WATER QUALITY IN THE LOWER FRASER RIVER BASIN:

A METHOD TO ESTIMATE THE EFFECT OF POLLUTION ON THE SIZE OF A SALMON RUN

by

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

The Department of Civil Engineering

We accept this thesis as conforming to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

June, 1976

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Date June 10, 1976

ABSTRACT

Water quality studies conducted in the recent past in the Lower Fraser River Basin indicated that locally some high pollution levels exist. With further urbanization and industrialization of the Vancouver region an increase in waste loadings and a degradation of water quality can be expected if no strict pollution control is applied. Of particular concern are biologically undegradable substances such as heavy metals and polychlorinated hydrocarbons. They accumulate in the sediments of the river and the estuary and become concentrated in organisms of the food chain.

Pollution is a gradually occurring process. Anticipation of potential problems is important for the decision maker responsible for water quality management. The Fraser River supports one of the largest salmon runs of the world and is abundant with other commercially and recreationally valuable fish. Salmon are very sensitive to pollution and could disappear from the Fraser river system as they already have from many other major rivers if pollution levels become too high. The Fraser River estuary has the function of a bottleneck. Adult salmon enter the river to migrate upstream to their spawning grounds, and juvenile salmon stay in the estuary for a while to acclimatize themselves to the saline environment.

In this thesis a method is presented to simulate the effects of potential pollution on the size of a salmon stock. A model which uses data from various life stages of a particular sockeye salmon run in the Fraser system is developed. Uncertainties due to environmental fluctuations are accounted for. Using this model the effects of an increase in mortality rate in two stages of the sockeye salmon life cycle on adult

return numbers are studied. The analysis showed that at a certain mortality rate chances are that the stock might not be able to recover.

In light of a planned salmon enhancement program to increase salmon stocks in various Pacific rivers, the fact that decreasing water quality could counteract all enhancement efforts should be a warning signal to the decision makers.

The development of a water quality index to predict future conditions is recommended and a possible procedure to relate water quality parameters to an increase in mortality rate is sketched out.

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ACKNOWLEDGMENTS

This thesis has been prepared in partial fulfillment of the requirements for the degree of a Master of Applied Science. In this study use was made of available information from experts in different scientific fields. They devoted much of their valuable time providing information and criticism. Thanks are owed to Dr. Jeff Thompson from the Pacific Environment Institute, West Vancouver; Otto Langer from the Fisheries and Marine Service, Environment Canada; Dr. M. Takahashi, presently with the CEPEX research group in Saanich Inlet, Vancouver Island; Dr. Carl Walters from the Institute of Animal Resource Ecology at the University of British Columbia; Dr. Ken Hall, Anthony Dorcey, and Fred Koch from the Westwater Research Centre at U.B.C., and many others. A great debt is owed to Dr. Jim Woodey from the International Pacific Salmon Fisheries Commission, New Westminster who provided some of the information used for the model and donated much of his time in discussing the results and making helpful suggestions. Finally, I owe a great debt of gratitude to Professor S.O. Russel for guiding me and having time whenever I needed advice or encouragement. Special acknowledgment is made to Mr. Richard Brun of the Department of Civil Engineering who did the drafting of all the figures presented in this thesis.

CHAPTER I

INTRODUCTION

"The Greater Vancouver Region reached a population of 1,140,000 people in 1974. It is currently growing at a rate slightly under 3% a year. Even at a lower rate of growth the population will reach nearly 1,500,000 by 1986, and approach 2,000,000 by the year 2000." This statement, made in the Liveable Region Plan (63) illustrates the rapid growth of urbanization in an area which is also considered as one of the most productive ecological systems on the North American continent: The Fraser River Estuary.

There has not been only a rapid rise in population, but also demand of more products which leads to increased production and increased waste generation by bothr producer and consumer. This concentration of people and industries in a localized area burdens the environment with very high waste loadings. Therefore, environmental management has to be a key factor in keeping the natural environment of Vancouver in the state that has been enjoyed by its residents for many years and made Vancouver a major tourist centre on the west coast. Environmental deterioration could also be economically damaging if it stifles development of some major service industries or research institutions (64).

Unfortunately, estuaries have often been regarded by modern man as useless because of their swampy lands. Therefore, he dyked them, landfilled them, and often developed industrial parks in these areas. This has happened in many estuaries all over the world. The facts, however, show that estuaries and the nearshore coastal lands are the biologically most productive areas of the marine ecosystem. There are great natural variations in the flora and fauna of these areas. Resident organisms can tolerate and compensate for the variable conditions that result from the tidal movements. For this reason the capacity of estuaries to accept pollutants which enhance natural variations is relatively great. However, there are limits to this environmental acceptance. We have to consider these in each case of development if we want to maintain the high natural productivity of the estuary.

There have been warnings from various sides regarding the impact of proposed development in the estuary on fish and wildlife (16, Int. Pac. Salmon Fish. Comm. Annual Report 1974). Each development reduces the area covered by mudflats and tidal marshland. The value of these marshlands is often underestimated. Many species of fish are dependent on the estuary for some part of their lives. Shell fish such as oyster, crab, and shrimp, depend on the coastal estuaries as well. Furthermore, the mudflats and the tidal marshland serve as a resting place for many shorebirds, waterfowl, and other wildlife. Thus, in function, this habitat cannot be replaced easily by some other land.

Westwater, an interdisciplinary research group at the University of British Columbia has conducted a study during the past three years to define the pollution problem in the Lower Fraser River, to bring it to the attention of the public, and to develop a policy to manage this important water system. In their conclusions they found that there are "clouds on the horizon". There is great uncertainty about some potentially harmful substances which have been encountered in the water, the bottom sediments, or the tissue of fish. Often the sources of these pollutants are not known; one can only estimate very crudely the quantities that are presently discharged to the river; only partial knowledge of their pathways through the aquatic system exists. Studies to determine their accumulation rates in the food chain have just been started (14,30).

There is great need for research into the processes and pathways of pollutants within the Fraser River system and for the study of the effects that certain pollutants can have on biological communities in relation to concentration and time of exposure. Most of the studies that have been undertaken involved sampling programs. There exists a lack of historical data for most water quality parameters. Almost nothing was known about the chemical composition of the bottom sediments, the concentration of trace elements in the tissue of some organisms, and the variety and number of species that inhabit the river system. Historical data are very important in order to decide whether measured concentrations reflect mainly natural background levels or man-made pollution. Water quality is usually described by physical and chemical parameters. The measured values are then related to the effects that they may have on man or aquatic organisms. At present we are mainly concerned to evaluate the existing water quality conditions.

As the region of Greater Vancouver grows in population and with it the economic activities increase, we have to expect higher waste loadings. We have to decide upon policies and abatement technologies to cope with the water pollution problem now if we want to prevent any deterioration of the water quality within the next 10 or 20 years. Preventive planning is better than passive adaptation. If we start correcting undesirable water quality conditions at a time when everybody can smell or see or quantify the pollution problem, costs will be much higher than if we stretch an abatement program over a number of years, or begin time consuming research now.

We have to decide now:

- whether to go for more dredging in the mouth of the river and thus destroy the marshland;
- whether to build more dykes which create areas of stagnating water in which several water quality parameters such as temperature, salinity, pH, ion concentration may change to an extent that this water can no longer support aquatic life;
- whether to treat stormwater runoff that carries street contaminants and washed-out pollutants from the air;
- whether to collect and treat leachate from landfills as they often contain very high concentrations of substances that are toxic to aquatic organisms;
- whether to reduce increasing concentrations of fertilizers and pesticides in agricultural runoff before it reaches the river.

All these problems are facing the decision makers who are involved in management and development of the Lower Fraser River basin.

One way to anticipate potential pollution and to estimate its effects is described in this thesis. As background Chapter II illustrates present water quality conditions and discusses the various users of Fraser River water. For this thesis salmon were chosen as an example to illustrate how future pollution could curtail biological productivity of the estuary. Salmon require water of high quality, free of harmful pollutants throughout the watershed. This valuable and most sensitive species of fish has disappeared from many European and North American rivers due to high pollution levels. Chapter III describes how information about a major salmon run in the Fraser River system can be brought into a form that allows description of uncertainty in terms of probabilities. This information is used as input data in a model which calculates expected return values of adult salmon. In Chapter IV the mathematical details of this model are presented. Chapter V gives a review of research on the effects that various pollutants have on salmon. In Chapter VI some of the studies on acute toxicity and sublethal effects conducted in the Lower Fraser River and the coastal waters are reviewed. It also presents the results of computer simulations that have been done to estimate future salmon return figures when the stock is subjected to various assumed mortality rates. This increase in mortality may result as the salmon has to pass through increasingly polluted waters of the Fraser estuary as this area continues to be developed in the future. In Chapter VII the construction of a water quality index for salmon as a major water user is proposed. Such a water quality index could be used to project the effects of future development in the river basin rather than forecasting loadings of each single pollutant. Possible relationships between such a water quality index and an increase in mortality rate are suggested. Chapter VIII contains a discussion and summarizes the conclusions.

CHAPTER II

THE LOWER FRASER RIVER AND ITS WATER USERS

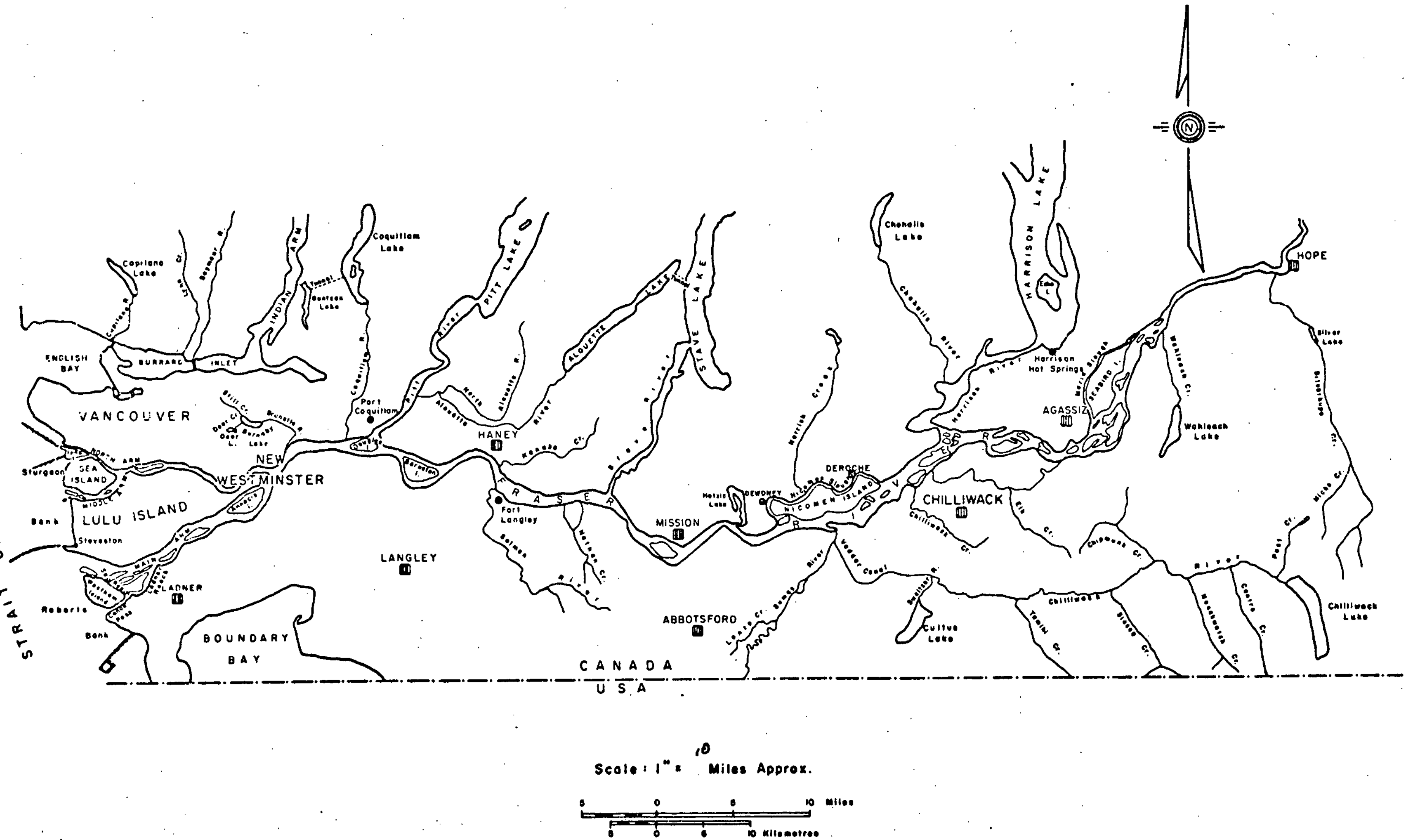
A. Description of the Lower Fraser River

The Lower Fraser system extends about 85 miles from Hope to the Strait of Georgia. It comprises several tributaries, small backwaters, side channels, sloughs, and marshes. Figure 1 gives an overview of the system. At New Westminster, the Fraser branches into the Main Arm (approximately 90% of the flow) and the North Arm (approximately 10% of the flow). The North Arm bifurcates at Sea Island thus creating another arm which is referred to as the Middle Arm.

Flow in the Fraser River and its larger, mountain tributaries is characterized by a winter minimum and a late spring maximum associated with runoff from snow melt. The mean discharge at Hope has been recorded as 94,600 cfs with extremes of 536,000 cfs and 12,000 cfs (6). Present uses and functions of the estuary are determined to a large extent by the New Westminster-Vancouver metropolitan area. The Greater Vancouver Region accommodates about 50% of the population of British Columbia. Doubling of its population is predicted for the turn of the century (63). Most of the new growth will take place to the south and east of Vancouver. This will place a heavy emphasis on the river with regard to residential, commercial, and industrial development. It can be expected that the Lower Fraser will attract more industries in the future because of its access to the open sea. More goods will be processed along the waterfront, and harbour facilities will be expanded as Canada's foreign trade increasingly shifts to the West

FIGURE 1

LOWER FRASER RIVER



(48). All this development will have implications for water quality. As there are many and sometimes conflicting water uses it is important that the impact of every new development on water quality be assessed. For doing so a sound basis of data reflecting water quality of the natural stream or at least with only minor changes is required. In the past 20 years several studies have been undertaken to establish this data basis.

B. Water Quality - Change of the pollution pattern? A review of recent water quality investigations.

Until the establishment of the Pollution Control Board (PCB) and the Greater Vancouver Sewerage and Drainage District (GVS & DD) in 1956, physical, chemical, and bacteriological data were collected by the Provincial Health Branch. A report published by the Pollution Control Board in 1967 concluded that the main stem of the Lower Fraser was found to be a "clean stream" in terms of BOD content; however, existing bacteriological levels were undesirably high (19).

Between 1963 and 1966 the International Pacific Salmon Fisheries Commission (IPSFC) conducted a survey of water quality and bottom organisms (54). The purpose of this study was mainly to provide background information on water quality before some pulp mills began operations on the Upper Fraser and Thompson rivers. This study was not a comprehensive survey of all types of possible pollutants. Samples taken were analysed for their content of organics (measured as BOD and COD), dissolved oxygen, and several other parameters that are related to pulp mill wastes. The composition of the population of bottom-dwelling organisms, including macroinvertabrates and bacterial slimes was also determined. This study was followed by a more comprehensive one during which samples were taken in the spring of

1966, 1967, and 1968 at some lake outlets, which serve as nursery areas for young salmon, and at Mission on the Fraser River. These samples were analysed for various substances considered as potentially toxic to salmonoids. The parameters included heavy metals, cyanides, surfactants, and chlorinated hydrocarbons (pesticides and herbicides). No harmful concentrations were detected. BOD was low with 90% of the samples showing a concentration of less than 2 ppm and 3.1 ppm the highest value. It was found that organic load, turbidity and solids were greater during the spring freshet than during the rest of the year which indicates that the sources are mainly natural. Higher levels of pollution were encountered in the North Arm of the river thus showing the effects of industrial development in this reach. This study emphasized that shifts of the biological community can reveal more than chemical water analyses. Changes in pollution are indicated by changes in composition of the biological community as some of the organisms are more sensitive to polluted conditions than others.

A monitoring program by the Fisheries Service, Department of the Environment, conducted during the summer-fall season over a three year period from 1969-1971 was primarily concerned with BOD and DO levels in the Roberts Bank, Sturgeon Bank, Iona Beach, English Bay, and False Creek areas. DO levels were generally greater than 90% saturation. Only at some stations in the North Arm were lower levels (77%-90% saturation) periodically detected (6).

Another report done by B.C. Research on water quality in the lower reaches below Port Mann Bridge during the fall of 1971 is contained in the Provincial Power Study of 1972 (4). This survey also included sediment sampling, and profile sampling at selected stations over a tidal cycle. In general, the dissolved oxygen levels were found to be near saturation, except for bottom samples and samples from isolated channels where some low dissolved oxygen levels were obtained. This can be expected as sloughs and backwaters are more sensitive to raised pollution levels. These shallow water bodies warm up more rapidly, the process of biodegradation is accelerated and therefore more oxygen is consumed. Pollutants are often not flushed out of the system because there is hardly any water movement. In this study some biologically significant concentrations of copper, zinc, and lead in some samples were reported; however, most analyses showed concentrations lower than those considered detrimental to fish life.

As part of its Lower Fraser River study Westwater Research Centre conducted two major water sampling programs. In a preliminary survey (6) during the months of July and August, 1972, when flows were high, samples were taken at 22 stations on the Fraser between Hope and the mouth of the river, and at 24 tributary stations. This study revealed that five tributaries, Chilliwack Creek, Salmon River, Sumas River, Brunette River, and Nicomen Slough, showed a lower water quality than the Lower Fraser River itself. Consequently, later studies were conducted on these small tributary basins. It also showed that potentially toxic materials such as heavy metals, PCB's (polychlorinated biphenyls), or DDT and its degradation products are more likely to appear in the sediment and tissue of aquatic organisms than in the water itself, because of their relative insolubility.

The second water quality study (22) was based on these findings. During February through May, 1973, when flows were low, samples were taken weekly from 9 stations in the Lower Fraser and 15 stations in selected tributaries. An additional 70 samples were taken to be analysed for pesticides. The results of these two programs showed that water quality was remarkably good in the Fraser River. Dissolved oxygen levels in the Main

Arm were close to saturation and slightly lower in the North Arm. Present BOD loadings and projected waste discharges are not expected to affect these high dissolved oxygen levels drastically. This result was observed from a study where a mathematical model was used to simulate dispersion and degradation of organic wastes (27). However, some depressed oxygen levels were encountered in several of the small tributaries where flows are not sufficient to dilute the wastes discharged to the river. A major water quality problem appears to exist in the high levels of indicator microorganisms in the Fraser and some tributaries. It was found that the bacteriological quality of the water gradually deteriorated from Hope to the Strait of Georgia. These high numbers of indicator microorganisms appear mainly to result from discharge of untreated domestic sewage. After completion of the Annacis Island treatment plant the bacteriological situation is expected to improve. Concentrations of some heavy metals were occasionally high but none reached levels that are considered acutely toxic to fish.

Since in this study only grab samples were taken once a week, these results have to be interpreted with some caution. As metal discharges by some industries are usually sporadic in nature a potentially short-term toxic situation, close to the outfall, might arise. Also, in periods of low flow, a body of water in the lower reaches of the river may move up and down the river through several tidal cycles before reaching the sea, giving rise to the accumulation of pollutants. Metal concentrations in a highly sediment-loaded river are usually not very high as the metals become adsorbed to the particulate material and sink to the river bottom. Sediment samples are therefore much more indicative of trace metal contamination.

However, it is difficult to decide which fraction of metal is attributable to leaching of mineral deposits in the mountain ranges and soils in the alluvial plain of the Fraser Valley and which fraction is attributable to urban-industrial sources. Most of the higher metal concentrations in the water and the sediment were encountered in the Brunette River Basin which drains an urban-industrial area (23,24). Particularly copper and lead showed fairly high and strongly fluctuating concentration levels. Also zinc concentrations were often above natural background level. Mercury concentrations in the water found between the Port Mann Bridge and the Strait of Georgia were higher than in the tributary system and can therefore not be explained as background levels. The analyses for pesticides in the water were all less than detection limits except for one sample.

As pesticides are very insoluble in water and become adsorbed to particulate material very rapidly, it was decided to take sediment samples. Between February and August, 1974 samples from the Brunette, Salmon, and Sumas rivers were analysed for pesticide residues by the Water Quality Branch of Environment Canada. The most contaminated river basin was the Brunette basin. Samples from its river sediments contained DDT, its degradation products, and polychlorinated biphenyls (PCB's), the last ones being the most prominent contaminants in this urban industrial drainage basin (23). To determine the impact of land use upon sediment quality, street surface materials were collected from four different land use areas and analyzed. The same chlorinated hydrocarbons were found in street surface samples as occurred in stream sediments.

Trace metal concentrations found in the sediments were particularly high near sewage outfalls. A major discharger in this regard is the Iona Sewage Treatment plant. A study done by B.C. Research in 1973 (5) reported that concentration levels of some metals exceeded quite significantly background levels measured some distance from the contaminated mudflats. There was a 1-6-fold increase over background for cobalt, nickel, and iron, and a 21-fold increase for lead. Chromium, copper, and zinc also showed higher levels. These concentrations should be of some concern as the possibility exists that these substances accumulate in crabs, shellfish, fish, and waterfowl, thus contaminating food for human consumption. A survey of the benthic animal community of the Fraser River mudflats during the summer of 1972 revealed that concentrations of mercury, silver, and copper in some animals from Sturgeon Bank were higher than samples from the adjacent Roberts Bank (47).

Analyses of the muscle tissue of 348 specimens representing 14 species of resident and migratory fish of the Fraser River showed concentrations of mercury, copper, zinc, iron, and manganese in virtually all fish (44). As fish move around, it is hardly possible to trace the accumulated trace metals back to their sources. Of most concern were the high levels of mercury found in two resident fish species, Squawfish and Prickly Sculpin, with concentrations ranging above the accepted level in Canadian food. These two fish species are not themselves food fish for man. The source of this contamination was not obvious. Trace metal concentration levels in salmon, a migratory fish, were very low.

In comparison to other rivers in North America and Europe the Lower Fraser River appears to be clean with regard to most toxic materials, but there is a potential for increases as is indicated by the results from some tributary rivers which drain the metropolitan area of Vancouver. In the main channel no problems should be met in the future as far as dissolved oxygen, BOD, or nutrient concentrations are concerned. However, we can expect localized situations of oxygen depletion, nutrient enrichment, high bacterial levels, trace metals, and chlorinated hydrocarbons in some tributaries, backwaters, and sloughs.

C. The Fraser River and its Water Users

In an area like the Lower Fraser River basin a multitude of activities place demands on the water resource. It is important to recognize the impact that each of them has on water quality in order to prevent or minimize conflicts between the different users.

