrium combination of catch and recruitment suggested by (1-4) could lead to a different least cost configuration of gear to minimize the costs of taking that catch. This altered configuration of gear would change the
marginal stock effect in (1-4) and lead to a different equilibrium combination of catch and recruitment. Therefore, the least cost programming solution and the equilibrium values for catch and recruitment must be simultaneously determined. One of the innovations in this study is the development of a programming algorithm which is capable of such simultaneous determination.

In addition to the intertemporal common property problem which arises from the capital theoretic nature of an open access fishery, there are spatial misallocations of harvesting effort which can also take place because of harvesting allocation externalities peculiar to a gauntlet fishery such as that for Fraser River sockeye salmon. The congestion leading to intra-seasonal stock effects of thinning will drive the fisherman to areas where gear is less crowded. In these poorer areas gear may be less productive in terms of catchability but overall recruitment availability is probably higher than in crowded areas where gear would normally be more productive. It is easy to confuse availability with efficiency of gear types. But what is in fact going on is a spatial misallocation of effort because fishermen are forced from areas where catchability is normally higher but availability is reduced because of crowding to areas of normally poorer catchability but where there is less thinning of the stock due to reduced crowding. This is particularly true for the harvesting model used in this study.

In addition to intra-gear interference of this type it is possible for there to be inter-gear interference as certain gear types must wait for the fish to come to them, whereas other gear
types can actively search for blocks of fish.

As well as these intra-seasonal stock effects, there are also inter-seasonal stock effects in an open access fishery because to one fisherman the shadow price on enhanced recruitment is always likely to be below the current landed price of fish. Fishermen tend to harvest more heavily today leading to an increase in future costs owing to the inverse relationship between availability and costs of harvesting. If fishing were halted, the biomass would grow at a greater relative rate (Hannesson, 1975, pp.161-2). But common property fishermen ignore this user cost because they have no way of capturing the investment "returns".

Open access and stock effects combine to produce a sub-optimal allocation of effort on a spatial basis during a single season and on an intertemporal basis over several seasons. If access were closed by handing the fishery over to a monopolist, he would increase productivity by spreading effort more evenly over the whole fishing gauntlet and over time so as to take advantage of availability differences, differences in catchability and differences in gear efficiency. These cost reductions would come about not because of avoiding diminishing returns but because of increased availability.

If the monopolist had sole rights through time as well, he could again reduce costs by in-kind investment through abstention from fishing. He would exploit his fishery until the fishery rate of return was equated with the social rate of discount giving the optimal solution (Brown, 1974, pp.167-8; and Clark and Munro, 1975, pp.95-96).
There are user costs associated with each of the intra-seasonal spatial and inter-seasonal temporal misallocations of effort. Even if the open access fisherman is a net present value maximizer, he will ignore these costs because of the overwhelming negative user cost associated with common property; there is no point in keeping an inventory or re-stocking one because your neighbour simply takes it from you (Brown, 1974, p.167). Even in a two person fishery, it can be shown that both will work to enhance their "take" of the neighbour's inventory to as close to 100% as possible (Clark, 1978).

If the fishery is turned over to a monopoly inventory manager, from his point of view it makes very little difference how the biomass grows: whether it be from increased flesh on existing fish or increased numbers of new fish. What does matter to him is the fact that catching one more fish today could mean more growth or less growth in tomorrow's biomass depending on the effects operating within the population. For sockeye salmon, the manager is faced with the fact that growth can only take place through new recruits because the parents die after spawning. The stock effect only comes through recruitment, not through surviving adults. And because of the four year cycle, the restocking of inventory is delayed for four years. Clark (1976b, p.7) has shown that in the case of non-survival of escaping fish, the delay can be collapsed into a single period. This would mean, in the case of sockeye, a "period" consisting of four years. In general, Clark has found that for models in which vulnerability of new recruits to the fishery is delayed, the most rapid approach to equilibrium values is not optimal.
But in the case of non-survival of escaping parents and constant opportunity costs (both basic assumptions in this study), the optimal approach, according to Clark, can be approximated by the most rapid approach to equilibrium values.

For this reason, the Fraser River sockeye fishery will be assumed to operate with a period of four years duration with appropriate adjustments in the discount rate. This should present no serious problems as each of the four year class runs of sockeye within each period appears to be independent both from a recruitment (Chapter Two) and a harvesting (Chapter Three) point of view. It will also be assumed, given constant opportunity costs, that the most rapid approach to the equilibrium biomass level is optimal. This should not be a problem in terms of sockeye management because the recruitments in every cycle year exceed the optimal escapement level. Therefore, in cycle years where optimal escapement is smaller than actual, catch would be increased; and in cycle years where optimal escapement is larger than actual, catch would be decreased.

Turning to the regulations to be used by the fishery manager, it is well known that controls play an important role in determining both the costs of harvesting and the costs of management itself. This study confines itself to direct quantitative controls over effort as other systems of regulation are either not feasible or prohibitively expensive. Direct quantitative control over effort abstention has taken place historically through area, time and season closures. One problem with using these direct types of controls to reduce exposure of
gear to fish is that it leads fishermen to invest in capital to enhance catching power during the brief exposure time. The problem with the stock of boats is the irreversible nature of this capital good. In order to avoid irreversibility in this study, capital goods will be converted into a flow which will be employed as an input to harvest sockeye salmon. Only least cost gear and vessels will be used and the rest will be offered lump sum compensation for their capital loss. In this way, the problems encountered with irreversible capital stocks can be avoided (see Clarke, Clark and Munro, 1979).

To avoid problems such as these, the choice of regime is also critical. Furthermore, the rights assigned under the regime must be such as to avoid dissipation of economic rent through inefficiency or open access problems. Munro (1979) has developed an approach to analyzing the transboundary management of a fisheries resource in which he allows conflict in management strategies to arise through differences in social rates of discount, harvesting costs and consumer tastes in the two consuming nations. Munro demonstrates that if there are no differences in social discount rates, consumer tastes or harvesting costs, bargaining devolves into sharing the harvest or the proceeds. For the purposes of this study it will be assumed that there are no differences in social discount rates or consumer tastes between the U.S. and Canada but that there are differences in harvesting costs. And the regime best suited to maximizing the present value of the Fraser River sockeye fishery will be assumed to be a sole owner: a hypothetical monopoly firm without ownership rights but with the rights to
use and disposition of the natural resource asset and charged
with the task of maximizing the present value of the fishery.

It will be assumed that the powers of the IPSFC will be
expanded to include such rights and duties. It is widely
recognized (Kasahara and Burke, 1973) that the most successful
international fisheries commission has just such powers under
the North Pacific Fur Seals Convention. The treaty was ratified
in 1911 and covers pelagic sealing in the Bering Sea. The
commission is charged with maximizing profit (albeit on a static
basis) and has full quantitative control over effort. However,
it is powerless without the unanimous vote of the members.

It will be assumed that neither the U.S. nor the Canadian
government would be prepared to allot the harvesting of the
catch on anything but an equal division basis between U.S. and
Canadian fishermen. A policy of hiring only the least cost gear
type areas would result in different catch proportions. For
these reasons, the optimal equilibrium management solution will
be calculated for both an unconstrained case in which the IPSFC
can choose to harvest where it wishes, and an alternative case
in which the IPSFC will be constrained to harvesting on an equal
catch share basis.

(3) Management Model

With this theoretical base for the optimizing model it is
now possible to construct the management model. The IPSFC will
be assumed to have the rights to harvest and manage the Fraser
River sockeye salmon and be charged with the responsibility to
maximize the present value of the fishery. It will operate
within the jurisdictional and physical limits outlined above and will hire gillnets and purse seines in the four, least cost fishing zones. The Fraser River sockeye fishery will be assumed to operate with a period of four years duration with appropriate adjustments in the discount rate. This should present no serious problems as each of the four year class runs of sockeye within each period appears to be independent both from a recruitment (Chapter Two) and a harvesting (Chapter Three) point of view. This implies that each cycle year within that four year period will have a different optimal catch level; and that it will take four years to reach those optimal equilibrium biomass levels. This rapid approach to the equilibrium biomass levels will be assumed to be the optimal approach.

The recruitment function is the basis of the biological system. The harvesting production functions are the basis of the least cost spatial location model. And the Clark-Munro equilibrium equation is the basis for the dynamic optimizing system. If the harvesting cost model were linear, the management part of the study would be fairly straight-forward. A single least cost harvesting gear type area would be chosen for each of the four cycle years; and the optimal escapement, recruitment and catch could be calculated by combining the information on the recruitment model and the harvesting model. This optimal management solution would take into account the impact of escapement on subsequent recruitment, and the impact of the latter on the amount of effort needed to take the specified catch; a fishery rate of return would then be calculated in terms of the current profits derived from exploitation, less the
costs or benefits associated with reduced or enhanced future catch and recruitment. And the present value of the fishery would be maximized when that fishery rate of return was equalized with the social rate of discount.

However, the harvesting cost model is not linear, and, as Flowchart (1-1) illustrates, this requires a selection of harvesting gear type areas simultaneously with recruitment. The recruitment model is initialized with a specific escapement and the model then calculates subsequent recruitment. Catch is simply that recruitment minus the specified escapement. The harvesting cost model then allocates the given catch and recruitment until it finds the least cost harvesting configuration. Programming criteria within the overall algorithm check to determine if this combination of escapement, recruitment and catch together with its least cost harvesting configuration is indeed optimal. If not, the program re-initializes the escapement value and goes through the same routine as above. The model keeps on iterating in this way until it achieves an optimal solution.

The name of the program package used in the programming was CONOPT which is part of a larger package for nonlinear function optimization called UBC NLP (Patterson, 1978). CONOPT uses a penalty function approach to remove constraints. Whenever a constraint is violated, the objective function value is adjusted by a smooth function (using a modified Lagrange multiplier approach) which places bounds on the feasible parameter values the program can consider. That is, a quasi-Newton algorithm is used to minimize the objective function; and if this solution
Flowchart (1-1): Optimal Management Program

1. **Initial Escape**
   - **Clark-Munro Equilibrium Algorithm**
     - **Optimal Equilibrium Escape**
     - **Recruitment Function**

2. **Recruitment**
   - **Recruitment Minus Escape**
     - **Sockeye Catch**
     - **Residual Escape**

3. **Least Cost Harvesting Program**
   - **Is Maximum Present Value Achieved?**
     - **Yes**
     - **No**
       - **Restart**

**Stop**
violates one of the constraints, a penalty function is called to adjust the objective function to be within certain parameter bounds. The optimizing algorithm evaluates the objective function and its first partial derivatives, and the constraints and their first partial derivatives with respect to the variables at any point. Subject to the penalty function, as soon as the partial derivatives are very close to zero (within some specified distance) the program stops.

Programming for the Clark-Munro equilibrium values involves a search for a zero. Because recruitment, catch and escapement are all functionally related, it is possible to re-arrange expression (1-4) to give:

\[(1-4') G(x) ((P(R(x)) + P(C(x)))/P(C(x))) - (1+s)^5 = 0\]

where \(x\) = optimal escapement
\(G(x)\) = derivative of recruitment function with respect to \(x\)
\(P(R(x))\) = derivative of profit with respect to recruitment as a function of \(x\)
\(P(C(x))\) = derivative of profit with respect to catch as a function of \(x\), allowing optimal escapement

The key, unknown variable is the escapement level and a program is used to search for a zero. As soon as a value of escapement is found which reduces this implicit function very close to zero (within some specified distance), the program stops.

Because of the simultaneous nature of the optimal solution, the problem becomes one of trying to bring both these programs together. CONOPT would then give a least cost harvesting configuration for specified levels of escapement, recruitment and catch and the search-for-zero program would then calculate the optimal level of escapement given that harvesting configuration. The innovation in this study was to simply make
the Clark-Munro equilibrium equation a binding constraint in CONOPT. Although the programming was non-trivial, the essential idea is very simple: CONOPT maximizes profit using a level of escapement which satisfies the Clark-Munro equilibrium equation. The profit function derivatives in the latter constraint are evaluated for each least cost harvesting configuration suggested by the recruitment/catch ratio derived from the current level of escapement.

In terms of running the program, all variable values are initialized at a starting point which does not violate the constraints (including the the zero value for the Clark-Munro equation). The program then alters the escapement level, leading to changes in catch and recruitment which then lead to a different, least cost harvesting configuration subject to all the constraints. These iterations continue until an escapement level is chosen which simultaneously maximizes profits and satisfies the Clark-Munro equilibrium equation. In this way, both the spatial and the intertemporal dimensions of the problem are simultaneously satisfied.

V SUMMARY AND CONCLUSIONS

Given the theoretical basis for the optimizing model in the survey of the literature and the assumptions needed for the management model, it is now possible to summarize the empirical approach used in this study to analyse optimal management of the Fraser River sockeye fishery.

The life cycle of the sockeye and their return migration demonstrates the two part nature of the problem: a recruitment
model which interacts with a harvesting model. The presence of a very strong four year cycle in both these models simplifies the task of developing them and plays a critical role in the management optimizing process by permitting the fishery to be broken up into four separate year class fisheries with four year lags between escapement and recruitment.

The evolution of fisheries economics has culminated in a capital theoretic approach to choosing a management solution. This solution is determined by the interaction between the own rate of growth of the stock (recruitment model) and the sensitivity of harvesting costs and profits to changes in catch and recruitment size (harvesting model). The stock effects and the problems associated with open access on the fishing grounds can be resolved by giving the fishery manager monopoly powers. The economically feasible control would be direct quantitative allocation of effort to achieve the least cost spatial distribution of harvesting effort and the optimal escapement for each cycle year.

It will be assumed that the IPSFC is granted use and disposition rights over the Fraser River sockeye salmon and that they are charged with maximizing the present value of the resource rent. The economic profit extracted from the resource asset can then be used to compensate vessel owners who are forced out of the sockeye fishery. Apart from this "as if" compensation, distributional aspects will be ignored. This is partially justified on the basis that all factor inputs will be paid their opportunity costs if they are used in the harvesting process. However, the IPSFC will use the factors in differing
amounts and periods of time depending on the cycle year. The costs of this "excess capacity" will be assumed to be borne by the vessel owners and no attempt will be made to include it in the opportunity cost factor rental payments.

Turning from these assumptions to the management approach used in this study, the optimal management solution for the Fraser River sockeye fishery will be obtained in three steps. In the first, the harvesting model developed in Chapter Three will be transformed into a cost model. Nonlinear programming will then be used to solve for least cost harvesting proportions amongst the six most important gear type areas, given recruitment and escapement (Chapter Three). The second step involves taking the least cost gear type areas for B.C. and the U.S. and substituting them plus the recruitment model (Chapter Two) into the Clark-Munro equilibrium equation. The discrete form of this equation is used as sockeye are only harvested at discrete intervals in their life cycle.

The most important and useful technique at this stage is the splitting of the Fraser sockeye into four separate year classes. Each year class will be assumed to be harvested quite separately from any other year class at discrete four year intervals. Although solving the equilibrium equation for the four year classes simultaneously with implicit interactions is possible, splitting the stock into four year class fisheries leads to a great improvement. This permits optimal escapement to be different for each year class, whereas simultaneous determination would yield only a single optimal escapement for all four year classes.
The third step toward the management solution involves calculation of optimal recruitment, from the recruitment function, given optimal escapement; and calculation of optimal catch, given the production functions for the least cost areas plus optimal escapement and recruitment. The results are then fed back into the least cost program to determine the least cost catch proportions given the new levels of escapement and recruitment. This iteration between the recruitment model and the harvesting model continues until the program converges to a solution.

It is then possible to calculate the net revenue from harvesting of that optimal catch with the least cost gear type areas and to compare this hypothetical net revenue with the actual average net revenue experienced under IPSFC management over the twenty-nine years from 1947 to 1975. The results would appear to support the hypothesis that actual management did not achieve optimal allocation of effort over that twenty-nine-year period at considerable cost in terms of foregone rent which could have been accumulated. It should be made clear, however, that the IPSFC has never been charged with the responsibility for optimal allocation of effort but has attempted, given the legal constraints of the convention, to allocate effort in as economically efficient a manner as possible. Less than half the hypothetical gain in potential economic rent comes about from a spatial relocation of harvesting gear and the rest comes from the optimal equilibrium values for escapement, recruitment and catch. It appears that a large part of these gains arises from a reduction in harvesting costs rather than by increasing revenue.
through enhanced catches. This emphasizes a need for economic considerations as both economic theory and the empirical work in this study indicate that profits can be significantly enhanced through reductions in cost rather than through increases in revenue only as a result of larger sustainable catches.

**APPENDIX**

**Derivation Of The Clark-Munro Equilibrium Equation**

To derive a formula for the optimal equilibrium solution to a discrete time fishery model with a nonlinear harvesting function Clark (1976b, pp.252-253) employs the discrete maximum principle. The objective functional is given by

\[(1-5) \quad J = \sum_{t=0}^{\infty} a^{t-1} P(R,C)\]

where \(a = 1/(1+s)\)

- \(s = \) social rate of discount
- \(P(R,C) = \) profit function dependent on recruitment \((R)\) and catch \((C)\)

The Hamiltonian is

\[(1-6) \quad H = a^{t-1} P(R,C) + K(t)(F(R-C) - R)\]

where \(K(t) = \) costate variable (shadow price)

- \(F(R-C) = \) subsequent recruitment dependent on escapement \((R-C)\) in previous time period (recruitment function)

The maximum principle implies (Neher's first condition):

\[(1-7) \quad H(C) = a^{t-1} P(C) - K(t)G(x) = 0\]

where \(H(C) = \) partial derivative of the Hamiltonian with respect to catch

- \(P(C) = \) partial derivative of profit with respect to catch
- \(G(x) = \) derivative of the recruitment function with respect to escapement \((x)\)
After re-arrangement this gives

\( K(t) = \frac{a^{t-1} P(C)}{G(x)} \)  

and

\( K(t) - K(t-1) = (a^{t-1} - a^{t-2}) \frac{P(C)}{G(x)} \)

Neher's second condition is fulfilled when

\( K(t) - K(t-1) = -H(E) \)

where \( H(E) = \frac{\partial}{\partial E} \text{Hamiltonian} \) with respect to the state variable (recruitment)

and the right hand side is

\( -H(E) = -a^{t-1} P(R) - a^{t-1} P(C)(1 - 1/G(x)) \)

where \( P(R) = \frac{\partial}{\partial R} \text{profit function} \) with respect to the recruitment

Equating expressions (1-9) and (1-11) and simplifying leads to

\( G(x) \left( \frac{(P(R) + P(C))}{P(C)} \right) = (1+s)^5 \)

The reason the discount factor is raised to the fifth power is because of the four year lag between escapement and subsequent recruitment. Neher's third condition is automatically met by \( G(x) \), the natural rate of growth in the stock allowing for harvesting.
CHAPTER TWO: THE RECRUITMENT FUNCTION

I STOCK MANAGEMENT

The management of the sockeye fishery requires two decisions: how much of the current recruitment can be harvested and in what way. Whatever the manager allows as an escapement bears a cost in terms of foregone catch in the current period but offers a return four years later (and subsequently) in terms of some recruitment. The larger the future recruitment, the larger the potential catch and the smaller the harvesting costs due to increased availability. Thus the manager can "invest" for the future by abstaining from harvesting today.

This chapter is concerned with estimating this basic biological investment function. The model used is the Ricker form of recruitment function which is the standard choice in salmon studies. The data used in the estimation process include observations on recruitment of biomass to the fishery, the harvesting catch made by the fishermen and the count of fish escaping to the spawning grounds. And the nature of the biological function is determined by which of reproduction, growth or reduced natural mortality offsets fishing mortality. Taking into account the cyclical nature of environmental influences, the recruitment model implies that control over fishing mortality is the main determinant of subsequent recruitment. It is in this way that the fishery manager controls the return on his in-kind investment.

The management decision to catch the current stock or allow it to escape as an indirect form of investment in a future stock
requires knowledge of the productivity of that investment. Consequently it is important to understand the rudiments of the biological processes involved in the mechanisms which control the stock.

Many biologists believe the most important control on the size of a salmon stock is achieved through density dependence. That is, the factors enhancing or retarding survivability and growth are turned on or off by the degree of stock density in a particular stage in the life cycle. It is usually assumed that there is some form of environmental limit on the stock size. That is, the aquatic environment can only support a certain size of stock which implies that there will be some maximum future recruitment, and investing through greater abstention yields no return. Often referred to as the ecological or environmental niche, the ultimate limit on the stock size is, therefore, determined by the external environment. And density dependence will be assumed to control the size of the stock within that basic environmental limit.

In addition to density dependent intra-species controls there are inter-species (predator-prey) interactions which are also thought to control the numbers and growth of the stock of interest at different stages and often in a density dependent way. However, the manager is interested in the biomass which is weight times numbers and either or both of weight and numbers may be affected, often inversely, by density. What is of importance is the investment function as it relates escapement to subsequent biomass recruitment. The use of catch data to estimate that function complicates an already complex situation
by introducing the new element of fishing mortality.

Ideally this investment function should take into account all environmental influences, all inter-species and intra-species interactions plus the effects of harvesting but reliable data simply do not exist to develop such a simulation model.

Environmental factors such as the temperature of the water and its chemical composition can control survival (numbers) and the metabolic rate (growth) by operating either directly on the species itself or indirectly through affecting its food supply. Competition for that limited food supply and for the environmental niche are important sources of control as are the species which form the food supply or which prey on the species of interest. These competitive and predator-prey relationships can occur through both inter-species and intra-species interactions. Intra-species interaction can also affect stock size indirectly through the impact of density on reproduction and growth rates. For sockeye, these density effects on reproduction appear to be particularly important.

In estimating the investment function the manager is faced with the task of deciding which environmental, inter-species and intra-species factors are to be treated as parameters and which can be handled as variables. He must also decide which factors are most important in different stages of the life-cycle.

The critical factor in making these decisions is the quality of the data. Commercial catch data, for example, merely give catch figures on an annual basis, the average size of fish caught and some estimate of the effort involved in harvesting the catch. And yet, most commercial fisheries, including the
sockeye fishery, are based on prolific stocks with large production surpluses. That is, quite a large part of the recruitment can be harvested leaving only a fraction of the stock to escape and reproduce. And it has been observed that larger production surpluses are associated with stocks subject to the greatest variability in the environment (Larkin, 1972, p.322). Thus the stocks of greatest fishery interest are the very ones for which control over abundance cannot be established by regulating fishing mortality only. As a result, a closer approximation to the ideal investment function is achieved when biologists allow the environment to enter: often in a stochastic way. In this study, however, environmental factors will be permitted to enter in a deterministic way.

Deterministic models based on intra-species interactions involve a simultaneous solution of the biological recruitment function and the harvesting production function (as illustrated in Figure (2-1) below). An identification problem arises because of the simultaneous nature of the solution: how does one distinguish between recruitment effects and harvesting effects? Observations on catch cannot help and this is why the assumption of steady state equilibrium is essential to most deterministic models. That is, harvesting effects are exactly offset by recruitment effects in equilibrium and there is no need to distinguish between them. Thus, a second heroic assumption is that harvesting can be treated like a parameter and the nature of the recruitment function is determined by which of reproduction, growth or reduced natural mortality offsets fishing mortality. The resulting equilibrium, or sustainable,
yield is that surplus production which, when harvested, leaves the stock abundance unchanged during the period under observation. Fishing mortality can be offset because of density dependence: for example, fishing also reduces the density of the parents, the spawn is smaller, and more larvae survive because of the reduced pressure on the limited food supply (environmental ceiling).

In order to study the interaction between catch and fishing intensity, we develop a production function to explain harvesting in relation to the biomass. The most common hypothesis for the harvest production function is

\[(2-1) \quad C = qfB\]

where \(C\) = catch
\(qf\) = instantaneous rate of fishing mortality
\(B\) = biomass of fish available to the gear

The yield in numbers is proportional to effort if we assume \(q\) is constant. This assumption is based on the belief that in equilibrium the stock level is constant and, on probabilistic grounds, that this constant stock level is equally dispersed throughout the fishing grounds at all times.