The Lower Fraser has historically been an important waterway for the transport of log booms from the upriver areas to the sawmills located on the estuary. Also, the estuary has always served as a log storage area, a use which can sometimes conflict with certain recreational demands such as boating and sportsfishing. The river is used by log rafts, barges, and deep sea vessels and provides docking facilities along its banks. The shallow-draft North Arm will likely continue to serve as a waterway for the various fish processing and woodproduct industries which are located along its waterfront. The harbour in the main stem of the Fraser River is presently Western Canada's second most important deep sea port. It has become the focus of considerable industrial interest because there are still extensive areas of land vacant along the waterfront. At present dock facilities for a new container terminal are under construction. In order to reduce the amount of dredging necessary to keep the channel at a depth of 33 ft, plans are being considered to construct training walls to contract the crossection and thus increase the velocity which would make the river self-scouring. Unfortunately this measure would cut off many fish species from the rearing and feeding areas in the backwaters and sloughs of the estuary.

Of the 133 miles of harbour waterfrontage, presently 76% are used for agriculture or are undeveloped, 11% are industrial and port, 6% is recreational, 4% is residential, and 3% is for transport (48). The Official Regional Plan which was adopted in 1966 by the Lower Mainland Regional Planning Board, its member municipalites and the Provincial Government, calls for a development as indicated in Figure 2. Land use determines to a great degree waste composition and water quality. Municipal zoning therefore has to be considered as a very important planning tool with regard to water quality.

Possible projects which could disrupt the ecology of the marshlands and mudflats include a new ferry terminal, expansion of the bulk terminal at Roberts Bank and a second parallel runway at Vancouver International Airport on Sea Island (16). New dykes would have to be constructed and large areas would be filled, thus further reducing valuable habitat land for fish and wildlife.

A river is often regarded as a servant for industrial purposes. Besides a transportation means for barges and deep sea vessels it has to carry away millions of gallons of waste water every day. The Fraser River receives waste water from domestic and industrial sources as well as storm water and agricultural runoff. Because of alarmingly high bacteriological counts in the water around the beaches of metropolitan Vancouver, it was decided to stop the dumping of raw sewage to the sea and to the river. In 1963 the Iona Island Sewage Treatment Plant (STP) started its operation, followed in 1973 by Lulu Island STP and Annacis Island STP in 1975. These three plants receive most of their waste water from residential, commercial, and institutional sources, and provide primary treatment (sedimentation)

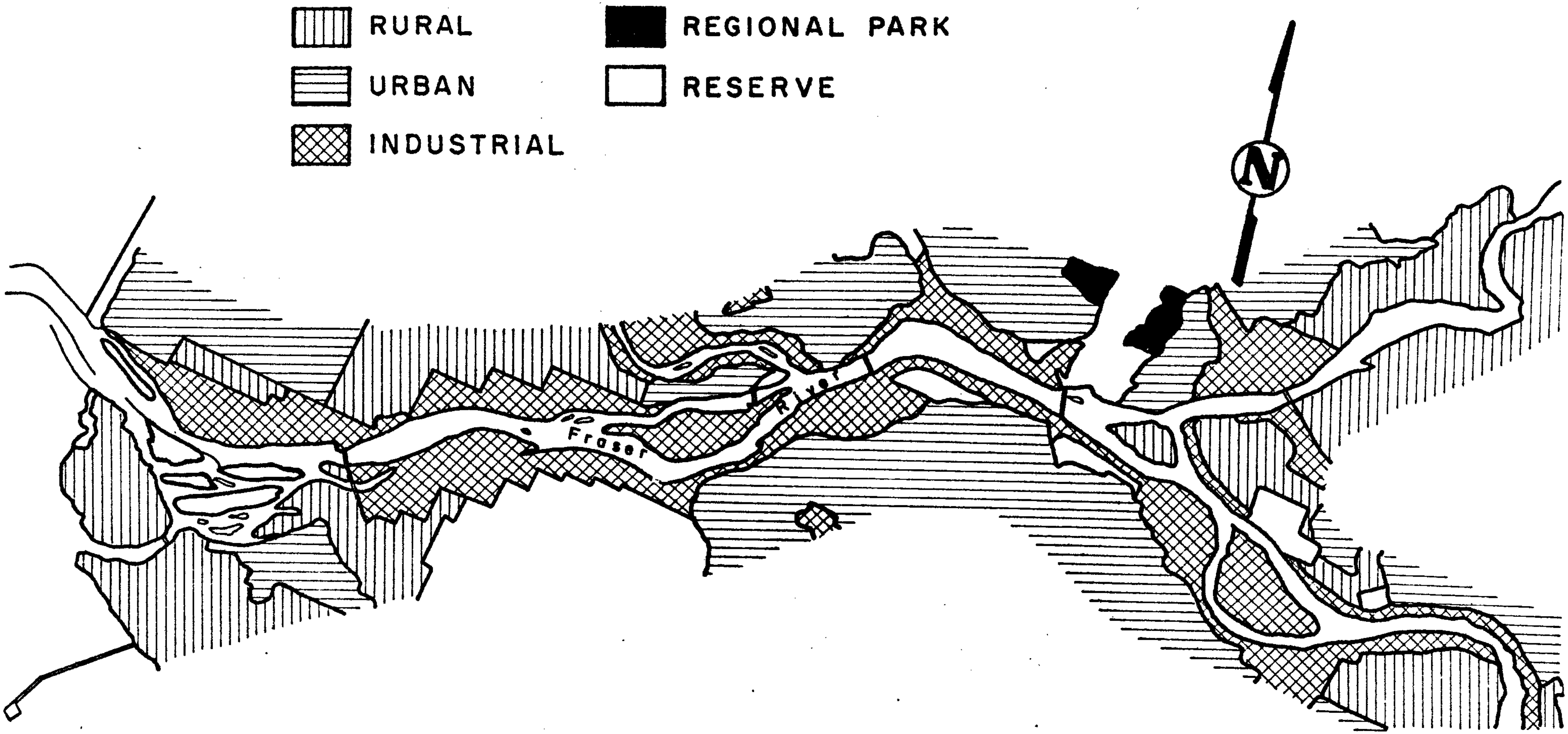


FIG. 2 OFFICIAL REGIONAL PLAN.

and chlorination for the waste water prior to discharging it to the river. This can create a problem as certain chlorinated organic compounds, toxic to fish, are formed (e.g. chloramines). Dechlorination is therefore applied at Lulu Island and being considered for the Annacis Island and the Iona plants. However, dechlorination might not be effective in breaking down some compounds such as the group of chlorinated phenyls (31). Primary treatment reduces mainly suspended solids, but does not remove toxic materials such as heavy metals, PCB's, and other chlorinated hydrocarbons very effectively. Additional treatment processes will have to be considered as the waste volume of these toxic substances increases. At present 83 million gal/day of industrial effluent are directly discharged to the river. Most of it is cooling water. However, one study done at two paint manufacturing companies revealed that effluent standards, set by most municipalities in their by-laws, are not very strictly enforced (9). Control is often only applied to remove the suspended solids, the visible fraction of pollutants. At present estimates of the quantities of pollutants that are discharged by industry are not available. Industrial wastes vary in their composition. It is known that a number of industries generate small amounts of toxic and flammable wastes, some of which are disposed of through sewers and outfalls (18).

A problem of great concern is the control of storm water runoff. Many storm sewers discharge directly to the river. Where sewer systems are combined urban runoff receives primary treatment. However, during rain storms, when flows are high, most of the incoming waste water is diverted to the river and receives no treatment at all. Westwater's studies indicated that there are considerable quantities of some trace metals in storm water, particularly during the first flushing after a long period of no rainfall (30). A first step to control some of these pollutants would be the construction of holding tanks where this first runoff could be stored and gradually be released later to the treatment plant.

Detailed monitoring programs will be required to calculate mass balances for critical groups of pollutants.

Thermal discharges, particularly to tributaries where low flows prevail, should be kept to a minimum as this might raise the temperature levels which can not be tolerated by salmonoid fish. At present only few industries take water for the purpose of cooling directly from the river. The Water Rights Branch has issued about 20 permits totalling to about 61 million gals/day (68). Because of its high silt loadings, Fraser River water has to be passed first through settling ponds in order to prevent abrasion and sedimentation problems in the piping system of the industry.

Water from the Fraser and its tributaries is not used for public water supply anywhere in the Lower Fraser Valley. Sufficient water of better quality from other sources is available to all municipalities.

For agricultural purposes water is mainly taken from the tributaries, sloughs, or groundwater wells. Only two cases are registered with the Water Rights Branch where water is taken from the Fraser River for irrigation. In some river basins a conflict of interest exists between agriculture and fisheries. For example, the bed of the lower Chilliwack River (Vedder Canal) has been improved to allow for higher flood flows. During the last flood event in 1975, farmers in the upper reaches got very upset when water levels receded only slowly because of the low flow capacity of the natural river bed. They would like to see the whole river canalized, something that would destroy most of the spawning areas of various fish species. Draining of the marshes, dyking and pumping installations have already reduced habitat of fish and waterfowl.

Damming of some smaller rivers to store water for irrigational purposes often submerges spawning grounds. Also, these stagnating waters warm up more rapidly and sometimes show signs of eutrophication due to nutrient input from agricultural sources. These areas are lost for spawning salmonoid species which need clear cool waters and unpolluted gravel beds.

Future needs might force people to grow more food in the Fraser Valley. To increase productivity more fertilizers will be applied, as well as insecticides to protect the crop. This will increase waste loadings of agricultural runoff. Presently vegetables and dairy farming predominate in the valley. There are some hog and poultry farms. Animal wastes from these farms are usually very concentrated and have to be treated. Otherwise a serious pollution problem in a small tributary river might arise.

Bad logging practices in the valley often cause a silt or debris problem. Siltation of the spawning grounds is considered to be one of the major threats to salmon in the future (36). Debris in the Lower Fraser is a serious problem. The damage done to boats and fishnets has been estimated as high as $500,000 per year (15).

The recreational aspect of the Fraser River is not very strong at present. Boating is perhaps the major recreational activity, besides bar-fishing, pleasure driving, horse riding, and picnicking on some dykes. People enjoy seeing such a mighty river. It can be expected that water quality will be valued more highly in the future as incomes rise and people also have more leisure time to spend. At present there are not too many access roads to the waterfront, and the shoreline is predominantly industrialized. As other recreation resources are used to capacity, more attention will have to be given developing parks and beaches along the river.

The estuary is famous for its duck hunting and for viewing many kinds of birds. There are at least 88 different species of birds whose common habitat is the river or its adjacent waters and whose major food source originates in the estuary (43). Still others use it as a flyway or migration corridor. The Lower Fraser River is known to support the largest wintering population of waterfowl in Canada.

Thirty-eight species of fish inhabit the Lower Fraser River. They are migratory, semi-migratory or resident. The Fraser and its estuary also support many other aquatic organisms which serve as food to the organisms higher up in the food chain. The crab fishery in the Fraser estuary gave fishermen an income of $281,000 in 1973 and represented 20.5% of the total B.C. catch (16). There is commercial, recreational, and Indian food fishing. By far the most important fish are the five species of salmon, resident in the Pacific region: sockeye, pink, chum, coho, and chinook salmon. They are especially prized by British Columbians, and people even often overestimate their importance in relation to other major sectors of B.C.'s economy (49).

D. The Salmon Resource

The Fraser River has the second largest salmon run in the world (only the Yukon River supports a bigger run). There is a continuous upstream migration of adult fish all year around. Pink salmon returns have averaged nearly six million fish in every odd numbered year since 1957. Virtually no fish enter the river to spawn in even numbered years (43). Next in numerical importance come the sockeye salmon with between one and ten million adult fish (depending on the cycle year) and an average of 45 million juveniles. Some half million chum adults move up the river and about 27 million smolts move downstream. The Fraser River chinook salmon support important commercial, recreational, and Indian food fisheries both near or in the river as well as along the coast. The average commercial catch has been estimated at some 480,000 fish. Coho salmon is also highly valued by commercial and sports fishermen. A minimum catch of 500,000 fish is estimated to originate from the Fraser River spawning grounds.

Altogether, the salmon represents an annual commercial catch value of $73 million (1973 prices), a recreational value of about $186 million, and a preservation value of $101 million, according to a household survey by Environment Canada, Fisheries and Marine Service (41). The commercial fishery has put high capital investments in its fishing fleet and processing plants. The expenditures by commercial and sports fishermen to maintain their boats and fishing gear support an important service industry.

It is planned to increase the current annual salmon production through an enhancement program which would involve the construction of artificial spawning channels, hatcheries, incubation boxes, and various stream improvement measures. Probable investments would total $250 to $300 million to be spent over the next 15-20 years for programs in various salmon rivers of the Pacific coast (46). Before the disastrous rock slide in 1913 which made the passage at Hell's Gate in the Fraser Canyon impossible for upstream migrating sockeye salmon, the sockeye run in the Fraser River had yielded a record catch of over 30 million fish. One run, the previous dominant 01 cycle, fell to a very low level in succeeding years and has never recovered since. Construction of fishways at various points in the Fraser Canyon by the International Pacific Salmon Fisheries Commission together with a finely tuned management program has helped to gradually increase the total stock of most cycle years again. It is hoped that through further enhancement programs the Fraser River may see the old record runs someday again.

However, enhancement without preservation of present water quality, which is already quite low in some tributaries and areas of the estuary, will most likely be a failure. Salmon are very sensitive fish and cannot adapt to higher river temperatures or increasing pollutant loadings. Pollution may also threaten its food organisms. Even if we keep the upstream spawning grounds of the salmon in perfectly good condition, the salmon runs might still decrease as water quality in the Lower Fraser and the estuary deteriorates. The transition from fresh to saline water is a very critical stage in a salmon's life involving considerable physiological adjustment. If further stresses in the form of increasing pollution levels are applied there, effects on the fish may be detrimental with regard to his survival chances in the ocean.

A decrease in water quality will show its effects on a fish population. As fish are a major user of the Fraser River water and have particular requirements with regard to water quality, it was decided to illustrate the effects of pollution on salmon. A particular sockeye salmon run of the Fraser system was chosen since most of the numerical knowledge that we have of the sockeye salmon's life cycle is related to this run.

CHAPTER III

LIFE CYCLE OF THE SOCKEYE SALMON

A. Introduction

The curves described in this chapter were based on information which was obtained from the International Pacific Salmon Fisheries Commission. These curves should not be interpreted as the results of a strict statistical analysis with analytically derived confidence limits, but rather as a general indication of values observed in the Chilko River system. More emphasis was placed on demonstrating a method to process such information than on numerical exactitude.

The Chilko River sockeye stock is the second largest in the Fraser River system. In two years out of each four about 25 to 65% of the catch of sockeye salmon from the entire Fraser River system originates from the Chilko River (71). The Chilko River stock is the most thoroughly studied run in the Fraser system. Since 1949 the International Pacific Salmon Fisheries Commission (IPSFC), established in 1937 by treaty between Canada and the United States, has conducted detailed survival measurements. The numbers of spawners, deposited eggs, emerged fry, smolts, and returning adults are estimated each year. The adults mature primarily as 4-year-old fish, causing a 4 year cyclic abundance pattern to dominate, but within cycles abundance varies substantially. Mortality rates in the different life stages may vary significantly (17,33,34,52,69). Sheehan (55) gives a summary and discusses the uncertainty factors in each life stage for Skeena River sockeye. It is possible to develop functional relationships to describe these life stages using observed data. The range of uncertainty can be indicated by upper and lower boundary lines. Figure 5 to Figure 9 show such relationships for the Chilko River sockeye. The curves are used as input in a probabilistic model which is described in Chapter IV. The graphs presented in this paper were developed with the help from the IPSFC. The life cycle of the Chilko sockeye salmon and relationships between the numbers entering and leaving each stage are described below.

B. The Chilko River Sockeye

Chilko Lake lies between the Pacific and the Chilcotin ranges of the Coast Mountains (Figure 3). Adult sockeye migrate over 380 miles from the mouth of the Fraser to the spawning grounds located at the outlet of Chilko Lake (Figure 4) to deposit their eggs in the gravel of the river bottom. The peak spawning of this run occurs in late September. In the following spring fry hatch from the eggs, emerge and later migrate upstream into the lake. Smolt migration takes place in April or May after one or two years of lake residence. The sockeye remain in the sea from 1½ to 3½ years before maturing and returning to their natal stream. Passing through the coastal waters they are harvested by Canadian and United States fishermen with gill nets, purse seines, or by trolling. When migrating up the river native Indians catch a portion of the escapement for food.

As in most other races of Fraser sockeye, a large (or "dominant") run returns every fourth year. The Chilko stock has two smaller ("off-year") runs and a medium sized run ("subdominant") between dominant years. When developing the curves the ranges of the three run sizes were pieced together to allow a continuous analysis. The five life stages were chosen with the intention of including pollution effects later in the model. From a biological point of view, the first relationship relating the number of

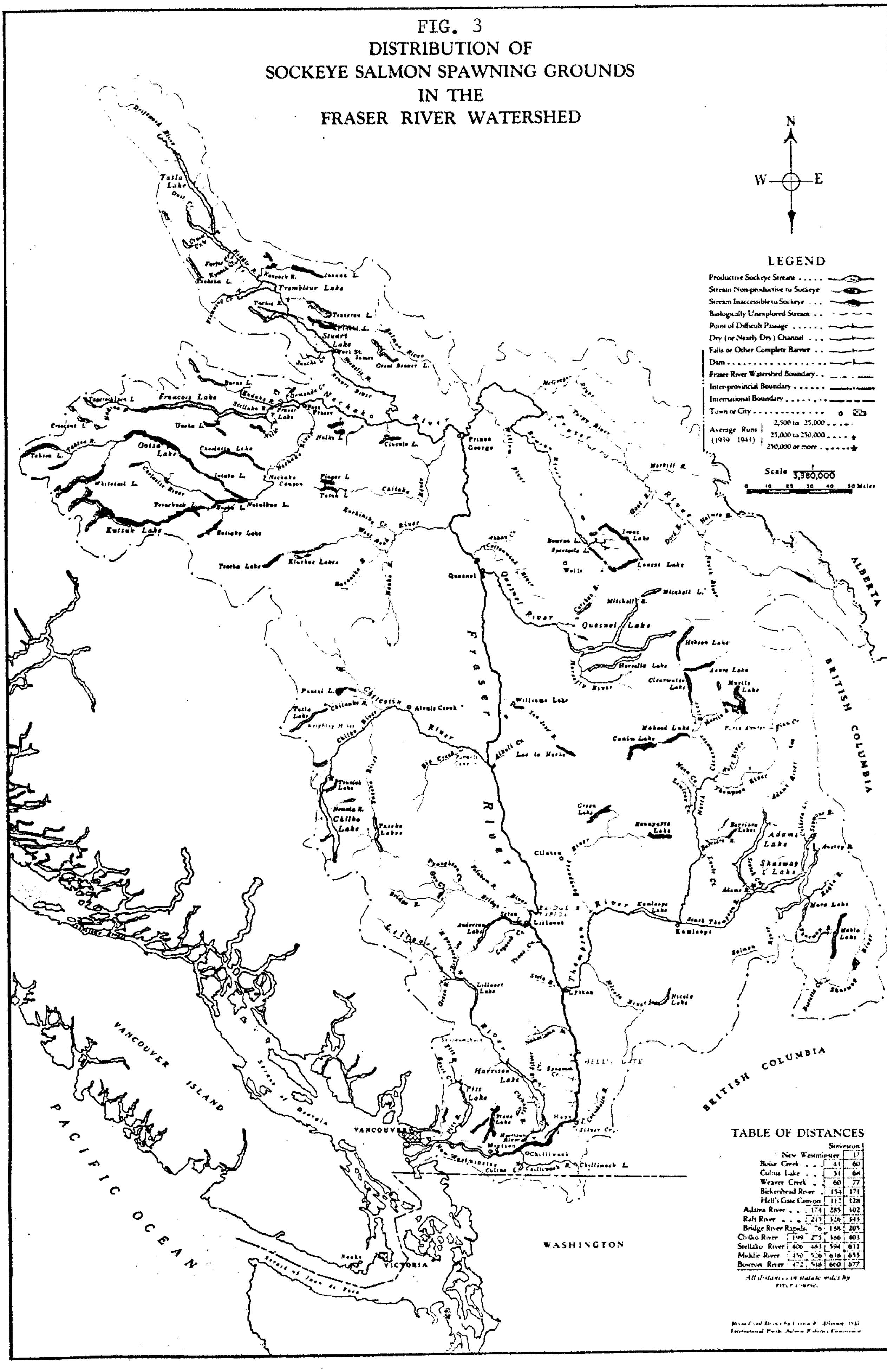


TABLE OF DISTANCES

				Steveston
New Westminster				17
Boise Creek			41	60
Cultus Lake			51	68
Weaver Creek			60	77
Birkenhead River			154	171
Hell's Gate Canyon			112	128
Adams River		174	285	302
Raft River		215	326	343
Bridge River Rapids		76	188	205
Chilko River	199	275	386	403
Stellako River	406	483	594	611
Middle River	450	526	638	655
Bowron River	472	548	660	677

All distances in statute miles by river course.

FIG. 3
DISTRIBUTION OF
SOCKEYE SALMON SPAWNING GROUNDS
IN THE
FRASER RIVER WATERSHED

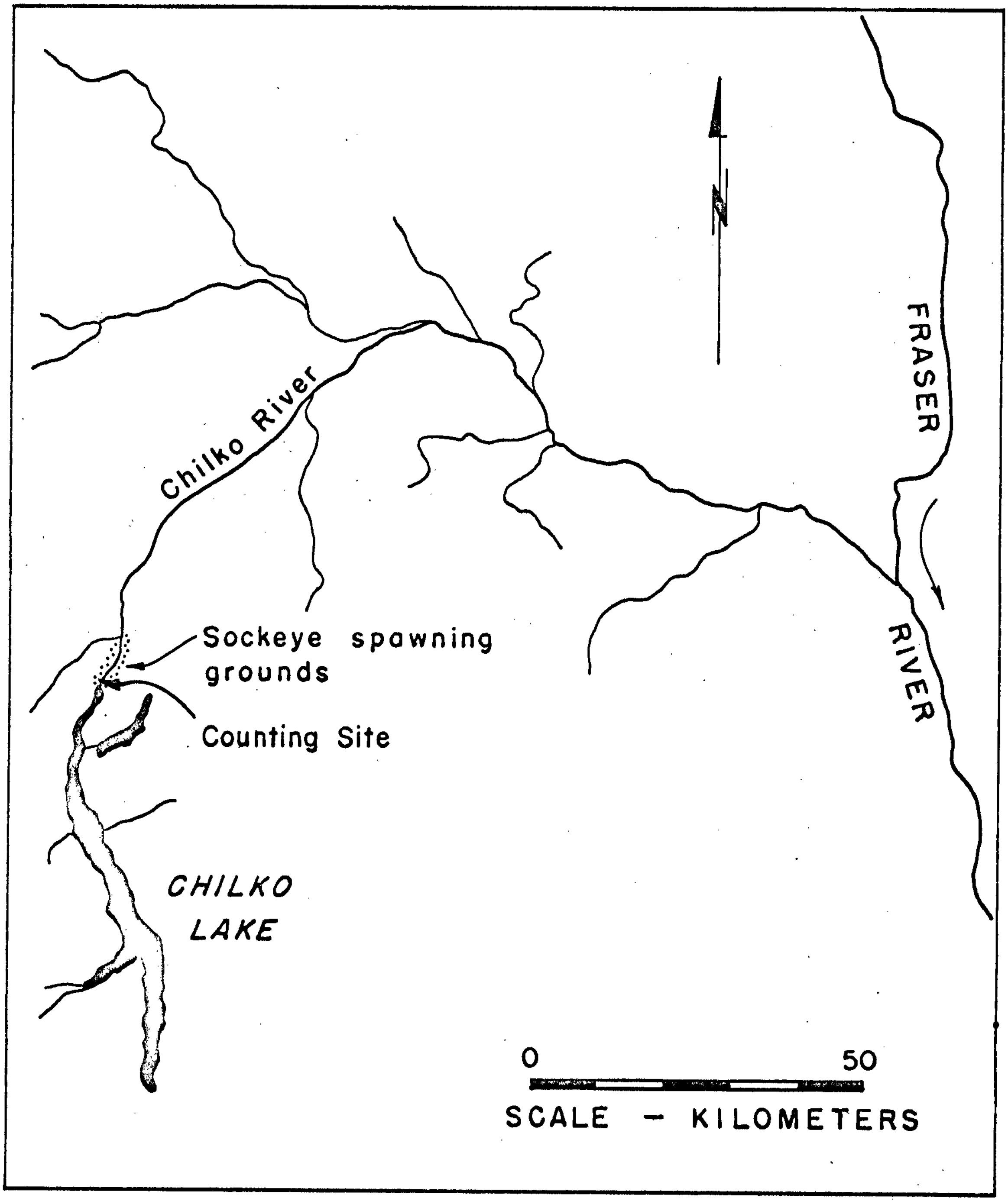


FIGURE 4. - Chilko Lake, Chilko River, and spawning grounds of sockeye salmon.

female spawners to the escapement might not be considered as a life stage. However, as the survival of future salmon generations depends on the safe passage of adult salmon through increasingly polluted waters of the Lower Fraser River, this "life stage" was incorporated into the model.