As biologists have shown, this equal spatial and temporal dispersion of stock is highly unlikely because of such factors as seasonal changes in feeding grounds, migration, the effect of weight and age on vertical allocation (affecting access to surface-set nets) and the fact that younger fish display seasonal schooling behavior (making them easier to catch with seine nets).

Furthermore, the unit of effort is unlikely to have remained constant over longer periods of time as technical
innovation increases both the power of boats and the effectiveness of gear. Increases in the size of vessel decrease the number of trips required to unload the catch, thus the actual time of exposure of the stock to the gear increases. That is, the ratio of steaming time to fishing time is altered, and yet most observations are for the two combined (Hannesson, 1974, chapt.2). For these reasons, the relationship between catch and effort is unlikely to be consistent and may be influenced by the biomass itself or the elapse of time. Thus not only is the biomass unlikely to be in equilibrium but even the tools used to indirectly measure biomass are changing.

Consequently we must specify a model which will allow us to analyse changes in "q". This model can be derived from one of three types of models used by biologists to describe the investment function for commercial fisheries. Both the first, the logistic model, and the second, the analytic model, are used for species which become vulnerable to fishing mortality at a certain age and remain vulnerable for the rest of their lives. The third, called the recruitment model, was developed for species like salmon which become vulnerable to fishing gear at one particular stage in the life cycle and are not vulnerable in later stages. Thus the stock consists of only a single cohort or year class. Reproduction depends on numbers and weight of those left over from the one vulnerable stage. And the biomass depends on the numbers and weight of those surviving from reproduction and passing through stages prior to the vulnerable one.
II  THE RECRUITMENT MODEL

The model to be used for the Fraser River sockeye fishery is the recruitment model which concentrates on the relationship between parents and new recruits. Stock control operates through the effect of density dependence on reproduction and then growth and mortality in subsequent stages. The number of mature fish which escape harvesting is the most important variable.

Data series on escapement and catch are available from 1938 to 1975 for Fraser River sockeye and have been collected in a consistent manner during that period. Therefore, a long, relatively distortion-free series of data are available to permit estimation of an escapement-recruitment relationship if it can be assumed that recruitment is completely accounted for by the sum of catch and escapement. As will be explained below, this is justified for the Fraser River sockeye fishery.

Equilibrium is an important assumption for the recruitment model. It involves the simultaneous solution of two relationships: the recruitment from a given stock, and the parent stock which results from a given recruitment subjected to harvesting. Figure (2-1) illustrates the intersection of these two relationships:

Where $R = \text{recruitment}$
E = escapement
y = recruitment relationship
x = equilibrium parent escapement from harvesting

Curve y illustrates the escapement-recruitment relationship and derives its shape and position from density dependent effects. Recruitment is defined as the biomass which becomes vulnerable to fishing gear at a specific stage in the life cycle. Note how recruitment increases rapidly with escapement but at a decreasing rate. The line x represents the equilibrium escapement which results from equilibrium recruitment subjected to equilibrium harvesting. As fishing intensity is increased the line x rotates in an anti-clockwise fashion indicating that equilibrium escapement from a given recruitment declines as the catch rate increases although recruitment increases at first and then declines as intensity increases. At point "B" for example, escapement is E1, recruitment for that escapement would be R1, and, extending back to the 45 degree line, the difference between point A (the equivalent of R1 along the E axis) and E1 is the catch. Only in equilibrium will the simultaneous solution be given by the intersection of x and y. The equilibrium intersections of fishing effort intensity with the escapement-recruitment relationship will then trace out the different sustainable catch levels associated with different levels of escapement. It is to be expected that the highest catch levels would be associated with intermediate escapement levels. Note that as the intersections are along y, while x can be rotated parametrically, the locus of equilibrium points would be curve y.

There are some general observations which should be
fulfilled by the parabolic relationship between recruits and escapement (Ricker, 1975, p. 281): it should be constrained to pass through the origin to comply with the basic assumption that without adults, there can be no reproduction; the rate of recruitment, $R/E$, should move inversely with the number of escaping adults; and recruitment must exceed the stock of escaping adults at some point, otherwise the stock would become extinct.

The path to equilibrium takes several periods to converge. If fishing intensity increases, the resulting escapement will be reduced from a given recruitment. This will lead to reduced recruitment in the next period and a smaller escapement which in turn, will lead to a further reduction in recruitment for the following period (Paulik and Greenough, 1966). One advantage of working with the Fraser River Sockeye stock is that this equilibrium problem is not very important. As the parent stock dies after spawning, a change in escapement level leads to equilibrium within one four year cycle. As there is only one year class for each cycle and all four cycles are assumed independent, there are no stock structure problems associated with alterations in the year class array within a given stock.

One major assumption of the model used in this study is that the "focus" is stable, although it is thought that this is not strictly correct for sockeye salmon. The convergence to equilibrium applies in the case of any disturbance, not just from imposed fishing mortality; and the escapement-recruitment relation is the mechanism for population stability and control.

External factors such as inter-species interactions and
environmental influences may have profound effects on the escapement-recruitment relationship, altering both the shape and position of the function. Most often there is no data available for these external factors and they are usually left to enter through the error term. This is a serious problem in the case of a migratory species like salmon because different stages of the life cycle are spent in totally different environments and the effects of density in one stage may be unrelated to survival in a subsequent stage.

The Fraser River sockeye have four distinct year class cycles because the lag between escapement and recruitment is four years. For most cycle years three year old and five year old fish represent less than 5% of the recruitment. If one regresses recruitment on escapement (in the log form of the Ricker function, expression (2-7) below) for the Fraser River sockeye the fit is poor. A glance at a scatter diagram of recruitment against escapement is enough explanation: the dots appear to be randomly distributed. However, one technique which does not appear to have been used before is the introduction of dummy variables in slope and in intercept form to allow for differences in parameters amongst the four year class cycles. Furthermore, statistical theory, emphasizing the use of as much information as possible, suggests taking account of the fact that data exist allowing escapement to be disaggregated into eleven races of sockeye associated with certain lakes in the Fraser River system. Regressing recruitment on disaggregated escapement using cycle dummies leads to a considerable increase in explanatory power. This would appear to indicate that
environmental influences or inter-species interactions or both can be modeled through the recognition of cycle differences in the recruitment function for the Fraser River sockeye stock.

Turning to the density dependent intra-species interactions, the various recruitment models are distinguished by their assumptions about the agent of density dependent control and its relationship to the escapement of parent fish (Chapman, 1973; Dahlberg, 1973; Doi, 1973; Larkin, 1973; Paulik, 1973; Paulik and Greenough, 1966; and Ricker, 1975, chapt. 11).

Most of these assume the fecundity of the parent stock remains constant and that the number of eggs hatched is proportional to the parent stock. Ricker, however, assumes that the number of predators is proportional to the parent stock and that mortality in the early stages of life is proportional to the predators. Thus, natural mortality of the progeny is proportional to the density of the parent stock. Predators are the agents of density dependent regulation (Larkin, 1973); mortality operates in a compensatory fashion and is related to stock abundance at a specific time. Thus, numbers in one stage are a simple function of numbers surviving from a previous stage where survival is a function of parent density:

\[ N(t+1) = N(t)S(E) \]

where \( N \) = numbers alive
\( S(E) \) = fraction surviving in each period and is a function of escapement of mature adults

The compensatory mortality assumption implies that the survival ratio is a monotonically decreasing function of the escapement and Ricker assumes the rate is exponential:

\[ S(E) = a\exp(-bE) \]
where $E =$ escapement of adult stock in numbers
$a, b =$ parameters

And as the progeny are assumed proportional to the parent stock, recruitment is given by

$$(2-4) \quad R = aE(\exp(-bE))$$

where $R =$ recruitment in numbers to the fishery

In the Ricker approach, only "compensatory" effects (density effects on growth and/or mortality increase with density) are permitted to work and yet there is evidence to show that "depensatory" effects (density effects on growth and/or mortality decrease with density) operate in at least one or two stages for most stocks. It is thought that depensatory predation is one of the main causes of cycles in recruitment (Dahlberg, 1973). Paulik and Greenough (1966) suggest altering the Ricker survival functions to allow both compensatory and depensatory factors to operate. For stock control to work in a density dependent way means that compensatory effects must eventually outweigh the depensatory effects, otherwise density dependence as a form of stock control would disappear. For the Ricker model the modification to expression $(2-4)$ implies:

$$(2-5) \quad R = aE^d(\exp(-bE))$$

where $d =$ index of density dependence

In general there are as many recruitment models as there are functional forms to express the relationship between recruitment and escapement. Different a priori assumptions about the density-dependent factors often lead to the same functional forms. Not only is there a lack of data on which to base a priori judgements but fluctuations of the environment make it
difficult to have any confidence in functions which do fit the observations on catch and escapement. Thus, the functions are useful "interpolations" but cannot be said to be estimators of biological parameters for the underlying population (Chapman, 1973, p.328). However, for a fishery manager who is only interested in estimating the return on his abstention investment, a reasonable interpolation is all that is needed.

Perhaps the most useful way to distinguish between alternative functional forms is the way in which the error term enters the relation. The error most likely summarises the unknown external factors which cannot be modeled either because of lack of knowledge of the way they enter or because of lack of data for use in empirical fitting (Larkin, 1973, p.322). But should the environmental effects be additive or multiplicative? From the point of view of logic "we should expect the effect of the physical environment normally to be multiplicative ...if conditions are favorable, all (fish) have a chance of benefitting; if unfavorable, a certain fraction (not a fixed number) will be lost" (Ricker, 1975, p.274). The next step is to determine the frequency distribution of the error. Both Ricker (1973a, pp.337-338) and Allen (1973, pp.353-355) have found that the ratio R/E is log normally distributed for many stocks. This skewed distribution of recruitment for given escapement is likely to be generated by multiplicative environmental effects. The hypothesis also receives support from the observation discussed earlier, that larger surplus productions are associated with stocks subject to the largest environmental variation.
A multiplicative error term can be added to the Ricker model in such a way as to retain the intrinsic linearity of the functions:

\[(2-6) \quad R = aE^d \exp(-bE) \exp(#)\]

where \( (#) = \text{error term} \)

This expression can be transformed into a linear estimator by taking natural logs:

\[(2-7) \quad \ln(R/(E^d)) = \ln a - bE + (#)\]

III  **SOCKEYE RECRUITMENT FUNCTION**

As expression (2-4) above indicates, the Ricker form of recruitment model needs observations on \( R \) and \( E \) to estimate the parameters \( a \) and \( b \). These data have been collected in a consistent manner by the IPSFC since 1938. Escapement data are based on actual counts of fish swimming in the spawning streams and rivers. Observations of catch are taken from commercial catch reports and DOE estimated catch reports and include sockeye taken off the west coast of Vancouver Island, those caught by U.S. and Canadian fishermen in the IPSFC convention area, those caught by Canadian fishermen in Johnstone Strait, and those caught by native Indians from the sockeye escaping up the Fraser River. Recruitment will be assumed equal to the sum of the escapement and the catch. As the Fraser River sockeye fishery has been operating since before the turn of the century, and there have been no dramatic changes in fishing or in the environment since 1938, it is probably safe to assume that it has been in equilibrium since 1938.
The escapement data display a cyclical trend for number and size of spawners and timing of spawning. If the only form of sockeye stock control were external, fluctuations in environmental factors are so great that changes in abundance would be quite large. Sockeye recruitment does fluctuate but in a cyclical fashion and only to a limited extent. The first and third years of the cycle are about the same size, twice as large as the recruitment for the second cycle year but only half the size of the recruitment for the fourth cycle year. The data can be used to account for these effects by analysing the impact of year class cycles in both weight and numbers on the basic escapement-recruitment relation.

There are eleven races of sockeye in the Fraser River system which means there is a multi-species harvesting problem (Bicker, 1973b, p. 1280). However, to determine race proportion of the subsequent recruitment and the influence of gear type catch on race recruitment to each subsequent fishing zone would require intra-seasonal analysis and complicate an already complex model. No attempt will be made to solve this multi-species harvesting problem. With differences in fecundity, growth and mortality rates, however, it is possible to analyse the significantly different impacts of these eleven races on the escapement-recruitment relation, owing to the availability of data by race escapement since 1938.

Turning to the estimation process, the whole objective has been to achieve the best parameter estimates possible for prediction purposes. Subsequent work in this study is based on the assumption that confidence can be placed in predicted levels
of recruitment given different levels of escapement. Otherwise, the calculations for optimal management become meaningless. Although use of cycle dummies and disaggregated race escapement does provide a testable hypothesis, the recruitment model hypothesis is not being tested so much as being used to derive the best parameter estimates for recruitment to the fishery.

On the grounds of simplicity, it was decided that intrinsically linear functions would be used; specifically,

\[ R = aE^d \exp(-bE)) \exp(#) \]

\[ R = aE^d \exp(#) \]

The ability to transform these into linear models makes ordinary least-squares estimation easier (Kmenta, 1971, p. 451). The linear versions of expressions (2-8) (following Ricker) and (2-9) are:

\[ \ln(R/E^d)) = lna - bE + (#) \]

\[ \lnR = lna + d(lnE) + (#) \]

Expression (2-10) presents a problem: the dependent variable, \( R \), is modified in some way by the independent variable, \( E \). In addition to the empirical problems which result from having linear transformations of the same variables appear on both sides of the equation, there is a problem that if the variance of \( E \) is larger than the variance of \( R \), it will tend to dominate the ratio in the estimation. It is possible to re-arrange (2-10) to give

\[ \lnR = lna - bE + d(lnE) \]

In addition to improving the estimation procedure, this form has the benefit of permitting the data to determine the depensation
However, one consequence of using (2-12) is that multicollinearity is likely to be high between $E$ and its monotonic transformation, $\ln E$. This can be reduced by using instrumental variable, $WE$, in place of either of the $E$'s (Kmenta, 1971, pp.309-313). $WE$ is simply escapement multiplied by the average cycle weight of sockeye and is thus a non-monotonic transformation of $E$. Furthermore, the use of biomass rather than numbers would take into account the factor of size of fish and its impact on survival during escapement upstream.

The estimation process was divided into two stages. In the first, expressions (2-10), (2-11) and (2-12) were estimated using disaggregated forms of $E$ and $WE$; that is, the eleven race escapements (in numbers or biomass form) were used in place of the aggregate forms of $E$ and $WE$. In the second stage, the functional forms which gave the best parameter estimates were used with dummy variables to mark the year class cycles. Dummy sequences in both slope and intercept form with two year (every other year), four year (once every four years), two/two year (two good followed by two bad years), and eight year cycles were used.

As an alternative way of picking cycles, a polynomial distributed lag was used with lengths of lag varying from two to eight years. This technique would imply that the cycle is some function of conditions in the environment in previous years and assumes that the weights on the previous escapements follow a polynomial of a specified degree (Kmenta, 1971, p.492-495). The sockeye recruitment hypothesis does not supply any a priori specifications for the degree and length of the polynomial and
an iterative approach was employed to allow the data to determine the most statistically significant results using the R-squared delete approach. As the results were not as significant using distributed lags as they were with cycle dummies in slope and intercept form, the latter were used instead of the former.

In terms of goodness of fit the estimation proceeded in the following way. Using the basic Ricker functional form with recruitment in terms of numbers regressed on escapement in numbers, the R-squared was .28. When escapement and recruitment were put in biomass form (weight times numbers) the fit improved to .35. When cycle effects were permitted to enter through escapement in dummy form, the fit improved to .64. And disaggregating escapement into the eleven races raised R-squared to .88.

The results for this last estimation are given in the Appendix (expression (2-14)). These parameter estimates will not be used in the management model because of the complexities involved in modeling a multi-species harvesting system. Therefore, the parameter estimates which depend on recruitment in biomass form regressed on escapement in biomass form distinguished by year cycle will be used in the management model in Chapter Four. The basic functional form is that of expression (2-8) and the parameter estimates are reproduced in expression (2-13) below.

A test was performed to check on the possibility of changes in parameter values over the thirty-four years under observation using modified chi-square variables to compute the F statistic
Both of the best estimated functions \((2-13)\) and \((2-14)\) passed this test with no problem which would indicate that basic parameter values have not changed significantly over the whole period.

One problem of importance in the estimation was the presence of autoregression. The success of the year class cycle dummies would indicate that the major influence on recruitment is the escapement four years earlier. It is likely, however, that the effect of disturbances does carry over into other year class cycles. The experience with distributed lags would tend to support this and indicates that the greater the number of periods between disturbances, the smaller the covariance. For this reason, it is probably safe to specify a first order autoregressive scheme (Kmenta, 1971, pp.271-273).

To test the significance of the calculated coefficient of correlation of disturbances, a standard two-tail \(t\) test was employed. It is usual in economics to use a one-tail test because it is assumed that if autocorrelation exists, it is positive. But in biology it is quite possible that environmental factors could lead to negative autocorrelation which is the reason for the two-tail test. The Cochrane-Orcutt routine was used with the best estimated function to determine the coefficient of correlation of the disturbances. In fact, this test did indicate significant first order autocorrelation.

It is possible to include parameter estimates adjusted for a coefficient of correlation different from zero in the estimated recruitment function. However, to do so would make the optimal escapement problem exceedingly complex. That is, as
explained in Chapter Four below, one of the advantages of using dummies to distinguish between year classes is that the recruitment for each year class can then be isolated from the recruitment for the remaining three year classes. The most exhaustive biological study of the Fraser River sockeye salmon (Foerster, 1968) would also tend to support the view that interdependence amongst year classes does exist (particularly in the freshwater lake residence period) but that it is too weak and inconsistent to have much impact. For these reasons, the autoregression problem will be ignored in subsequent work.

The final results of estimation gave the following parameters with R-squared in brackets after the dependent variable and t statistics in brackets after the relevant explanatory variable. Note that the estimation procedure was not split into four cycle periods, but the results below are given in cycle year form to make explicit the manner in which biomass recruitment (WR) can be predicted from escapement in numbers (E) and in biomass (WE) form.

\[(2-13) \text{WR}.64 = \exp(-.000000694227E) (-5.4) D41WE^{1.15}(75.4) D42WE^{1.13}(54.3) D43WE^{1.15}(74.4) D44WE^{1.18}(69.8)\]

Where WR = biomass (weight times numbers) recruitment
WE = mass of escapement (weight times numbers) lagged four periods
E = escapement in numbers lagged four periods
prefix D = indicates that this variable is in dummy form
41,2,3,4 = four year cycle with the weight in the first, second, third or fourth year of cycle

The functional form used to derive these parameter estimates was taken from expression (2-12). Note that the compensatory parameter "b" in (2-12) is indeed negative in (2-13) and that the depensatory parameter "d" in (2-12) is positive
The expression in (2-13) implies that biomass recruitment is directly related to cycle year biomass escapement with depensatory coefficients distinguished by year class cycle. To offset this effect, biomass recruitment is inversely related (through the exponential operator) with escapement in numbers but the compensatory coefficient is not sensitive to the year class cycle.

The purpose of this chapter has been to estimate the recruitment function: the basic investment function which tells the fishery manager what "in kind" return to expect on his "in kind" investment in future recruitment through current abstention. External effects do not have to be left out and can be included by allowing cycle differences between year classes to be represented by dummy variables and by allowing the effects of weight on cycle year differences to be included through the use of biomass forms of the variables rather than just the numbers form. The use of these techniques with a modified form of the Ricker exponential recruitment function leads to parameter estimates which support the hypothesis that recruitment four years hence can be predicted from current escapement. As the period analysis did not indicate any significant change in parameter values for the thirty-four year period under study, these parameter estimates for the escapement-recruitment function can be used with confidence in the Clark-Munro equilibrium equation to estimate the optimal escapement for each year cycle.
APPENDIX

Compilation Of Catch And Escapement Data

Although observations on catch of sockeye salmon date back to 1894, observations on escapement from the fishery are only available after 1937. There is a distinct truncation in catch data resulting from the landslide into the Fraser River in 1913. Thus it can be assumed that any accumulated recruitment potential was well used up by 1938 and that the sockeye stocks have been in some form of equilibrium ever since.

The basic source for the data is the observations made by scientists working for the IPSFC as published each year in the IPSFC annual reports. The other major source of data is the Department of the Environment (DOE) revisions of the IPSFC catch data (Anderson, 1976).

Data on escapement by race of sockeye are available for the forty-four creeks and streams feeding into the eleven major river-lake systems which belong to the Fraser River watershed. Data on catch are available for sockeye entering the fishing gauntlet prior to ascending the Fraser River to spawn. It is not available by race. Fraser sockeye caught in non-treaty waters are not included in the IPSFC catch totals. This is the reason for including the DOE revisions. By summing revised catch and escapement, the migration of recruitment figure is obtained.

The best explanation of observations on escapement is given in the 1943 IPSFC annual report:

"1) The total run may be individually counted through an opening in a fence or weir. 2) The total number of salmon may be estimated by determining the ratio
established by marking a known number in the run, or by counting a sample which has a known ratio to the total. 3) A comparison of the magnitude of the runs from year to year may be based on counts which may be assumed to be constant but actually an unknown proportion of the whole" (IPSFC, 1943, p.38).

Weirs are seldom used because of the cost and the methods used most frequently are visual counts of live spawners and physical counts of the dead after spawning. Map (1-1) illustrates the extent of the job involved: "each racial escapement is enumerated by tagging, by proven line count indices or in some cases by weirs" (IPSFC, 1953, p.36).

In addition to the usual errors arising from changes in water level, temperature and weather, the greatest source of error is that escapement observations are for net escapement and not gross escapement. That is, the count is not of the numbers escaping fishermen's nets but of numbers reaching the spawning grounds. Mortality in the upstream migration can vary from 5% to as much as 60%. Thus true recruitment is not given by summing net escapement and catch. However, counts on the spawning grounds do give a more accurate figure for the number of spawners involved in the formation of the the next year class. A possible justification for using net rather than gross is that "only the peak of the run is properly synchronized with the reproductive environment and ...the fish from the beginning or end of each run are not normally capable of reproduction at a maximum rate because of their early or late migration" (IPSFC, 1955, p.8).

This is helpful in terms of escapement but still does not help in calculating migration totals. It will be assumed, therefore, that escapement mortality is fixed on a proportionate basis according to year class cycle which implies that the measurement
error for recruitment is multiplicative.

The index system of enumerating escapement is most often based on a visual count. This does not give the absolute figures but does allow comparison of the index year by year. If the population is counted in any year, the index in past years can be adjusted to reflect the true absolute count rather than the relative count. This accounts for the many subsequent corrections in previous years' escapement totals. These annual revisions meant that escapement totals for the forty-four streams and creeks from 1938 to 1975 had to be checked and re-checked to make sure the latest corrections had been included.

The difference between gross and net escapement is also affected by the Indian catch which takes place after the salmon escape the commercial fishery and before they reach the spawning grounds. The 1944 annual report included a report on the catch statistics for the Indian fishery (pp.65-74). The Indian catch statistics are obtained from Protection Officers of Canada, Department of Fisheries. These inspectors control the taking of sockeye for food by the Indian population residing throughout the Fraser River watershed. The IPSFC estimates of Indian catch date back only to 1941. Foerster's estimates of Indian catch are used for 1938, 1939 and 1940 (Foerster, 1968, p.58).

Another potential source of error is the blockage of the Hell's Gate section of the Fraser. The fishways were completed and used by the spawners in 1945 (IPSFC, 1946, p.5). Subsequent counts indicated that these fishways led to an average 100% increase in escapement to spawning grounds above Hell's Gate. This once-and-for-all change in escapement should not affect
estimation too seriously because the figures on escapement had been "in situ" counts on spawning beds. And as recruitment only included net escapement and not gross escapement, it meant that recruitment and escapement prior to 1945 were net of the effects of the Hell's Gate obstruction. Subsequent figures would include the increased net escapement both in recruitment totals and in escapement totals. That is, subsequent counts would simply indicate a larger escapement from the fishery and the observations would be for a different range of the escapement-recruitment function.