B.1. Relationship Between Escapement and Female Spawners

In convention waters catch and escapement is regulated by the IPSFC. At the beginning of the fishing season a return figure is projected for each stock based on the number of smolts migrating to the sea, the number of jacks (mature 3-year-old males) that returned the year before, and other data. A target escapement is established. The actual escapement is managed on a day to day basis. The escapement figures are estimated by means of test fishing, and more recently by echo sounding in the Lower Fraser River. The spawning population is enumerated using the Peterson mark recapture method. After they have spawned the salmon die. Between 20% and 40% of the carcasses are recovered and the tags are counted. The proportion of female spawners and their success in spawning is determined. Counting the tags the total population number can be estimated using the relationship

$$N = \frac{nT}{t}$$

where N = total population

n = number of recovered fish

T = number of initial tags

t = number of recovered tags

The probability band in Figure 5 accounts for uncertainty factors such as variability in sex ratio, Indian catch, and the mortality en route to spawning grounds. The portion of females out of the total escapement can vary between 49% and 60% (29,71) with an average of 53% to 57% (20). Gill

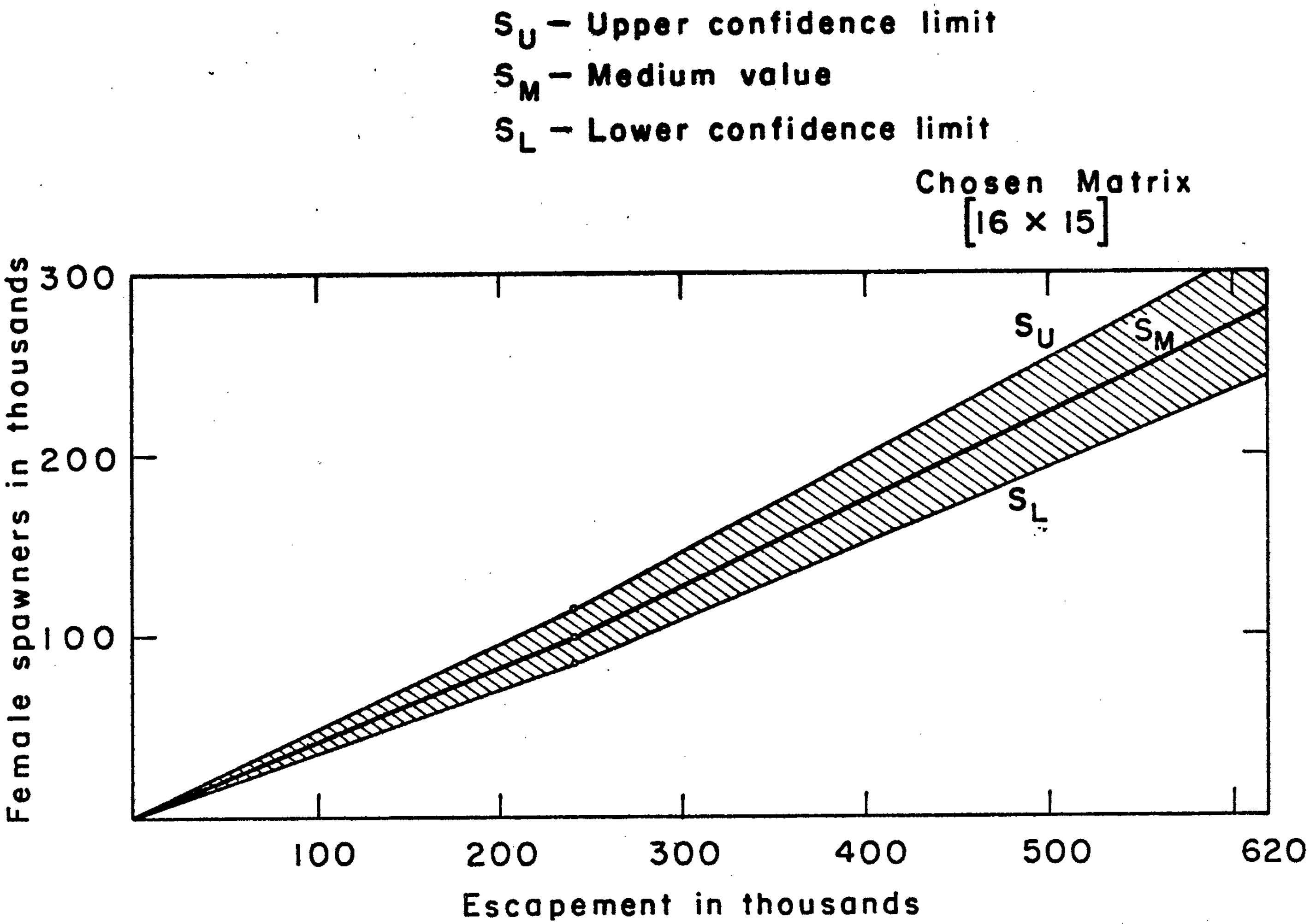


FIG. 5 RELATIONSHIP BETWEEN ESCAPEMENT AT THE MOUTH OF THE RIVER AND FEMALE SPAWNERS REACHING SPAWNING GROUNDS.

netting, for example, is sex selective, as males are more prone to this form of capture. The Indian removal can vary between 15% and 25% depending on the size of the run. The curves in Figure 5 were constructed using the published escapement data (29) and the extreme values for the sex ratio and the Indian harvest rate. A change in slope for about 240,000 fish was made, as the proportion caught by Indians was less at higher escapements. Environmental effects on this life stage can be caused by small landslides which temporarily obstruct the migration route.

B.2. Relationship Between Female Spawners and Deposited Eggs

Fecundity is a function of female length. A regression analysis relating to fecundity and body length is done for a sample of 50 females each year. Spawning success is expressed in terms of "effective" female spawners. This is based on the eggs retained in the carcasses of the recovered dead females. However, not all females successfully spawn due to several possible reasons. Water temperature and bacterial infection may play an important role in the pre-spawning mortality problem. Other factors could become important such as exposure to polluted waters during the upstream migration. Variation in success of spawning and fecundity is not large as indicated by the relatively narrow probability band in Figure 6. Spawning escapements at Chilko River (effective females) have ranged from 10,000 to 328,000 and averaged 109,000 during the past 25 years (20).

B.3. Relationship Between the Number of Deposited Eggs and the Number of Fry

It is necessary to discriminate between the calculated egg deposition from the actual deposition. As female spawners which arrive later will

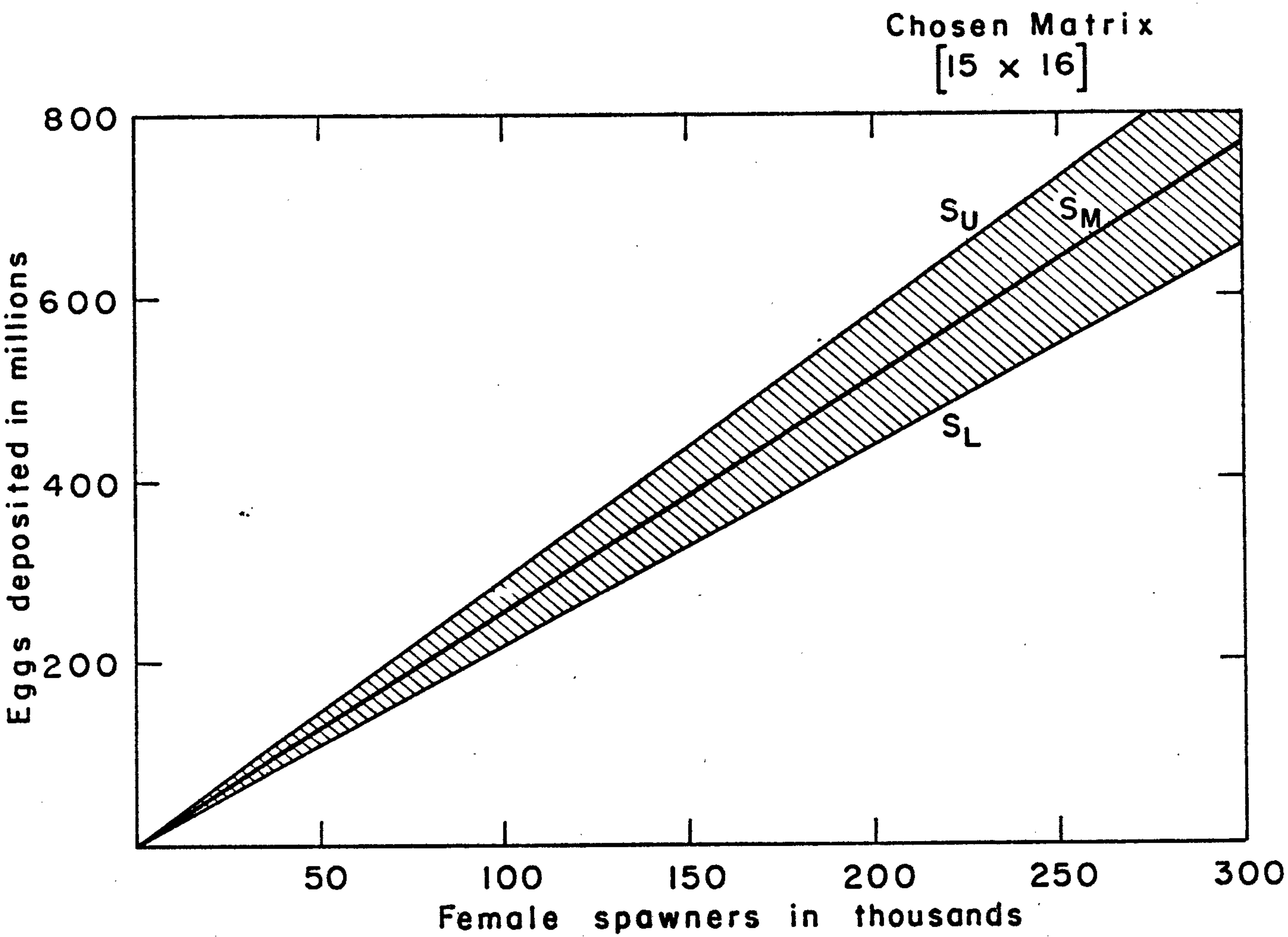


FIG. 6 FEMALE SPAWNERS VS. EGGS DEPOSITED.

often dig out eggs deposited by earlier spawning females, the number of actual eggs in the gravel at completion of spawning will be lower than estimated. In the case of overcrowding this effect can be very substantial and has a compensatory mortality effect. High escapement numbers therefore can cause damage to the process of egg deposition on the limited area of the spawning ground. There is a carrying capacity for each spawning ground.

Environmental factors such as water flow, water temperature, sediment load of the stream, concentrations of NH_4, NO_2, NO_3, CO_2, and oxygen, as well as ice formation all affect the number of fry that will hatch from the eggs. As Chilko Lake is oligotrophic water quality presently is not a problem. In the winter or cold nights radiational cooling of bottom rocks may result in the formation of anchor ice. Anchor ice prevents the exchange between stream water and intergravel flow. The eggs may not obtain enough oxygen and therefore die. Low flow conditions can result in the freezing or dessication of eggs deposited on the higher stretches of the gravel banks.

In the past 25 years the survival rate for the eggs-to-fry stage has varied between 4% and 14% (69). The probability band is indicated in Figure 7.

B.4. Relationship Between the Number of Fry and the Number of Smolt

After emerging from the stream gravel the Chilko sockeye fry are carried downstream to a quiet water area where they remain for a short period of time. Fry then migrate upstream along the shores in low velocities into the lake. The number of fry was determined for a number of years using a photographic technique. The camera was installed above the water

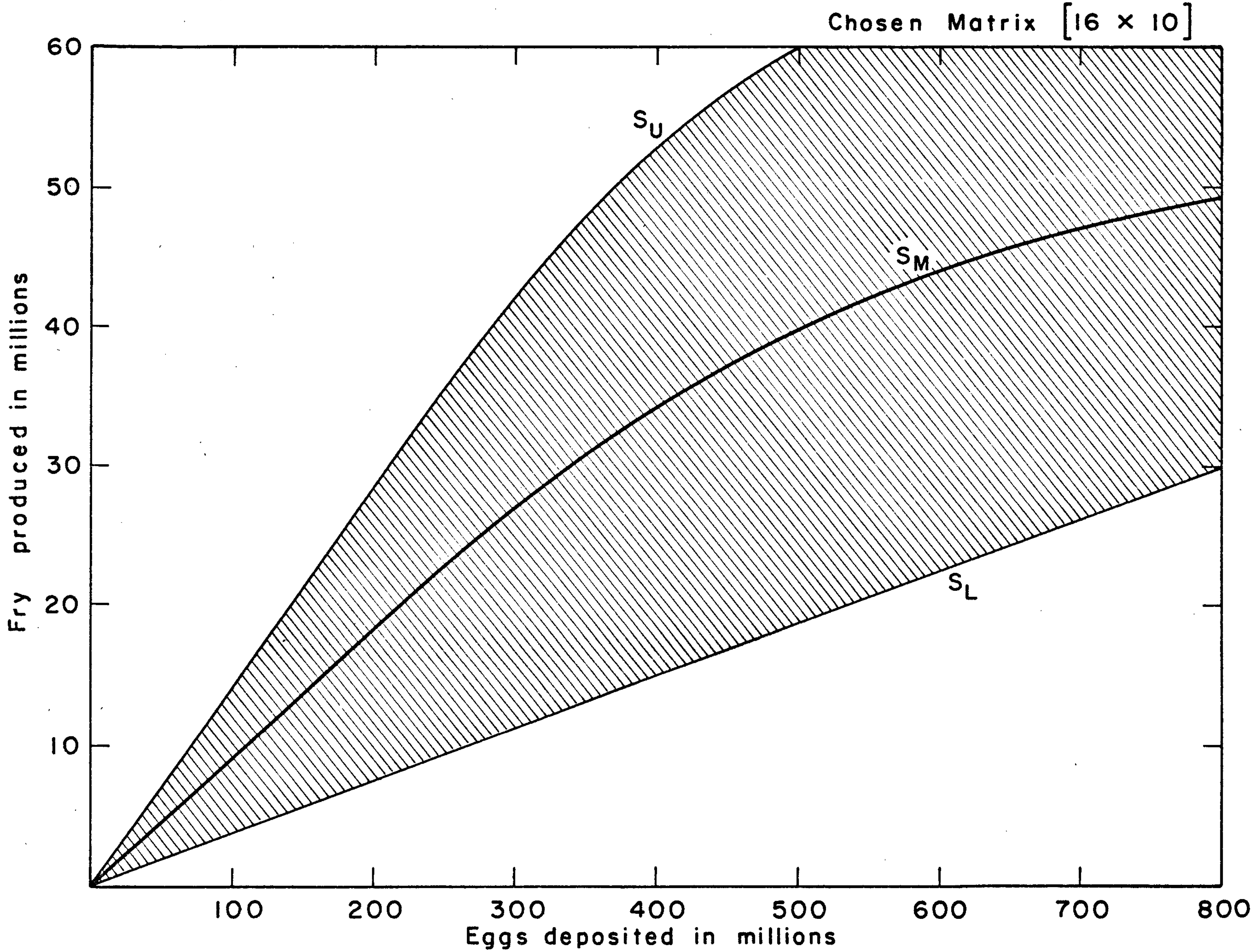


FIG. 7 EGGS DEPOSITED VS. FRY PRODUCED.

surface and a white board in the river bed was used as a contrast medium. More recently an index count has been used. Visual estimates are made at regular intervals. These counts are then related to past estimates and extrapolated to a total fry estimate.

Once sockeye fry have entered the rearing lake, two main factors appear to govern the survival rate: food supply and predators. Food supply may be most important when the fry enter the lake. If they enter the lake very early in the year there might not be sufficient food available to them as the productivity of the lake increases with increasing temperature and solar radiation. Goodlad et al. (20) hypothesized that variation in the length of the growing period and in initial rearing temperature have greater influences on growth than other factors. The fry first feed on emerging insects and later on crustacean zooplankton. In the oligotrophic Chilko Lake there is a comparatively low standing crop of zooplankton as has been measured for several years. With regard to predation, the size of the predator compared to its prey is most important. Apparently, Chilko Lake has a very low population of predators which feed on the sockeye fry. As a consequence the survival rate in this life stage is very high and has ranged from about 32% to 73% as indicated in the probability band of Figure 8.

B.5. Relationship Between the Number of Smolts and the Number of Returning Adults

After one year of lake residence, most of the young sockeye begin their journey to the ocean. The number of migrants is enumerated photographically. The sockeye smolts apparently move fairly quickly out to the open sea after reaching the river mouth. The survival rate in the ocean

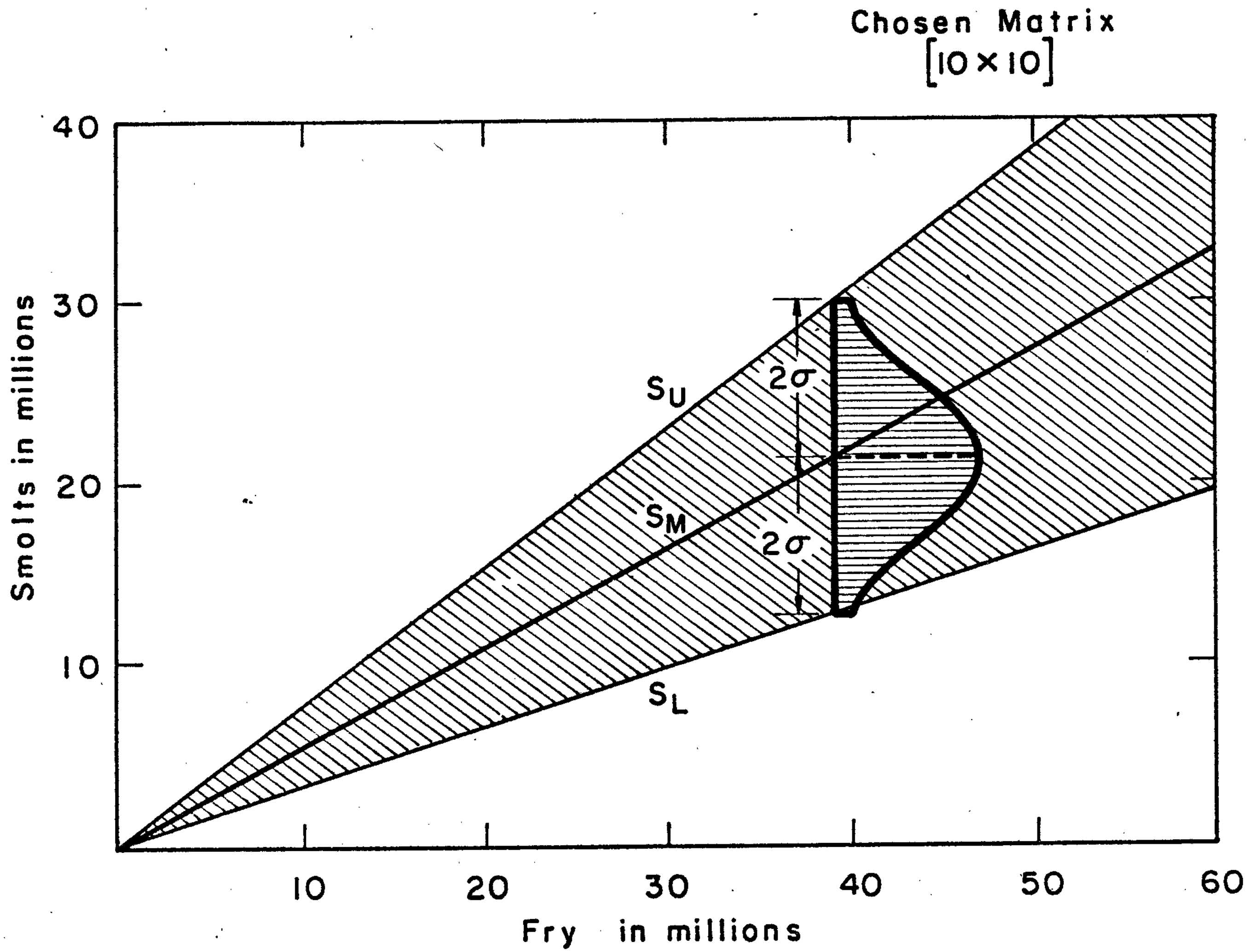


FIG.8 FRY VS. SMOLTS.

appears to depend on some environmental factors prevailing in the river during migration time. Correlation analysis by Williams (69) indicates a relationship between river discharge during smolt migration and subsequent marine survival. Water quality could become of critical importance if the pollution level continues to increase in the estuary. There already exists a higher pollution threat in the North Arm reaches. It is believed that the numbers of migrating smolts are presently divided between the arms in proportion to their respective flows (43).

The survival chances of the young smolt against its predators in the ocean depend very much on the size of the sockeye smolt compared to the size of the predator. Growth rate thus becomes a significant effect in mortality rate. Therefore, it is quite important how far the feeding grounds are away from the mouth of the river. Parsons (62) found in simulation studies of phytoplankton growth in the Strait of Georgia that pollution of the coastal waters (e.g. in the form of coal dust from a new coal terminal) could change the light absorption and thus reduce the growth of the phytoplankton in an area which can be reached by the young salmonoids fairly quickly (phytoplanktonic organisms are the first step in a food chain which supports salmon).

The factors which might have an influence on the survival of the salmon in the ocean are not well understood. It is not surprising that the probability band is very wide (Figure 9) showing a survival rate that can vary between 1% and 22%.