It was not until 1952 that the importance of cycles was noted. It was recognized that the "factors controlling quadrennial dominance in productivity in the reproducing areas above Hell's Gate may perhaps be of greater importance than the size of escapement " (IPSFC, 1952, p.26). To avoid changing the cyclic character

"escapements are controlled to fit the historical pattern of productivity in each of the four cycle years. A large escapement is provided in the year of the dominant run, a reduced number of fish in the year of sub-dominant run and lesser numbers of fish are permitted to escape under normal circumstances in the two 'off-years'" (IPSFC, 1965, p.3).

The justification for this policy is that consistent size of escapement would tend to interfere with the predator, fish, food and prey relations and lead to cycles of a different sequence.

This means that escapement regulation which was initiated in 1946 has not offset the natural cycles. This gives even more support to the use of cycle dummies to act as a proxy for external influences.

Catch statistics are recorded by the IPSFC through the log
book system instituted in 1941 (IPSFC, 1941, p.9). A check of cannery records plus the fish tickets, buyer tallies and wharf tallies at each cannery or buyer are used to enumerate daily landings (IPSFC, 1944, pp.52-53). The system has not changed radically as the original system has worked well. The IPSFC is charged with the task of dividing the convention catch equally between the U.S. and Canada. Thus there has always been a great deal of pressure for accuracy.

In some years the sockeye become vulnerable to fishing in non-convention areas such as the west coast of Vancouver Island and in Johnstone Strait. Until 1958, the IPSFC did not publish data for these catches despite the obvious distortions to migration totals. This was not possible after 1958, the year in which a third of the commercial catch of Fraser sockeye was taken in Johnstone Strait. DOE estimates of non-convention catch are used as a check on the IPSFC published catch reports and the former do agree with the maximum of the two IPSFC estimates for each year. The DOE estimates are likely to be more accurate because the IPSFC has no jurisdiction over non-convention catch. Lack of data prior to 1951 is unlikely to be too serious an omission as few Fraser sockeye were caught in non-convention areas.
**Recruitment Function Estimation**

The estimation procedure was divided into two stages. The key to the eleven race escapements is given below with the freshwater residence lakes in brackets (see Map (1-1) for the spawning areas of the Fraser River watershed):

- ELF = Lower Fraser (Pitt)
- EH = Harrison (Harrison)
- ELC = Lillooet, Fraser Canyon (Nahatlatch)
- ESA = Seton-Anderson (Seton and Anderson)
- EST = South Thompson (Shuswap and Adams)
- EMT = North Thompson
- EC = Chilcotin (Chilko)
- EQ = Quesnel (Quesnel)
- EN = Nechako (Francois and Fraser)
- ES = Stuart (Takla, Trembleur, Stuart)
- ENE = Northeast (Bowron)
- R = total migration of Fraser sockeye
- E = total escapement lagged four periods
- L = natural logarithmic operator; any variable prefixed by this symbol is in log form
- W = weight operator; any variable prefixed by this symbol is in biomass rather than numbers form; it is lagged four periods when used with escapement
- SER = standard error of regression
- C = constant
- D = dummy operator; any variable prefixed by this symbol is in dummy form
- OLSQ = ordinary least squares
- PDLL = polynomial distributed lag
- CORC = Cochrane-Orcutt iterative least squares routine to estimate rho
- Rho = coefficient of correlation between successive disturbances

**Stage One**

LB, LWR, and L(R/E) were regressed on C plus the appropriate form of E or its transform (ie: WE or LE) plus eleven race escapements either in biomass or numbers form.

All the best parameter estimates were then transformed back into non-linear form and actual recruitment was regressed on
predicted recruitment to check the fit.

**Stage Two**

LR, LWR and L(E/E) were regressed on C, the appropriate form of E (log transform or biomass) and the best of the eleven race escapements in appropriate form (numbers or biomass) either in dummy form or PDL form with the sequences or lags as above. In every case the dummy sequences gave better results than the PDL and the latter technique was dropped in favor of the former in subsequent work. That is, the hypothesis that the cycle is some function of conditions in the environment in previous years does not appear to be supported. The alternative hypothesis that environmental influences simply act in a four year cycle does appear to be supported.

The depensatory parameter was taken from the LWE coefficient in the expression (2-12) form of the Ricker model (the same as (2-13) without the cycle dummies, just WE) and used in conjunction with the L(E/E) version.

The best parameter estimates are given in equation (2-14) below. This version had a corrected R-squared of .81 and a critical t statistic of 2.08 at the 5% level of significance.

\[
(2-14) \ \log(\frac{WR}{WE*}) (0.88) = +.43(3.2) - .11E(-4.9) \\
- .13D41E(-3.0) - .18D42E(-4.2) + .15WEH(3.0) \\
- .32D43WEH(-3.5) + .03WEST(3.4) + .18EC(3.1) \\
- .37D224EC(-4.2) + .23D43WELC(3.7) - .21EQ(-2.2) \\
- .32WESA(-2.7) + .6D22WESA(2.7)
\]

Where WR = biomass (weight times numbers)  
WE = mass of escapement (weight times numbers)  
E = escapement in numbers lagged four periods
prefix $D = \text{indicates that this variable is in dummy form}$

$41,2,3,4 = \text{four year cycle with the weight in the first, second, third or fourth year of cycle (1 0 0 0)}$

$D21,22 = \text{two year cycle with the weight in the first or second year of cycle (1 0)}$

$D224 = \text{four year cycle with the weight in the second and third year of cycle (0 1 1 0)}$

$\text{WEH = mass escapement to Harrison}$

$\text{WEST = mass escapement to South Thompson}$

$EC = \text{escapement in numbers to Chilcotin}$

$\text{WELC = mass escapement to Lillooet, Fraser Canyon}$

$\text{EQ = escapement (in numbers) to Quesnel}$

$\text{WESA = mass escapement to Seton-Anderson}$

The second step involved estimation in split period form. The best estimator had a sum of squared residuals (SSR) of .2435 for the period 1942 to 1958, an SSR of .0986 for the period 1959 to 1975 and an SSR of 1.2848 for the period 1942 to 1975. These gave an $F$ statistic of 1.743 which was well below the critical $F$ value of 3.26 at the 5% level of significance and meant that the null hypothesis of unchanged parameter values could be accepted.

The third step involved the use of CORC to estimate the value of rho for the best estimator. The Hildreth-Lu routine was used as a check on CORC to make sure the iteration did not stop at a local minimum SER rather than at the global. The best estimator had a value for rho of .64 with an $R$-squared of .9.

The final step involved converting the parameter estimates back into non-linear form and regressing recruitment against predicted. The best parameter estimates (expression (2-14) above) had an $R$-squared of .9 and an SER of .7.
CHAPTER THREE: HARVESTING: THE PRODUCTION AND COST FUNCTIONS

I INTRODUCTION

The recruitment function estimated in Chapter Two will tell the manager of the fishery what recruitment to expect four years after allowing a certain level of escapement. But the manager needs to be able to compare this investment return with the return he could expect if he were to harvest more of that escapement and invest the net profit at the social rate of return. In making this comparison the next step is to estimate the costs of harvesting a specified catch from a given recruitment of Fraser River sockeye salmon. But before going to a description of the procedure for determining these costs, it is useful to review some of the characteristics of the Fraser River sockeye salmon fishery. This review will help provide some insight into the appropriate specification of the salmon production function from which harvesting costs are eventually derived.

As described in Chapter One and Map (1-2), the first zone to receive biomass recruitment is the west coast of Vancouver Island where troll fishing for sockeye is successful (net fishing is illegal) but is not substantial in terms of total harvest. The reason is that sockeye stop feeding and concentrate their energy instead on the spawning migration when they enter the gauntlet. Thus they are not vulnerable to lures nor to bait on hooks. This explains why virtually no sockeye are caught by the sport fishery (Sinclair, 1960, p.36). Once the reduced
recruitment passes Mission on the Fraser River, commercial fishing is illegal. Native rights have permitted Indian fishing of sockeye in certain areas of the Fraser River system. This Indian fishery is modest in comparison to commercial sockeye harvesting and most of the catch is made for their own consumption. However, the Indian catch does affect the migration up the Fraser River and will be included on an average cycle year basis in subsequent work with escapement.

The gear types used in the fishery consist of trolls, gillnets and purse seines in Canadian waters and gillnets, reefnets and purse seines in Washington waters. A study made of the important trends in the B.C. salmon fishery (Campbell and Roberts, 1967) indicated that the troll catch of sockeye was almost negligible. The Department of the Environment (Canada, 1951-1975) reports on catch by gear support this view, particularly in inside waters where the troll catch of sockeye represents less than 1%, by weight, of the total troll catch of salmon. The only significant troll catch of sockeye is off the west coast of Vancouver Island.

The traditional type of gear used to catch sockeye has been the gillnet. Its effectiveness depends on the relationship between the mesh size and the weight of the fish. If the mesh is too small, the head of the fish cannot penetrate deeply enough into the net to enmesh the gills. If the mesh is too large, the fish simply swim through without too much trouble. Studies conducted by the IPSFC culminated in 1948 in an eight inch linen mesh and in 1951 in an eight and three-quarter inch nylon mesh.

Gillnet fishing is essentially passive in that the nets are
set, usually in fairly shallow and confined channels of water, and the fishermen wait for migrating fish to become entangled. There is a law prohibiting the use of the boat to herd the fish into the net. But fishermen are permitted to patrol the net to judge when it is full enough to pull and clear.

With the increasing use of purse seines in the early part of the gauntlet, the biomass availability for gillnet fishermen in the later parts of the gauntlet has declined steadily. The availability to Fraser River gillnetters dropped from nearly 100% of the potential Canadian catch in 1944 to 65% in 1956 (IPSFC, 1956, p.20). As a result, gillnet fishermen started moving into the earlier part of the gauntlet, although with limited success at first (IPSFC, 1954, p.27 and 1955, p.25). However, as fishing methods adjusted to the new technique of "drift netting" in unconfined waters, the gillnet catch in the Strait of Juan de Fuca has become very significant, especially in years when sockeye drift rather than swim.

A hybrid form of gillnet is the reefnet used by a small proportion of Washington fishermen. As the name implies, the net is used in the vicinity of reefs where waters are very confined and sockeye are forced into heavy concentrations. Fishermen wait until the concentration builds up and then quickly set the reefnets. Once again, increasing use of gear in earlier parts of the gauntlet has caused a steady decline in biomass availability to reefnets until, in 1963, there were no sockeye available at all (IPSFC, 1963, p.16, and 1966, p.17). To counteract this problem, the IPSFC adjusted their open time of day regulations to permit the reefnet open days to start earlier than for any
other type of gear throughout the season (IPSFC, 1967, p.25).

After the gillnet, the purse seine is the most important type of gear for harvesting salmon. It involves active fishing in the sense that the boat must search for salmon and, when a sizable block is sighted, the set is made by encircling the fish with a curtain of net which is then closed at the bottom by pursing the seine. The entrapped fish are then brailed into the hold of the vessel. Because of the size and complexity of the operation, the average purse seine carries a crew of five as opposed to the one man troll and gillnet operations. The investment in the purse seine and its gear is proportionately greater as well.

Purse seining has been considerably streamlined since the introduction of the Puretic power block in 1953 and the use of a drum rather than a table to haul the net (IPSFC, 1954, p.22; 1955, p.25; and 1956, p.19). These innovations have permitted the average crew size to fall from eight or more to five with catch per man increasing simultaneously (Sinclair, 1960, pp.213-214; and Royce, Bevan, et al., 1963, p.2).

If a block of sockeye are found milling close to the surface, the purse seine is an extremely effective type of gear. Once the set is made and the net pursed, the fish can be brailed aboard within a short time. Thus, the catching power of purse seines is much higher, on average, than for gillnets or trolls but the variance is also much greater.

In some years certain gear types are more successful than others and in other years, less successful. Catchability is the factor which can be used to account for much of the year-to-year
and area-to-area differences in catch per unit of effort and appears to be influenced by the cyclical nature of run sizes, weight of fish etc. Availability of recruitment for all cycle years, however, appears to follow a fairly standardized path. The analysis of sockeye salmon migration performed by the Royce-Bevan study in order to construct time of entry curves indicated the following average pattern: about 94% on the Canadian side in the outer Strait of Juan de Fuca; 20% then leave the Strait of Juan de Fuca to spend one day in the Westbeach area in Washington waters; these later rejoin the remaining 80% in the San Juan Islands area in Washington waters; then about 95% of the remainder swim past and through the Point Roberts area on the Washington side; and finally, 100% of the remainder swim into the Fraser River mouth (Royce, Bevan, et al., 1963, p.21).

There are daily effort data available for each of four main areas in Washington waters and eleven main areas in Canadian waters. But the Royce-Bevan study had the greatest success using data aggregated on a monthly basis for the following areas only: the west coast of Vancouver Island, Strait of Juan de Fuca, southern Vancouver Island including Maru Strait and Stuart Island, Westbeach, San Juan Islands (Rosario Straits), Point Roberts, the mouth of the Fraser River and the Fraser River itself (1963, p.31).

Whereas the Royce-Bevan group looked at only six years of data (1956 to 1961), the present study uses twenty-five years (1951 to 1975) of observations on gear type effort to estimate the production function. And despite the many changes in gear location in the gauntlet during that time, there is a surprising
consistency in the gear types used in each of the above named areas over that period of time. These are the same areas of sockeye migration chosen by Sinclair as well (1960, p.29).

For the most part the favorite gear type for each area is a result of catchability conditions there which are peculiar to the needs of the gear type. It is important to note, however, that certain gear types have been prohibited from harvesting in certain areas by the IPSFC (1953, p.7). In particular, area 19 was closed to commercial fishing to permit sport fishing (Sinclair, 1960, p.34) and areas to seaward of the black line on Map (1-2) are closed to net fishing. Purse seines, for example, have been tried over the years in the Fraser River below Mission but with very little success. The reason is that by that late stage in the gauntlet, sockeye are coming through in only small groups. There is very little bunching except at the peak and a block of fish is rare. Gillnets are ideally suited for this type of fishing. Another example is reefnets in the Westbeach area which have met with very little success. Again both purse seines and gillnets were tried in area 21 with some success but they were prohibited after 1957. And area 19 has long been poor for Canadian fishermen because the sockeye have a tendency to shoot by with currents into Washington waters.

Thus the following harvesting zones have become associated, either through custom or regulation, with the following areas and gear types. Note that the official areas within each zone have been aggregated to simplify the analysis. In every case these aggregations were checked with the department of fisheries concerned and they conform with official practices. Within each
zone, there may be more than one gear type operating. To avoid confusion over the expression "gear type zone" when these are really fishing zones, they are referred to as "gear type areas" in this study. This also avoids the confusion which can arise when referring to sixteen "gear types" when, in fact, there are only four (trolls, gillnets, purse seines and reefnets).

Therefore, there are sixteen gear type areas operating within the seven fishing zones. The seven zones with their associated gear type areas are, zone one: west coast of Vancouver Island, consisting of areas 21, 23, half of 24, and International Area "C", harvested by troll; zone two: the Canadian section of the Strait of Juan de Fuca, consisting of areas 19 and 20, harvested by gillnets and purse seines; zone three: the Washington section of Strait of Juan de Fuca (after 1957) and Westbeach, harvested by gillnets and purse seines; zone four: the San Juan Islands in Washington waters, harvested by gillnets, purse seines and reefnets; zone five: Point Roberts in Washington waters, harvested by gillnets, purse seines and reefnets; zone six: the Strait of Georgia in Canadian waters, consisting of areas 17 and 18, harvested by trolls, gillnets and purse seines; and zone seven: the Fraser River area, consisting of areas 29A, 29E, 29C and 29D, harvested by trolls and gillnets. These areas and gear types account for 95% of the commercial sockeye salmon harvest in most years in the fishing gauntlet.

These seven harvesting zones and their sixteen gear type harvesting areas have been aggregated, therefore, from thirty-four different gear type areas. It will be assumed that within
each zone recruitment availability is the same for all gear types but that catchability is different. From one harvesting zone to another it will be assumed that the recruitment availability has been reduced by the catch taken by all the gear types in the previous zone. Of the sixteen gear type areas which can be distinguished in the gauntlet, only six have accounted for 90% of the average catch taken over the period 1951 to 1975. Although production functions were estimated for all sixteen gear type areas, the ten gear type areas accounting for only 10% of the average catch were all more costly in terms of harvesting than the six gear type areas accounting for 90% of the average catch. For this reason, only the six major gear type areas will be discussed in terms of both production function estimation and programming for cost minimization. These areas are as follows: CZ2GN and CZ2PS, Canadian gillnets and purse seines in the outer Strait of Juan de Fuca; USZ4GN and USZ4PS, U.S. gillnets and purse seines in the San Juan Islands; USZ5PS, U.S. purse seines in the Point Roberts area; and CZ7GN, Canadian gillnets in the mouth of the Fraser River.

In addition to sockeye, four other species of salmon are caught in the gauntlet during the Fraser River sockeye season. However, the multi-species nature of escapement and harvesting will be ignored for most of this study to concentrate on harvesting and escapement for sockeye only. The catch of other salmon will be recognized only to the extent that it lowers the costs of harvesting for sockeye. The model used will be very basic in that the average cycle catch of other salmon will be allowed to flow into each zone to be harvested by gear operating
there for purposes of catching sockeye. Gear will be permitted to harvest other salmon either to the extent of remaining capacity after harvesting sockeye or to the historical extent associated with average cycle catch of other salmon per unit of effort, whichever is smaller. Thus the model assumes that gear concentrate on catching sockeye and harvest other salmon on an incidental basis only according to excess capacity. Nevertheless, sockeye may be an incidental catch for some gear in some years because the fishermen are intent on harvesting pink salmon. For this reason, catchability of sockeye may vary on a year cycle basis simply because of the joint production nature of harvesting.

Although data do exist to permit estimation of recruitment and production functions for these other salmon, because of the complexities involved in modelling a multi-species fishery, no attempt will be made to estimate either recruitment or production functions for pink, chum, chinook or coho salmon. This is partially justified on the basis of the fact that the cost minimization program will choose the least cost method for harvesting sockeye and in so doing will automatically exclude a portion of the catch of "other" salmon. Sockeye will represent a very large component of the catch for the least cost areas simply because of the density of sockeye which are permitted through the gauntlet to be caught by those least cost harvesting areas.

Both pink and sockeye salmon are managed by the IPSFC and the reports indicate that the job is not easy. Although the peaks of the sockeye and pink runs do not coincide, there is
enough overlap to cause problems with species escapement. Pink salmon represent the greater weight of "other" salmon caught in "on" years, while chum, chinook and coho represent a sizeable weight in the "off" years for pink. This can lead to serious problems with investment in enhancement or even in in-kind abstention investment. If the reproduction potential of sockeye is raised without a corresponding increase for another species, the increased harvesting rate needed for catching the enhanced sockeye catch could seriously deplete the other stock (Crutchfield and Pontecorvo, 1969, p. 180).

In summary, the thirty four original gear type areas in the gauntlet have been aggregated into seven major fishing zones consisting of one or more gear type areas, to give sixteen gear type areas in all. Within each of the seven major fishing zones, it is assumed that recruitment availability is the same to each gear type operating within that zone. However, recruitment availability varies from zone to zone according to the size of catches made in previous zones. Within each zone, gear type catchability is permitted to vary on a cycle year basis. Although production functions for all sixteen gear type areas were estimated, in fact only six gear type areas proved feasible in terms of cost. Only these six gear type areas operating in zones two, four, five and seven will be retained for work with the least cost program and the management model.
II PRODUCTION FUNCTION ESTIMATION

(1) Production Function Specification

The approach taken in this study is to calculate costs by estimating a production function first. The most common hypothesis for the harvest production function is

\[ C = qBf \]

where \( C \) = catch
\( q \) = catchability of biomass (constant)
\( B \) = recruitment availability (variable)
\( f \) = a composite unit of effort (variable)

For a non-migratory species, \( q \) is sometimes assumed to be constant which implies that the stock of fish is equally dispersed throughout the fishing grounds at all times. For a migratory species like sockeye, the first change is to make \( B \) sensitive to the movement of the biomass through the gauntlet. However, in this study there will be no intra-seasonal analysis of availability differences. In any one season, the recruitment will be available to the first fishing area in the gauntlet in unmodified form. It will be available to the second fishing area in a reduced amount because of the fishing in the first area. As the migration proceeds, recruitment availability is continually reduced by the catch in the preceding area until only the escapement is left after the last fishing area. As total catch represents about 70% of recruitment (leaving 30% for escapement), the reduction in availability can be considerable by the time the seventh fishing zone has been reached.

Given the recruitment availability from a previous zone, certain factors operate which affect the catchability of the
biomass which is available from that previous zone. If recruitment is composed of smaller fish, these will tend to school and swim closer to the surface which makes them more vulnerable to purse seines and, because the gill circumference is smaller, less vulnerable to gillnets. On the other hand, larger fish tend to swim more independently and at greater depths, making them less vulnerable to surface nets like purse seines but more vulnerable to gillnets. Other factors affecting catchability are weather, tides, currents and water temperature.

However, in the above, well known, formulation for harvesting production functions, it is sometimes assumed that catchability of the available biomass is constant on an inter-seasonal basis. Catch is regressed on effort and the biomass recruitment to arrive at parameter estimates. Part of the reason for this unrealistic catchability assumption has arisen from the data constraints which have forced biologists to estimate stock abundance using catch per unit of effort (assuming constant catchability) in analytic models. This assumption will not be necessary to the biological work in this study because of the use of escapement to estimate recruitment independently. Thus, it will be possible to estimate varying catchability of biomass as well.

Many studies have treated fish catchability as a constant (see, for example, Crutchfield and Pontecorvo, 1969, chapt.2; Gordon, 1954, pp.139-142; Hannesson, 1975, pp.152-153; IPSFC, 1944, pp.23-26; and Sinclair, 1960, p.67). Hannesson discusses the fact that availability (what is called catchability in this study) is a function of both effort and biomass for cod but
concludes that in the long-run cod are probably evenly dispersed and that availability (catchability in this study), therefore, is constant (1974, chapt.2, part 4). Although biomass availability of cod varies with the size of the stock, even for cod the catchability appears to vary with year class strength, geographical location and weather. Why else would cod fishermen wait for the right tides and weather and jockey for the "best" positions on the fishing grounds?

The harvesting production function in expression (3-1) implies that the more dispersed the fish, in a given fishery, the more effort must be expended to catch them. To clarify the distinction between availability and catchability of biomass, and technical change of effort, it is useful to modify expression (3-1) to give:

\[ (3-2) \quad C = qBpf \]

where \( C \) = catch
\( q \) = biomass catchability index
\( B \) = recruitment availability
\( p \) = effort efficiency index
\( f \) = harvesting effort

Note that catchability as well as availability can now affect the scale of operation. For most harvesting production function estimation, \( B \) and \( f \) are allowed to vary according to the data. But \( q \) is sometimes assumed to be constant. If this is the case, then actual fluctuations in biomass catchability are absorbed by an error term. This procedure can result in inferior fits for the production function. Most researchers have then turned to modifying the effort index to allow for changes in efficiency. The biomass index is usually left alone and fluctuations in catch per unit of effort are diagnosed in terms of changes in
It is true that the unit of effort is subject to criticism because it is a composite measure of a vessel and its complement of men and gear multiplied by the number of hours or days of fishing. And it is obvious that virtually all components of such an index must have changed over time. For example, although it is probably safe to assume that labour productivity has changed very little in the B.C. salmon fishery (Canada, DOE, 1971), not only has relative efficiency between gear types changed considerably but changes within gear types have been very rapid since World War II. Therefore, some account must be taken of the large increase in the catching ability of the different gear types.

Any attempt to measure technical innovation in gear or vessels is going to be of little use unless some adjustment for fluctuations in catchability can be made. If not, the measure of effort will have absorbed the fluctuations in biomass catchability over the years as well. The technique employed by Tomkins and Butlin (1975, p.115) to "eliminate the effects of varying stock abundance between years" involved standardizing the average catches of other gear types "relative to the performance of the drift boat sector in each year, since there has been very little change in the technology of drift net fishing over the years". The problem with using this approach is that it assumes that biomass catchability was constant within each season for all gear types. While this is unlikely even in a cod fishery, it is impossible in the sockeye salmon gauntlet. Some means, external to the production function, must be found
to adjust effort for technical change. If the estimating process itself is allowed to compensate for these errors in effort measurement, fluctuations in catchability of biomass and technical change will become confused.

The problem is that catch per unit of effort varies from season to season for three basic reasons. The first reason is that the availability of fish varies from season to season. Most harvesting production function work does not suffer from a lack of observations on availability and this influence can be removed. The second reason is that gear efficiency changes from season to season because of changes in vessel and gear productivity. The third reason for fluctuations in catch per unit of effort arises from the nature of the stock of fish (whether it schools or not), its spatial dispersion (tides and currents prevent equal dispersion) and the vertical displacement in the water (how deep the fish swim). This affects the catchability to various gear types.

Observations on catchability do not exist for many fisheries. Any attempt to allow the estimating process to account for changes in productivity is bound to pick up the effects of catchability. This is why it is so important to account for changes in productivity or catchability outside the estimating process itself.

In the present study, independent measures of technical change external to the production function are available both in IPSFC reports and in measures of gear and vessel value changes. And it will be possible to adjust the measure of effort. The improvement in fit is significant for most of the gear type
areas in the Fraser River sockeye fishing gauntlet. However, it is not possible to measure fluctuations in catchability externally to the production function. Instead, dummy variables in slope and intercept form will be used with biomass recruitment (adjusted for availability in each fishing zone in the gauntlet) to allow the estimation process itself to estimate the catchability parameters. The very strong four year cycle which results would tend to support the hypothesis that catchability is mainly influenced by year class cycles which may result from cyclical environmental factors. As it is highly unlikely that technical progress advances and retreats in a four year pattern, it is probably safe to assume that this method of adjustment is not confusing catchability of a given recruitment of sockeye with enhanced catching power of gear (efficiency).

In summary, biomass recruitment can be adjusted to reflect availability in each fishing zone by subtracting the previous zones’ catch from available biomass recruitment in that zone. Efficiency indexes and gear and vessel value indexes can be used to adjust effort for technical change in a manner external to the production function. And the estimation process itself, through the use of dummy variables which distinguish biomass availability according to cycle year, can be used to estimate the catchability parameters. The harvesting model used in this study will be a non-linear homogeneous production function:

\[ C = a((pf)^b)(B^\gamma)(\exp(#)) \]

where 
- \( C \) = gear type catch by area
- \( a, b \) = parameters
- \( pf \) = gear type effort by area adjusted by an index of technical progress in gear type productivity (in deflator form)
- \( B \) = biomass availability by gear type area
\( q = \text{catchability parameter} \)
\( \# = \text{error term} \)

Expression (3-3) is intrinsically non-linear and in logarithmic form looks like:

\[
(3-4) \quad \ln C = \ln a + b(\ln (pf)) + q(\ln (B)) + \# 
\]

Expression (3-4) is the basic equation used in all production function parameter estimation.

(2) Technical Progress

Before estimation can take place the effort data have to be adjusted for technical progress. Furthermore, the data are for deliveries or landings only, not for the amount of time spent searching, catching and processing. A delivery or landing is assumed to be one day's worth of effort in the data reports. Thus the effort variable "\( f \)" must be adjusted to reflect the true amount of effort and the productivity index "\( p \)" must be calculated to reflect changes in that productivity.

First we deal with the problems experienced with the reported measure of effort over time. Some vessels may deliver twice a day while others may deliver every two or three days; and yet the first is officially reported to have used two units of effort to catch the harvest while the second is reported as having used a single unit of effort. The favorite fishing ports and fishing grounds have changed over the period 1951 to 1975 to the extent that gear has moved out to the open areas of the gauntlet. Thus running distances have changed, although with the advent of more powerful engines, it is not clear how much of
this increase in distances has been offset by greater speed. Gear still fishing in traditional areas is unlikely to have experienced much change in running times or distances. Therefore, with more powerful engines, electronic equipment and ship-to-ship radio, it must be assumed that search time has been reduced over the years for some gear but not for others.

The length of exposure of the gear to the biomass has also changed because the hauling and clearing of gear has been greatly speeded up with the addition of power to skiffs, rollers, pulleys and brailers. This means that purse seines can be set twelve times a day instead of nine; gillnets can be cleared more often and more quickly, resulting in fewer fish lost from unmeshing and predation, and trolls can haul, clear and re-bait their lines more often and more quickly. There has also been a tendency to ice the catch in order to forestall delivery until an area is closed or to permit running from a closing area to an opening area without the need to spend time delivering.

Deliveries or landings record the actual number of times the vessel unloaded its catch. Because of the effort involved in travelling, searching, fishing and processing during a day, deliveries do give an approximation to days fishing for some gear. The exception would be the larger open water gear types with on-board icing facilities. For this reason, it will be assumed that adjustment of the effort variable can be made through the index of technical productivity. This productivity index will have to reflect both changes in productivity and the need to adjust the effort variable to reflect true effort. For
some areas deliveries are a very close approximation to true
daily effort but for others effort must be adjusted to give the
true daily effort.

To this end, two indexes of productivity for each gear type
were developed. The first was an index of gear efficiency which
simply reflected the major technical innovations over the period
under study. The second was an index of gear and vessel values
which should reflect both gear efficiency changes and the
changes in open-water vessel size and facilities. For gear
operating in confined waters, it was assumed that once
deliveries had been converted for efficiency changes (the first
index), the 1951 equivalent deliveries would be the same as 1951
equivalent days of fishing effort.

These gillnet and purse seine efficiency indexes do not
handle the problem of changes in vessel size and power which
reduce running and search times and permit catch to be held over
several days before the vessel is forced to make a delivery.
However, running time and search time are not of great
importance to vessels located near traditional fishing grounds.
Nor is unloading a problem because canneries have located close
to traditional fishing grounds and offer tendering services when
they cannot locate close enough. In many cases, because of the
confined working space in traditional fishing areas, it is not a
great advantage to have a large vessel. And, as the vessels are
close to delivery points, it is easier to deliver once a day
than to take the time to ice the catch. This is not the case for
vessels engaged in harvesting in more open waters in the
gauntlet. These operations involve a certain amount of running
and searching. Both seine and gillnet vessels involved in open water operations have grown steadily larger and more powerful with more sophisticated electronic gear and icing facilities. This has increased the number of effective hours of fishing and the number of days per delivery.

The second index of productivity, therefore, was designed to pick up these open water effects through indexing the value of gear and vessels used in salmon fishing. Gear and vessel value indexes were constructed for purse seines and gillnets based on data available in annual reports from the federal Department of Fisheries. In brief, an index of average gear and vessel values deflated by the appropriate price index and adjusted for license capitalizations was constructed for gillnets and for purse seines. The construction methods are discussed in greater detail in the Appendix below. These gear and vessel value indexes should pick up the influence of the switch from table to drum seines and from linen to nylon nets, simply because more efficient vessels and gear are worth more. Thus these gear and vessel value indexes can be used in place of efficiency indexes to convert deliveries into 1951 equivalent days of fishing effort. It was assumed, therefore, that this second index of productivity would adjust effort both for changes in productivity and for the actual number of days of effort involved in making a delivery.
(3) **Biomass Availability And Catchability**

Equally as important as the effort variable is the biomass variable. There does not appear to be any published data available for biomass and we are left with the recruitment variable estimated in connection with the recruitment function in Chapter Two. Preparing this variable for use in parameter estimation for the production function involves two steps. The first is to adjust downward the flow of biomass recruitment into each of the major zones in the gauntlet for catches made in the previous zone. This establishes the biomass availability to each fishing zone. The second step is to estimate the catchability parameter to reflect the gear type catchability of sockeye from the available biomass in each zone.

From the successful use of cycle variables in the recruitment function in Chapter Two, it would be logical to assume there is probably a cyclical element in biomass catchability. For example, it is known that average weight of fish plays a critical role in terms of both schooling behavior and vertical dispersion in the water. It will be assumed that the many dispersion effects can be summarized by the character of each of the four year cycles. Thus each year class of the four year cycle is assumed to be different from the other three year classes in terms of catchability. Furthermore, the catchability for any single year class will be assumed to be consistent from one four year period to another. In terms of the production function this cyclical variation will be estimated through the use of four year slope and intercept dummies. The latter should also pick up changes in gear type gauntlet
position due to harvesting for pinks rather than sockeye. Therefore, dummies in intercept and slope form for biomass, numbers and weight were used in cycles of two years, two/two years (two good followed by two bad), four years and eight years. Cycles of odd numbered years were tried with little success.

Returning to the first step, the adjustment of recruitment for biomass availability, the following procedure was used. For each year of the twenty-five year period, known biomass recruitment of sockeye was used as the available biomass for zone one. The biomass for zone two was simply the biomass for zone one minus the actual historical catch of sockeye in zone one. It was assumed that within each zone there was no serious gear interference between gillnets and purse seines: the IPSFC opens areas for different gear at different times. The biomass for zone three was the zone two biomass minus the gillnet, purse seine and Sooke trap catches in zone two. (As the fish traps in Sooke Harbour only operated for seven years between 1951 and 1958, no production function was estimated for them. However, their catch must be subtracted from zone two biomass to give the true biomass in zone three.) This biomass calculation routine was followed for the subsequent zones.

According to the IPSFC, the catch in Johnstone Strait consists of biomass which separates itself from the main body of sockeye before entering the gauntlet and swims through waters north of Vancouver Island in order to reach Johnstone Strait. In most recent years the Johnstone Strait catch represents less than 5% of the total sockeye catch. But in some years it has
reached as high as 33%. For this reason it is important to discover just how the Johnstone Strait sockeye got there.

Tests were performed with the production functions to see if inclusion or exclusion of Johnstone Strait catch in the biomass of sockeye made significant changes. In each test it became clear that exclusion of the Johnstone Strait catch from the biomass from every zone except zone seven led to significantly poorer results. These tests would support the hypothesis that sockeye caught in Johnstone Strait do not detach themselves from the main body of sockeye until they have passed through each zone in the gauntlet with the exception of zone seven (mouth of the Fraser River). That is, they appear to reach Johnstone Strait by swimming through the gauntlet waters south of Vancouver Island. There appears to be some support for this hypothesis in a recent study by Anderson (1976). For some reason the sockeye appear to swim past the mouth of the Fraser River and into Johnstone Strait. The biological reason could be connected with the fact that the years of largest Johnstone Strait catch are also years when the recruitment of sockeye is exceptionally large.

Availability of sockeye must depend primarily on the biomass of sockeye migrating through the gauntlet. However, for gear types like troll, gillnet and reefnet, the actual numbers of fish rather than the biomass weight are probably more meaningful. An estimate for available recruitment in numbers for each year was obtained by dividing available biomass by the average weight of sockeye for that year. The reason numbers may be important is that gillnets catch salmon through entanglement.
of the gills in the net. For purse seine gear the biomass is likely to be of greater importance because the fish are caught in blocks rather than individually. What the parameter estimation showed, however, was that all gear operating later in the gauntlet were more sensitive to numbers than gear operating in earlier parts of the gauntlet. This was supported by the fact that in years of poor recruitment (fewer blocks) almost all gear types were more sensitive to numbers; whereas in years of heavy recruitment almost all gear types were more sensitive to the biomass form. Therefore, this further adjustment to the biomass variable appears to be justified.

(4) The Harvesting Production Functions

Given effort, derived from deliveries and adjusted for technical change, and recruitment, adjusted for catches in previous zones and in cycle year dummy form to allow for the influence of catchability, the results for the six major gear type areas are as follows (with R-squared in brackets after the dependent variable and t statistic in brackets after the relevant explanatory variable):

(3-5) $\ln C2\text{GNS}(.82) = -12.95(2.3) + 1.31\ln C2\text{GND}(7.7) + 1.141\ln D41\text{CZ2N}(.1) + 1.18\ln D42\text{CZ2N}(3.1) + 1.041\ln D44\text{CZ2B}(3.3)$

(3-6) $\ln C2\text{PSS}(.7) = -20.01(3.7) + 0.51\ln C2\text{PSD}(2.1) + 1.79\ln C2\text{B}(5.2)$

(3-7) $\ln US4\text{GNS}(.81) = .781\ln US4\text{GND}(6.0) + 4.211\ln D41\text{US4B}(6.0) + 4.81\ln D42\text{US4N}(6.5) + 4.421\ln D43\text{US4B}(6.2) + 4.141\ln D44\text{US4B}(6.1)$

(3-8) $\ln US4\text{PSS}(.89) = .681\ln US4\text{PSD}(3.7) + .61\ln D41\text{US4N}(5.9) + .61\ln D42\text{US4N}(6.6) + .541\ln D43\text{US4B}(6.1) + .551\ln D44\text{US4B}(6.5)$
\[(3-9) \ln{\text{USZ5PS}}(.88) = .561 \ln{\text{USZ5PSD}}(2.7)
+ .611 \ln{\text{D41USZ4B}}(5.8) + .681 \ln{\text{D42USZ4N}}(6.2)
+ .611 \ln{\text{D43USZ4B}}(5.9) + .621 \ln{\text{D44USZ4B}}(6.3)\]

\[(3-10) \ln{\text{CZ7GNS}}(.70) = .791 \ln{\text{CZ7GND}}(3.5)
+ .42 \ln{\text{D41CZ7B}}(2.9) + .48 \ln{\text{D42CZ7N}}(2.9)
+ .43 \ln{\text{D43CZ7B}}(3.0) + .43 \ln{\text{D44CZ7B}}(3.1)\]

Where GN = gillnet
PS = purse seine
suffix S = sockeye catch in weight
suffix B = sockeye recruitment in weight after deduction of previous zones' catches
suffix N = sockeye recruitment in numbers after deduction of previous zones' catch
suffix D = effort in 1951 equivalent days of fishing
suffix W = average cycle weight of sockeye
prefix D = variable is in slope dummy form
41,2,3,4 = four year cycle with the weight in the first, second, third or fourth year of cycle
prefix CZ = Canadian zone
prefix USZ = U.S. zone

These are the parameter estimates which will be used in the cost programming to determine the least cost harvesting configuration. Note that only the first two gear type areas have intercepts and that none of the gear type areas are sensitive to the cycle influence in dummy intercept form. However, except for zone two purse seines, all gear type areas appear to be sensitive to the cycle influence in slope form. It is also interesting to note that in cycle year two (D42) almost all gear type areas are more sensitive to recruitment in numbers form, whereas in cycle year four they are all sensitive to recruitment in biomass form. This is reasonable as cycle year two has a recruitment one quarter the size of that for cycle year four. That is, the fish tend to migrate in blocks in the fourth cycle year because of the large numbers but tend to swim individually in cycle year two.

The final point of interest is the comparison between
recruitment elasticities. The log coefficients for recruitment in both biomass and numbers form is much larger for the open water gear types in zone two than for the confined water gear types in zones four, five and seven. Within these two categories, purse seine recruitment elasticities are much larger than those for gillnets. That is, purse seines, in general, are far more sensitive to recruitment than gillnets. This implies that unit effort costs drop rapidly for purse seines, compared with gillnets, when large recruitment is available. This same conclusion also applies to the comparison between open water and confined water gear types.

The cycle influence can be seen more clearly by breaking the harvesting production functions for Canadian zone two gillnets into four cycle years, inverting the function to put it in terms of deliveries required to land a catch of sockeye given a certain recruitment in biomass or numbers term, and taking the antilogs.

\[(3-5') \quad CZ2GND = 288310.9(CZ2GNS^{.97}) \quad D41Z2GN^{-1.11} \quad D42Z2GN^{-1.14} \quad D43Z2GN^{-1.11} \quad D44Z2GB^{-1.01}\]

Note that effort in each cycle year is directly related to the sockeye catch in the same way, 288310.9(CZ2GNS^{.97}). However, effort in each cycle year is inversely related to recruitment availability in a different way for each cycle year. For the first three years, recruitment in the form of numbers is used, whereas for the fourth cycle year it appears as biomass. Furthermore, the negative exponents are different for each year of the four year cycle. These differences reflect the catchability varying from cycle year to cycle year.
The major conclusion which can be drawn after working with the production functions and the catchability exponents is that the way sockeye swim, their schooling behavior, the areas in which they prefer to swim and the routes they take during migration are closely related to the year class in which they were spawned. Thus mature sockeye not only return to the same natal stream to spawn, they appear to take the same route as their parents to get there.

It is interesting to note that for zone two purse seines, biomass is a more powerful explanatory variable than the dummy versions in general. From 1951 to 1958, there were salmon traps operating in Sooke Harbour and the catch and effort for traps and purse seines were reported in aggregated form. As explained in the section of the Appendix dealing with the compilation of catch and effort data, an interpolation routine was devised to try and separate the two gear types from each other but there may have been serious errors involved leading to distortions in the effort and catch variables which may have prevented catchability from being estimated in a significant way.

For fifteen out of the sixteen gear type areas, catchability of sockeye was a significant improvement over the use of biomass. As the fits were so good for key areas such as zone four gillnets and purse seines, zone five purse seines and zone seven gillnets, the hypothesis that biomass availability should be adjusted to reflect catchability would appear to be supported. The use of biomass adjusted for catchability appears to be more important than unadjusted biomass in explaining catch of sockeye for almost all of the sixteen gear type areas which
have accounted for 95% of the sockeye catch over the last twenty-five years.

## III THE HARVESTING COST FUNCTIONS

### (1) Production Function Conversion

In order to form a profit function for use in the Clark-Munro equilibrium equation, the production functions must be converted into harvesting cost functions. Profit is simply total revenue minus total costs. And total revenue is given by the catch of sockeye times the price per pound. Total costs are given by the sum of the costs associated with taking a specified catch of sockeye in each gear type area given a certain recruitment to each fishing zone.

As demonstrated in expression (3-5') above, cost functions are derived from the production functions by inverting the function so that deliveries are some function of catch and biomass availability, taking the antilogs and multiplying by gear type costs. Taking the first cycle years only for the production functions in expressions (3-5) to (3-10) we get,

\[
\begin{align*}
(3-11) \quad \text{CZ2GND} & = 44.83(288310.9)(\text{CZ2GNS}^{0.97})(\text{CZ2B}^{-1.11}) \\
(3-12) \quad \text{CZ2PSD} & = 240.55(1.04)(\text{CZ2PSS}^{1.96})(\text{CZ2B}^{-3.5}) \\
(3-13) \quad \text{USZ4GND} & = 37.07(\text{USZ4GNS}^{1.28})(\text{USZ4B}^{-0.54}) \\
(3-14) \quad \text{USZ4PSD} & = 179.87(\text{USZ4PSS}^{1.46})(\text{USZ4B}^{-0.88}) \\
(3-15) \quad \text{USZ5PSD} & = 179.87(\text{USZ5PSS}^{1.79})(\text{USZ5B}^{-1.09}) \\
(3-16) \quad \text{CZ7GND} & = 37.07(\text{CZ7GNS}^{1.27})(\text{CZ7B}^{-0.54})
\end{align*}
\]

The first term on the r.h.s. of each expression is the unit cost
associated with a single 1951 equivalent day of effort for that gear type area. Note how much higher unit effort costs are for open water gillnets and seines (CZ2GN and CZ2PS) as compared with confined water gillnets and purse seines (USZ5PS and CZ7GN). GNS and PSS refer to sockeye catches (in pounds) made by gillnets and purse seines respectively. N refers to recruitment in numbers while B refers to recruitment in biomass form. Total cost for cycle year one is simply the sum of (3-11) through (3-16) as determined by the program. That is, right hand sides of all six equations are summed: while the program allocates catch and recruitment to each area for the catch and recruitment values.

A similar format is followed for the other cycle years using different effort costs and year class catchability exponents. The use of cycle dummies permits the four year classes of sockeye to be split into four separate fisheries so that each year class can be treated as a stock subjected to harvesting every four years in the cycle. Mathematical programming must be used to isolate the lowest cost gear type harvesting areas because no other technique can vary harvesting configurations as many times as is necessary to find the cheapest way to harvest. The cost functions given in expressions (3-11) to (3-16) are nonlinear which means that nonlinear programming techniques are required to solve for minimum cost.

The log coefficients in expressions (3-5) to (3-10) have become the exponents when in anti-log form in expressions (3-11) to (3-16). Their size for all gear type areas imply that these Cobb-Douglas production functions are not linearly homogeneous.
but display increasing returns to scale. These scale effects vary according to cycle year because the catchability exponents vary, although the effort exponents remain the same (expressions (3-5) to (3-10)). The only area for which this is not true is Canadian zone two purse seines which is not sensitive to cycle year catchability.

The stock of fish, i.e., recruitment, is a free input to the harvesting process, whereas effort bears a cost. The cost minimization program does not take advantage of these scale economies so much by altering scale (inputs are changed proportionately) as it does by altering the flow of recruitment. That is, some areas, such as Canadian zone two gillnets, have very high recruitment elasticities but these are offset by very high effort elasticities (expression (3-5)). Therefore, the program takes advantage of the free input (recruitment) only to the extent that it can offset the costly input (effort) and no single area will be chosen as the most cost efficient. Instead, a combination of areas will be used to exploit the recruitment elasticities. In other words, directing more and more of the recruitment into one area implies a larger catch must be taken by that area (otherwise it will have to be taken by another area receiving less and less of the recruitment). This, in turn, implies that more effort is needed and effort costs money.

One problem associated with the cost programming for harvesting other salmon as well as sockeye is the recognition of the opportunity cost of the other salmon catch foregone for the increased sockeye catch. It will be assumed that the only harvesting of concern is of sockeye salmon. Any other salmon
caught at the same time will reduce the costs of harvesting sockeye but no attempt will be made to deliberately harvest other salmon. Catch of other salmon will be permitted up to the amount of excess capacity left after harvesting sockeye. This excess capacity will be the average (1951 to 1975) cycle weight per unit of gear type effort (for all salmon) minus the weight of sockeye harvested per unit of effort. Given excess capacity per delivery, other salmon will be permitted to be caught up to the average (1951 to 1975) cycle weight of other salmon per delivery. One or the other of these capacity constraints will be binding or the maximum permissible cycle year catch of other salmon for the fishery will be binding, whichever of the three is smaller.

One problem which arises out of this method of harvesting other salmon is that no distinction is made between the four species of other salmon. Each species of salmon has a different price per pound with the highest price twice as large as the smallest. A compromise adjustment was made; of the five races of salmon: sockeye, chinook, chum, coho and pink, sockeye has traditionally received the higher price per pound. Chinook and coho are worth about 80% to 90% of the sockeye price and chum and pink about 45% to 67%. The differentials have narrowed over the period 1951 to 1975 and are slightly larger for Washington than for B.C. The proportion of the races of other salmon caught depends on the gear type area. Just as it is impossible to do other than guess with regard to the displacement effect, it is impossible to know how catch proportions would change with the altered patterns of harvesting sockeye. However, the effect of
the pink harvest in alternating years is so overwhelming that it is possible to at least distinguish between the catch value of other salmon in alternating years. The following compromise was used to reflect both the narrowing of differentials over the years and the altered patterns of catching other salmon. In "off" years for the pink, other salmon are valued at 67% of the sockeye price per pound and in "on" years for the pink, other salmon are valued at 50% of the sockeye price per pound. These rather conservative estimates will tend to understate the impact of other salmon harvesting in the net profit comparisons below.

As explained in Chapter One, all fixed costs are converted into variable costs. Thus fixed costs appear in an amortized way equal to the depreciation plus the opportunity cost social rate of return on the money invested in the capital equipment. There are only a few cost observations available for the full twenty-five year period under study and much bridging and interpolation was required to build consistent indexes of gear type costs. The only consolation is that despite radically different parameters for the production functions, the cost programming indicated that the six major gear type areas are very competitive in terms of costs of harvesting. No single area stands out as being very high cost or very low cost.
Flowchart (1-1) in Chapter One introduced the idea of the programming needed to obtain optimal values for escapement, recruitment and catch and the accompanying least cost harvesting configuration to take that catch given the recruitment. The programming in this chapter relates strictly to the choosing of the least cost harvesting configuration given specified levels of escapement, recruitment and catch. No attempt is being made to choose optimal values. In fact, the specified levels are simply the average year cycle historical totals for escapement, recruitment and catch which are to be allocated to each gear type harvesting area by the program.