As the genetics of the Chilko Lake stock have apparently not changed significantly over the past 25 years, all the collected data are of equal importance. In the following chapter a method is outlined for using this information in a model that incorporates the effects of uncertainty. With

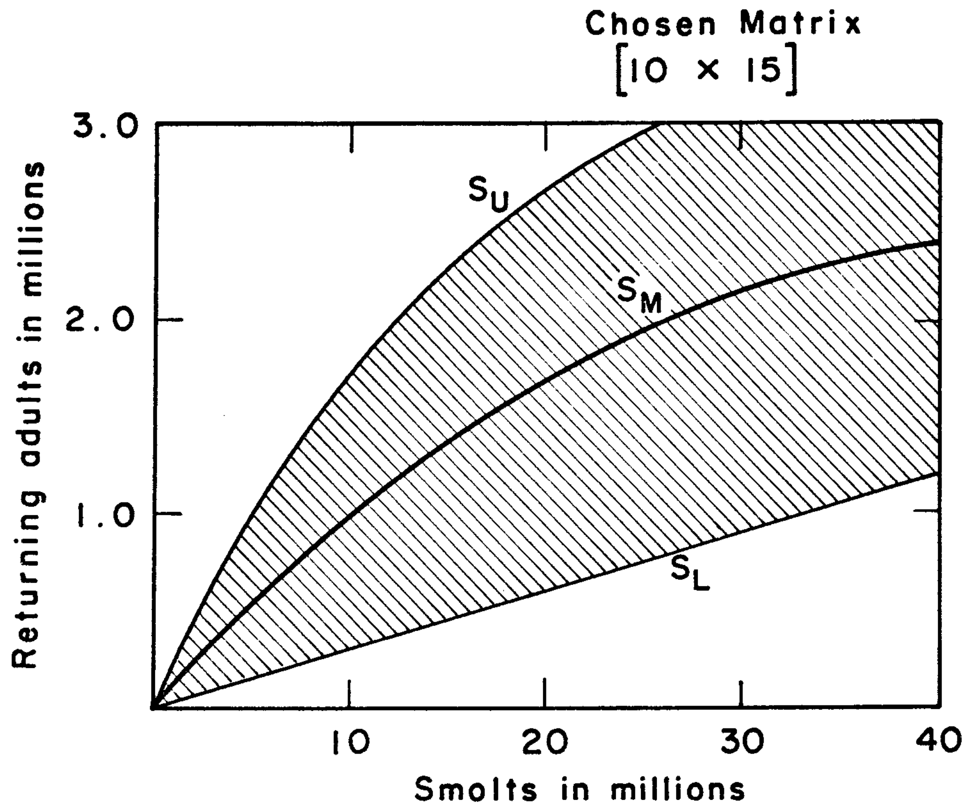


FIG. 9 SMOLTS MIGRATING TO THE OCEAN VS. RETURNING ADULT SALMON.

this model changes in the stock/recruitment relationship can be estimated given that the conditions for survival in the above life stages change. Thus, possible consequences of enhancement techniques can be evaluated as well as potentially detrimental effects due to decreasing water quality.

CHAPTER IV

A MODEL USING DATA RECORDS WHERE AVAILABLE AND JUDGMENT OF EXPERTS

A. Introduction

Many efforts have been made in the past to model the salmon life cycle (32,33,34,35,52,67). The existing models can be viewed as deterministic with stochastic components to account for random processes such as environmental variability. Larkin (32) described his model as one which produces a spectrum of answers - because of the fluctuation of the random factors - and thus it is "virtually untestable using historical data." He also pointed out that in most cases we would tend to argue that a model which reproduces an observed pattern is good, whereas if the pattern appears only infrequently, "one is left to decide whether the model is 'poor' or whether the particular sequence of environmental effects that occurred naturally was indeed a quite unusual sequence that pushed the system in an unlikely direction" (35).

Introduction of more building blocks and further equations to describe interactions does not seem to increase the predictive capacity of a model. Random factors seem to govern the process chain and therefore we can expect a spectrum of answers of varying probabilities. An escape from this dilemma is rather obvious and has been proposed by Larkin himself (35).

". . . avoid the theoretical assumptions, accept the past as evidence of the association between stock and recruitment and proceed on the basis that the same will happen in the future. This correlative kind of approach makes no pretence at understanding nor prediction beyond the available range of observation. It has the merit of simplicity and with modern computing facilities, presents no difficulties of empirical analysis."

Most of the existing data are on stock and recruitment. (In the following these will be termed escapement and returning adults.) A smooth curve can be fitted through the data points and an empirical probability distribution of recruitment for each conceivable spawning stock can be calculated. Walters (67) argued that this probability distribution should be approximated by a lognormal distribution function as environmental effects are multiplicative in nature and can be considered to be more or less independent of one another. (The lognormal distribution function is discussed more explicitly in Appendix 1.) Also, Ricker (52) had pointed out that the distribution function should be skewed in shape. He used various theoretical reproduction curves for the mean curves and superimposed randomly-occurring environmental variability by using a random selection of multipliers whose frequencies were normally distributed. This procedure results in an asymmetrical distribution of the progeny numbers. Existing data on stock/recruitment curves have been analysed fairly well for the Skeena River sockeye salmon (56,57,67), and a lognormal distribution seems to describe the observed fluctuations appropriately.

For the purpose of this thesis the author has attempted to go one step further and study the effects of changing environmental conditions on each life stage of the salmon cycle. This procedure is promising for a number of applications such as in the study of enhancement techniques which improve the survival rates at any one stage of the salmon life cycle, or as in the present study, in the simulation of the overall effects of pollution if poor water quality conditions affect one life stage in particular.

In Chapter III the functional relationships for each life stage for the Chilko River salmon run were presented in the form of graphs. It has been pointed out that the data base is still quite small (estimates have only been made since 1949) and certain difficulties exist in deriving the mean, upper, and lower curves.

For the following discussion it is assumed that these graphs represent the best information presently available for the Chilko River stock. They describe our present understanding of each life stage and the uncertainties associated with each of them are indicated by the width of the band between the upper and lower confidence lines.

The next step is to integrate the five life stages into a single stock/recruitment curve. (We shall refer to this later as an expected return given a certain escapement.) Then one can change the survival rate in each life stage thus simulating enhancement or pollution effects and study the relative changes in returning adult numbers. By better control techniques we might also be able to narrow the uncertainty band in some life stage. This would result in a reduced uncertainty of the final outcome. We now want to formalize this procedure in mathematical terms.

B. Uncertainty and Expected Return

Uncertainty is often described by weighing possible values with the likelihood of their occurrence. The same can be done in predicting a salmon return. Even if we were able to formulate all interactions as concisely as possible we would still have to account for random processes such as predation or changing environmental conditions. All predicted (or expected) values should therefore have probabilities associated with them. The expected value E(X) of a discrete random variable X is defined as:

$$E(X) = \sum_i X_i \, p_x \, (X_i) \qquad \text{(A)}$$

where X_i are possible values for the variable x and p_X are their respective likelihoods.

If we specify return classes we would like to know the probability of returning salmon being in a certain class given a fixed escapement value. A simple example will illustrate this:

Given an escapement of 420,000 adult salmon, how many adults will return in four years time? We cannot ask for an exact number but rather are interested to know the probabilities that 1.0 to 1.2, 1.2 to 1.4, 1.4 to 1.6 million salmon, etc., will return. For the x_i we take the median value of each return class. Our model will calculate the probabilities of their occurrence.

How do we include the probabilistic nature of the problem in our model? As an example let us take the graph which illustrates the relationship between the number of fry hatched from the eggs and the number of smolts leaving the lake after feeding for about a year (Figure 8). The biologist has done a regression analysis on his observed data and has given us a linear function describing this salmon life stage. In addition to fitting a curve to his mean values, he has indicated the range of possible values which can be either observed extreme data points or best estimates at that time.

It is common in applications of probability theory to speak of the "one-, two-, and three sigma bounds" of a random variable, thus considering the boundaries which cover 65%, 95%, or 99.7% of all observed values.

After some experimentation with the model it was decided to use two standard deviations thereby assuming that 95% of all possible events lie between the given confidence limits. Hershman (25) and Sheehan (55) had used in their modeling three standard deviations and a skew normal distribution function. It was felt for this study that imperfect knowledge of the numerical values in each life stage would not warrant such precision.

The next step is to find a probability distribution function which best describes the data observed between the confidence lines. In the case where we have enough data it can be analysed and fitted to a common type of distribution function such as a normal, lognormal, or Gamma distribution. This distribution function then can be used for all future analyses.

C. Choice of a Distribution Function

It is often very convenient to use a particular distribution because it is well known, well tabulated, and easily worked with. In many situations we are inclined to try a normal distribution first because of the ease in working with it. Especially in the case where we have little or no data, a normal distribution is often adopted as a "not unreasonable" first model.

For the Chilko Lake stock only slim data have been collected so far. To mathematically derive any distribution function from these would have been premature. Also, the accuracy of the data points could not be guaranteed. With the echo sounding technique replacing the photographic enumeration procedure more data will become available within the next years from a number of lake systems. A frequency analysis of the data from these life stages could then be done and a probability distribution could be derived.

As this paper is mainly concerned to demonstrate a methodology where new information can easily be incorporated, the simple case of a normal distribution was chosen. However, we have to be aware that this choice will influence our results to a certain extent. We should therefore not compare simulated results with observed data in a too critical way.

The simulated numbers have only illustrative value and can only reflect reality if the input into the model were to be improved.

In a later stage of this work it was felt that a lognormal distribution would have probably described the variability in a better way. A discussion of the two distribution functions has therefore been added to the Appendix.

When a normal model is adopted, it should be noted that its validity may break down outside the region about its mean. Tails of the distribution are much more sensitive to errors in the model formulation than the central region.

D. Development of the Probability Matrices

The information contained in graphical form (Figures 5 to 9) has to be transformed into discrete numbers in order to be in a useable form for the computer program. Looking at Figure 5 it was decided to choose 16 classes for the escapement and 15 classes for the resulting female spawners. We therefore have to determine the probability distributions at the 20,000 (40,000) 620,000 lines. (This abbreviated writing means starting from the 20,000 line we go in interval steps of 40,000 until an escapement value of 620,000). On the female spawner axis we have 15 classes with an interval length of 20,000 spawners. To determine the probability that a normal random variable lies in any interval, the integral of $p_X(X)$ over the interval is required. Interval length is 20,000 spawners. To demonstrate the foregoing an escapement figure of 420,000 is chosen. The probability of having spawners in the 160,000 to 180,000 range is 0.376, between 180,000 and 200,000 is 0.591, and between 200,000 and 220,000 is 0.033. The probabilities for all other spawner classes are zero.

This is done for all other set escapement levels and the probabilities are written in matrix form. We thus arrive at a matrix of 16 x 15 elements. The integral over the normal distribution which is geometrically the area under the curve is 1.0. By using two standard deviations for our upper and lower curves we have cut off the tails and therefore have to normalize the calculated probabilities so that they add up to 1.0.

In the next step the spawners are represented on the x-axis. To avoid integration of a two-dimensional distribution function (remember that we had a normal distribution parallel to the "spawner" axis and now have a normal distribution parallel to the "eggs deposited" axis as well) the mean value of each spawner class is taken as the new integration line. The loss in precision by using this procedure is considered minor compared to the fact that a normal distribution function with two standard deviations for the confidence limits had been assumed without any analysis of the data.

To continue our algorithm we now are interested to know how many eggs with which probability will result from 170,000 ($= \frac{160,000 + 180,000}{2}$) spawners, how many from 190,000 and 210,000. These probabilities as well as for other spawner values are written down in form of a second probability matrix.

To combine the two life stages one could ask directly how many eggs will result from a given escapement value. Mathematically speaking, this means multiplication of the two probability matrices. Each element C_{ij} in this product matrix is calculated corresponding to

$$C_{ij} = \sum_{k=1}^{n} a_{ik} \, b_{kj}$$

where C_{ij} is the scalar product of the i^{th} row vector of A and the j^{th} column vector of B. Thus, multiplication of a (16 x 15) matrix with a

(15 x 16) matrix will yield a (16 x 16) matrix. In the next step this product matrix is multiplied by a matrix describing the eggs to fry stage. After four matrix multiplications we arrive at a matrix which contains the probabilities relating a given escapement to various return classes. (In Appendix 2 a flow chart of the computer program is given.) All these probabilities are now multiplied with the mean value of each return class and thus an expected return value is constructed corresponding to equation (A). Figure 10 shows the plot of this expected return curve and the confidence limits are given as well.

E. Conclusions

This new probability distribution does not follow any known mathematical distribution function. In the case of a lognormally distributed variable a lognormal distribution should result again after n multiplication steps (the distribution of a product of lognormals is lognormal again(7)).

In order to verify a lognormal distribution governing each life stage the parameters for this probability distribution function would have to be estimated using the available data. This is the only way to judge the validity of the proposed model.

In Figure 10 the "replacement" line has been included. This is the number of spawners necessary to maintain the stock at its existing level. If the return is lower or equal to the replacement value no catch can be permitted. The maximum average catch is calculated as the difference between the expected return curve and the replacement line.

In Chapter VI a methodology will be developed whereby the model is used to study the effects of potentially increased mortality due to poor water quality conditions on the stock size. First, however, a review of

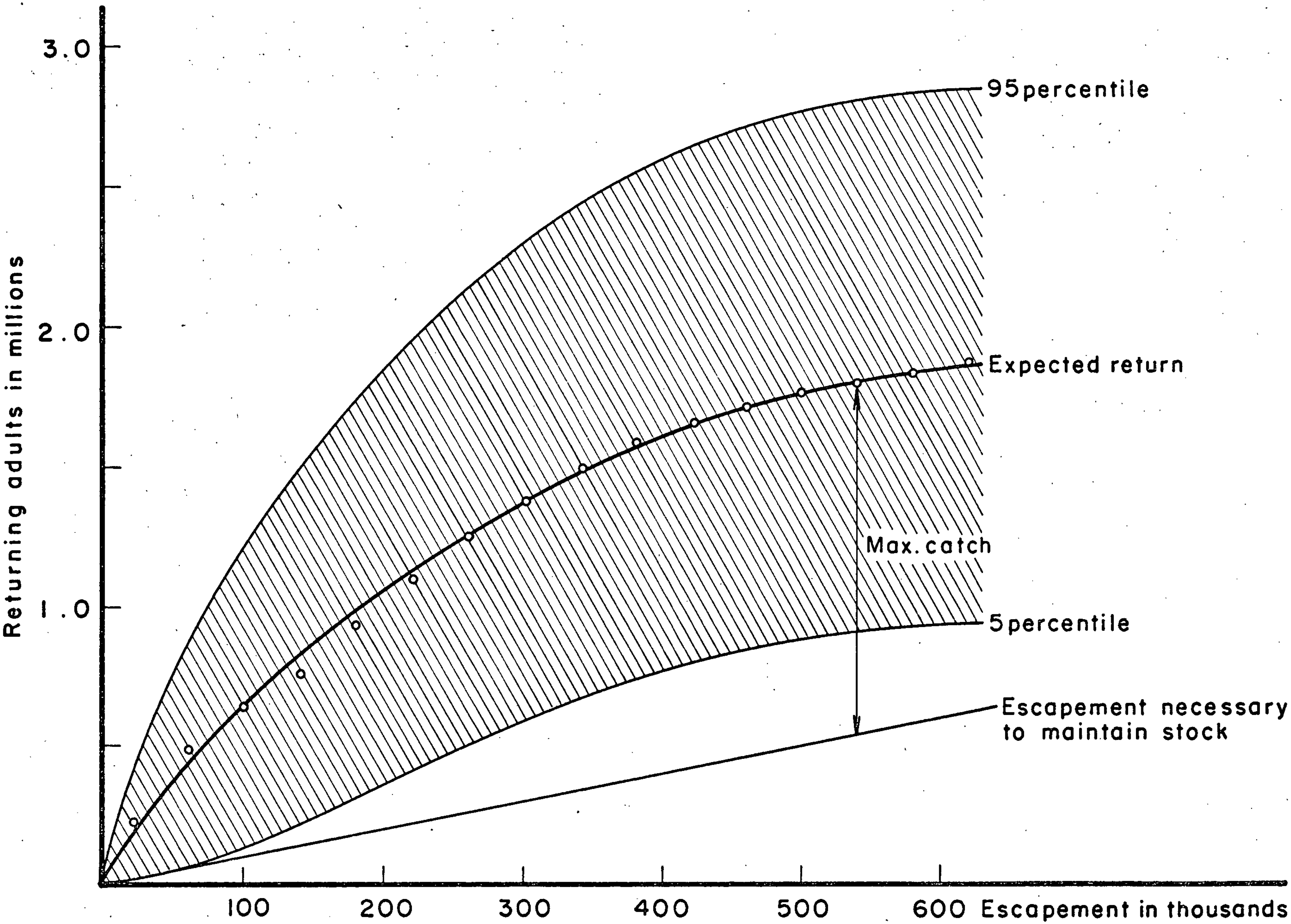


FIG. 10 EXPECTED RETURN [MORTALITY RATE 0%.]

the literature on the effects of pollution on salmonoid fish is inserted to give the reader an idea of the complex nature of the problem.

CHAPTER V

THE POLLUTION EFFECTS ON SALMON

HOW MUCH DO WE KNOW? -- A REVIEW

A. Introduction

From studies undertaken by various agencies we know that materials are discharged to the Fraser River which can be toxic to some aquatic organisms at certain concentration levels. In order to predict potential damage to salmon in the future we have to identify critical pollutants, study how they affect those species of the ecosystem which support the salmon, and also what direct effects they have on the fish. Since there is currently a great deal of interest in the future development of the Lower Mainland in British Columbia, it appears that knowledge about the behaviour of a salmon stock exposed to varying and increased pollution levels should be of importance to various decision making groups.

In fishery laboratories around the world tests with many pollutants and various species of fish in different life stages have been undertaken during the past 20 years. In this section some of the studies which relate to salmon and its food organisms are reviewed. These show that it is not possible to develop a simple model which describes the toxic and sublethal effects of all the various pollutants on salmon. In order to study possible changes in the population of a sockeye salmon stock, resulting from pollution, given the present level of knowledge, some rough approximations must be made.

B. Critical Pollutants in the Salmon Food Chain

Effluents from industrial, domestic, and storm sewers contain many chemicals which can be toxic once they reach a certain concentration level in the aquatic environment or in the tissue of an organism. However, the biologist is not just interested in the pollutants at levels of concentrations which would be lethal to fish within hours. This type of pollution effect is visible, and the public would certainly be very upset by such incidents and demand an investigation. Scientists are often more concerned about chronic or sublethal concentration levels where it is often difficult to relate cause and effect. These sublethal toxic concentrations impose added stresses on an organism which reduce the likelihood that it will survive in a competitive environment. The weakened fish will be more prone to predation or disease and will also not be able to compete as effectively for a limited food supply. Important pollutants which have been studied most frequently are listed in groups and discussed below.

1. Heavy Metals

The most toxic metals to aquatic organisms are mercury, silver, and copper followed by cadmium, zinc, lead, chromium, nickel, and cobalt. This order of toxicity varies somewhat for different species and it depends on the size of the organism, its life-stage, its absorption, excretion, storage, and regulatory mechanisms (10). Heavy metals precipitate out of the water after exceeding their solubility product or are adsorbed to sediment particles. Benthic organisms which live at the bottom of the river and its estuary therefore have often very high concentrations accumulated in their body tissue. In Table 1 the factors influencing the toxicity of heavy metals to aquatic organisms are summarized.

TABLE 1

Factors Influencing the Toxicity
of Heavy Metals to Aquatic Organisms

Form of metal in water	soluble	ion complex chelate compound
	particulate	precipitate adsorbed
Presence of other metals or poisons	antagonistic effects additive effects synergistic effects	
Factors influencing physiology of organism and possibly form of metal in water	salinity temperature dissolved oxygen pH hardness other pollutants, e.g. hydrocarbons, phenols	
Condition of the organism	stage in life-history changes in life-cycle size of organism activity of organism acclimatization to metals	

2. Pesticides

Depending on the application we differentiate between insecticides, herbicides, and fungicides. Pesticides are used in agriculture, horticulture, and the veterinary and medical field. Many of them end up in our rivers and ultimately in the sea. As pesticides are very insoluble a water quality analysis will often not tell us if we face a contamination problem. Sediment and fish tissue analyses have to be done additionally. Only a limited number of analytical techniques is available for determining residues at the low levels occurring in the environment. Acute toxicity generally results only from high shock loads to the receiving water after accidental spillages or careless disposal of surplus concentrates. However, we can also observe some long-term effects of certain pesticides on the aquatic flora and fauna although these generally are not accompanied by acute toxicity. A herbicide may destroy the rooted vegetation of a stream or pond, drastically changing the environment of small fish and many species of invertebrates. The structure of the fish population may thus be disturbed, and the invertebrate fauna which constitutes the food of many species of fish can be seriously reduced. Some insecticides are particularly toxic to zooplankton and insect larvae, and their destruction will reduce the food supply of fish.

Very often pesticides are more toxic to the food of fish than to fish themselves. Interference with the diversity or abundance of invertebrate fauna can have far-reaching consequences for a fish population.

3. Chlorine and Chloramines

For hygienic reasons sewage effluent is chlorinated prior to discharge. The residual chlorine may undergo chemical reactions with some of the organic material. One class of these reaction products, the chloramines, are extremely toxic for aquatic organisms (53).

4. Ammonia, phenols, PCB's (polychlorinated biphenyls) and some detergents have been shown toxic to fish or its food organisms (40,58).

5. A low dissolved oxygen level in the water, high water temperatures, extreme pH values, high concentrations of bacteria in the water, excessive dissolved solids concentrations have been found to impair the survival chances of fish (1,50).

C. Experimental Evidence

Most of the facts about the effects of hazardous pollutants on the aquatic environment have been acquired from laboratory studies. We would like to have more data from field observations since an increase above the natural mortality rate would most likely have a serious effect on the population. However, the complexity of the aquatic environment with its variety of species, their interrelationships, population numbers, seasonal and annual changes in the flow and temperature regime of the river make such an undertaking very difficult. Consequently, the influence of some pollutants in causing chronic toxic effects will usually pass unrecognized. We have to establish the possible risk to fish or to other components of the freshwater community indirectly by relating measured concentrations in the water, sediment or organism to experimental observations in the laboratory.

Bioassays to study acute toxicity caused by one or more chemicals are the most frequently used tests. In these tests adult or juvenile fish are exposed for time periods varying from 24 to 96 hours to different concentrations of the pollutant under investigation and the number of fish killed during the experiment is recorded. Most of the available acute toxicity data are reported as median lethal concentration (LC50) which signifies the concentration at which 50% of the test organisms survive within a specified time span, usually in 96 hours. By using acutetoxicity tests it has been shown (2,21,38) that changes in the chemical and physical characteristics of the water have a marked effect on the toxicity of a poison to fish.

Heavy metals are more toxic in soft water than in hard, the toxicity of ammonia varies with the pH value and the temperature of the water, and low levels of dissolved oxygen decrease the resistance of fish to pollutants. In the case of copper, for example, it has been hypothesized that only the ionic fraction of the total copper is toxic. Organic compounds have been shown to chelate dissolved copper. The complexing agents can be humic acids, amino acids, or polypeptides (70). Thus, when we talk about the toxicity of copper to aquatic organisms we have to determine the fraction which is biologically available (37).