The purpose of presenting the least cost program at this point is simply to make explicit the nature of the problem involved in choosing least cost harvesting configurations. Furthermore, the results are a very useful guide to the gains to be achieved from optimal spatial allocation of harvesting gear. The least cost programming results give us some idea of the rent loss incurred by the spatial misallocation arising from the common property problem in an open access fishery. That is, fishermen do not go to the area where catchability is greatest for their gear type, given availability; instead, they migrate to earlier portions of the gauntlet to harvest in areas where recruitment availability is greater because catch has not reduced availability so much in previous zones but where catchability may be poor for their gear type. By eliminating this common property problem, the least cost program can then allocate catch and recruitment so as to take advantage of the
technical efficiency of different gear types and their
sensitivity to recruitment and area catchability.

The format used for laying out the programming problem was
taken from Beale (1968) and Pfaffenberger and Walker (1976,
pp. 3-133). Rather than program for each of the twenty-five years
from 1951 to 1975, a representative average cycle year for each
of the four cycle years was used instead. The study is concerned
with finding the lowest cost gear type area on average for each
cycle year. As some gear type areas were not exploited until the
1960's and as there was a process of migration to earlier areas
of the gauntlet throughout the twenty-five years, the average
cycle year should give a better reflection of costs of
harvesting.

Flowchart (3-1) illustrates the rather complex nature of
the least cost program. The program takes the average
recruitment for the cycle year and allows it to flow through to
zone two. The recruitment observations are in biomass form
(weight times numbers) but as some areas are more sensitive to
numbers, a routine is included which transforms biomass into
numbers using the average cycle year weight of sockeye.

The program then subtracts the gear type sockeye catches
(if there are any) in zone two from the recruitment and allows
this reduced recruitment to flow through to zone four. The same
procedure as above is followed for zones four and five and the
remaining recruitment flows through to zone seven after the
average cycle year Johnstone Strait catch is subtracted. After
recruitment is further reduced by gear type catch in zone seven,
the reduced recruitment is permitted to flow through as average
cycle year Indian catch and escapement up the Fraser River.

With the escapement, recruitment and catch constraints satisfied, the various unknowns in the total cost function will then be established (see expressions (3-11) to (3-17)). The program then checks the partial derivatives of the cost function to determine if, in fact, a minimum has been achieved. If not, the program re-shuffles the catch and recruitment allotments according to a penalty function algorithm based on the gradients of those partial derivatives. After a number of iterations, the configuration will indeed give the minimum cost. A few tests were performed to ensure that a global minimum resulted but as the catch proportions changed so radically from one iteration to another, it is probably safe to assume the solutions are indeed global.

Turning to Flowchart (3-2) in which both sockeye and other salmon are caught, the same average cycle year values were used as above with the addition of the average cycle year catch of other salmon, gear type capacity for total catch and gear type capacity for other salmon. These capacities are based on a linear transformation of the average cycle year catch, by weight, of all salmon per unit of effort for the first and other salmon only per unit of effort for the second.

The program takes the required gear type deliveries to land the proposed catch of sockeye, determines the available capacity and compares it with the average cycle year gear type capacity for catching all salmon. If the proposed catch of sockeye exceeds the capacity, in terms of weight of salmon per delivery, no other salmon are permitted to be caught. If the proposed
Flowchart (3-2): Least Cost Program to Harvest Sockeye and Other Salmon Assuming Average Historical Cycle Recruitment, Catch and Escapement.
catch of sockeye is less than the capacity in terms of weight of salmon per delivery, other salmon are permitted to be taken. The second capacity constraint then comes into effect. Other salmon are permitted to be caught up to either: a) the total salmon gear type catch capacity (the first capacity constraint) or b) the other salmon gear type catch capacity (the second capacity constraint). In the event that both these capacities are very large, a third constraint equal to the maximum average cycle year catch of other salmon limits the total catch of other salmon landed by any single gear type and by all combined. Thus for each gear type area, the catch of other salmon is limited by one or other of the capacity constraints; and all gear type catches of other salmon combined are limited by the third constraint. Once again, the program always evaluates the partial derivatives of the cost function after each iteration to determine if a minimum has been reached.

Without a joint production function for catching both sockeye and other salmon, the approximating technique outlined above cannot be used with confidence. For this reason, the main criterion used for choosing the least cost/most profitable gear type areas will depend only on the results for catching sockeye. However, an example showing the economic rent earned by harvesting for both sockeye and other salmon will be included for comparison purposes.

If the total cost functions were linear with given or fixed recruitment, escapement and catch, the cost program would choose a single area to harvest the total catch. With constant marginal opportunity costs, one area would always be least cost. This
least cost function could then be converted into a profit function by subtracting costs from the value of the catch. This profit function could then be used with the recruitment function in the linear cost version of Clark and Munro's optimal equation (Clark, 1976, pp.243-245). The latter would give the optimal escapement which could then be used with the recruitment function to give optimal recruitment. The former would then be subtracted from the latter to give optimal catch.

But note that the catch and the biomass availability obtained from the optimizing process would be different from those used to choose the least cost area. From expressions (3-11) to (3-16) it is obvious that this could have an important impact on which area was the least cost because some areas are very sensitive to biomass availability while others are not. Therefore, a smaller or larger catch (reduced or increased cost) associated with a smaller or larger recruitment (increased or reduced cost) could cause changes in the relative costs of harvesting. It is probable that the changes for linear cost functions would not be so radical as to cause the program to choose a different area as the new least cost harvesting area.

However, with nonlinear cost functions recruitment elasticities can play a large role in determining the least cost area. Certain gear type areas will be cheap to use for harvesting up to a certain point after which it may be cheaper to harvest the next increment in another gear type area which has not been used before. One would expect, therefore, that the least cost program would choose to harvest any given catch using most of the six gear type areas simultaneously. With rare
exception, this is exactly what happened when the cost program was applied using average cycle recruitment, catch and escapement.

This approach means that the optimal solution depends critically on what areas are being used and in what proportions. Using the nonlinear version of Clark and Munro's equation (Clark, 1976, pp.252-253) the optimal escapement, and subsequently the optimal recruitment and catch, can be calculated. But the changes in recruitment and catch which result from obtaining the equilibrium values for the optimal solution may have a profound effect on the least cost way of harvesting. Costs move directly with catch and inversely with recruitment; and as the catch/recruitment proportions are changed, the solution is bound to be different. For this reason it is important that least cost gear type areas and the optimal escapement, recruitment and catch be determined simultaneously.

(3) Net Profit Comparisons

The first net profit comparison permits the cost program to choose the least cost harvesting proportions given average cycle year catch of sockeye (no other salmon), recruitment, escapement, Johnstone Strait catch and Indian catch.
TABLE (3-1): UNCONSTRAINED AVERAGE HISTORICAL CYCLE CATCH OF
SOCKEYE ONLY IN 000'S OF POUNDS, PROPORTIONS OF GEAR TYPE AREA
CATCHES AND RESULTING COSTS AND PROFITS IN 000'S OF 1951 DOLLARS

<table>
<thead>
<tr>
<th>Catch</th>
<th>Cycle 1</th>
<th>Cycle 2</th>
<th>Cycle 3</th>
<th>Cycle 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C22G</td>
<td>C22P</td>
<td>USZ4G</td>
<td>USZ4P</td>
</tr>
<tr>
<td></td>
<td>18,359</td>
<td>11,717</td>
<td>19,380</td>
<td>34,930</td>
</tr>
</tbody>
</table>

|         | 60%      | 0%       | 20%      | 55%      |
|         | 8%       | 2%       | 6%       | 30%      |
|         | 5%       | 48%      | 15%      | 0%       |
|         | 7%       | 17%      | 9%       | 5%       |
|         | 7%       | 7%       | 10%      | 3%       |
|         | 13%      | 26%      | 40%      | 7%       |

<table>
<thead>
<tr>
<th>Value</th>
<th>$6,294</th>
<th>$4,173</th>
<th>$6,993</th>
<th>$11,916</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>$5,536</td>
<td>$3,161</td>
<td>$4,800</td>
<td>$3,965</td>
</tr>
<tr>
<td>Net Profit</td>
<td>$758</td>
<td>$1,012</td>
<td>$2,193</td>
<td>$7,952</td>
</tr>
<tr>
<td>Actual</td>
<td>$246</td>
<td>$466</td>
<td>$1,145</td>
<td>$5,748</td>
</tr>
<tr>
<td>Gain in</td>
<td>$512</td>
<td>$546</td>
<td>$1,047</td>
<td>$2,203</td>
</tr>
</tbody>
</table>

Note that "Net Profit" is economic rent according to the program's calculations given average historical catch and a new allocation of harvesting effort. "Actual" net profit is what can be calculated from given average historical catch and gear type effort. According to these cost calculations, fishermen are receiving an economic rent, particularly in the fourth cycle year when economic "rent" exceeds the "cost" of landing the average sockeye catch. The "Gain in" net profit indicates how much extra economic rent could have been earned if harvesting had been least cost. Even if opportunity cost estimates are too conservative and what is recorded as actual net profit is really part of opportunity cost, following a least cost program could have yielded a fairly substantial economic rent as recorded in the gain in net profit. This gives some idea of the rent loss incurred from the common property trade-off of availability for catchability.
Turning to the changes in proportions of gear type catches, it is interesting to note how recruitment elasticities are so important to open water gear (Canadian zone two) in the fourth year of very large runs. Alternatively, the confined water gillnets (USZ4G,CZ7G) do well in the second cycle year with low recruitment when there are very few blocks moving through the gauntlet. In addition to wide swings amongst different gear types, it is obvious that catches are anything but equally divided between the U.S and Canada.

It is highly unlikely that the IPSFC would be permitted to harvest the sockeye catch without dividing the harvest equally between both countries. Table (3-2) illustrates the case for an equal division of catch between U.S. and Canadian fishermen.

Comparing the results in Tables (3-1) and (3-2) it is obvious that Munro's (1979) plan for using the lowest cost country for harvesting the total catch and pensioning off the highest cost country would indeed increase economic rent. But what is surprising is that with the exception of the fourth cycle year, the differences in rent are not larger. Despite large differences in actual catch of sockeye and other salmon and the differences in cost between gear types, the economic rents earned are very close. This would confirm the hypothesis that fishermen are indeed mobile between areas (and possibly countries) and very profit conscious. Or perhaps, what is even more important, is that despite severe constraints on their attempts to limit potentially disastrous overfishing, the IPSFC has been able to apportion gear type catches in such a way as to preserve the economic viability of the fishery.
The second net profit comparison is similar to the first except that the IPSFC is now constrained to an equal division of the catch.

**TABLE (3-2): CONSTRAINED AVERAGE HISTORICAL CYCLE CATCH OF SOCKEYE ONLY IN 000'S OF POUNDS, PROPORTIONS OF GEAR TYPE AREA CATCHES AND RESULTING COSTS AND PROFITS IN 000'S OF 1951 DOLLARS**

<table>
<thead>
<tr>
<th>CATCH</th>
<th>CYCLE 1</th>
<th>CYCLE 2</th>
<th>CYCLE 3</th>
<th>CYCLE 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>CZ2G</td>
<td>18,359</td>
<td>11,717</td>
<td>19,380</td>
<td>34,930</td>
</tr>
<tr>
<td>CZ2F</td>
<td>7%</td>
<td>0%</td>
<td>13%</td>
<td>17%</td>
</tr>
<tr>
<td>USZ4G</td>
<td>26%</td>
<td>29%</td>
<td>28%</td>
<td>6%</td>
</tr>
<tr>
<td>USZ4P</td>
<td>14%</td>
<td>13%</td>
<td>15%</td>
<td>29%</td>
</tr>
<tr>
<td>USZ5P</td>
<td>10%</td>
<td>8%</td>
<td>6%</td>
<td>15%</td>
</tr>
<tr>
<td>CZ7G</td>
<td>16%</td>
<td>48%</td>
<td>30%</td>
<td>10%</td>
</tr>
</tbody>
</table>

| VALUE  | $6,294  | $4,173  | $6,993  | $11,916 |
| COST   | $5,692  | $3,167  | $4,860  | $5,131  |
| NET PROFIT | $602  | $1,006  | $2,133  | $6,785  |
| ACTUAL " | $246    | $466    | $1,145  | $5,748  |
| GAIN IN " | $356    | $540    | $988    | $1,037  |

Except for cycle year two, it appears that moving into earlier parts of the gauntlet has made good economic sense for Canadian gillnetters moving from zone seven to zone two. In two out of four cycle years, the Strait of Juan de Fuca gillnetters harvest a larger proportion of the catch than the gillnetters left in the mouth of the Fraser River. Once again, recruitment elasticities are very important for purse seines which fare very poorly in cycle year two (23% of catch) but are rewarded with large catches in cycle year four (67% of catch).

Ignoring the catch of other salmon, this is the most feasible case for minimizing the costs of harvesting Fraser River sockeye. It appears from these hypothetical examples that open access has resulted in a significant loss of economic rent
in terms of spatial misallocation of harvesting effort.

The third and fourth net profit comparisons permit the cost program to harvest other salmon as well as sockeye given average cycle year catches of sockeye and other salmon, recruitment, escapement, Johnstone Strait catch and Indian catch. Table (3-3) gives the comparisons assuming the IPSFC is unconstrained by any division of the catch and Table (3-4) assumes the IPSFC is constrained by an equal catch division agreement.

**TABLE (3-3): UNCONSTRAINED AVERAGE HISTORICAL CYCLE CATCH OF SOCKEYE AND OTHER SALMON IN 000'S POUNDS, PROPORTIONS OF GEAR TYPE AREA CATCHES OF SOCKEYE AND RESULTING PROFITS IN 000'S OF 1951 DOLLARS**

<table>
<thead>
<tr>
<th></th>
<th>CYCLE 1</th>
<th>CYCLE 2</th>
<th>CYCLE 3</th>
<th>CYCLE 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOCKEYE</td>
<td>18,359</td>
<td>11,717</td>
<td>19,380</td>
<td>34,930</td>
</tr>
<tr>
<td>ALL OTHER</td>
<td>42,006</td>
<td>8,540</td>
<td>29,532</td>
<td>10,943</td>
</tr>
<tr>
<td>% CATCH</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>CZ2G</td>
<td>55%</td>
<td>34%</td>
<td>52%</td>
<td>50%</td>
</tr>
<tr>
<td>CZ2P</td>
<td>8%</td>
<td>3%</td>
<td>10%</td>
<td>27%</td>
</tr>
<tr>
<td>USZ4G</td>
<td>6%</td>
<td>24%</td>
<td>2%</td>
<td>1%</td>
</tr>
<tr>
<td>USZ4P</td>
<td>7%</td>
<td>11%</td>
<td>4%</td>
<td>9%</td>
</tr>
<tr>
<td>USZ5P</td>
<td>9%</td>
<td>6%</td>
<td>3%</td>
<td>10%</td>
</tr>
<tr>
<td>CZ7G</td>
<td>15%</td>
<td>22%</td>
<td>29%</td>
<td>3%</td>
</tr>
<tr>
<td>NET PROFIT</td>
<td>$7,933</td>
<td>$2,817</td>
<td>$7,385</td>
<td>$10,421</td>
</tr>
<tr>
<td>ACTUAL</td>
<td>$6,688</td>
<td>$2,302</td>
<td>$5,733</td>
<td>$7,844</td>
</tr>
<tr>
<td>GAIN IN</td>
<td>$1,246</td>
<td>$515</td>
<td>$1,652</td>
<td>$2,578</td>
</tr>
</tbody>
</table>
### TABLE (3-4): CONSTRAINED AVERAGE HISTORICAL CYCLE CATCH OF SOCKEYE AND OTHER SALMON IN 000'S OF POUNDS, PROPORTIONS OF GEAR TYPE AREA CATCHES OF SOCKEYE AND RESULTING PROFITS IN 000'S OF 1951 DOLLARS

<table>
<thead>
<tr>
<th></th>
<th>CYCLE 1</th>
<th>CYCLE 2</th>
<th>CYCLE 3</th>
<th>CYCLE 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOCKEYE</td>
<td>18,359</td>
<td>11,717</td>
<td>19,380</td>
<td>34,930</td>
</tr>
<tr>
<td>ALL OTHER</td>
<td>33,605</td>
<td>8,540</td>
<td>22,740</td>
<td>9,739</td>
</tr>
<tr>
<td>% CATCH</td>
<td>80%</td>
<td>100%</td>
<td>77%</td>
<td>89%</td>
</tr>
<tr>
<td>CZ2G</td>
<td>36%</td>
<td>37%</td>
<td>20%</td>
<td>37%</td>
</tr>
<tr>
<td>CZ2P</td>
<td>6%</td>
<td>2%</td>
<td>10%</td>
<td>12%</td>
</tr>
<tr>
<td>USZ4G</td>
<td>36%</td>
<td>32%</td>
<td>22%</td>
<td>14%</td>
</tr>
<tr>
<td>USZ4P</td>
<td>3%</td>
<td>13%</td>
<td>18%</td>
<td>24%</td>
</tr>
<tr>
<td>USZ5P</td>
<td>11%</td>
<td>6%</td>
<td>10%</td>
<td>12%</td>
</tr>
<tr>
<td>CZ7G</td>
<td>8%</td>
<td>10%</td>
<td>20%</td>
<td>1%</td>
</tr>
</tbody>
</table>

**NET PROFIT** $6,073 $2,802 $6,332 $9,405  
**ACTUAL** $6,688 $2,302 $5,733 $7,844  
**GAIN IN** $-615 $500 $600 $1,561

Comparing the unconstrained catches of sockeye in Tables (3-1) and (3-3) reveals just how important the catch of other salmon is in terms of reducing gear type effort costs. Sockeye catch proportions are not too different for cycle years one and four. But note the radical shift in catch proportions for cycle year two. In particular, Canadian zone two gillnets which were not used when catching sockeye only are now used to the extent of taking thirty-seven percent of the sockeye catch when other salmon are permitted to be caught. A similar radical change can be detected for cycle year three.

Comparing the unconstrained and constrained cases of catching both sockeye and other salmon (Tables (3-3) and (3-4)) it is clear that there is a case to be made for international bargaining over the catch divisions. The most obvious effect of constraining the sockeye catch is the reduction in catch of...
other salmon it would be potentially possible to take. The constrained results indicate that there is not enough capacity left over from harvesting the specified sockeye catch to catch the other salmon, whereas the unconstrained program is able to allow enough capacity to land one hundred percent of the potential catch of other salmon for each cycle year.

It is important to remember that the programming system used to harvest other salmon is only an approximation to the real harvesting process. Therefore, the profit comparisons are not very useful. What is interesting, however, is that economic rent, whether actual or hypothetical, is really rather large. And one can presume that in a proper multi-species harvesting program, least cost allocation of gear would lead to even larger economic rent (see for example the gain in net profit in Table (3-3) where 100% of the potential catch of other salmon is taken).

Finally a comparison of the constrained catch proportions in Tables (3-2) and (3-4) reveals the importance of Canadian zone two gillnets in landing other salmon as compared with gillnets operating in the mouth of the Fraser River: only pink salmon out of the other four species, spawn in the Fraser River system exclusively. Table (3-2) indicates that Canadian zone two gillnets are important in terms of least cost harvesting of sockeye but Table (3-3) demonstrates that this open water gear type is vital to least cost harvesting of other salmon. In a sense the other salmon case is always unconstrained because there is no equal division of the catch of other salmon between U.S. and Canadian fishermen. This is not exactly correct in real
life as the IPSFC does divide the pink salmon catch equally. As explained earlier, however, no attempt is made to deal with this multi-species harvesting problem except to reduce the costs of catching sockeye salmon. Thus, no provision was made in the program to divide the catch of other salmon equally.

One conclusion which emerges from all the comparisons is that least cost spatial allocation of the gear can be profitable despite the closeness in profitability of many of the areas. What is of great interest is that so little extra profit can be obtained through optimal allocation of harvesting effort. This would support the hypothesis that fishermen have a shrewd idea of the lowest cost areas to harvest in terms of biomass availability and the catchability peculiar to their gear types. However, as the IPSFC regulates gear type effort within the constraints proscribed by the convention, it is more correct to say that the IPSFC has been extremely adroit at taking many of these relevant biological and economic parameters into account in limiting gear type area harvesting. The loss in profit indicated by profit comparisons arises because of the spatial misallocation of effort resulting from the open access nature of the fishery.

This chapter has taken the available effort data and adjusted them to reflect true effort plus changes in productivity. The available recruitment data have been adjusted to reflect availability in each fishing zone. The adjusted effort and the adjusted biomass availability have then been used to estimate parameters for the six major gear type area production functions allowing catchability to vary by cycle year.
through the use of dummies. These production functions have been converted into cost functions which illustrate that total cost varies directly with size of catch but inversely with biomass availability (depending on the cycle catchability parameter).

Because the cost functions are nonlinear it was explained that the cost program would choose to allot the available catch on a proportionate basis amongst the gear type areas. With several gear type areas harvesting simultaneously it follows that the optimal escapement, recruitment and catch derived from Clark and Munro's optimal equation will depend on the catch proportions, which in turn depend (directly on catch and inversely on recruitment) on the optimal solution. For this reason the optimal program must involve a simultaneous solution for the least cost harvesting proportions and the optimal escapement, recruitment and catch. However, it has been possible, using average cycle year total catch and recruitment, to compare net profit obtained through least cost harvesting with actual historical net profit: without using optimal values for recruitment and catch. And finally, the cost program is permitted to harvest other salmon to demonstrate how catch proportions change when other salmon are harvested as well as sockeye.
APPENDIX

Compilation Of Catch And Effort Data

Data on catch of sockeye, catch of all other salmon species (during the sockeye harvest period), deliveries and days fishing are available by gear type on a daily basis since 1951 for all areas in the gauntlet. None of these data are available in machine readable form and all of it had to be compiled by hand from books available at the Departments of Fisheries headquarters in B.C. and Olympia Washington.

If the statistics had been compiled on a daily basis, it would have involved handling over 200,000 separate observations for the five species of salmon plus deliveries for thirty gear type areas fished for an average of three and a half days a week for an average of thirteen weeks a year for twenty-five years. The daily data had been aggregated into monthly form and, although this is less accurate, it reduced the number of observations to 14,000 for the five species of salmon plus deliveries for the thirty gear type areas fished for three months a year for twenty-five years.

The Royce-Bevan project found the monthly aggregates as accurate as the daily basis totals for their study of harvesting. However, the problem with monthly aggregates is that the timing of sockeye runs does not conform precisely with the July, August, September schedule. In some years the runs start earlier or run later; but for the most part these account for less than 5% of the total catch for the whole gauntlet. The reason for not including June and October for all parts of the gauntlet is that fishermen are out catching salmon other than
sockeye; and to include June and October totals for deliveries, sockeye catch and other salmon catch would distort the picture for sockeye deliveries. That is, to include June and October deliveries for all parts of the gauntlet would overstate the deliveries necessary to take 95% of the sockeye run in July, August and September only and overstate the proportion of other salmon to sockeye.

A study was made of the gauntlet patterns over the years and the following months were chosen as the best overall aggregates to approximate the deliveries needed to take at least 95% of the sockeye catch and the other salmon associated with the sockeye harvest. For the outer gauntlet: June, July, August and September; for the middle of the gauntlet: July, August, and September; for the end of the gauntlet: July, August, September, and October.

The data for B.C. waters were in terms of weight for the Canadian sector of the gauntlet. The Washington data were in terms of numbers of fish for the U.S. sector. The average seasonal weight for each species was obtained by dividing the Puget Sound catch in weight by the Puget Sound numbers for each year as reported in the State of Washington, Department of Fisheries, Fisheries Statistical Report for each year. These yearly average weights were then used with numbers of salmon to convert them into salmon catch in terms of weight for the U.S. sector.

For 1974 and 1975 the Washington data were not available in aggregate form by months for major areas and the daily totals for disaggregated areas were aggregated by hand following the
July, August, September schedule (all U.S. fishing takes place in the middle of the gauntlet). From 1951 to 1955 inclusive, the B.C. data did not distinguish between fish traps in Sooke harbour and purse seines outside the harbour. An interpolation routine was devised based on IPSFC reports of the catch for the Sooke traps, which split the totals into those for traps and those for seines.

All totals for both B.C and Washington were calculated twice to check for errors. The IPSFC reports of yearly gear type catches for the whole gauntlet by numbers were multiplied by yearly average weights of sockeye as reported by the IPSFC to get yearly gear type catches by weight for the Canadian sector and the U.S. sector. The Canadian sum of yearly gear type catches by area and the U.S. sum of yearly gear type catches by area were compared with the IPSFC totals as a final check on sockeye catch. There was less than a 5% discrepancy either way in most years. Where the discrepancies did exceed 5% in a year, the totals for that year were completely recalculated.

As the IPSFC totals are calculated on the basis of weight slips at the canneries and not from the data as reported by Washington or B.C., it is a credit to all concerned that there are only two or three years out of twenty-five for each gear type where the discrepancies exceed 5%. The only exception is the Canadian troll catch, most of which is taken in areas outside the jurisdiction of the IPSFC. As the Canadian troll catch is insignificant in most years, no attempt was made to discover the cause of the discrepancies.
Technical Change

The IPSFC has kept a record of major technical innovations and performed tests to measure their impact on gear efficiency. As a check on the IPSFC calculations, other sources such as monthly issues of Western Fisheries since 1951, Crutchfield and Pontecorvo (1969), the Royce-Bevan project (1963), the Sinclair report (1960) and the Washington State, Department of Fisheries, Fisheries Research Papers (1954, pp. 48-51) were used as well. There was surprising agreement amongst the sources with respect to the dates of the advent of new technology and only minor differences on the estimates of the impact on gear efficiency.

The major changes occurred in the early 1950's with the replacement of linen filament with nylon for the nets, the application of power to pulley blocks, the introduction of the powered drum for seines, the replacement of linen lines with wire lines, the application of power to gurdies (reels for troll lines) and the substitution of hydraulic power transmission for mechanical gear transmission. Even though nylon nets did save time for purse seines in terms of repairs, the biggest impact from nylon nets was felt by the gillnet fishermen. The power drum and Puretic power block were very important in improving purse seine efficiency by replacing the cumbersome roller table. Wire lines and powered gurdies meant fewer broken lines and faster hauling and clearing for trolls.

It must be remembered, however, that cost saving technical innovation is quite different from technology which increases the actual efficiency of gear harvesting. It is the latter which must be measured to obtain an efficiency index. With this in
mind and using the sources discussed above, efficiency indexes were constructed for gillnets and purse seines.

**Calculation Of Costs And Prices**

In calculating costs two alternative methods can be used. The first consists of using the lowest daily catch per unit of gear type effort for each season. This approximates the opportunity cost for one day's effort by that gear type (Hannesson, 1974, p.72-74). Daily figures are available for the U.S. but only weekly totals are available for Canada. They can be divided by the known legal number of fishing days per week to get the average daily minimum for that week. However, this would have required searching and comparing 200,000 daily totals by hand to arrive at a figure which is probably a very poor approximation to opportunity cost.

Instead a second method of calculating costs was used. This involved splitting effort into three cost components: labour, operating and fixed costs. Only one observation on cost was available for Washington fisheries. It was obtained by surveying vessel owners in 1962 as part of the Royce-Bevan study (1963). The results of the survey are discussed in the study but the cost data are not listed anywhere and is given in only highlight form. For example, the average gear and vessel value for gillnets in Washington in 1962 was estimated by Royce-Bevan (1963, pp.121-22) as $6,000 to $7,000 which compares with my 1962 cost calculation of $6,908 for average gear and vessel value for gillnets in B.C.

Dr. Crutchfield, a member of the Royce-Bevan study group, explained to me that there are no cost figures available for
Washington except for their 1962 survey, and that the survey gave only a rough approximation as the reporting system was not complete and the sampling procedures were non-random. No figures were available for reefnets as the fishermen surveyed refused to respond. The above comparisons indicate that gillnet values were quite similar between Washington and B.C. but that purse seine values differed by about 25%. Errors of measurement could account for the discrepancy particularly as the bias in the sample came from a low response amongst smaller vessel owners. In the light of these results and noting that data are not available for any other years in Washington, it was decided that B.C. cost data would be used for both B.C. and Washington fishermen.

The other serious omission is the absence of cost data for reefnets. As this gear does not operate in B.C. waters, there are no cost estimates for them in B.C.; nor did the Royce-Bevan study produce any reefnet estimates. It is known that reefnets are highly competitive with gillnets in Washington waters and that the crew from one gear type are not adverse to switching to the other. Thus productivity differences between the gear types in Washington waters are probably closely approximated by cost differences. And the former can be used as an estimator for the latter.

In a study conducted by Junge (1959) estimates were made of comparative productivity differences between purse seines, gillnets and reefnets. The results indicated that reefnets were 2.83 times as productive as gillnets on average. The increase in net efficiency which resulted from replacement of linen by nylon
nets in the early 1950's is thought to have had more application to gillnets than to reefnets because of the more highly specialized nature of reefnet fishing. Thus reefnet costs will be assumed to be 2.5 times gillnet costs on average for the period 1951 to 1975 in this study.

Turning to the calculation of labour costs, from discussions with fisheries officials in both departments of fisheries in B.C. and Washington and from published reports on fishermen's incomes (Canada, "Some Economic Aspects...", 1971; and Hunter, 1971), agriculture and the forest industry appear to be the most popular forms of alternative employment for fishermen. As the agricultural wage index is of doubtful accuracy due to non-monetized aspects, the forest industry average weekly wage was chosen as the best alternative.

In the 1950's fishermen used to fish for approximately eight hours a day, five days a week for a forty hour work week. By the 1970's this had fallen to three and a half days a week because of area closures. However, during those days most fishermen worked a twelve hour day for approximately a forty-two hour week. Thus the effort in days of fishing, once corrected by efficiency or gear and vessel value indexes, would probably closely approximate the number of hours worked in 1951.

The days of fishing effort given by the production functions is in terms of 1951 effort. Thus dividing the average weekly wage in the forest industry by five should give the daily opportunity cost for labour in the salmon fishing industry. It will be assumed that 1.2 men work on gillnets and trolls on average. For purse seines the recent average has been 5.5 men
(see for example, Fraser, 1975, p.66) but in the early 1950's it was as high as 7 men because of the large table seines. Thus an index is used to correct for the decline in numbers working purse seines.

The average weekly wage for the forest industry in B.C. was obtained from Statistics Canada (catalogue:72-202) for the years 1951 to 1961 and from Cansim (Statistics Canada, Cansim 1493.1.1, code=d704260) for the years 1961 to 1975. The average was taken from the weekly wages for July, August and September each year.

One final note on labour costs relates to the use of later years' higher average wages with later years' deliveries converted into 1951 equivalent deliveries. Obviously if effort is in 1951 delivery terms, then no more should be charged than 1951 equivalent days of labour. Thus the index of labour costs per unit of effort (one day's fishing) must be deflated by the efficiency or gear and vessel value index used to inflate the units of effort. Thus if three and a half days of fishing in 1975 costs $57 per day in labour (twelve hour days) for a total of $200, then five days of 1951 fishing effort incurred in 1975 should cost $39.90 per day (eight hour days) for a total of $200. That is, the costs have been deflated by the same index used to inflate effort.

For fishermen the rental cost of boat capital consists of depreciation on gear and vessel value plus the market rate of return foregone on the capital value of the vessel plus the value of the license attached to the vessel. This last figure was obtained only for the years 1973, 1974, and 1975. The reason
is that prior to 1973, licenses bore very little value as new vessels were simply larger than the old. It was not until the tcn-for-ton regulations came into effect that fishermen were forced to buy more licenses to build a larger vessel. The capital value of licenses was calculated by subtracting adjusted gear and vessel value from actual gear and vessel value. And finally, the appropriate inflation-free market rate of return on capital was assumed to be 3.5% (Campbell, 1973).

From the point of view of society the opportunity cost of boat capital (market rentals) should not include the market rate of return foregone on the capital value of the licenses attached to the vessel. This is an example of a situation where private opportunity costs exceed social opportunity costs. Unfortunately, this private opportunity cost was not excluded in the work with the cost functions in both Chapters Three and Four.

License values were used only for 1973, 1974 and 1975, therefore, the discrepancies were not too great and only occurred in cycles one, three and four. The discrepancies are as follows with the higher (wrong) daily cost followed by the lower (correct) daily cost. For confined water gillnets: cycle one, 37.07/36.99; cycle three, 35.60/35.59; cycle four, 35.05/34.86. For open water gillnets: cycle one, 44.83/44.77; cycle three, 45.44/45.44; cycle four, 46.10/45.96. For confined water purse seines: cycle one, 179.87/178.89; cycle three, 172.33/172.05; cycle four, 171.11/169.44. For open water purse seines: cycle one, 240.55/239.49; cycle three, 247.67/247.32; cycle four, 246.17/244.29.
As the discrepancies were so small, it was decided not to re-run all the optimal and cost programming as the expense in computer time would have been very high and the results are not sensitive to changes in cost (see the results in Tables (4-4) and (4-5) in Chapter Four).

Following the lead of several studies of salmon fishing costs in B.C. (Buchanen and Campbell, 1957; Sinclair, 1960, pp. 163-238; Royce-Bevan, 1963, pp. 33-45, 121-122; Campbell, 1969, pp. 48-57; Canada, "Some Economic Aspects...," 1971; Canada, "An Analysis of Gross Returns...," 1971; Grauer, 1973; and Canada, "You Are Operating...," 1971) depreciation on vessel values was estimated at 7.5% for all gear types annually. For gear values the appropriate annual depreciation appears to be 33% for seine vessels and 100% for gillnets and trolls. As the main gear expense is the net or troll lines which last approximately three years for seines and one year for gillnets and trolls, these appear to be reasonable. Foregone market rate of return on gear and vessel value was assumed equal to an inflation-free 3.5% per year.

The three components of the rental cost for boat capital were divided by seventy-five to give the average expected rental per day of fishing. Fishermen are actually engaged in fishing for only about seventy-five days out of every year on average but frequently spend another seventy-five days a year aboard the boat either repairing it or preparing it for fishing. Vessels in the sockeye fishery are only used three and a half days a week now instead of five but it is thought by most fishermen that the actual wear and tear on a weekly basis is about the same for the
reasons discussed under labour costs. Thus, for similar reason, fixed cost rentals must also be deflated by the same index used to inflate effort to the 1951 equivalent.

Operating costs are the most difficult to calculate as there are no indexes and the few observations available are scattered over the years. The cost references used for calculating depreciation were used to try and relate operating costs, if possible, to the three consistent and continuous indexes available: gear and vessel value, wages in alternative employment, and effort in 1951 days of fishing. For the years 1951 to 1956, the monthly magazine, *Western Fisheries*, was used as a source for vessel insurance rates, gear depreciation, vessel depreciation, food and fuel costs; for the years 1953 to 1954, Buchanan and Campbell (1957) were used for cost breakdowns on fuel, bait, gear repairs and purchases, vessel repairs and engine purchases, wages, license fees, interest costs and equipment rentals; for 1958 the Sinclair report (1960, pp. 163-238) was used for broad breakdowns on the relationship between fixed, operating and labour costs; for the years 1959 to 1962, the Royce-Bevan study (1963, pp. 121-122) gave the rough values for vessels and gear; for the years 1965 to 1967, Campbell (1969, pp. 48-57) was used for estimates for fuel, food, vessel value, gear value, maintenance, insurance, wages, wharfage and depreciation costs; for the years 1966 to 1970, studies by the Canadian department of fisheries ("Some Economic Aspects...," 1971; and "Analysis of Gross Returns...," 1971) were used for figures on vessel values, income earned, alternative employment earnings and average number of days fishing per year; and for
1971, the study by Grauer (1973) was used for figures on gear repairs and purchases, vessel and engine repairs and purchases, food, fuel, equipment leasing, insurance, depreciation, wages and license fees.

Food costs were directly related to the number of days involved in a fishing day and four meals per day per man were assumed. 1951 prices for the average meal were taken from Statistics Canada (catalogue: 62-002) as were food cost indexes. These were used to deflate prices for the years 1951 to 1975 to put food costs in 1951 dollars.

With the advent of the Fishing Vessel Insurance Plan sponsored by the federal government and taking into account the refunds on private insurance premiums on plans operating before the federal scheme, it was assumed that basic vessel fire insurance amounted to 2.5% of the vessel value each year.

Fuel costs were estimated on the following basis: purse seines are mainly diesel and use twelve gallons per set and make an average of six sets per day for a total of seventy-two gallons per day; trolls are mainly gasoline and use 2.5 gallons per hour of fishing for twelve hours per day for a total of thirty gallons per day; and gillnets use two gallons of gasoline per hour and fish for twelve hours a day for a total of twenty-four gallons per day. As these are all maximum number of fishing hours and 1951 effort assumes fewer fishing hours, this should allow for an additional two to four hours of steaming time per day.

1951 wholesale (commercial) prices for gasoline and diesel were taken from Statistics Canada (catalogue: 62-002) from which
fuel cost indexes were also obtained. These were used to deflate fuel costs for the years 1951 to 1975 to put fuel costs in 1951 dollars.

Equipment leasing and rentals are extremely difficult to estimate as shore facilities differ, electronic equipment has replaced older types of equipment and wharfage and slip charges are simply not available. Judging from the scattered observations, it would appear that they average about 2.5% of vessel value each year. The same problem applies with regard to bait and ice, taxes, licenses and fees. These were lumped together as miscellaneous and were valued at 2% of gear and vessel value each year. The results appeared to conform reasonably well with the few observations available.

Finally, for the same reasons as for labour and fixed cost rentals, operating costs were deflated by the same index used to inflate days of fishing into 1951 equivalents. Thus all costs were put in 1951 constant dollars first through using their appropriate price indexes and were then further deflated by efficiency or gear and vessel value indexes to put them in 1951 equivalent days of effort costs.

Prices for the various races of salmon caught in B.C. were taken from two sources: British Columbia Catch Statistics (Canada, Department of the Environment, Fisheries Service, 1951-1975) and the Annual Statistical Review of Canadian Fisheries (Canada, Department of the Environment, Vols. 1-9). From 1951 to 1971 the sockeye prices were used as given but for the period 1972 to 1975 adjustments were required. According to various sources in the Department of Fisheries in B.C. and amongst
fishermen, after 1971 the prices paid at the processors no longer reflected true landed price. The union had agreed to allow landed prices to be less than true landed prices in order to allow boat owners to use lower prices for calculating shares to pay their workers. Apparently many boat owners were in serious financial difficulty because of the rapid rise in vessel building and repair costs. The boat owner (or skipper) was paid a bonus at the end of the season based on his landed catch which brought the landed price of fish up to the actual landed price. What is published is the announced price and not the actual price.

To convert the reported price into actual price for the years 1972 to 1975 the following procedure was used. Landings and Landed Value of sockeye were taken from the Annual Statistical Review of Canadian Fisheries for the years 1953 to 1975. Wholesale Product and Wholesale Product Value for sockeye for the same period and from the same source were also compiled. The landed price was calculated by dividing landed value by landings in weight (metric tons converted to pounds). The wholesale price was calculated by dividing wholesale product value by wholesale product weight adjusted because the latter was reported in thousands of 48 pound cases. The ratio of landed to wholesale price was then calculated and it varied from a high of 36.4% in 1968 to a low of 26.9% in 1973. The period 1972 to 1975 was consistently lower, confirming the reports of the difference between actual and reported prices of landed sockeye. The average ratio for the period 1953 to 1971 was calculated as 33.7%. This average ratio was applied to the period 1972 to 1975
to inflate reported prices up to actual prices for landed sockeye.

Prices for the five races of salmon caught in Washington waters were taken from two sources: unreported sockeye prices obtained by the Department of Fisheries in Washington and the ratio of Catch Value to Total Pounds Landed as reported in the annual issues of the Fisheries Statistical Report (State of Washington, 1951, 1957-1974). The two sockeye prices were exactly equivalent and it is to be assumed that the unreported prices are simply calculations made of the ratio of Catch Value to Total Pounds Landed. There were no unreported prices for the period 1952 to 1956 and there were no annual issues of the Fisheries Statistical Report published in those years. This would tend to confirm the fact that the unreported prices were based on those Statistical Reports.

Breakdowns by gear type for sockeye catches were not available for B.C. They were available for the period 1965 to 1974 for Washington in the form of unreported prices. The differentials were not great as all three gear types use nets and it is undamaged frozen fish which command a premium. Nor were the differentials consistent: some gear types earned more in some years and less in others. It is true that troll gear in B.C. are reported to receive about 5% more per pound because the fish are undamaged by nets and are packed individually in ice. However, because of the premium for undamaged frozen fish, both purse seines and gillnets have taken great care over the years to ice their catch where possible and to minimize the net damage. For this reason, no attempt was made to calculate
differentials in sockeye price by gear type.

Canadian prices were used for the catches made by both B.C. and Washington fishermen. The differential between the two prices has remained fairly stable, including the exchange rate differential, at about 15% to 17% higher for sockeye sold into Washington. This effect will be picked up in Chapter Four below where the U.S. costs are permitted to be 15% less than for Canadian fishermen.

The prices of other salmon were then taken as a percent of sockeye prices and the catch of other salmon were then taken as a percent of sockeye catches over the years. Although catch proportions varied over the years and the differentials for race prices also changed over the years, the most dramatic change was in the catch of pink salmon every second year. For this reason and for the reasons discussed in the programming section above, the value of other salmon caught was estimated as 50% of sockeye prices for Canada and the U.S. in "on" years for the pink and as 67% of sockeye prices in "off" years for the pink.

Gear And Vessel Value Indexes

The gear and vessel value indexes used in Chapter Three to correct reported effort were calculated as follows. Observations on average value for gillnet, purse seine and troll gas and diesel vessels in B.C. were available from 1953 to 1975. Observations on average gear value for gillnet, purse seine and troll vessels in B.C. were available from 1953 to 1971. Observations on average yearly expenditure on gear for gillnet, purse seine and troll vessels in B.C. were available from 1967
Observations on average yearly new engine expenditures for the same three gear types for the same period were also available. All these observations were taken from Fishery Statistics of B.C. (1951-1975). The same series were also available in the annual May issue of the magazine, Western Fisheries (1951-1956).

The first step was the construction of a complete series on average vessel value. This involved multiplying average vessel values by the number of reporting vessels to arrive at total vessel values for each gear type for gas and diesel. The total gas vessel values and total diesel vessel values were summed to get the total fleet value by gear type. These total fleet values were then divided by total vessel numbers (both gas and diesel) in each gear type to arrive at the respective average vessel values for each fleet.

The second step involved the construction of a Boat Building and Repair Index (BBRPX). A BBRPX was available from Statistics Canada (catalogue: 62-515) from 1956 to 1959. A BBRPX was available from Cansim (Statistics Canada, Cansim 429.1, code=d587101) from 1961 to 1971. A BBRPX was available from Statistics Canada (catalogue: 62-002) from 1971 to 1975. These indexes were all consistent in terms of the sources used by Statistics Canada to generate BBRPX. However, there was no continuous index for the period 1951 to 1975.

To interpolate for the missing years a Transport index was used. This was derived from sub-indexes such as BBRPX and was continuous for the whole period (Statistics Canada, catalogue: 62-002). For the years 1951-1955 and 1960, the BBRPX
interpolated as equal to 1.05 the Transport index for those years for the same base. This partially interpolated BBRPX for 1951 to 1960 was then spliced onto the BBRPX which was available from 1961 to 1971. And finally, the latter was spliced onto the BBRPX from 1971 to 1975. The resulting BBRPX with a base of 1951=100 was then compared with the overall Transport index, the Consumer Price index and the General Wholesale Price index with similar bases. The BBRPX conformed favorably with the characteristic that it accelerated at a faster rate than any of the others. This is consistent with Statistics Canada reports on the more rapid inflation in the boat building and repair industry (various issues of catalogue: 62-515 and 62-002).

The third step removed the influence of the license limitation program on the value of vessels. This involved deflating average vessel values for gillnets, purse seines and trolls by the BBRPX from 1953 to 1975. These deflated values were then regressed on the years 1962 to 1972 to isolate the 10 year trends prior to license value increases. The fit for the gillnet, purse seine and troll vessel value trends were all between an R-squared of .85 and .95. These trends were then extended, using the parameter estimates, for the years 1973 to 1975 to derive adjusted vessel values for those years. These adjusted vessel values were then inflated with BBRPX and substituted for the average vessel value for the years 1973 to 1975. The adjusted vessel value indexes were then subtracted from the average vessel values indexes (unadjusted) to arrive at estimates of the influence of license values on vessel capital values. The results are rather similar to newspaper reports on
per ton license values.

The fourth step is similar to the first step in the construction of a complete series on average gear value. It involved multiplying average gear value by the number of reporting vessels to derive total gear values for each gear type for gas and diesel. Total fleet values were then calculated by summing gas and diesel figures and then transformed into average gear type values by dividing by fleet size.

A similar procedure was involved in deriving average yearly gear expenditure by gear type. First differences on a yearly basis were taken of average gear value and compared with average gear expenditure for the years 1966 to 1971. An average multiplier was calculated which gave a reasonably consistent relation between these first differences and the yearly expenditures for each gear type. These multipliers were then used with the average gear expenditure figures for the years 1972 to 1975 to estimate average gear values by gear type for the missing years. The resultant index was called adjusted gear value.

The fifth step involved summing the adjusted average vessel value and adjusted average gear value for each gear type to give a gear and vessel value index. This was deflated by BBPXP.

Finally, it was assumed that gear and vessel values did not change for the years 1951 to 1953. The reason this was done was that there were no data available anywhere to indicate how to interpolate for the missing years, 1951 and 1952. The only justification for assuming that deflated gear and vessel value indexes were unchanged for those three early years is that the
efficiency indexes as compiled in Chapter Three indicated no serious change in the productivity or efficiency of catching fish for each gear type in the years 1951 to 1953. Furthermore, vessel values are likely to react with a lag to any productivity changes. Comparing the efficiency indexes with gear and vessel value indexes indicates that the latter are more like moving averages of the former. That is, it takes time for technological change to show up in gear and vessel values.
CHAPTER FOUR: THE OPTIMAL MANAGEMENT SOLUTION

I INTRODUCTION

Using the recruitment function from Chapter Two and the cost functions from Chapter Three, the management model presented in this chapter will derive the equilibrium values needed for optimal management of the Fraser River sockeye fishery. The first part of this chapter brings together all the assumptions basic to the management model which have been discussed in the previous three chapters. The management model will then be used in four hypothetical case studies and the results compared with the actual historical management experience.

In the first case sockeye only will be caught using a constrained example in which the IPSFC will be forced to use both U.S. and Canadian fishermen to land 50% of the catch each. An unconstrained example will also be used in which the IPSFC can apportion the catch as it sees fit amongst the lowest cost gear type areas. In the second case, the constrained example of harvesting sockeye only will be used to examine the impact of altering discount rates on optimal escapement, recruitment and catch and the net profit. In the third case, costs will be varied, using both constrained and unconstrained examples, to examine the impact of altering costs on optimal escapement, recruitment and catch and on the least cost gear type harvesting proportions. In the fourth case, other salmon, as well as sockeye, will be permitted to be caught up to the capacity limits described in Chapter Three. Both an unconstrained and a
constrained example will be used.