Different species of fish vary in their resistance to poisons; in general, coarse fish are more resistant than salmonid species. Therefore, many tests are being conducted using trout or salmon as test fish. Also important is the sensitivity of the various life stages of organisms. Many organisms are most sensitive in the larval, nymphal, molting, or fry stage. Evaluation of toxicity to a species, therefore, cannot solely be based on the adult organism. Some pesticides have been shown(26) to affect reproduction (failure of eggs to hatch). High concentrations of heavy metals in the water have adverse effects on the eggs deposited on the spawning grounds.

Another problem area is the study of effects which mixtures of poisons have on the organism. As polluted rivers usually contain more than one poison the contribution of each one to the total toxicity needs to be assessed. We have to differentiate between synergistic, antagonistic, and additive effects. By synergistic action the combined influence of several substances results in greater toxicity to the organism than the sum of the individual effects taken independently. Therefore, lethal threshold concentrations determined for various pollutants separately in laboratory tests cannot simply be transferred to the field where a wide variety of substances might interact with each other and result in a much higher toxicity. On the other hand, certain combinations of compounds act to repress the deleterious effects of one another (antagonistic). It has been found that the ratio in which the pollutants are present is quite important (59).

While the study of lethal effects of poisons on fish is fairly straightforward, experiments to study sublethal effects are much more difficult to design. Sublethal effects include changes in histology, physiology, growth, swimming ability, respiration rates, behaviour, and reproduction. There are three major types of tests to study sublethal effects: the physiological test, the behaviour test, and the life-cycle test.

A physiological test can consist, for example, in the measurement of increased urine production by the fish as a response to increasing ammonia concentration (38), or the measurement of the change in the oxygen consumption rate, or observation of an excessive mucus secretion on the gills (13,40). The limitations of this type of approach are that the physiological response should be both essential to the well-being of the fish as well as being the one most sensitive to the poison under test. Hatch (reported in 38) devised a graphical relationship between an increase in physiological stress and the degree of impairment of bodily function (Figure 11).

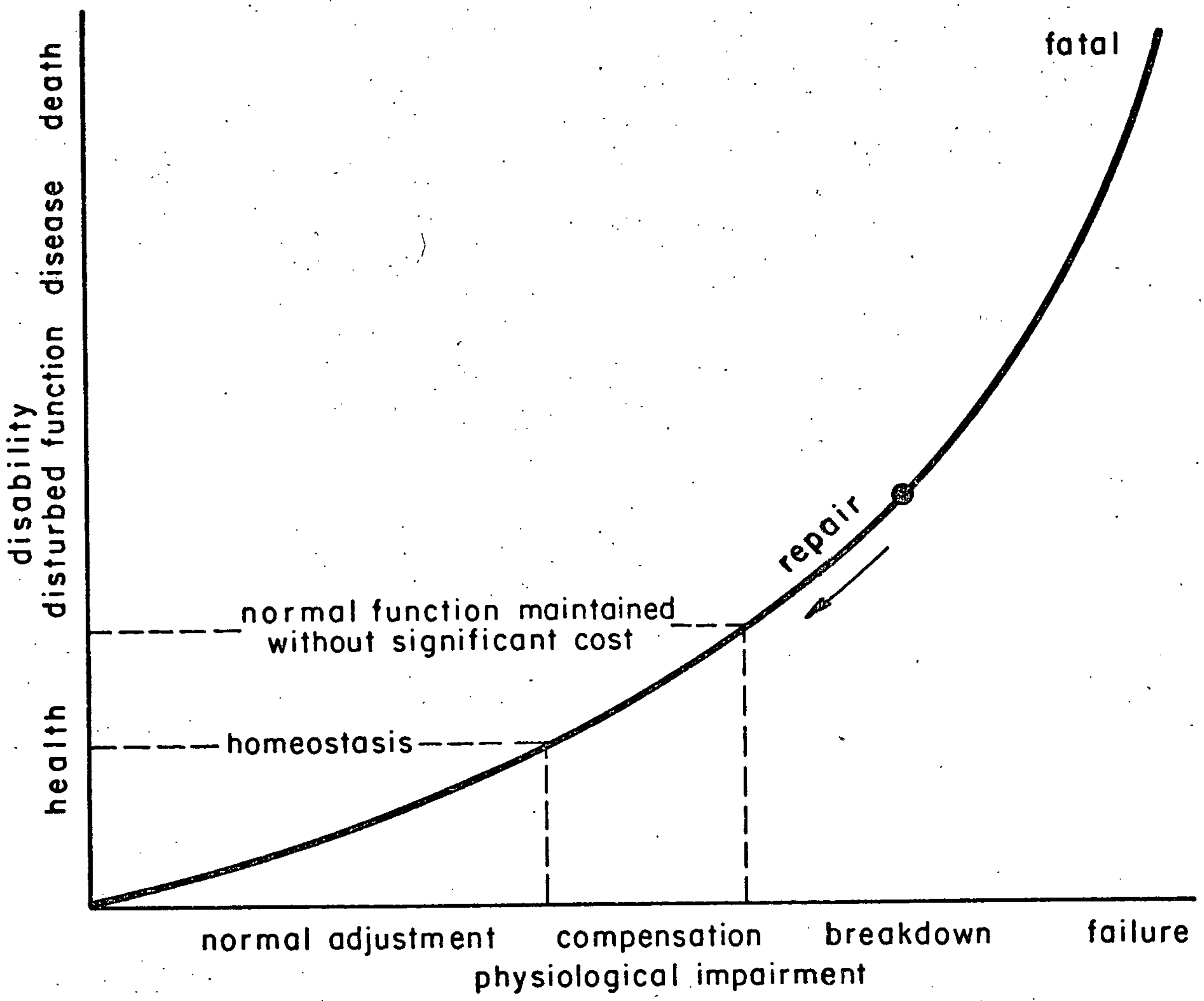


FIG. 11 A POSSIBLE RELATION BETWEEN PHYSIOLOGICAL IMPAIRMENT FOLLOWING INCREASING EXPOSURE TO POLLUTANTS AND THE CONSEQUENT DISABILITY OF THE FISH (AFTER HATCH).

In behaviour tests the threshold concentration is determined at which fish, given a choice between contaminated and clean water, is able to avoid the polluted region. Usually there is a clear interface between the two conditions and no external stimuli. This, of course, is not typical for natural waters where a clear-cut line between polluted and unpolluted areas does not necessarily exist. Other behaviour patterns, such as migrating or territorial behaviour, may have an overriding effect. For example, it was found that salmon on their upstream migration were turned back only when the combined levels of a copper/zinc concentration were 20 times higher than the ones found in a laboratory test where non-spawning salmon had been used as a test fish (60). Another test to find out the behaviour of fish to a reduction in the dissolved oxygen level is reported in (38). Here the number of fish are counted leaving an area which becomes suddenly depressed in dissolved oxygen. Lethargic behaviour of juvenile sockeye is reported by Servizi (40) when the fish were exposed to detergent levels which were nontoxic to them.

In a life-cycle test fish are exposed to constant levels of poisons for periods up to 11 months to determine the concentration at which the growth rate and breeding success is similar to that of control fish. The drawbacks of this test are:

(a) It is time consuming and extensive testing facilities are required.

(b) Fish are fed with artificial food and treated with antibiotics to prevent disease.

(c) Fish are exposed to constant levels of poison, whereas in their natural environment the concentration normally fluctuates.

Summarizing we can say:

Acute toxicity tests can be used to measure the effect of chemical and physical variables on the toxicity of poisons and on the resistance of fish to them. In order to use data obtained from short-term laboratory experiments to set up water quality criteria to guarantee a healthy environment for fish, application factors should be used. An application factor converts lethal concentrations found in a short-term test to a concentration which is harmless under conditions of long-term exposure (51). Results from sublethal tests can give an insight into the mechanism of toxic action and experiments should be designed to show the level of no adverse effect. Field observations can provide valuable information on the levels of pollutants at which fisheries are unaffected and, in some cases, the graded effect of increased pollution on the deterioration of a fish population.

It can be said that there is no such thing as the concentration of a poison above which fish will be absent and below which they will flourish. Rather, there is a range of increasing concentrations within which fisheries will likely show a progressive deterioration, either in quality or in numbers or both.

The next desirable step is to process the amount of information available from all these tests and observations in a way which is comprehensible to the decision maker who might not be an expert in fisheries, toxicology, or aquatic chemistry. In order to simulate pollution effects on a salmon stock and to make a forecast of the probable numbers of returning adults when the stock has been exposed to different pollution levels, a common "yardstick" for all the various pollutants is needed.

CHAPTER VI

SIMULATION OF A SALMON STOCK UNDER VARIED LEVELS OF POLLUTION

A. Introduction

In the previous chapter some of the many pollutants which can have adverse effects on salmon at certain concentration levels were discussed. It was pointed out how difficult it is to describe the synergistic effect of the multitude of pollutants encountered in the waste discharges from an urban industrial area. Sublethal effects are very insidious in nature but they do not result in an immediate increase in mortality. Their cumulative effect, however, can be seen in a lower overall return rate. A weakened organism will be more prone to predation in the ocean, its life expectancy may be shortened, and its fecundity may be reduced.

In the Fraser River itself there have been no documented fish kills due to acute toxicity conditions in the water. Problems are more likely with sublethal effects. Water quality will vary with place and time because of changes in stream flow, tidal action, seasonal differences in temperature, and fluctuating waste discharges, both in volume and strength. Long-term averages, for instance, do not reflect the short-term stress that may be imposed on an organism by a shock load of a harmful material. The best way to monitor water quality over time is to use an organism which depends on good water quality, for example, salmon. The organism integrates its response through time and reacts to all synergistic and antagonistic effects of combined pollutants or stresses. This being recognized, in situ bioassays at points in the river where critical water quality conditions are expected are presently the most popular method to relate measured physical and chemical parameters to the survival or physiological well-being of fish.

B. Fish Tests in the Fraser River and the Coastal Zone

Every time the Pollution Control Board receives an application for a permit to discharge waste water to the Fraser River, other government agencies including the federal Fisheries Service and Environmental Protection Service, the International Pacific Salmon Fisheries Commission (IPSFC), and various public interest groups are asked to comment. In cases where these wastes might contain substances which are believed to be toxic to salmon, IPSFC usually conducts bioassay tests in its laboratory. Such studies, for example, investigated lethal and sublethal effects on juvenile sockeye and pink salmon due to de-inking wastes from a proposed new paper mill using waste newspaper as its major raw material (40). The fish were exposed to a series of dilutions. Results indicated that these de-inking wastes were even more toxic than wastes from kraft pulp mills. Furthermore, it was found that the detergents in these de-inking wastes caused lethargy, excessive mucous secretion on the gills, and depressed oxygen consumption of the salmon fry at concentrations less than the lethal level.

At major sewage outfalls, for example near the three municipal treatment plants which discharge to the Fraser, in situ bioassay tests have been done recently on an annual basis to assess acute toxicity. Researchers from the Fisheries Service of Environment Canada keep coho fingerling salmon in cages near the Annacis Island sewage outfall, every year two weeks prior to the beginning of the freshet (31).

IPSFC has undertaken several bioassay studies to assess acute toxicity of municipal sewage to fingerling sockeye and pink salmon (39,53).

It was demonstrated that effluent from a primary municipal sewage treatment plant is toxic to fish, especially when chlorinated. Dechlorination was considered necessary to eliminate this toxicity resulting from several newly formed chlorinated organic compounds.

Recently, more attention has been given to the analysis of muscle tissue from fish and other commercially valuable marine organisms. Analyses are made for heavy metals, particularly mercury and cadmium, PCB's and pesticides in tissue samples. The high content of mercury found in the tissue of crabs was cause for the closure of the commercial fishery in Howe Sound (66). Later on this decision was revised so that migratory species, such as salmon, could be caught.

Our knowledge about the accumulation of toxic materials through the food chain is very poor. At present an international research team at Saanich Inlet (off the coast of Vancouver Island) are trying to evaluate the pathways of some heavy metals, such as copper, mercury, cadmium, and lead through the ecosystem. The experiments are done in huge plastic bags which are open at the top so that the exchange with the atmosphere can continue. Efforts are made to have the marine environment undisturbed as much as possible. Concentrations of the heavy metal added to the water in this enclosed ecosystem were sometimes as high as 250 times natural background level. Samples are taken from the water, the detritus, the phyto- and the zooplankton as well as cultured chum fingerling salmon (only in some experiments) to determine the distribution of the metal.

In another study possible shifts in the ecosystem due to increased levels of hydrocarbons, such as refinery oil and fuel, are investigated. In the case of phytoplankton it was observed that a shift from big cells to small cells occurred (61). This finding is of great importance as larger zooplankters, which form the main diet for fish, do not feed on these small phytoplankton cells. Could this mean a diminishing food supply for fish as a result of increasing pollution in the ocean? The studies are being continued and more data will either confirm or disprove this hypothesis.

All these studies indicate how much research work still has to be done in order to get good data on which future hypotheses and models can be based.

C. Effects of Various Mortality Rates on the Size of a Sockeye Salmon Stock

As has been pointed out in the discussion of previous sections, present understanding is not sufficient to relate pollution levels in the water to possible changes in the stock/recruitment relationship. We do not know what effects some waste chemicals have on the upstream migrating spawners. Do they have a masking effect, thus interfering with the salmon's sensing system which enables the fish to find its way back to its homestream? (It is believed that salmon are able to recognize the chemical characteristics of the water and sediment and find their way back.) We do not know if the survival chances of juvenile salmon migrating downstream and having to pass polluted water are reduced due to additional stress on the organism. What are the effects of increased pollution levels on other organisms in the estuary which are a food source for the juvenile salmon? It is known that young salmon feed on river invertebrates during this journey downstream. Some salmon species (not so much sockeye juveniles) stay up to three months in the estuary and feed there (16,43). Could there be a decrease in returning adults due to such changes of the estuary environment?

For the following simulation studies it was postulated that in the future, as is the case now, acute toxicity conditions will not be the normal case but rather be limited to accidental spills that can cause temporarily unfavourable water quality conditions. More important is the water quality generally encountered which can be characterized by its BOD, temperature, dissolved and suspended solids, ammonia, etc. There is no doubt that increasing waste discharges to the Fraser River will cause a deterioration of water quality if at the same time efforts are not made to reduce the loadings of pollutants through appropriate treatment processes.

Poor water quality conditions are assumed to affect both the up-river migrating adult spawners and the young smolts migrating to the ocean and thus result in lower survival rates during these two life stages. The only parameter used to express the underlying sublethal effects was increase in natural mortality rate (or decrease in survival rate). Lacking any information from data several alternative values for the reduction in survival rate during these two life stages were tried. The effects of various mortality rates of up to 50% on the stock size were calculated using the computer model which has been described in detail in Chapter IV. Increasing mortality rates result in lower expected return values. The results are shown in Figures 12 to 17. It will be noted that at a mortality rate of 30% there exists a 5% probability that the stock size reaches such a low level from that it may not recover again.

The allowable catch is the difference between the expected return and the necessary escapement to continue the cycle. This difference becomes further depressed with increasing mortality rate.

As a next step the equilibrium levels corresponding to different mortality rates were computed. This equilibrium level is the salmon run

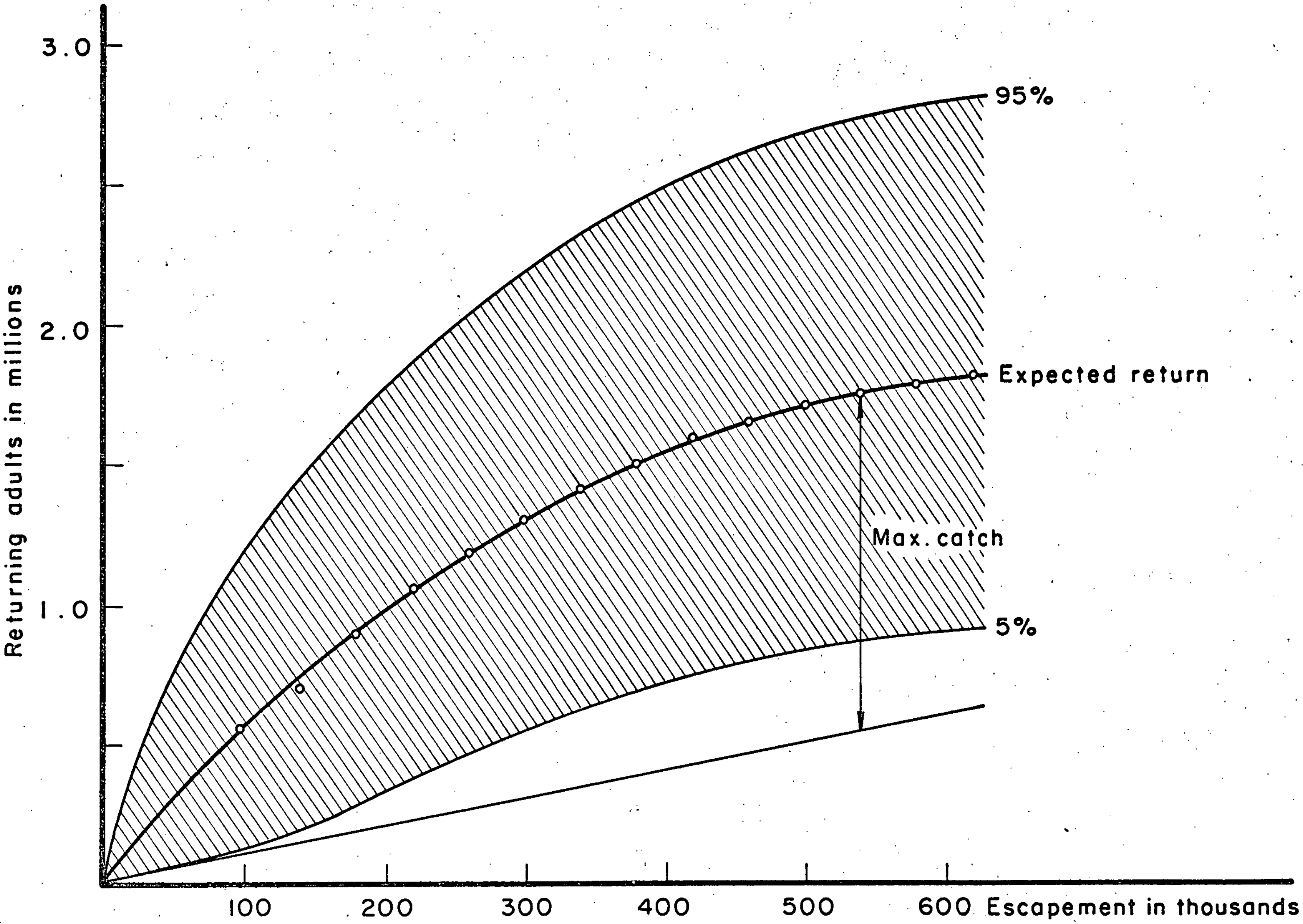


FIG. 12 EXPECTED RETURN [MORTALITY RATE 5%.]

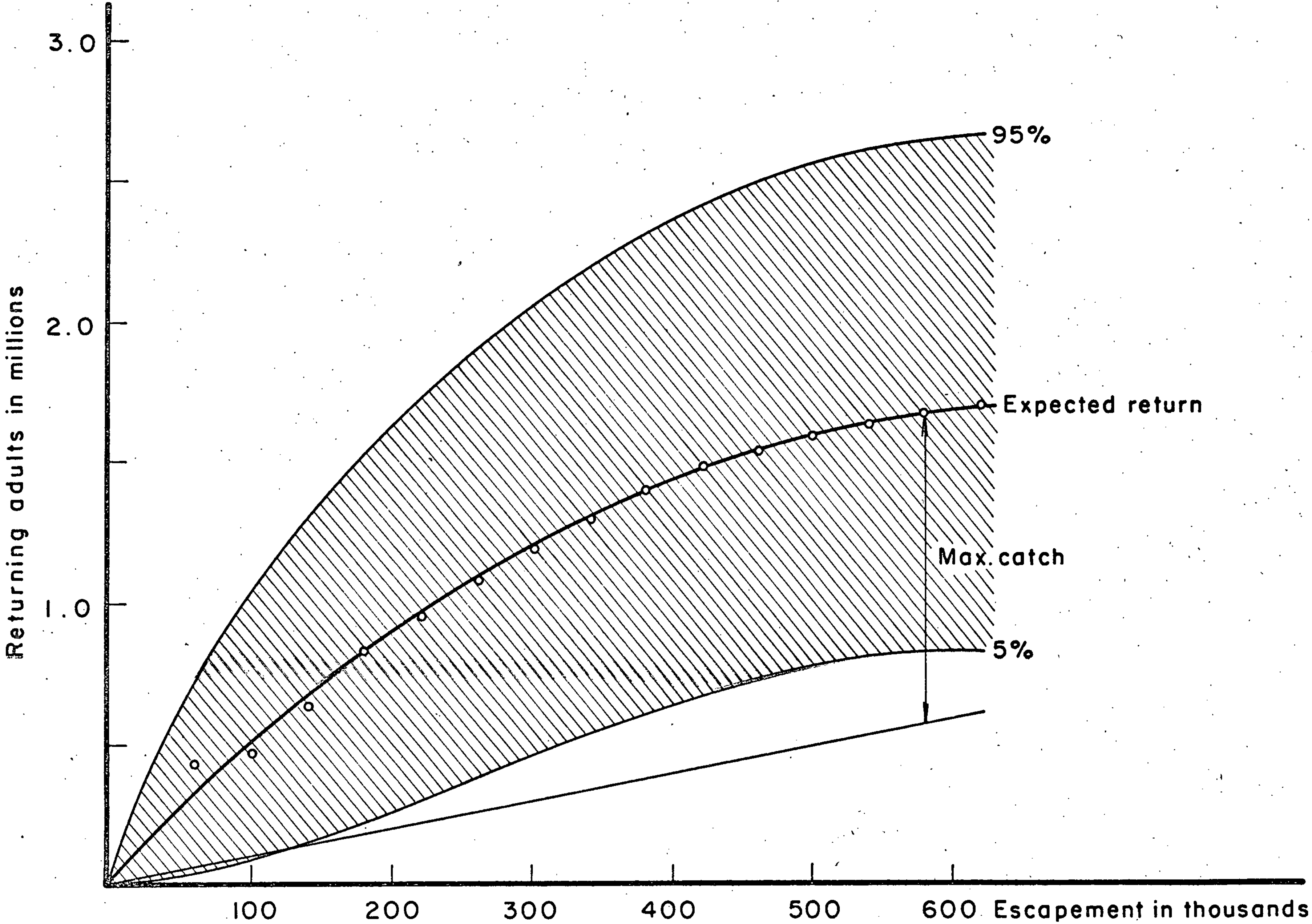


FIG. 13 EXPECTED RETURN [MORTALITY RATE 10%.]

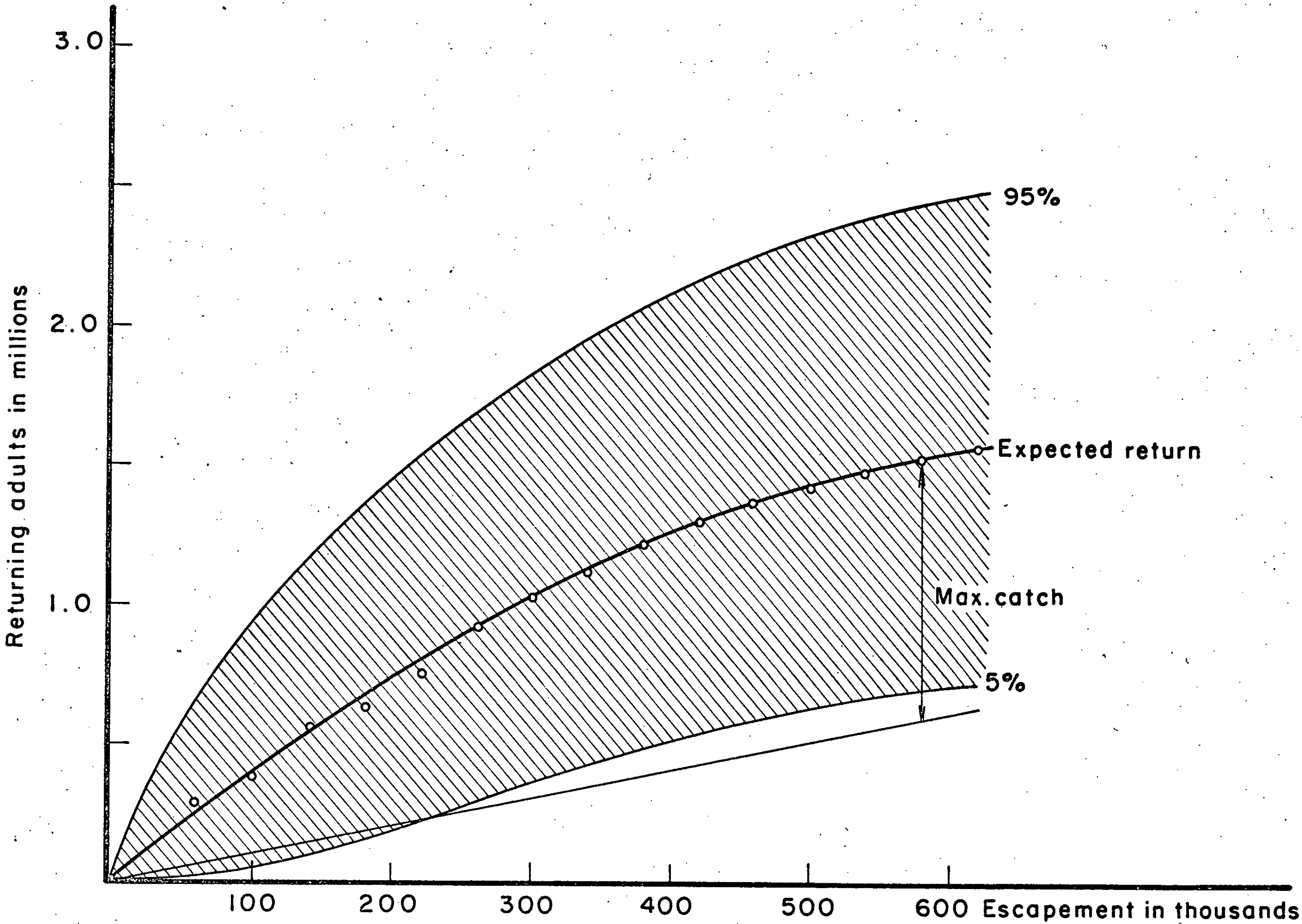


FIG. 14 EXPECTED RETURN [MORTALITY RATE 20%.]

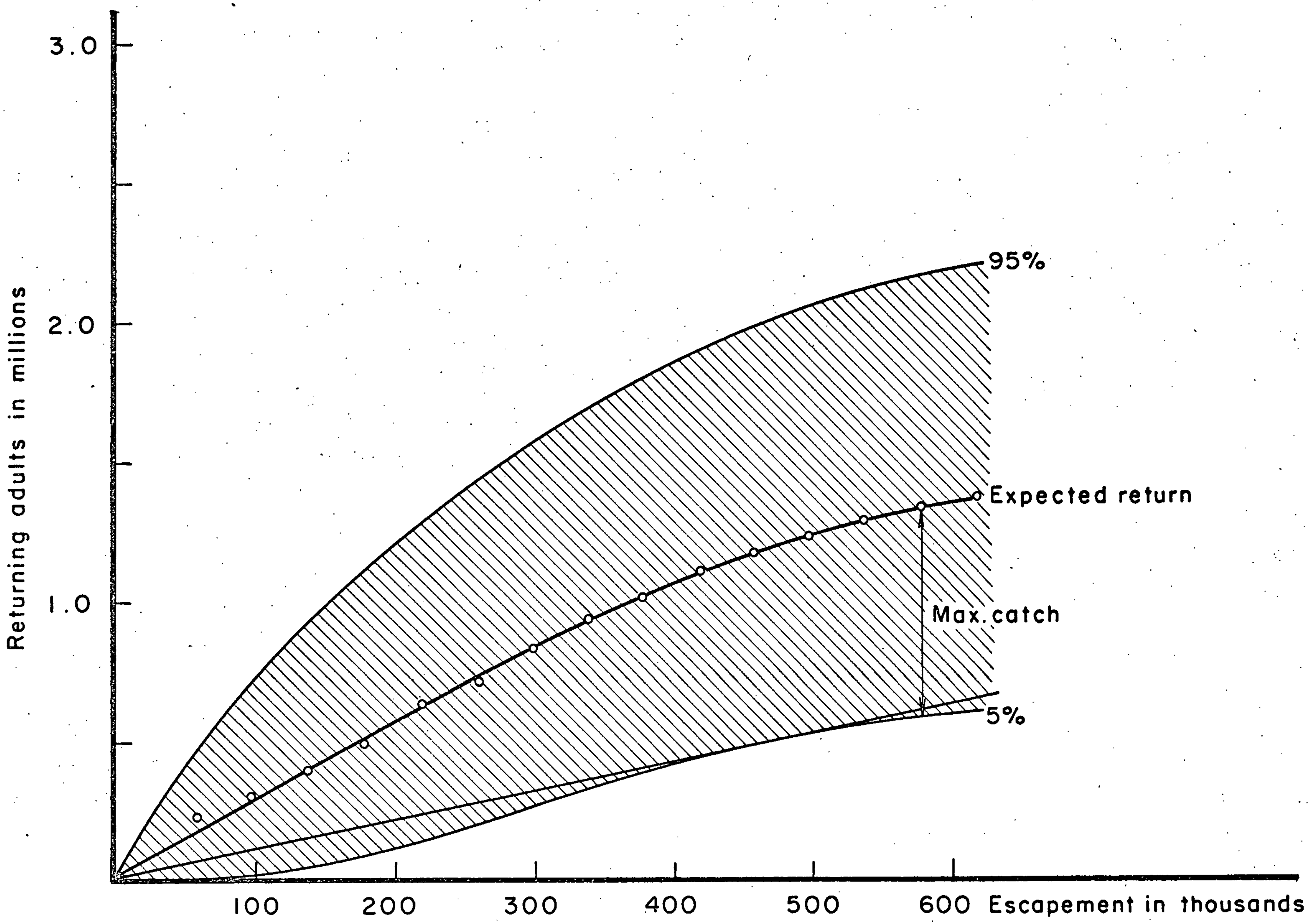


FIG. 15 EXPECTED RETURN [MORTALITY RATE 30%.]

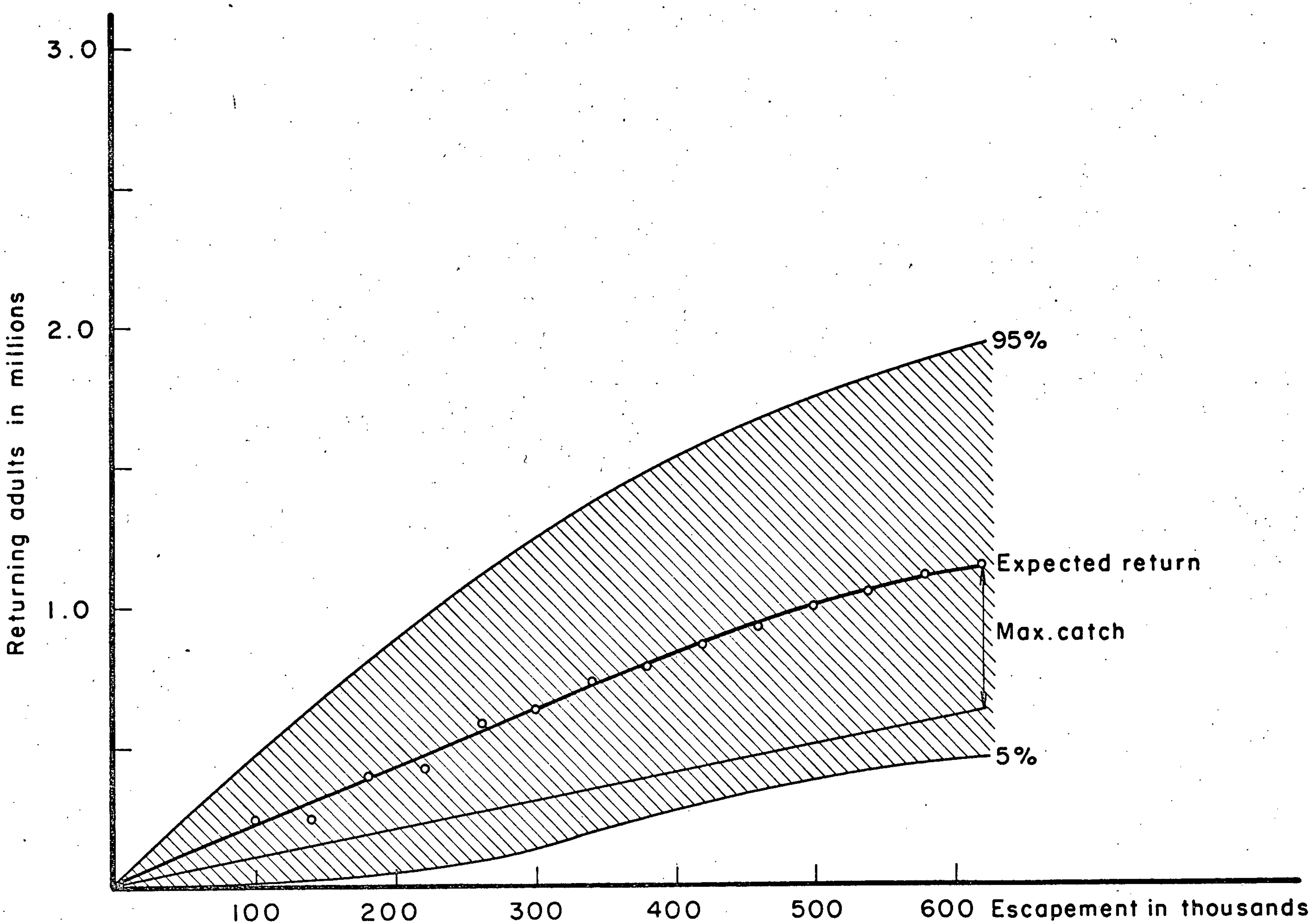


FIG. 16 EXPECTED RETURN [MORTALITY RATE 40%.]

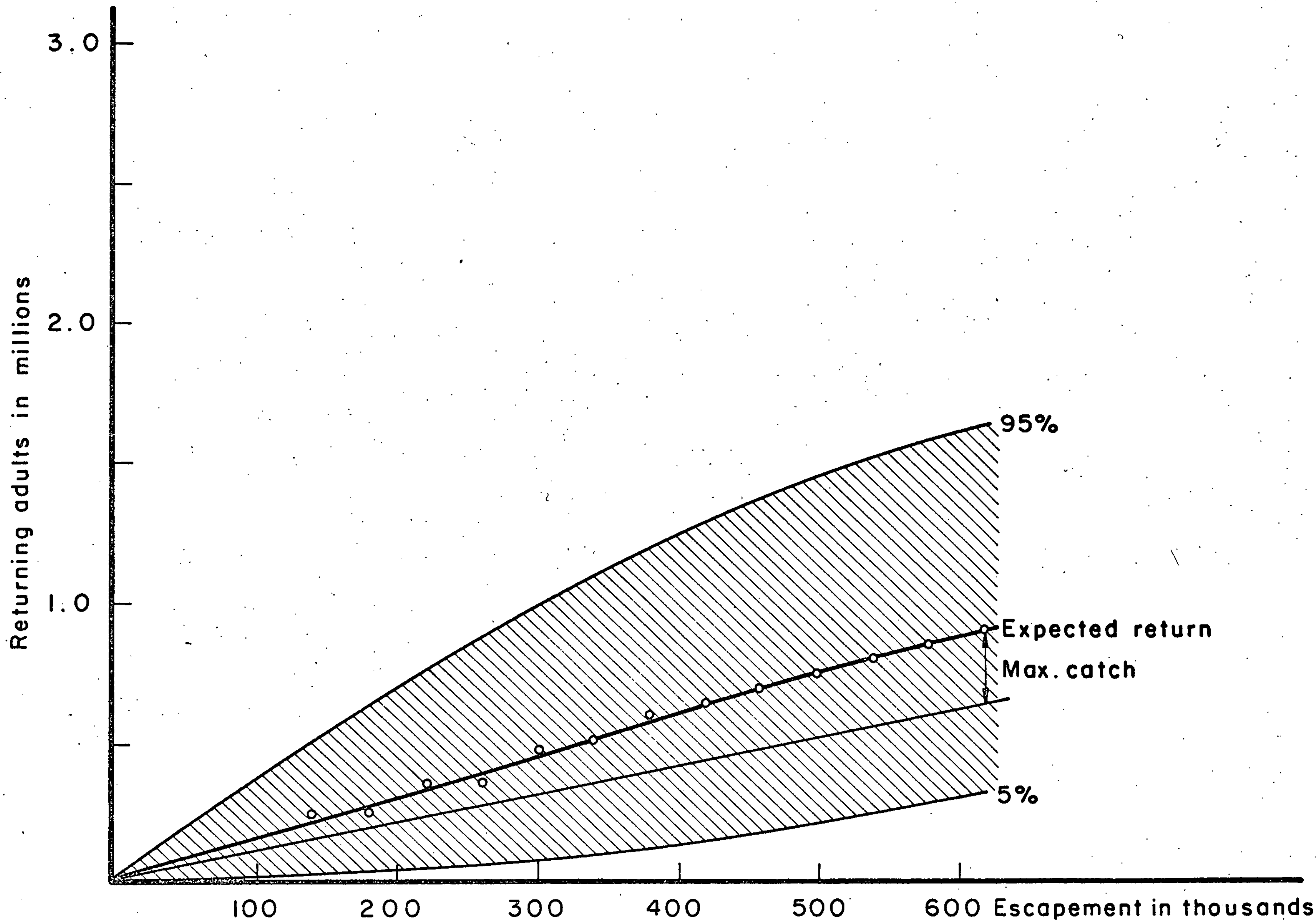


FIG. 17 EXPECTED RETURN [MORTALITY RATE 50%]

sustainable under water quality conditions which would cause a certain mortality to passing salmon. In order to calculate this equilibrium it is necessary to assume a relationship between returning adults and the chosen escapement. This last relationship closes the salmon life cycle. Figure 18 proposes such a mangement scheme for harvesting salmon. In the lower return ranges the manager will try to build the stock up by allowing up to 50% escapement whereas for bigger return values a higher percentage can be allotted to the fishermen. (This strategy should not be confused with the present strategy used to manage Fraser salmon and maintain its dominant, subdominant, off-year pattern. It was rather devised to counteract the effect of reduced reproduction due to pollution problems and to rebuild the stock size.)

The information from this set of curves is brought again into matrix form. Now the computer model can calculate continuously as many salmon life cycles as are necessary to stabilize return values at an equilibrium for each specified mortality rate. This equilibrium indicates the level to which one can sustain the stock with the proposed management scheme and under the given mortality rate. Results of these simulations were used to draw the curves in Figure 19. It can be noticed again that at a mortality rate of 30% the stock size reaches a critical level.

The calculations done in this simulation study can be regarded as a first attempt to describe the interdependence of pollution and the size of a salmon stock. Mortality rate was the only parameter used to demonstrate the change in the stock/recruitment relationship due to poor water quality conditions. Constant reductions in survival had been assumed in the two life stages under consideration. If the nature of changes due to sublethal effects were better known a new set of curves could be constructed

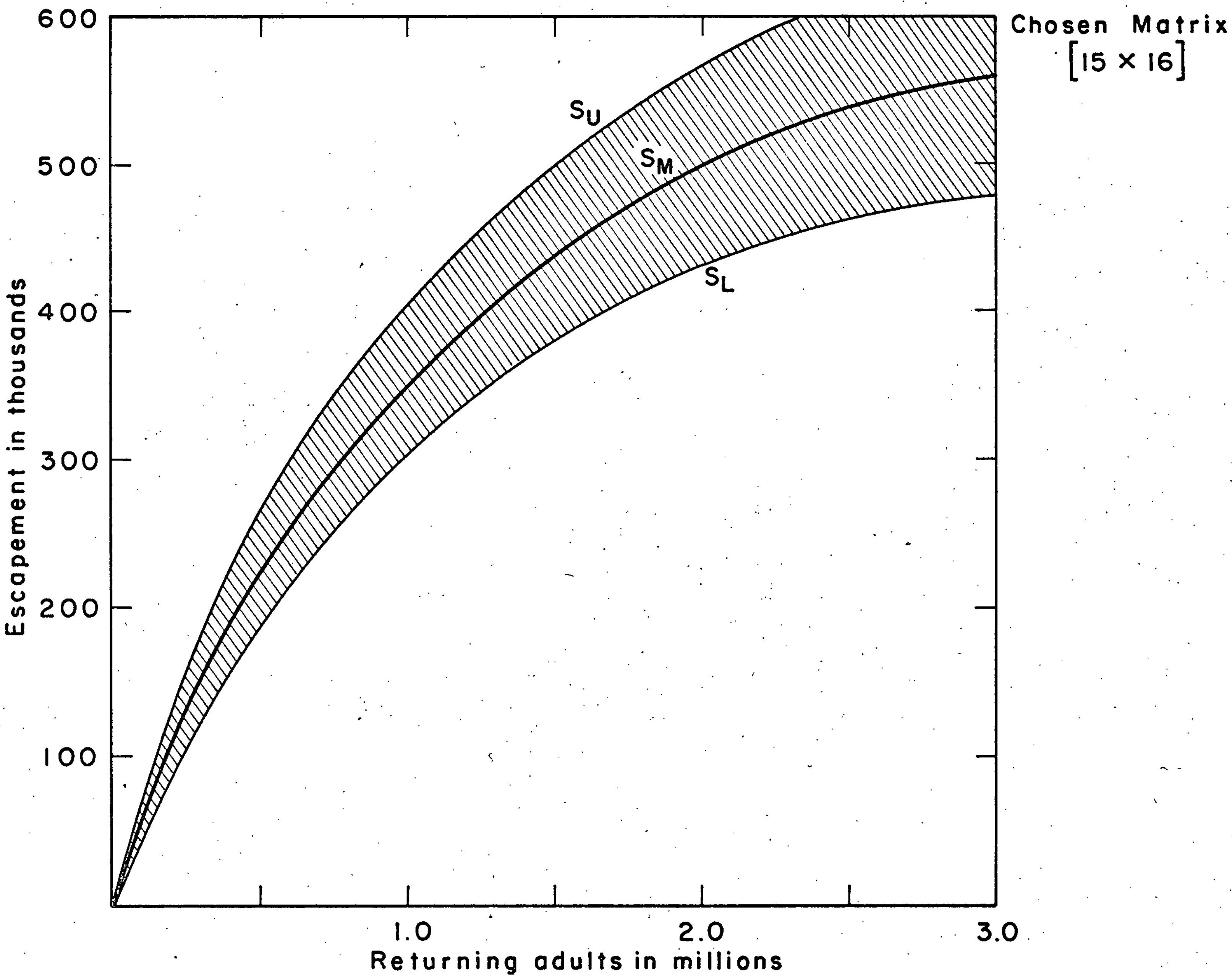


FIG. 18 POSSIBLE MANAGEMENT SCHEME TO HARVEST SALMON.

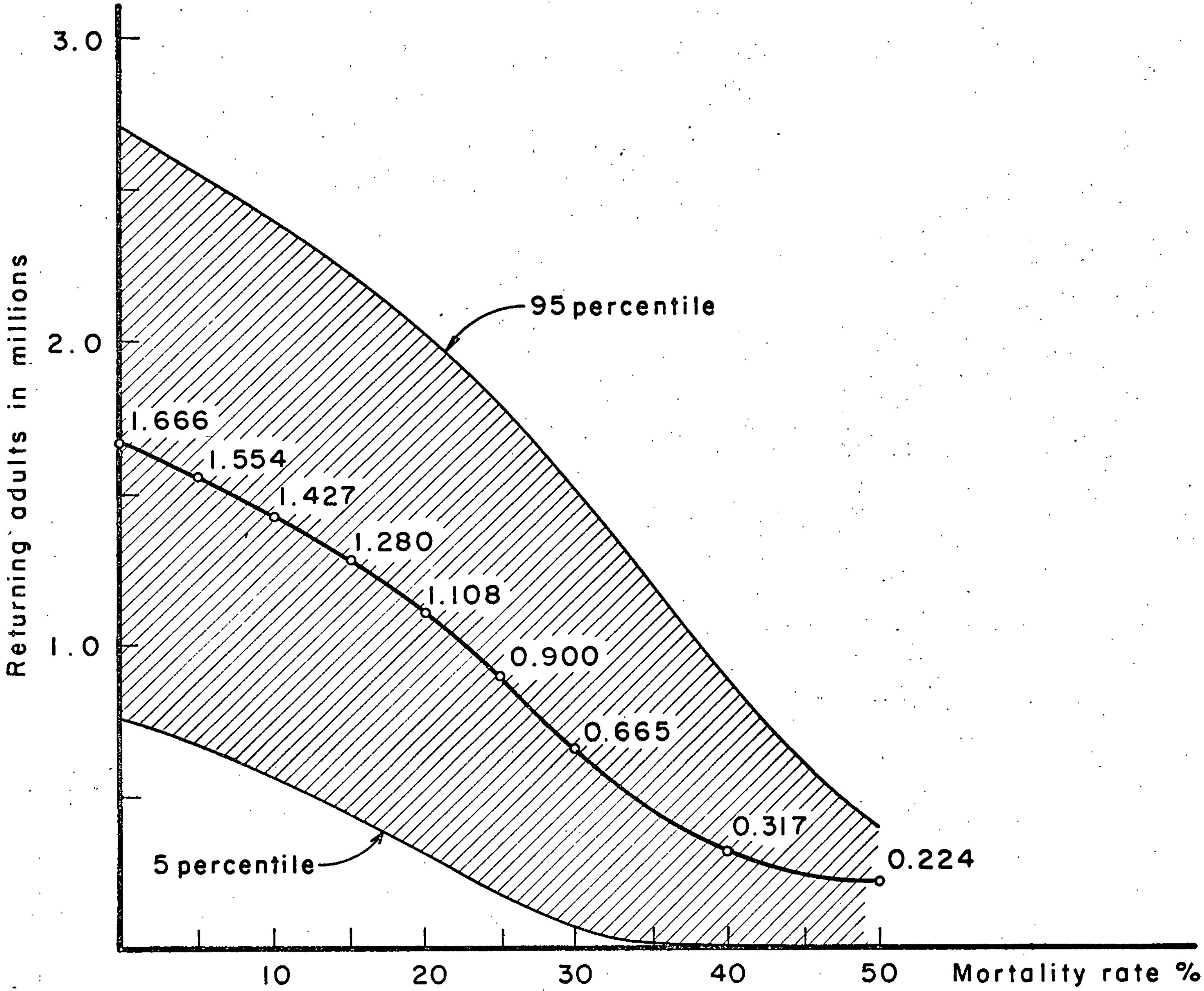


FIG. 19 SUSTAINABLE RUN WITH ESCAPEMENT STRATEGY OF FIG. 18
[EQUILIBRIUM LEVEL]

and used as input to the model. Another hypothesis is that pollution might cause a shift in the distribution function between confidence limits leading to a more accentuated skewness. For example, it is known that raised water temperature has an effect on prespawning mortality. Figures from such observations could be fed into the model. In the next chapter the possibility of constructing a pollution index from a variety of water quality parameters and relating it to an increase in mortality is discussed.