All the previous cases will be based on annual net profit once equilibrium has been achieved. A full comparison between the historical net profit and the net profit derived from the optimal management model should include the periods during which the management model adjusts to the equilibrium values. The best way to do this appears to be to study the period 1951 to 1975 plus the four years from 1947 to 1950 during which escapement levels would hypothetically be adjusted to the optimal values. Compounding the annual net profits forward from 1947 to 1975 will then permit comparison of present values for both the historical experience and the optimal management case.

The final section of this chapter presents a brief summary of the whole study and the major conclusions to emerge from working with the management model.

The first basic assumption of the management model is that the IPSFC has been given the monopoly powers of a sole owner and charged with the task of maximizing the present worth of the Fraser River sockeye fishery. It will be assumed that least cost gear are paid their opportunity costs and that net revenue is divided equally between the U.S. and Canadian governments.

The methods used by the IPSFC to achieve its management objectives will include quantitative control of gear type effort in the sixteen different gear type areas. This is similar to its present method of controlling escapement except that it will now be permitted to close ten gear type areas completely and to control the gear type numbers involved in harvesting the remaining open areas.
It will be assumed that the most rapid approach to the equilibrium level of escapement is the optimal harvest policy (see Clark, 1976b, pp. 245-248). And it will be assumed, for the purposes of this study, that those optimal escapement levels could have been achieved in the four years before 1951. In some cases the results suggest that historically the IPSFC has allowed too large an escapement and in others, too small an escapement. For cycle years where there has been underfishing, increasing exploitation is no problem. But for overfished cycle years, allowing the optimal escapement will entail a sacrifice the first years.

Achieving these optimal levels of escapement in each cycle year is very simple as the sub-optimal recruitments in all cases exceed the optimal escapements which are required. Therefore, the IPSFC simply reduces or increases effort in each cycle year to allow the optimal escapement. Except for this adjustment period, however, the optimal solutions are equilibrium values which implies they are the same for each point in time thereafter.

In order to harvest the recruitment resulting from this optimal escapement, the IPSFC needs some guide to choosing the least cost methods. These are derived in Chapter Three from production functions using 1951 equivalent days of fishing effort and available recruitment varying by year class cycle catchability. Although there are sixteen traditional gear type areas, only six will be used. For the three troll gear areas, sockeye is still only an incidental catch despite great improvement in catching efficiency. Both reefnet areas appear to
be marginal even at the best of times. Recruitment to the U.S. side of the outer Strait of Juan de Fuca and the Westbeach area is highly restricted making zone three gillnets and purse seines inefficient. And the recruitment to the Canadian area in the Strait of Georgia outside the mouth of the Fraser River is highly variable. Except for years of exceptionally large recruitment when sockeye migrate past the mouth of the Fraser into Johnstone Strait, this Strait of Georgia fishing area could never land a substantial portion of the catch. For these reasons all these ten areas experienced higher costs on average than the six most productive and consistently less costly areas. And it will be assumed that the IPSFC will close them to all fishing during the sockeye season.

This leads to the problem of redundant gear in certain areas (Clarke, Clark and Munro, 1979). This redundant gear can be accommodated by either forcing it into other salmon fisheries (outside the six week sockeye fishery) or by relocating the gear in the six most productive gear type areas. The redundant gear types which cannot be relocated, such as reefnets, can be compensated out of the larger rent which accrues through the optimal management of the fishery.

For the six remaining gear type areas, some cycle years are good and some are bad in terms of excess capacity. In particular, cycle four makes very heavy use of purse seines and open water gillnets because of the larger recruitment elasticities which make them sensitive to availability in years of large migrations. But other years make much heavier use of gillnets. That is, the exponents on the recruitment variables
for purse seines and open water gillnets are larger than for gillnets in confined waters and this reduces unit effort costs considerably in years of large recruitment availability such as for cycle four.

A closer study of harvesting patterns reveals the following: cycle year two is poor for all gear type areas as it is an off year for pink salmon and the smallest cycle year recruitment for sockeye. Cycle years one and three are good for gillnets in terms of sockeye and they are also "on" years for pink. Thus all gear types appear to benefit from the good sockeye catches and heavy pink catches. Cycle year four is an off year for pink which is more than offset by the enormous recruitment for sockeye. On the surface, cycle year four appears to be excellent for purse seines and poor for gillnets. But on closer examination it turns out that the harvest for gillnets is only poor in comparison to the large purse seine catches. In fact the gillnet catches are almost the same absolutely as those for cycle years one and three and it is only in cycle year two that they are poor.

The variance of catch is greatest for purse seines and it is very convenient that they are the most mobile of the gear types. The mobility of purse seines into other fisheries plus the very large purse seine catches of sockeye in cycle year four will be assumed to adequately compensate purse seines for their excess capacity in poor years.

The discussion of pink salmon introduces the problem of the joint production nature of the fishery. Because of the complexities involved in modelling a multi-species harvesting
system, this study has focused on the sockeye almost exclusively. This will be continued in searching for an optimal management solution. The chief objective for the IPSFC will be to maximize the present value of the sockeye. However, an alternative model will be presented which allows other salmon to be harvested on a capacity basis (as in Chapter Three) in order to demonstrate the impact of the joint production on the optimal management of sockeye.

The choice of the least cost gear type harvesting areas given nonlinear cost functions is determined by the size of catch, the size of biomass recruitment, the catchability of that biomass and the efficiency of the gear type areas. The gear type area effort has been standardized into 1951 equivalent days' of effort (see the Appendix to Chapter Three for details) and catchability for each gear type has been standardized on a year cycle basis. But catch and recruitment depend on the optimal solution which in turn depends on the proportion of catch taken by each area. As discussed in Chapter One, the optimal solution must determine least cost gear type harvesting proportions and optimal catch and recruitment simultaneously.

The system of least cost harvesting uses the cost functions in Chapter Three and optimal escapement is obtained by using Clark and Munro's equilibrium equation. The algorithm was developed by Clark (1976b, pp.252-253) specifically for discrete-time metered models such as the Fraser River sockeye which uses a modified Ricker form of recruitment function. The specific form of the algorithm used in this study is:

\[(4-1) \, G(x) \left( \frac{P(R(x)) + P(C(x))}{P(C(x))} \right) - (1+s)^5 = 0\]
where \( x = \text{optimal escapement} \)

\[ G(x) = \text{derivative of recruitment function with respect to } x \]

\[ P(B(x)) = \text{derivative of profit with respect to recruitment as a function of } x \]

\[ P(C(x)) = \text{derivative of profit with respect to catch as a function of } x, \text{ allowing optimal escapement} \]

\[ D = \text{discount factor equal to one plus the social rate of discount} \]

In the model in this study there is a four year lag between escapement and recruitment, therefore the discount factor is raised to the fifth power to reflect this compounding effect. The fishery will be broken up into four separate cycle year fisheries which will allow for the different periodic influences for each cycle year. Therefore, the Clark algorithm in expression (4-1) will be used to obtain the optimal values assuming each of the four fisheries is harvested only once every four years.

Flowchart (4-1) illustrates the alterations needed to transform the least cost harvesting program (Flowchart (3-1)) into a program which simultaneously determines the optimal escapement and the least cost gear type harvesting proportions to land the subsequent catch. As explained in Chapter One, the program closes the loop between the residual (escapement) and the initial values (recruitment and catch). Given initial values for catch and recruitment, the model apportions the gear type catch so as to minimize cost of harvesting, calculates the own rate of return on the fishery and subtracts the (compounded) social rate of return. If the resulting value is different from zero, the program specifies a new level of escapement, uses the recruitment function to estimate recruitment and subsequent catch, and goes through the same steps as above. These
Flowchart (4-1): Program to Maximize Present Worth of Sockeye Fishery Assuming Sockeye Harvesting Only.

1. Initial escapement is specified discount.

2. Clark-Munro equilibrium algorithm.

3. Optimal equilibrium escapement.

4. Recruitment function.

5. Recruitment minus escapement, including John, Strait catch.


7. Residual escapement.

8. Flowchart (B-1) least cost harvesting program.

9. Is maximum present value achieved?
   - Yes: Stop
   - No: Restart
iterations will continue until a level of escapement is reached where the own rate of return on the fishery equals the four year compounded social rate of discount.

Note that in all subsequent work it is assumed that the Johnstone Strait catch and the Indian catch will remain at the average cycle year level. As it is impossible to guess how these catch proportions would change and as they represent only a small proportion of total catch, no attempt will be made to modify them.

II CASE ONE: HARVESTING SOCKEYE ONLY

Table (4-1) gives the comparison between actual historical average cycle year profit and the annual net profit obtained from the optimal policy assuming: only sockeye are caught, an inflation free social discount rate of three and a half percent, and the IPSFC constrained to an equal division of the catch between U.S. and Canadian fishermen.
### Table 4-1: Constrained Optimal Catch of Sockeye Only, Historic and Optimal Cycle Year Escapement, Recruitment and Catch in 000's of Pounds; Proportion of Gear Type Area Catches; and Resulting Annual Net Profit in 000's of 1951 Dollars Using a Discount Rate of Three and a Half Percent

<table>
<thead>
<tr>
<th></th>
<th>Cycle 1</th>
<th>Cycle 2</th>
<th>Cycle 3</th>
<th>Cycle 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Historic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Escape</td>
<td>5,809</td>
<td>4,274</td>
<td>7,033</td>
<td>15,482</td>
</tr>
<tr>
<td>Recruit</td>
<td>27,602</td>
<td>18,217</td>
<td>29,992</td>
<td>59,275</td>
</tr>
<tr>
<td>Catch</td>
<td>18,359</td>
<td>11,717</td>
<td>19,380</td>
<td>34,930</td>
</tr>
<tr>
<td><strong>Optimal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Escape</td>
<td>7,996</td>
<td>8,085</td>
<td>9,437</td>
<td>10,946</td>
</tr>
<tr>
<td>Recruit</td>
<td>34,887</td>
<td>23,713</td>
<td>32,043</td>
<td>64,504</td>
</tr>
<tr>
<td>Catch</td>
<td>23,456</td>
<td>13,402</td>
<td>19,026</td>
<td>44,695</td>
</tr>
<tr>
<td>CZ2G</td>
<td>.5%</td>
<td>11%</td>
<td>9%</td>
<td>21%</td>
</tr>
<tr>
<td>CZ2P</td>
<td>12.5%</td>
<td>4%</td>
<td>9%</td>
<td>24%</td>
</tr>
<tr>
<td>USZ4G</td>
<td>22%</td>
<td>28%</td>
<td>27%</td>
<td>10%</td>
</tr>
<tr>
<td>USZ4P</td>
<td>16%</td>
<td>13%</td>
<td>14%</td>
<td>28%</td>
</tr>
<tr>
<td>USZ5P</td>
<td>12%</td>
<td>9%</td>
<td>9%</td>
<td>12%</td>
</tr>
<tr>
<td>CZ7G</td>
<td>37%</td>
<td>35%</td>
<td>32%</td>
<td>5%</td>
</tr>
<tr>
<td><strong>Net Profit</strong></td>
<td>$1,535</td>
<td>$1,754</td>
<td>$2,507</td>
<td>$8,302</td>
</tr>
<tr>
<td><strong>Actual</strong></td>
<td>$246</td>
<td>$466</td>
<td>$1,145</td>
<td>$5,748</td>
</tr>
<tr>
<td><strong>Gain In</strong></td>
<td>$1,289</td>
<td>$1,288</td>
<td>$1,362</td>
<td>$2,554</td>
</tr>
</tbody>
</table>

As this is the case closest to the historical experience it will be used as the reference case in subsequent work. The first point to note is that the optimal program is assuming equilibrium has been achieved in the past. Thus "Net Profit" is the annual cycle year profit assuming optimal equilibrium escapement, recruitment and catch. The "Actual" net profit is the average annual cycle year profit between 1951 and 1975. And the "Gain In" net profit is the difference between hypothetical net profit and historical actual net profit: it gives an indication of the gains to be expected from optimal management of the Fraser River sockeye fishery. Note that what is referred
to here is the net profit on an annual basis once equilibrium has been achieved. The smaller net profit experienced in the adjustment year is ignored for now but will be included in the net worth comparisons below.

For the first three cycle years, optimal escapement is much larger than the average historical escapement permitted by the IPSFC while optimal catch is not much greater than historical catch for the first two cycle years and is actually slightly less for cycle year three. In fact, the greatest increase on a percentage basis is for optimal recruitment. This illustrates the important role for optimal management in reducing the costs imposed by the common property problem. IPSFC management appears to have been primarily concerned with an equal international division of the catch and the prevention of potentially disastrous overfishing resulting from this common property problem. Apart from cycle year four, it is apparent that historical levels of escapement have been lower than optimal which would suggest that the IPSFC has been under considerable pressure from a fishery dominated by a drive to avoid the common property abstention costs. Because of these costs, the private discount rates are very high and it would appear that the IPSFC has been forced to use unreasonably high discount rates in determining escapement levels (see, for example, Table (4-3) below). Optimal management, however, is concerned with maximizing profit and this requires balancing the increment in profit associated with larger catches against the increment in cost in harvesting that catch. Enhanced recruitment is a very important way to reduce fishing costs and the program has made
full use of this fact. Once the common property problem has been eliminated, the IPSFC will be able to make full use of these intertemporal gains.

Cycle year four is different from the first three in that optimal escapement is smaller, optimal recruitment slightly larger but optimal catch very much larger than the historical equivalents. This illustrates very clearly the rather unique way in which recruitment elasticity effects can work in a fishery. The efficiency of gear does not alter from cycle year to cycle year and working with larger and larger recruitments quickly drops the average costs of taking any catch. But by the time very large recruitments, such as those of cycle four, are experienced, net profit can be increased more rapidly by increasing catch. The program's efforts to enhance recruitment rather than catch for years with poor recruitment while enhancing catch rather than recruitment for the one cycle year where recruitment is already high implies that the tradeoff between the recruitment elasticity cost effects and the enhanced revenue from greater catch has tipped in favor of the latter. The reason is the relationship amongst escapement, recruitment and catch. That is, recruitment cannot be enhanced much more by sacrificing catch but catch can be enhanced considerably by reducing escapement without affecting recruitment too seriously.

Comparing Tables (4-1) and (3-2) reveals important changes in gear type catch proportions. This makes sense in a program that now has the capacity to juggle catch and recruitment in such a way as to take full advantage of areas which are very sensitive to one or the other in terms of cost saving. This is
the "stock effect" referred to by Clark and Munro (1975). What is most interesting is that the shifts amongst gear types from year to year of the cycle are not nearly as radical in this optimal program. Some areas are still favored in certain years but now the catch is spread more evenly over most areas. However, the shift toward purse seines and open-water gillnets is still very pronounced for the fourth cycle year.

The final point worth noting is that net profit is not always directly related to size of catch. Cycle years two, three and four conform to the conventional notion that as catch size increases, so does net profit. But cycle year one has a larger catch and recruitment than both cycle years two and three and yet experiences lower net profit. The catchability parameter plays a key role because not only is cycle year one an "on" year for pinks but the run of pinks is over thirty percent higher than for cycle year three (the other "on" year). It is likely that the pink catch is so valuable to fishermen that they are relocating in the gauntlet at the expense of catchability of sockeye. A comparison of historic catch, recruitment and net profit indicates the same trend. In fact, once the catch of other salmon is included (Tables (4-6) and (4-7) below) the usual relationship between catch and net profit is re-established.

Table (4-2) gives much the same comparisons as those in Table (4-1) with the exception that the IPSFC is no longer constrained to an equal division of the catch.
TABLE (4-2): UNCONSTRAINED OPTIMAL CATCH OF SOCKEYE ONLY.

OPTIMAL CYCLE YEAR ESCAPEMENT, RECRUITMENT AND CATCH IN 000'S OF POUNDS; PROPORTION OF GEAR TYPE AREA CATCHES; AND RESULTING NET PROFIT IN 000'S OF 1951 DOLLARS USING A DISCOUNT RATE OF THREE AND A HALF PERCENT

<table>
<thead>
<tr>
<th>Optimal</th>
<th>Cycle 1</th>
<th>Cycle 2</th>
<th>Cycle 3</th>
<th>Cycle 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Escape</td>
<td>9,584</td>
<td>8,211</td>
<td>9,382</td>
<td>10,922</td>
</tr>
<tr>
<td>Recruit</td>
<td>35,519</td>
<td>23,776</td>
<td>32,042</td>
<td>64,503</td>
</tr>
<tr>
<td>Catch</td>
<td>22,501</td>
<td>13,339</td>
<td>19,080</td>
<td>44,719</td>
</tr>
<tr>
<td>CZ2G</td>
<td>54%</td>
<td>10%</td>
<td>20%</td>
<td>29%</td>
</tr>
<tr>
<td>CZ2P</td>
<td>12%</td>
<td>5%</td>
<td>8%</td>
<td>24%</td>
</tr>
<tr>
<td>USZ4G</td>
<td>5%</td>
<td>33%</td>
<td>13%</td>
<td>5%</td>
</tr>
<tr>
<td>USZ4P</td>
<td>3%</td>
<td>18%</td>
<td>9%</td>
<td>13%</td>
</tr>
<tr>
<td>USZ5P</td>
<td>8%</td>
<td>7%</td>
<td>8%</td>
<td>10%</td>
</tr>
<tr>
<td>CZ7G</td>
<td>18%</td>
<td>27%</td>
<td>42%</td>
<td>19%</td>
</tr>
</tbody>
</table>

NET PROFIT $2,406 $1,759 $2,538 $8,724
ACTUAL "$246 $466 $1,145 $5,748
GAIN IN "$2,160 $1,303 $1,393 $2,976

The first difference from the previous example is the increase in both escapement and recruitment for cycle years one and two accompanied by a reduction in catch. Unfettered by the equal catch division constraint, the program is, once again, attempting to take advantage of sensitivity to greater recruitments. The pronounced changes in catch proportions would indicate how important recruitment elasticities are for the open-water gillnets (CZ2G). Except for cycle year two, there is a dramatic increase in usage of this particular gear. It is obvious that once recruitment passes a critical level (larger than that in cycle year two) Canadian gillnets in the first and last parts of the gauntlet are the favored gear.

Note the dramatic increase in net profit for cycle year one as a result of the reallocation of harvesting effort. The cost
of constraining the IPSFC to an equal division of the catch in cycle year one amounts to nearly $900,000 in 1951 dollars. Including the catch of other salmon does not reduce this sharing cost if one compares Tables (4-6) and (4-7) below.

Finally, comparing Tables (4-2) and (3-1) leads to much the same conclusions as for the previous example: shifts in catch proportions between cycle years are not nearly as dramatic and the catch appears to be spread more evenly over most areas.

III CASE TWO: ALTERING DISCOUNT RATES

Table (4-3) gives the cycle year changes in optimal escapement, recruitment and catch and net profit for different discount rates assuming: only sockeye are caught and that the IPSFC is constrained to dividing the catch equally between the U.S. and Canada.
TABLE (4-3): CONSTRAINED OPTIMAL CATCH OF SOCKEYE ONLY, OPTIMAL ESCAPEMENT, RECRUITMENT AND CATCH IN 000'S OF POUNDS, AND RESULTING NET PROFIT IN 000'S OF 1951 DOLLARS

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Escape</th>
<th>Recruit</th>
<th>Catch</th>
<th>Profit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1% Discount</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycle 1</td>
<td>8,089</td>
<td>34,962</td>
<td>23,438</td>
<td>$1,553</td>
</tr>
<tr>
<td>Cycle 2</td>
<td>8,174</td>
<td>32,043</td>
<td>19,019</td>
<td>44,694</td>
</tr>
<tr>
<td>Cycle 3</td>
<td>9,444</td>
<td>32,043</td>
<td>19,019</td>
<td>44,694</td>
</tr>
<tr>
<td>Cycle 4</td>
<td>10,947</td>
<td>64,504</td>
<td>44,694</td>
<td></td>
</tr>
</tbody>
</table>

3.5% Discount

| Cycle 1 | 7,996 | 34,887 | 23,456 | $1,535 |
| Cycle 2 | 8,085 | 32,043 | 19,026 | 44,695 |
| Cycle 3 | 9,437 | 32,043 | 19,026 | 44,695 |
| Cycle 4 | 10,946 | 64,504 | 44,695 |

10% Discount

| Cycle 1 | 7,739 | 34,651 | 23,478 | $1,553 |
| Cycle 2 | 7,837 | 32,043 | 19,027 | 44,707 |
| Cycle 3 | 9,437 | 32,043 | 19,027 | 44,707 |
| Cycle 4 | 10,933 | 64,503 | 44,707 |

20% Discount

| Cycle 1 | 7,300 | 34,151 | 23,416 | $1,535 |
| Cycle 2 | 7,392 | 32,043 | 19,031 | 44,743 |
| Cycle 3 | 9,437 | 32,043 | 19,031 | 44,743 |
| Cycle 4 | 10,896 | 64,502 | 44,743 |

30% Discount

| Cycle 1 | 6,811 | 33,435 | 23,190 | $1,235 |
| Cycle 2 | 6,885 | 32,043 | 19,035 | 44,794 |
| Cycle 3 | 9,429 | 32,043 | 19,035 | 44,794 |
| Cycle 4 | 10,869 | 64,500 | 44,794 |

Clark (1976b, pp.47-51) has given a similar comparison for the Pacific Halibut and the Antarctic fin whale, the former with a high population growth rate and the latter with a low growth rate. Although the example for sockeye is not strictly comparable because the program simultaneously determines optimal stock values and least cost harvesting configurations while Clark's gives optimal stock values given a least cost harvesting system, the results are rather similar. That is, like the Pacific Halibut, Fraser River sockeye salmon have a high
intrinsic growth rate (albeit over four years) and the optimal catch levels are rather insensitive to the discount rate. Biological overfishing does not become optimal unless the discount rate exceeds 10% for cycle year one, and 30% for the other three cycle years.

This illustrates the basic choice confronting the fishery manager: should he catch more now to enable him to invest at the social rate of return or should he abstain in order to earn at a rate of return equal to the "fishery rate of return" on the stock? High intrinsic growth rates imply that future net profits are enhanced not only by increased harvest but also by the reduction in harvesting costs resulting from larger subsequent recruitments.

The results in Table (4-3) follow the traditional pattern of sacrificing escapement to enhance current catch as discount rates rise. However, the impact on recruitment is very slight for the third and fourth cycle years. For the first two cycle years recruitment falls steadily as discount rates (and catches) rise which indicates that intrinsic growth rates are not as high. For the third and fourth cycle years the "fishery rates of return" are so high that it takes a higher opportunity cost rate of return to induce the manager to sacrifice future catches and recruitments by catching more today. It is important to note that these are the equilibrium values for catch and it is implicit that in the adjustment year catches would have been higher because of reduced escapements.
IV CASE THREE: VARYING HARVEST COSTS

Table (4-4) gives the comparison between actual historical average cycle year profits and the annual net profit obtained from the optimal policy assuming: sockeye only are harvested, an opportunity cost social rate of discount of three and half percent, and the IPSFC constrained to an equal division of the catch between U.S. and Canadian fishermen. It is also assumed that unit effort costs are raised by 15%. The discount rate used in transforming boat capital into a flow is not raised as it is assumed to be exogenously determined.

TABLE (4-4): CONSTRAINED OPTIMAL CATCH OF Sockeye ONLY, OPTIMAL CYCLE YEAR ESCAPEMENT, RECRUITMENT AND CATCH IN 000'S OF POUNDS; PROPORTION OF GEAR TYPE AREA CATCHES AND RESULTING NET PROFIT IN 000'S OF 1951 DOLLARS USING A DISCOUNT RATE OF THREE AND A HALF PERCENT AND ASSUMING OPPORTUNITY COSTS ARE 15% HIGHER FOR ALL GEAR TYPES

<table>
<thead>
<tr>
<th></th>
<th>CYCLE 1</th>
<th>CYCLE 2</th>
<th>CYCLE 3</th>
<th>CYCLE 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPTIMAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ESCAPE</td>
<td>8,943</td>
<td>8,639</td>
<td>9,773</td>
<td>11,000</td>
</tr>
<tr>
<td>RECRUIT</td>
<td>35,422</td>
<td>23,945</td>
<td>32,021</td>
<td>64,504</td>
</tr>
<tr>
<td>CATCH</td>
<td>23,044</td>
<td>13,079</td>
<td>18,669</td>
<td>44,642</td>
</tr>
<tr>
<td>CZ2G</td>
<td>.5%</td>
<td>11%</td>
<td>9%</td>
<td>21%</td>
</tr>
<tr>
<td>CZ2P</td>
<td>12.5%</td>
<td>4%</td>
<td>9%</td>
<td>18%</td>
</tr>
<tr>
<td>USZ4G</td>
<td>22%</td>
<td>30%</td>
<td>27%</td>
<td>16%</td>
</tr>
<tr>
<td>USZ4P</td>
<td>16%</td>
<td>11%</td>
<td>13%</td>
<td>23%</td>
</tr>
<tr>
<td>USZ5P</td>
<td>12%</td>
<td>9%</td>
<td>10%</td>
<td>11%</td>
</tr>
<tr>
<td>CZ7G</td>
<td>37%</td>
<td>35%</td>
<td>32%</td>
<td>11%</td>
</tr>
<tr>
<td>NET PROFIT</td>
<td>$764</td>
<td>$1,341</td>
<td>$1,865</td>
<td>$7,036</td>
</tr>
<tr>
<td>ACTUAL &quot;</td>
<td>$-661</td>
<td>$-90</td>
<td>$268</td>
<td>$4,823</td>
</tr>
<tr>
<td>GAIN IN &quot;</td>
<td>$1,425</td>
<td>$1,431</td>
<td>$1,597</td>
<td>$2,213</td>
</tr>
</tbody>
</table>

The first point to note is that the actual historical net profit has also been adjusted to reflect a fifteen percent increase in costs for all gear types used to land the average
annual historical cycle year catch. Comparing the gains in net profit with those of the reference case in Table (4-1) it is immediately obvious that the extra degree of freedom given by control over escapement, recruitment and catch in the hypothetical example permits the program to reduce the catch in all four cycle years to compensate for increased harvesting costs. This is why, despite lower net profits, the gains in net profit actually rise for the first three cycle years.

It is interesting to note how insensitive the model is to changes in cost. Once again, the reason would appear to be the high intrinsic growth rates: an increase in costs is somewhat similar to a decrease in the discount rate. Thus catches are reduced and escapements increased, as traditional theory would suggest, but not by a great deal. Finally, as one would expect with relative costs unchanged, there is very little change in the catch proportions when compared with those of the reference case in Table (4-1).

Table (4-5) gives the comparison between actual historical average cycle year profits and the net profits obtained from the optimal policy assuming: opportunity costs (except the discount rate) are lower by 15% for U.S. gear only, sockeye only are harvested, an opportunity cost social discount rate of three and a half percent and the IPSFC unconstrained as to sharing the catch.
TABLE (4-5): UNCONSTRAINED OPTIMAL CATCH OF SOCKEYE ONLY.

OPTIMAL CYCLE YEAR ESCAPEMENT, RECRUITMENT AND CATCH IN 000's OF POUNDS; PROPORTION OF GEAR TYPE AREA CATCHES; AND RESULTING NET PROFIT IN 000's OF 1951 DOLLARS USING A DISCOUNT RATE OF THREE AND A HALF PERCENT AND ASSUMING OPPORTUNITY COSTS ARE LOWERED BY 15% FOR U.S. GEAR ONLY

<table>
<thead>
<tr>
<th>CYCLE 1</th>
<th>CYCLE 2</th>
<th>CYCLE 3</th>
<th>CYCLE 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ESCAPE</strong></td>
<td><strong>RECRUIT</strong></td>
<td><strong>CATCH</strong></td>
<td><strong>ESCAPE</strong></td>
</tr>
<tr>
<td>9,570</td>
<td>35,519</td>
<td>22,515</td>
<td>10,919</td>
</tr>
<tr>
<td>CZ2G</td>
<td>CZ2P</td>
<td>USZ4G</td>
<td>USZ4P</td>
</tr>
<tr>
<td>54%</td>
<td>11%</td>
<td>5%</td>
<td>4%</td>
</tr>
<tr>
<td>20%</td>
<td>5%</td>
<td>3%</td>
<td>8%</td>
</tr>
<tr>
<td>30%</td>
<td>23%</td>
<td>6%</td>
<td>12%</td>
</tr>
<tr>
<td><strong>NET PROFIT</strong></td>
<td><strong>ACTUAL&quot;</strong></td>
<td><strong>GAIN IN &quot;</strong></td>
<td><strong>NET PROFIT</strong></td>
</tr>
<tr>
<td>$2,540</td>
<td>$700</td>
<td>$1,840</td>
<td>$1,893</td>
</tr>
<tr>
<td>$1,984</td>
<td>$744</td>
<td>$1,240</td>
<td>$2,683</td>
</tr>
<tr>
<td>$2,683</td>
<td>$1,584</td>
<td>$1,099</td>
<td>$9,071</td>
</tr>
</tbody>
</table>

Actual historical costs have been adjusted to reflect a fifteen percent reduction in costs for U.S. gear only. Although net profit rises in every cycle year, as one would expect, the gains in net profit fall for all four cycle years when compared with the unconstrained case in Table (4-2). One possible reason is that decreasing costs lead to an increase in catch for all four cycle years with virtually no increase in recruitment.

Earlier discussion has revealed how sensitive the program is to recruitment elasticities and that open water Canadian gear are favored in this regard. What is most interesting is to compare the catch proportions with those in Table (4-2). U.S. catch rises from sixteen to eighteen percent in cycle one, stays the same in cycle two, falls from thirty to twenty-nine
percent in cycle three and rises from twenty-eight to thirty-two percent of the catch in cycle four. As in the previous example where the impact of raising costs was only slight, the high intrinsic population growth rates appear to reduce sensitivity to decreases in cost as well. Reducing costs is roughly comparable to an increase in the discount rate and appears to have very little influence in the face of a high "fishery rate of return".

The perverse result in cycle three could be explained by the sensitivity of the program to the critical interrelationship between escapement, recruitment and catch. That is, if the program were only concerned with the spatial configuration it would probably reallocate more of the catch to U.S. zones, but the optimal intertemporal part of the program calls for a change in escapement, recruitment and catch. This last effect, to which the program is so sensitive in allocating catch, presumably outweighs the cost effect and results in a slightly larger allocation to Canadian gear. This tradeoff may, in fact, account for the absence of any change in cycle two and the rather small changes in cycle years one and four.

V CASE FOUR: HARVESTING OTHER SALMON

The use of the program illustrated by Flowchart (3-2) in place of that in Flowchart (3-1) is all that is needed to change the optimal program illustrated by Flowchart (4-1) into a program to harvest both sockeye and other salmon by simultaneously determining optimal escapement and least cost gear type harvesting proportions to land the subsequent sockeye
catch and the average cycle year catch of other salmon. Once again, the program illustrated in Flowchart (4-1) simply closes the loop between escapement, recruitment and catch through the recruitment function subject to the optimal control constraint.

Table (4-6) gives the comparison between actual historical average cycle year profit and the net profit obtained from the optimal policy assuming: both sockeye and the average cycle year harvest of other salmon are caught, an inflation free opportunity cost social rate of discount of three and a half percent and no constraint on IPSFC allotment of catch proportions.

**Table (4-6): Unconstrained Optimal Catch of Sockeye and Average Historical Cycle Catch of Other Salmon in 000's of Pounds; Gear Type Area Proportions; and Resulting Net Profit in 000's of 1951 Dollars Using a Discount Rate of Three and a Half Percent**

<table>
<thead>
<tr>
<th>CYCLE</th>
<th>Sockeye</th>
<th>All Other</th>
<th>CZ2G</th>
<th>CZ2P</th>
<th>USZ4G</th>
<th>USZ4P</th>
<th>USZ5P</th>
<th>CZ7G</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22,491</td>
<td>42,005</td>
<td>54%</td>
<td>10%</td>
<td>6%</td>
<td>6%</td>
<td>9%</td>
<td>15%</td>
</tr>
<tr>
<td>2</td>
<td>13,471</td>
<td>8,540</td>
<td>34%</td>
<td>3%</td>
<td>24%</td>
<td>11%</td>
<td>6%</td>
<td>22%</td>
</tr>
<tr>
<td>3</td>
<td>19,111</td>
<td>29,532</td>
<td>52%</td>
<td>10%</td>
<td>2%</td>
<td>4%</td>
<td>3%</td>
<td>29%</td>
</tr>
<tr>
<td>4</td>
<td>44,786</td>
<td>10,943</td>
<td>50%</td>
<td>27%</td>
<td>1%</td>
<td>9%</td>
<td>10%</td>
<td>3%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>CYCLE 1</th>
<th>CYCLE 2</th>
<th>CYCLE 3</th>
<th>CYCLE 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NET PROFIT</strong></td>
<td>$9,625</td>
<td>$3,768</td>
<td>$7,771</td>
<td>$12,404</td>
</tr>
<tr>
<td><strong>ACTUAL 'n</strong></td>
<td>$6,688</td>
<td>$2,302</td>
<td>$5,733</td>
<td>$7,844</td>
</tr>
<tr>
<td><strong>GAIN IN 'n</strong></td>
<td>$2,937</td>
<td>$1,466</td>
<td>$2,038</td>
<td>$4,560</td>
</tr>
</tbody>
</table>

Note that actual historical net profit has been adjusted to include the increased revenue from catching other salmon. The allowable catch of other salmon in the hypothetical example is the same size as that for the actual historical case. Comparing the gains in net profit with those in the unconstrained example
in Table (4-2) indicates that the ability to juggle catch of other salmon as well as sockeye escapement, recruitment and catch gives the program enough freedom to raise net profit even more, particularly in the fourth cycle year.

Comparing optimal catch with that in Table (4-2) shows catch increased in the last three cycle years but reduced in the first. What is more remarkable, however, is that catch proportions in cycle year one are hardly altered while those in the remaining cycle years have been dramatically altered. In every cycle year, except two, the open-water gillnets (CZ2G) land fifty percent or more of the sockeye catch. Although the capacity constraint approach to harvesting other salmon does not include a "recruitment of other salmon" variable, it is obvious that the catch of "All Other" salmon together with the sockeye recruitment to which this gear is so sensitive makes the use of this gear type so profitable.

However, comparing these results with those for the static case in Table (3-3) reveals very little change in catch proportions. It is obvious that the impact of the catch of other salmon has an overwhelming influence in terms of profit on the sockeye catch proportions as the latter determine the capacity for catching other salmon. That is, despite the large changes in sockeye catches, the cost differences between gear type areas in terms of catching sockeye are not enough to overcome the need for gear type capacity to land the large catch of other salmon as cheaply as possible.

Table (4-7) gives the same comparison as that in Table (4-6) with the additional constraint that the IPSFC divide the
catch equally between the U.S. and Canada.

**TABLE (4-7):** CONSTRAINED OPTIMAL CATCH OF SOCKEYE AND AVERAGE HISTORICAL CYCLE CATCH OF OTHER SALMON IN 000'S OF POUNDS; GEAR TYPE AREA PROPORTIONS; AND RESULTING NET PROFIT IN 000'S OF 1951 DOLLARS USING A DISCOUNT RATE OF THREE AND A HALF PERCENT

<table>
<thead>
<tr>
<th></th>
<th>CYCLE 1</th>
<th>CYCLE 2</th>
<th>CYCLE 3</th>
<th>CYCLE 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOCKEYE</td>
<td>23,155</td>
<td>13,036</td>
<td>18,948</td>
<td>44,730</td>
</tr>
<tr>
<td>ALL OTHER</td>
<td>42,005</td>
<td>8,540</td>
<td>29,532</td>
<td>10,943</td>
</tr>
<tr>
<td>CZ2G</td>
<td>23%</td>
<td>42%</td>
<td>18%</td>
<td>32%</td>
</tr>
<tr>
<td>CZ2P</td>
<td>14%</td>
<td>2%</td>
<td>12%</td>
<td>16%</td>
</tr>
<tr>
<td>USZ4G</td>
<td>13%</td>
<td>18%</td>
<td>22%</td>
<td>16%</td>
</tr>
<tr>
<td>USZ4P</td>
<td>21%</td>
<td>17%</td>
<td>18%</td>
<td>26%</td>
</tr>
<tr>
<td>USZ5P</td>
<td>16%</td>
<td>14%</td>
<td>10%</td>
<td>8%</td>
</tr>
<tr>
<td>CZ7G</td>
<td>13%</td>
<td>7%</td>
<td>20%</td>
<td>2%</td>
</tr>
<tr>
<td>NET PROFIT</td>
<td>$8,720</td>
<td>$3,843</td>
<td>$6,922</td>
<td>$10,964</td>
</tr>
<tr>
<td>ACTUAL</td>
<td>$6,688</td>
<td>$2,302</td>
<td>$5,733</td>
<td>$7,844</td>
</tr>
<tr>
<td>GAIN IN</td>
<td>$2,032</td>
<td>$1,541</td>
<td>$1,189</td>
<td>$3,120</td>
</tr>
</tbody>
</table>

Comparing these results with those of the reference case in Table (4-1) shows a fall in optimal catch of sockeye in the first three cycle years and an increase in catch for the fourth cycle year. Once again, the allowable catch of "All Other" salmon is the same as the annual average historical catch. Note how the gains in net profit increase for every cycle year except the third. As in the previous example, this can be explained in terms of the extra degree of freedom in the program's juggling of other salmon catch as well as optimal sockeye escapement, recruitment and catch.

Once again, note the dramatic change in catch proportions. Despite the equal catch division constraint, the program favors the use of open-water gillnets to take the Canadian harvest, particularly in cycle two. This heavy use of open-water gillnets in cycle year two is a departure from the usual catch...
proportions in other constrained examples and can be explained by the equally dramatic reduction in catch taken by the U.S. zone four gillnets. The latter's sensitivity to reductions in recruitment resulting from large catches in zone two, appears to be overcome by the profitability of landing both sockeye and other salmon in the previous zone.

When these results are compared with the static ones in Table (3-4), it is immediately obvious that this pattern of favoring the open-water gillnets in cycle year two is important. Note, however, that the catch for U.S. zone four gillnets is still very high in the static example. Apart from cycle year two, the catch is now spread more evenly over most areas as is the case in several previous examples when the optimal case is compared with the static one. The gains in net profit, however, are not strictly comparable with those in Table (3-4) because the static program could not create enough capacity in cycle years one, three and four to take the allowable catch of other salmon. Once again, even with the equal catch division constraint, the program has enough freedom to juggle escapement, recruitment and catch to take the full allowable catch of other salmon in the optimal case.

VI. MAXIMIZING PRESENT WORTH

Assuming the reference case of harvesting sockeye only (Table (4-1)) is the most feasible version of the optimal management policy, it is desirable to compare the net worth derived from this case with the actual historical net worth. The adjustment period involved in reaching the equilibrium values
should also be included to present a fair comparison. It will be assumed that the fastest approach to equilibrium is optimal and, in the present case, it will be assumed that optimal escapement levels will be permitted for the four cycle years from 1947 to 1950. The net profits from these adjustment years plus those from the equilibrium years, 1951 to 1975, will then be compounded forward to 1975. Except for cycle year four, the results in Table (4-1) show that historical management has resulted in overfishing. This will entail sacrifices in the adjustment years in terms of foregone catches in 1947, 1948 and 1949.

**TABLE (4-8): COMPOUNDED NET PROFITS OR LOSSES IN 000's OF 1975 DOLLARS DURING THE PERIOD 1947 TO 1975, ASSUMING ALL MANAGEMENT ADJUSTMENTS CARRIED OUT IN THE FIRST FOUR YEARS OF THE CYCLE AND COMPOUNDING WITH A SOCIAL RATE OF RETURN OF THREE AND A HALF PERCENT**

<table>
<thead>
<tr>
<th></th>
<th>CYCLE 1</th>
<th>CYCLE 2</th>
<th>CYCLE 3</th>
<th>CYCLE 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPSFC</td>
<td>6,143</td>
<td>11,236</td>
<td>26,659</td>
<td>129,229</td>
</tr>
<tr>
<td>OPTIMAL</td>
<td>33,803</td>
<td>36,873</td>
<td>52,328</td>
<td>183,669</td>
</tr>
<tr>
<td>DIFFERENCE</td>
<td>27,660</td>
<td>25,637</td>
<td>25,669</td>
<td>54,440</td>
</tr>
<tr>
<td>TOTAL FOR ALL FOUR CYCLE YEARS</td>
<td>$133,406</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The first line entitled "IPSFC" gives the net profits for each of the cycle years compounded from the period when each occurred until 1975 and summed for each cycle year. The next line gives the results when the same procedure is followed for the management model's net profits. The third line gives the difference, on a cycle year basis, between the previous two totals. The final line gives the total of all these differences for the twenty-nine year period from 1947 to 1975. Note that...
these figures are all in 1975 dollars.

The first conclusion to emerge is that present worth under historical management (IPSFC) implies that fishermen may have been earning substantial economic rent. This is a remarkable feat on the part of the IPSFC given the severe constraints of the convention and the considerable pressure arising from the common property problem. Secondly, if we assume that historical present worth is actually opportunity costs unaccounted for, then the gain in present worth resulting from optimal management (Difference) indicates the potential economic rent which could have been earned in the period 1947 to 1975 if the IPSFC had been given the freedom to manage optimally. And finally, the sum of this hypothetical rent increase over historical management (Total) indicates that there would have been more than enough revenue for the IPSFC to compensate redundant vessel owners forced to retire from uneconomic gear type harvesting areas.

VII SUMMARY AND CONCLUSIONS

This thesis has presented an empirical study of the optimal management of the Fraser River sockeye salmon fishery. Chapter One included a survey of the relevant economics literature to provide the theoretical base for the optimizing model and a discussion of the basic assumptions and the approach used to quantify that model.

Chapter Two discussed the factors involved in fisheries stock management from a biological point of view. A recruitment function was derived based on the Ricker model but re-specified to allow for the influence of the four year cycle on parameter
values. This recruitment model established the essential link between escapement and subsequent recruitment.

Chapter Three presented a re-specified version of the traditional production function. An effort efficiency index was included to remove exogenous changes in gear efficiency. And a biomass catchability index was introduced to permit recruitment availability to be qualified as to the degree of catchability. No external data was available to permit construction of a biomass catchability index and the estimation process itself was permitted to derive values for the catchability parameters allowing for the influence of the four year cycle.

Chapter Three also presented a cost programming model which allocated gear type effort according to least cost harvesting configurations in the gauntlet for each cycle year. The net profits from this model were then compared with those earned historically on an average annual basis between 1951 and 1975. The comparisons indicated that even if the equal catch division constraint were in effect, the gain in net profit from optimal spatial allocation would be well worthwhile.

A final cost model using a capacity constraint approach to landing the historical catches of other salmon as well as sockeye was also included. Although the capacity approach makes the results unreliable, the same pattern appears to emerge in terms of harvesting: certain gear are better or worse than others in different cycle years and optimal spatial management can make a worthwhile contribution to net profits.

Combining the recruitment model in Chapter Two with the harvesting costs model in Chapter Three provides the management
model used in this chapter. It was assumed that the IPSFC would be transformed into a monopoly manager charged with maximizing the present worth of the Fraser River sockeye fishery. Several case studies were presented leading to the following general conclusions. First, optimal management of this fishery could lead to a significant increase in net profit. The increase appears to be large enough to adequately compensate redundant vessel owners in the first few years. Subsequent net profit could either be divided equally between the U.S. and Canadian governments or used to enhance the spawning systems in the Fraser River.

The second conclusion to emerge is that for cycle years where recruitment is low, the program attempts to increase recruitment much more than catch, whereas for the fourth cycle year where recruitment is already large, the program increases catch much more than recruitment. This indicates that the "stock-effect" isolated by Clark and Munro (1975) plays a very important part in increasing profits. The cycle year catchability coefficients establish the sensitivity of the gear type areas to the size of recruitment. And the tradeoff between those unit cost effects resulting from recruitment sensitivity and the revenue effects from larger catches allows the program, in certain year cycles, to increase net profits more by reducing unit effort costs than by increasing revenue through enhanced catches.

These results highlight two points. The first is that economic theory and the empirical work in this study indicate that profits can benefit just as much, if not more in some
cases, from reductions in cost as from increases in revenue as a result of greater catches. The second point is that the specification of the production function is critical in allowing this effect to emerge. That is, as much care must be taken in specifying catchability of the available biomass as has been taken with specifying catching power (efficiency) of gear. Perhaps, however, other economic specifications would lead to even more interesting results.

A third conclusion about the results is that the equal catch division constraint can impose a noticeable cost in certain cycle years. This is true even when other salmon are permitted to be caught in addition to sockeye. This is a deadweight loss as neither party gains from the inefficient allocation of effort resulting from an equal division of catch.

A fourth conclusion is that high intrinsic population growth rates make the model rather insensitive to interest rates. The same insensitivity to changes in costs would imply that price and cost effects are not as important in this model as the underlying biological link between escapement, recruitment and catch and the recruitment elasticities in the harvesting production functions.

The last point emerges even more clearly when other salmon, as well as sockeye, are harvested. The radical shifts in gear type area catch proportions indicate the critical nature of the relationship between catch and recruitment availability and catchability in terms of the sensitivity to recruitment.

A fifth conclusion which emerges from the study is that even if it is not feasible to alter escapement and catch levels
to achieve the optimal values, the results in Chapter Three indicate that there are worthwhile gains to allocating gear in a spatially least cost manner. However, the present worth comparisons between the historical experience and the hypothetical optimal management over the period 1947-1975 indicate the costs of not pursuing an optimal management policy in terms of the economic rent which could be earned.

Comparing the least cost programming results in Chapter Three with the results from hypothetical optimal management in this chapter leads to the final conclusion: the gains contributed by the optimal values for escapement, recruitment and catch outweigh the gains from least cost spatial allocation of harvesting gear. This implies that fishermen are profit conscious and, except for the spatial misallocation arising from the open access nature of the gauntlet, are very close to achieving the right trade-off between catch, recruitment availability and biomass catchability. Of greater importance is the critical role played by the management of the IPSFC, not only in dividing the international catch and preventing catastrophic overfishing but in assigning gear type area catches in a manner very close to the optimal spatial configuration. This was done despite the severe legal constraints of the convention and the considerable pressure arising from the common property problem. As the comparison between historical and optimal catch levels in Table (4-1) appears to indicate, optimal management by the IPSFC could lead to increases in both sustainable catch and recruitment with subsequent gains in net economic profit.
There are many implications which arise from this study of the Fraser River sockeye fishery. Perhaps the most important is that the enlarging of the economic as well as biological base has been shown to aid in transnational bargaining over the fishery. This bargaining is likely to occur quite soon because of the need to re-assess all transnational fisheries in the light of the new two hundred mile economic zone. Furthermore, the recent enhancement program will soon start to take effect with, hopefully, substantially increased catches of sockeye. As Canada, rather than the U.S., has made this investment, it is obvious that some very hard bargaining on catch sharing will soon take place.

With regard to the enhancement program itself, it is interesting to note that its avowed purpose is to double yields but at considerable expense in terms of enhancing spawning and migration routes in the Fraser system; whereas the management model in this study indicates how net profit yields can apparently be more than doubled at virtually no extra expense. We are at a critical juncture in terms of this fishery because there is current over-capacity in terms of effort and yet the promise of substantial increases in future recruitments and catches. If effort is simply allowed to expand as in the past, the potential increase in economic rent will be reduced and dissipated. Instead, it is the hope of this study that the management model presented here can be used to take advantage of this potential increase in economic rent by optimally allocating effort on both a spatial and an intertemporal basis. The increases in economic rent which would result could start paying
back some of the heavy investment expenses of the enhancement program. It would appear that all the parties involved in the Fraser River Sockeye fishery could gain by re-negotiating the terms of the convention, expanding the powers of the IPSFC and allowing the IPSFC to manage the fishery in an optimal manner.
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