CHAPTER VII

THE USEFULNESS OF AN INDEX TO FORECAST WATER QUALITY CHANGES AND THEIR EFFECTS ON WATER USE

A. Pro and Contra for Developing a Water Quality Index

There is a growing need to turn from management by reaction to management by anticipation of problems. This anticipatory approach to management requires techniques for forecasting. We are still in a very primitive stage with respect to developing adequate forecasting models. In order to predict future events a thorough analysis of the past and the present is required. One way to aggregate and to summarize the available data on a particular problem is to construct an index. Indices are a very effective way to aggregate and communicate information on trends to the policy-makers and the general public. They are a device for establishing where we are and how we are progressing. For years we have been operating with indices in economics and social sciences to demonstrate change and trends. Only recently has an interest been taken in developing environmental indices (11,65).

Unfortunately, many scientists have very strong reservations about a numerical indexing procedure. They feel that the problem is far too complex to be adequately represented by a single value. However, collecting an abundance of data on the chemical, physical, and biological condition of a river and relating all these data to something such as well-being of fish generally confuses the policy-makers and the general public. An index would facilitate communication between the scientist and the non-scientific community. It would also help to highlight major trends. By using an index to describe the condition of a river we have to accept some reduction in precision. However, we gain in our ability to communicate. An index can always be backed up by more detailed data to allow specific analysis.

One way to construct a pollution index is described by Nemerov (42). Each value for a pollutant is related to a standard value which is, in most cases, the permissible water quality level. These relative terms are all summed up assuming an additive pollution effect of the several pollutants. This approach is often taken to describe the total toxicity when several toxic materials (T_1, T_2, T_3, ...) coexist in a water body. Their permissible levels (TL_1, TL_2, TL_3, ...) are determined in bioassay tests. Total toxicity then equals:

$$TT = \frac{T_1}{TL_1} + \frac{T_2}{TL_2} + \frac{T_3}{TL_3} + \ldots$$

If this sum exceeds the value of 1.0, the water in question is considered toxic for the specific use. Synergistic or antagonistic effects can be included by multiplying some components with appropriate weighting factors.

Another method to construct a water quality index relating to the specific water use of fish and wildlife is described by O'Connor in his dissertation (45). This seems to be a promising step in the right direction and will therefore be presented in the context of this paper.

B. Construction of a Water Quality Index for Fish and Wildlife

O'Connor based his research on a study which had been undertaken by Brown *et al.* (8). In this study experts were asked to designate parameters to be included in an index, to weigh these parameters in terms of their relative importance to overall water quality, and to draw curves indicating water quality as a function of each parameter on a scale reaching from 0 to 100. The result was an additive index of overall water quality involving nine parameters. Many experts participating in this study agreed that it is easier and more meaningful to construct an index for a specific water use. Judgments concerning parameter inclusion, weighting, and scaling vary as a function of the water use. O'Connor therefore tried to develop in his dissertation valid indices for very divergent uses of water and determined how much the resulting numbers differed for different users when he computed the indices of selected water samples. One index chosen described the quality of a surface body of raw water sustaining a fish and wildlife population. O'Connor defined the problem of developing a water quality index as one of ". . . finding a suitable mathematical function, involving an appropriate set of parameters, which assigns to a complex multi-attributed stimulus, a surface body of raw water, a number which adequately represents for a particular decision-maker and with respect to a particular criterion, the worth of that stimulus."

The mathematical function was assumed to be additive and written in the form:

$$W(X_i) = \sum_{j=1}^{n} \nu_j \, \omega_j \, (X_{i,j})$$

where:

X_i = a n-dimensional stimulus

ω_j = the value of the quality curve for parameter level X_{ij} (utility)

ν_j = the average importance weight assigned to the j^{th} dimension.

To derive the utility function, six experts in the field of water quality were consulted. A test containing over 30 parameters generally associated with water quality was presented to them. O'Connor used a modified version of the "Delphi" technique (12) where the participants are confronted with a series of questionnaires. After each round of questionnaires, O'Connor informed the members of this group about their answers without revealing names of the individuals holding these opinions. He also evaluated the results and proposed a compromise for the next discussion round. In the first questionnaire the experts had to agree upon some critical parameters to be included in the index. If too many parameters are used to construct the index, the decision-maker's capacities break down or perform sub-optimally. The nine parameters X_i decided upon for inclusion into the fish and wildlife water quality index and their importance weights ν_j in normalized form are given in Table 2. The quality curves yielding the ω_j for the analysis are shown in Figures 20 to 28. These curves are compromise curves proposed by O'Connor after discussion and were accepted by the experts.

In O'Connor's approach the function $W(X_i)$ is regarded to be additive in nature. This only holds if the parameters measured are in a reasonable range. For extreme parameter values, the effect would be the same as with toxic substances. They then cannot be traded off against other dimensions in terms of water quality. For example, extreme values for dissolved oxygen concentration, temperature, pH, ammonia, nitrates, and phenols have been found to indicate water quality conditions which are lethal to fish. O'Connor therefore decided to set the index value to zero if water quality reached zero on any of the nine dimensions. In the presence of toxic materials, such as heavy metals and pesticides, tolerance values have to be

TABLE 2

Parameters and Their Importance Weights for Construction of a Water Quality Index for Fish and Wildlife

Parameters	Importance Weight	Normalized Weight
Dissolved oxygen	100	.206
Temperature	82.5	.169
pH	69	.142
Phenols	48	.099
Turbidity	43	.088
Ammonia	41	.084
Dissolved solids	36	.074
Nitrates	36	.074
Phosphates	31	.064

used. If the concentration of any toxicant is above its critical value, the water quality is set to zero.

C. Forecasting Potential Pollution Effects

How could such an index be used to relate water quality in the Fraser River to sublethal effects on salmon?

As has been stated previously there are several substances which are potentially harmful to salmon at certain concentrations. Extensive and sometimes tedious work is necessary to determine present loadings of each single pollutant in the river. Some work in this direction has been

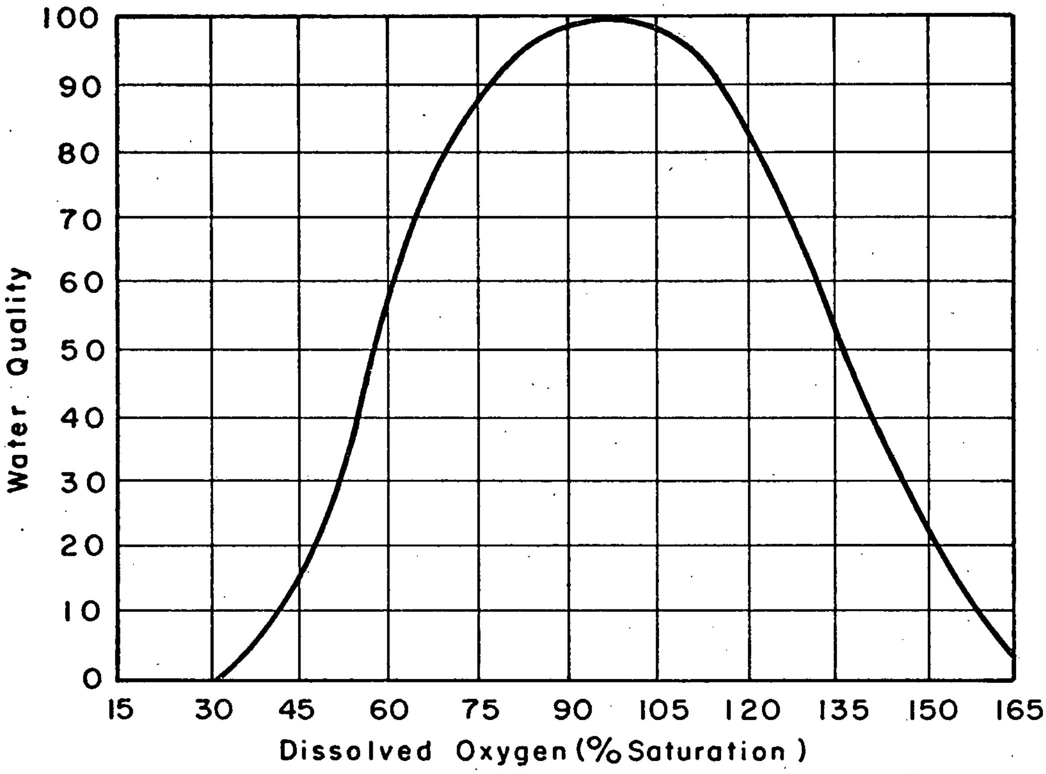


FIG. 20 WATER QUALITY AS A FUNCTION OF D.O. SATURATION, SUMMER TEMPERATURES.

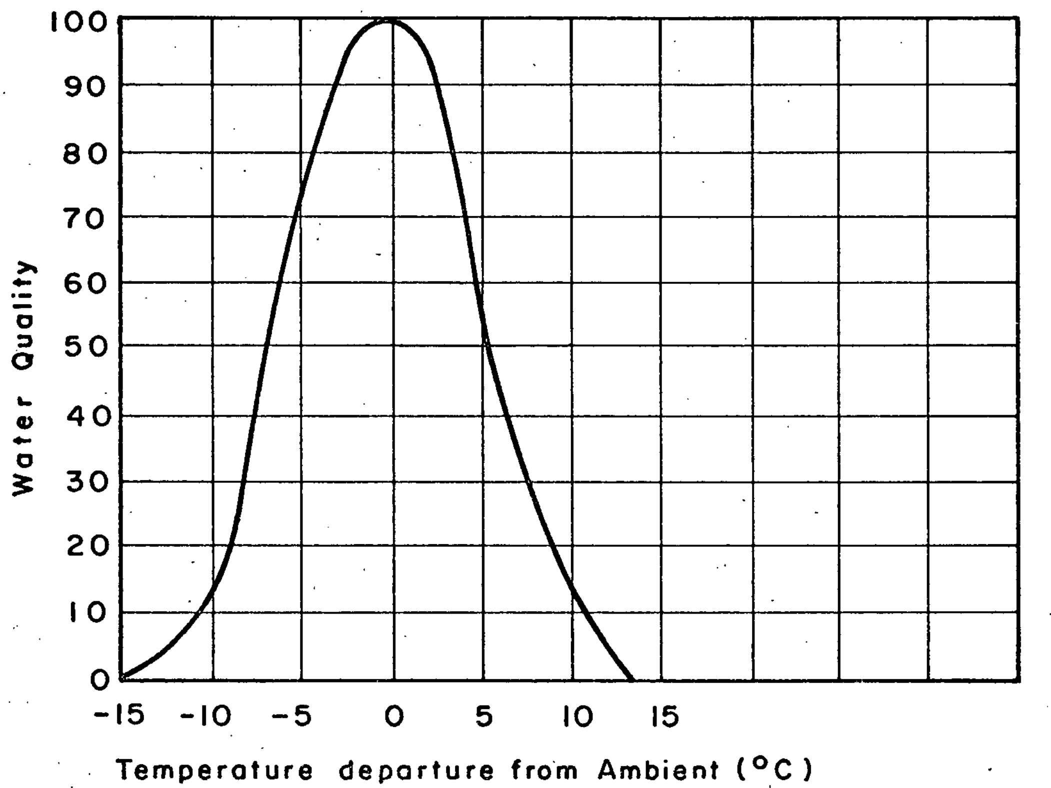


FIG. 21 WATER QUALITY AS A FUNCTION OF TEMPERATURE DEPARTURE FROM AMBIENT.

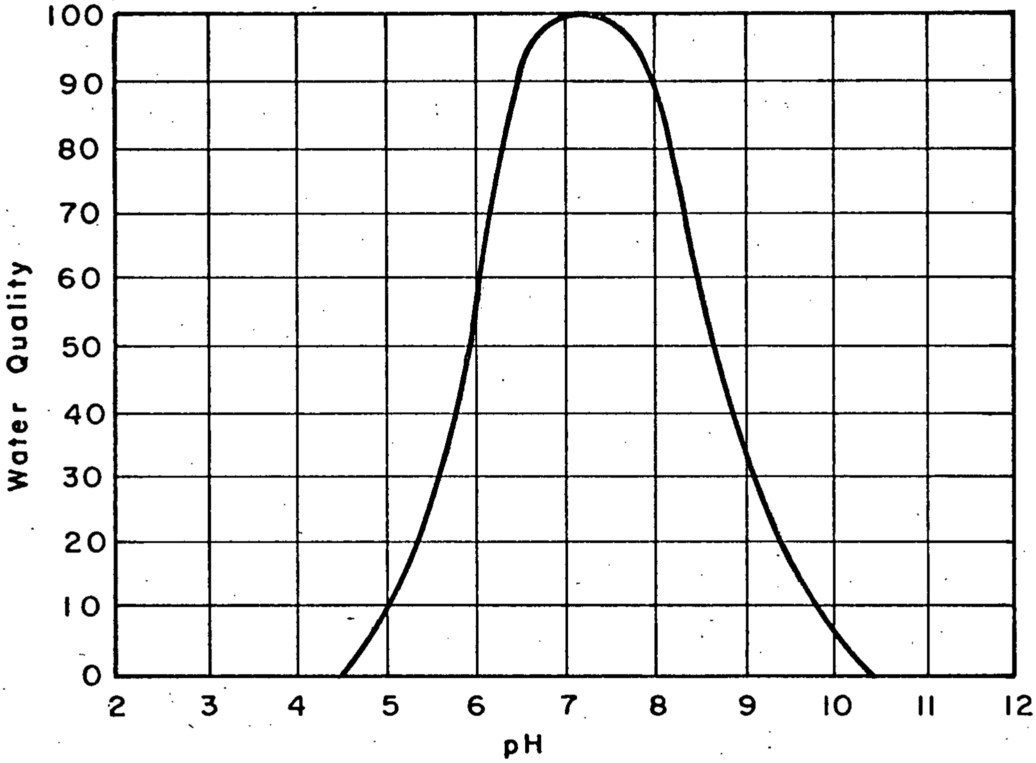


FIG. 22 WATER QUALITY AS A FUNCTION OF pH.

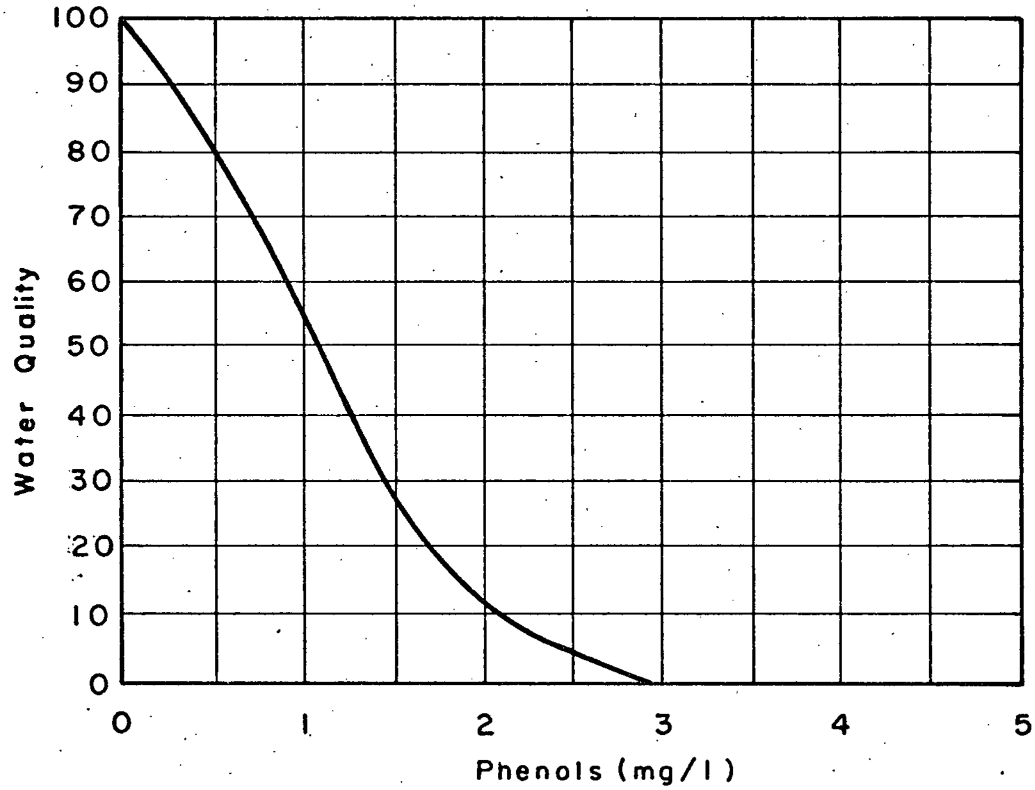


FIG. 23 WATER QUALITY AS A FUNCTION OF PHENOL CONCENTRATION.

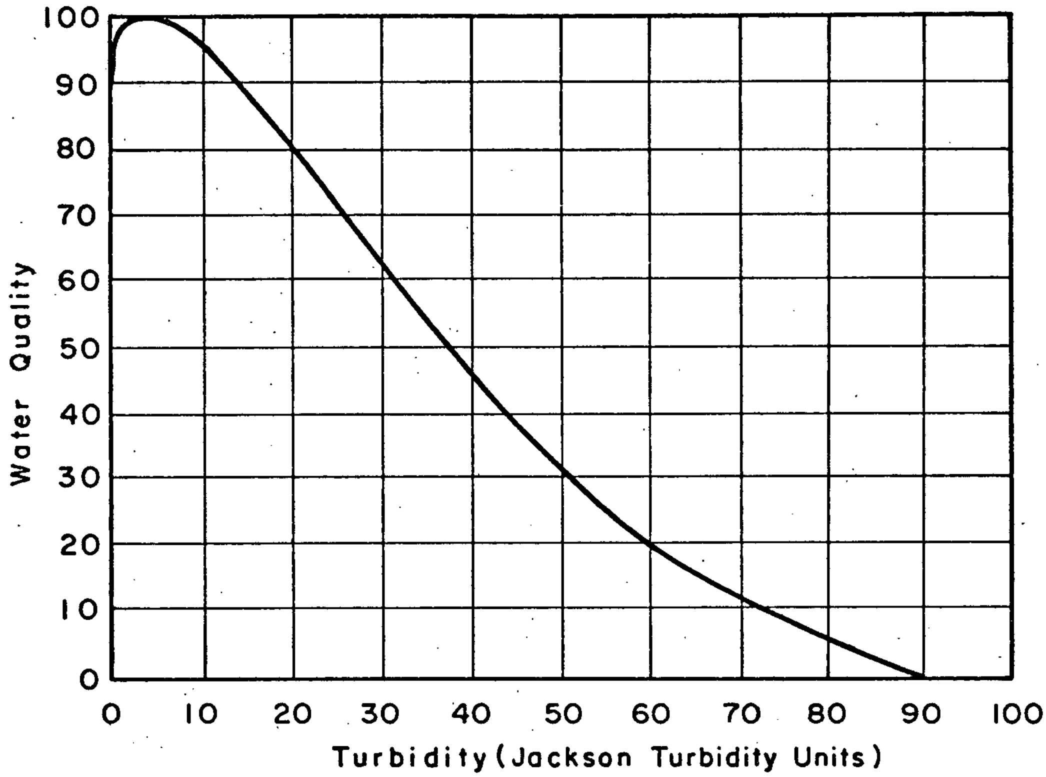


FIG. 24 WATER QUALITY AS A FUNCTION OF TURBIDITY.

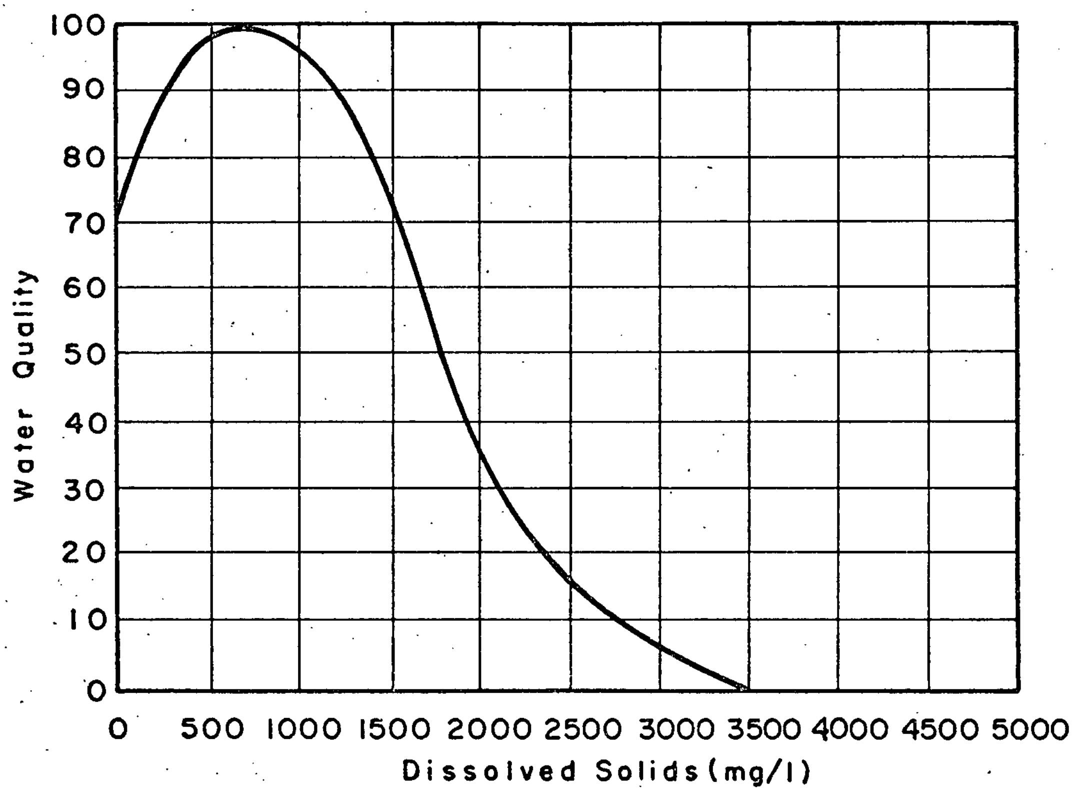


FIG. 25 WATER QUALITY AS A FUNCTION OF DISSOLVED SOLIDS CONCENTRATION.

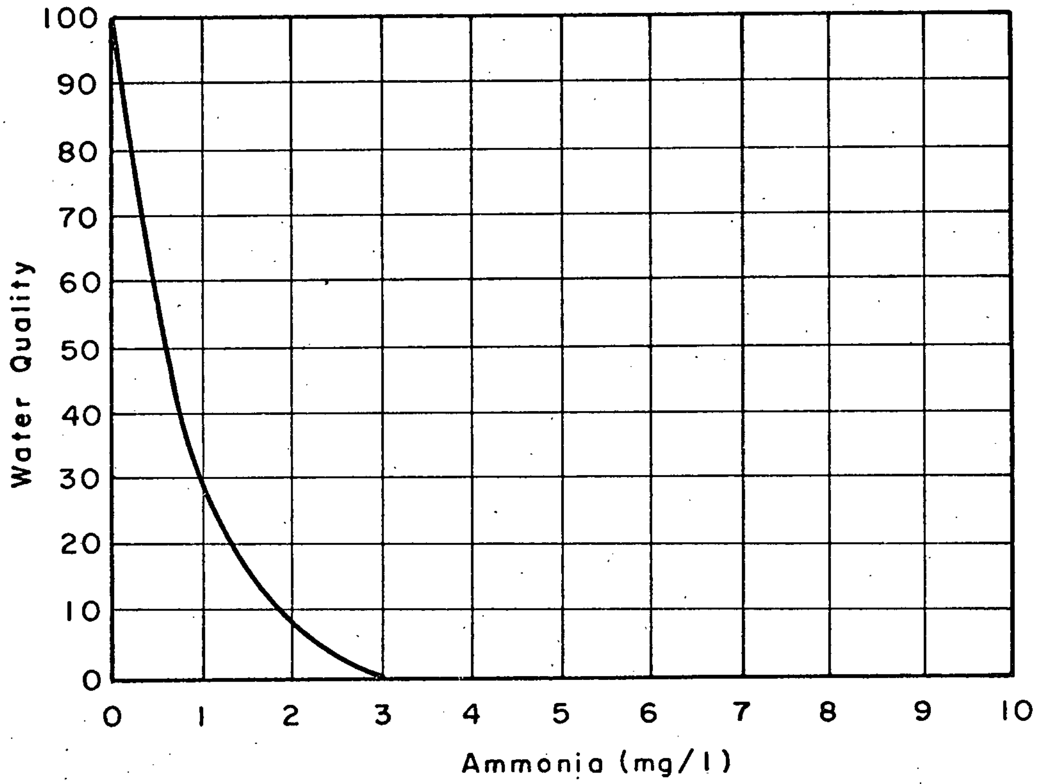


FIG.26 WATER QUALITY AS A FUNCTION OF AMMONIA CONCENTRATION.

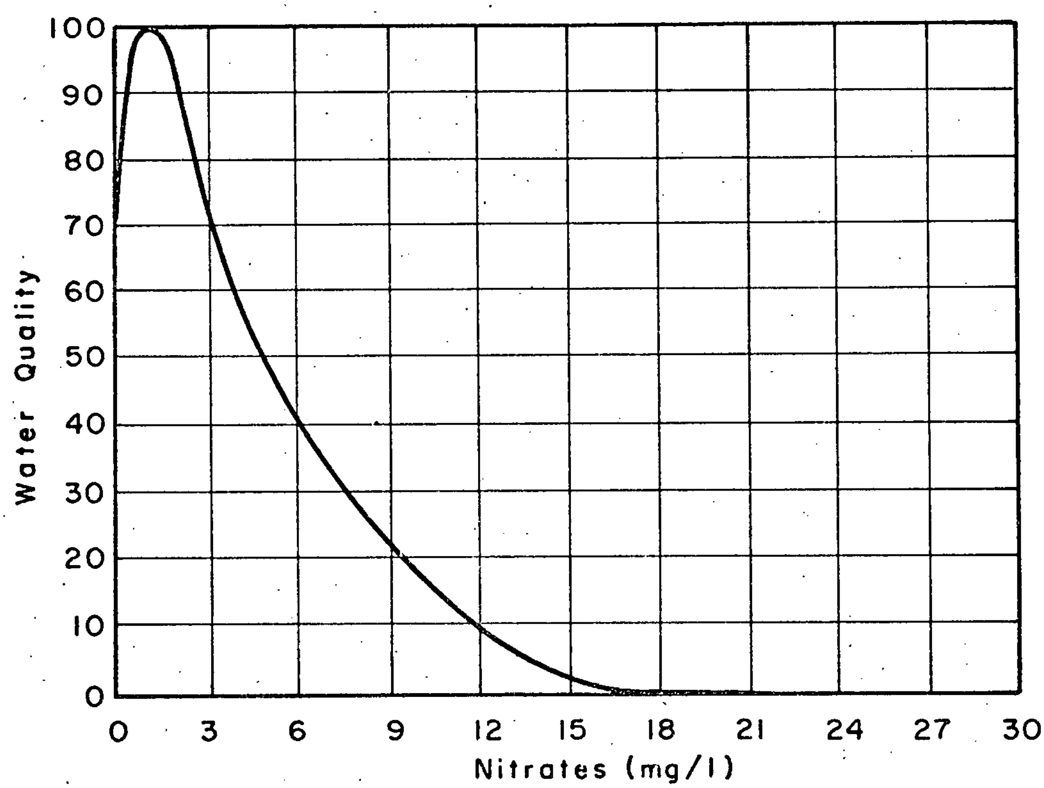


FIG.27 WATER QUALITY AS A FUNCTION OF NITRATE CONCENTRATION.

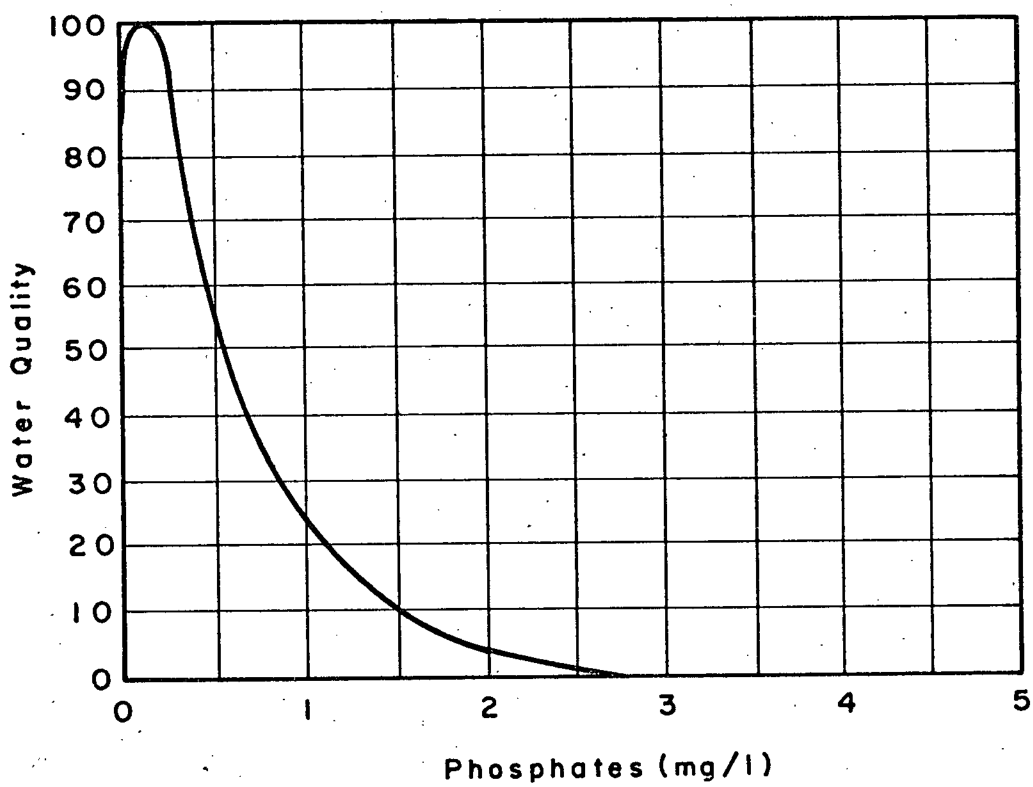


FIG.28 WATER QUALITY AS A FUNCTION OF PHOSPHATE CONCENTRATION.

done by Westwater in its studies on the pollution aspects of the Lower Fraser River (30). It is, however, impossible to predict future concentration levels of each single, potentially toxic substance in the water, the sediment, and the organisms on which salmon feeds. Too little is known about sources of pollutants, pathways, accumulation rates in the food chain, and future discharges to the river. New production processes, changed consumer habits, technological innovations in the field of waste water treatment, all bear on the composition of the waste effluents discharged to the Fraser. There is definitely a need to give those who are involved in decision making a tool which allows the assessment of the present water quality status and a prediction of changes in that status. A water quality index as outlined in this chapter, could reflect changes in pollution patterns resulting from future urban and industrial development or better waste treatment plants. To have only one parameter, an index, would facilitate the problem of predicting trends in water pollution. Figure 29 illustrates what possible development such an index could show over time. These trend curves can be based on forecasts of population growth, industrial activities in the region, waste disposal methods, and so forth. The problem of uncertainty can be taken care of by using upper and lower bounds again.

The next important step then, consists in relating a declining water quality index to an increase in mortality rate (above natural mortality). This mortality rate can also be regarded as a reduced reproduction rate due to sublethal effects of some pollutants. With our present understanding of the problem, intuitive judgment will be required to develop such functional relationship. Possible curves are shown in Figure 30. Curve I is based on the assumption that a decrease in water quality will

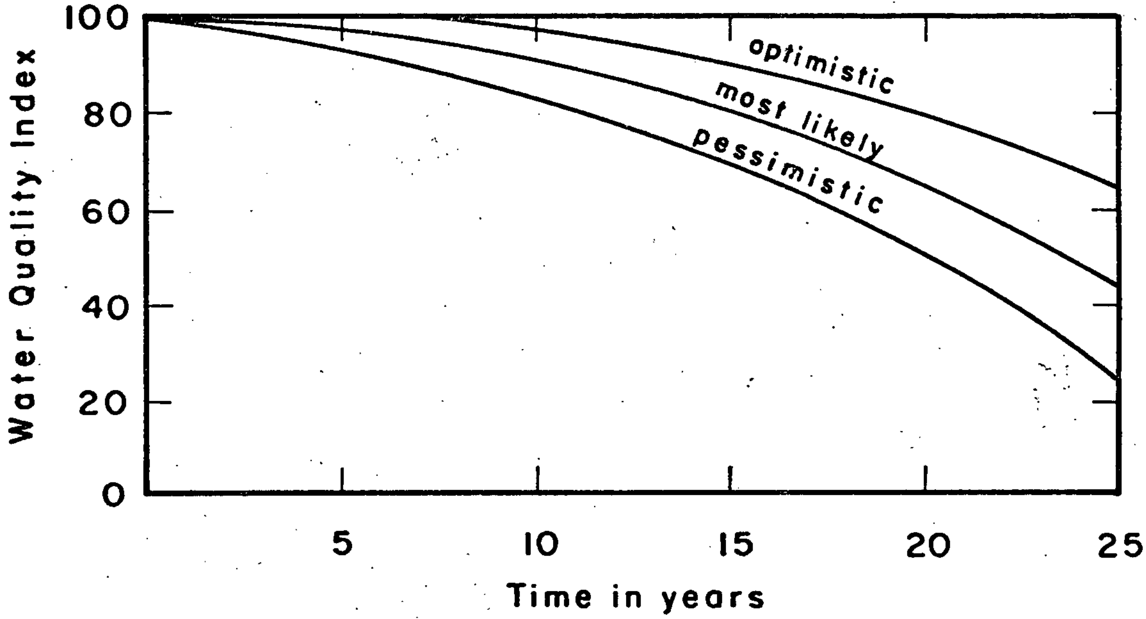


FIG.29 WATER QUALITY INDEX OVER TIME.

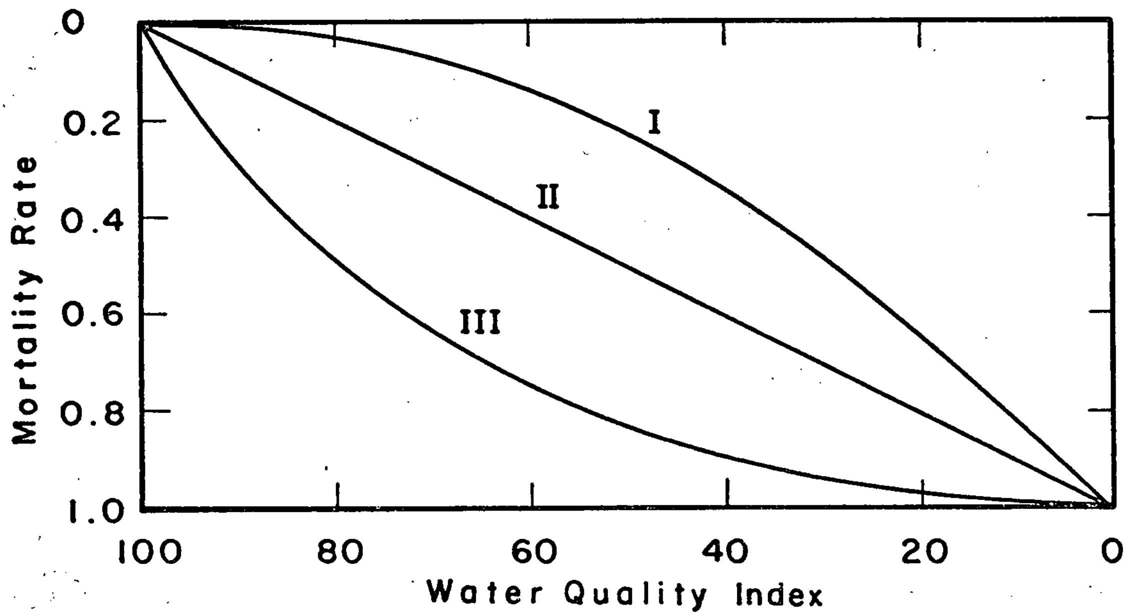


FIG.30 POSSIBLE RELATIONSHIPS BETWEEN A WATER QUALITY INDEX AND MORTALITY RATE (SOCKEYE SALMON).

not cause an immediate steep rise in the mortality rate (optimistic view). Curve II illustrates a linear relationship, something which may be used as a first approximation. Curve III illustrates the case where even a slight decrease in water quality results in a sharp increase of the mortality rate (pessimistic view).

A set of such curves cannot be constructed in a deterministic way. Perhaps a fishery biologist who is familiar with pollution effects on fish would be willing to express his subjective judgment in form of such graphs. The curves in Figure 30 are hypothetical at this point in time and have not been included in the model presented in this paper.

CHAPTER VIII

DISCUSSION AND CONCLUSIONS

In this thesis an attempt was made to describe potential pollution problems in the Lower Fraser River and to delineate what effects a decrease in water quality may have on salmon. It was argued that environmental degradation should not have to be proven beyond a reasonable doubt before correcting measures are taken. Pollution is a gradual process and increases as population and urban industrial activities increase. When planning present pollution abatement programs, we have to consider uncertainties. Environmental strategies have to be preventive rather than corrective.

We have just begun to understand about the danger of some modern synthetic chemical products and their persistence in the environment. The accumulation of toxic materials such as heavy metals, PCB's, and pesticides in some lake and stream sediments in Ontario should be an early warning signal to the decision-makers who are responsible for water quality in British Columbia. Oil pollution is a possibility in the coastal waters as soon as tankers start transporting Alaskan oil along the Pacific coast to refineries in Western Washington. Off-shore oil drilling on the coast of Washington is considered and might cause oil spills as well. Also, the past has shown that there are adverse environmental and ecological effects associated with most large-scale engineering efforts such as mining and logging operations in the upper watershed of a river or increased harbour activities in the estuary. We certainly have the capacity to significantly alter ecological systems but in most instances we are not able to predict the extent and nature of such changes.

In the case of the Fraser River studies conducted during the past three years by Westwater Research Centre showed that waste loadings to the river are increasing and that composition of the waste water is becoming more complex. Westwater's studies pointed out potentially harmful pollutants, where to look for them, and what control options are available to the decision makers. Water quality was found to be much lower in some tributary sub-basins than in the main river. Also, the accumulation of some substances found in sediments or in the tissue of bottom dwelling organisms is a matter of concern, as this may have long-term biological effects. For example, the elimination of smaller stream organisms may be largely undetected but will be critical for the stream's capacity to sustain fish some of which are of great commercial and recreational interest. Various planned developments could place a heavy demand on the mudflats and marshland areas, thus changing the land use pattern in the estuary. With our present understanding of the complex interrelationships in the Fraser's ecosystem we are not able to quantify most consequences that increased waste loadings or a reduction in habitat may have on the productivity of the Fraser estuary.

Decisions with regard to land use, industrial development, effluent standards, waste treatment technology and so forth, have to be made now in order to perserve water quality in a rapidly developing estuary. In this thesis salmon has been identified as a major user of the Fraser River which requires water of good quality. The Fraser River system is one of the world's largest producers of salmon. At present time, a salmon enhancement program with possible expenditures of hundreds of millions of dollars is in its planning stage. For a fisheries manager, therefore, it seems to be quite important to have an understanding of the dynamics of a salmon run. He would like to know in which life stage of the salmon he should concentrate his efforts and increase survival rates, or where he has to carefully monitor conditions in order to avoid degradation of the salmon's habitat.

In this thesis a specific sockeye run was chosen to apply a new method whereby the life cycle was divided into five major life stages. The area of uncertainty in each life stage was indicated by upper and lower bounds. As distribution function a normal distribution function was assumed between these bounds. This can be changed as soon as more data allow analysis of the distribution function. Mathematically the five life stages were combined by multiplying matrices. As a result, an expected return value for each given escapement value was computed and the range of uncertainty was indicated.

The advantage of having the life cycle divided into life stages lies in the fact that changes in each life stage due to enhancement or pollution effects can be built into the model. The model then calculates the overall effect of such changes on adult return. For the present study the possible increase in mortality due to poor water quality conditions in the estuary was investigated. It was assumed that due to sublethal effects the number of successful spawners after migrating through increasingly polluted estuarine waters would decline. Also, survival rates of juvenile sockeye in the ocean were assumed to be lower after being exposed on their downstream migration to sublethal concentrations of pollutants in the Lower Fraser River.

In this study water quality was not directly related to survival rates as too little is known about sublethal effects. Increase in mortality rate was the only parameter used to reflect worsened water quality conditions. The simulation results indicated that at a mortality rate of about 30% a probability of 5% existed that the simulated salmon stock declined to such a low level that it might not be able to recover. The validity of the numbers can be debated. Factors such as distribution function and area of uncertainty expressed by its standard deviation influence the actual numbers. As more data become available and as we gain more knowledge about pollutant concentrations and their physiological effects on fish this analysis can be reviewed and numerical values be updated.

One problem to be further investigated is the prediction of future water quality conditions without having to forecast loadings of each single pollutant. A water quality index to be developed for salmon as a major water user has been proposed. Such an index could be projected on the basis of information about population growth, industrial development of the region, future waste disposal methods and so forth. As long as we cannot quantify sublethal effects in an easy manner, it may be necessary to hypothesize various relationships between such a water quality index and increases in mortality rate. Subjective judgment by the expert has to be used where analytical data are not available.

The intention of this thesis was to discuss the many uncertainties and complexities encountered by the decision maker when managing a large river system for multiple water use. Increasing waste loadings and shoreline land demands are threatening the salmon in its abundance. Obviously it is not possible to have a very productive salmon river and a cheap waste carrier at the same time. We cannot industrially develop the mudflats and marshland areas without reducing the habitat of fish and wildlife. The salmon has disappeared from many rivers in the world because of severe degradation of its environment. The large amounts of natural material carried by the Fraser which give the water often a very muddy appearance is no excuse for using the river as a dumping ground for complex and often undegradable wastes from household and industries.

In ancient days the Bella Coola Indians used to apply capital punishment to anyone who contaminated the river by throwing waste into it. They recognized the importance of the water for sustaining their livelihood and way of life. It should also be mandatory for us to provide treatment for all discharges to the river such that toxic substances are removed or their concentrations are reduced to a level which does not impair the physiological well-being of fish. Such water quality will also benefit man in his various recreational activities.

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APPENDIX 1

LOGNORMAL VERSUS NORMAL DISTRIBUTION

Very often the uncertainty in a physical variable results from the fluctuation of many factors each of which is difficult to isolate and to observe. In the case of salmon, for example, some life stages are governed by various environmental factors, such as temperature, oxygen, water flow, lake productivity (in itself a composite of many factors), predation, and so forth. If we know the mechanism by which these factors affect the variable of interest we can derive the distribution function for this variable without studying in detail the individual effects. If the individual causes are additive in nature application of the Central Limit Theorem will lead to a normal distribution; if they are multiplicative in nature we will arrive at a lognormal distribution (7). For both cases it is necessary that the number of causes be either large or that each of them have only a small effect on the sum (product). In other words, none of them should be dominating.

A normal distribution can be written in its standard form as:

$$(1) \quad f(x) = \frac{1}{\sigma_x \sqrt{2\pi}} \quad \exp\left[-\frac{1}{2}\left(\frac{x - m_x}{\sigma_x}\right)^2\right]$$

σ_x, the standard deviation, and m_x, the mean value, are two parameters which describe this distribution function (Figure 1A). The normal distribution is symmetrical with regard to the mean value.

In the case of this study a normal distribution function was assumed to describe the values between upper and lower curves. The distance between mean and upper or lower bound was assumed to be two standard deviations. The area under the normal distribution function is defined as 1.0. By cutting off the tails one has to introduce a correction factor which normalizes all computed probabilities. Using two standard deviations this factor is $\frac{1}{1 - 0.0455}$.

While a normal distribution results from the summation of many small effects, it is desirable also to consider the distribution function which arises as the result of the multiplative nature of random events. A frequently used example is that of sediment transport in streams where the final size of a particle results from a number of collisions of particles of many sizes travelling at different velocities. Each collision reduces the particle by a random proportion of its size at the time. Therefore, the size Y_n after the n^{th} collision is the product of Y_{n-1} (its size prior to that collision) and W_n (the random reduction factor). Mathematically, we can formulate this chain process as:

(2) $Y_n = Y_{n-1} W_n = Y_{n-2} W_{n-1} W_n = \dots . Y_o W_1 W_2 \dots . W_n$

The processes governing the salmon's life cycle can be thought analogously. As an example, let us consider the life stage Eggs desposited/Fry produced. Various random processes affect this life stage. The final number of surviving fry will be the number of eggs initially deposited multiplied by the survival rate after each random process has occurred. For example, the number of eggs which have survived an unfavourable water temperature or a low oxygen concentration may also be subjected to washouts due to extreme flow conditions or predation by other fish, or may, in addition, become exposed to severe ice conditions.

In all these cases where the variable of interest Y can be expressed as the product of a number of variables we can apply the following. Taking the natural logarithms of both sides in equation (2) leads to:

$$\ln Y_n = \ln Y_o + \ln W_1 + \ln W_2 + \ldots \ln W_n$$

Since the W_n are random variables, the functions $\ln W_n$ are also random variables. Applying the Central Limit Theorem, one can say that the sum of a number of these variables will be approximately normally distributed. In this case, then we expect ln Y to be normally distributed. A random variable Y whose logarithms are normally distributed is said to have a lognormal distribution.

The most common form to write the lognormal probability distribution function is:

$$(3) \quad f(y) = \frac{1}{y\sqrt{2\pi}\ \sigma_{\ln y}} \quad \exp \left\{- \frac{1}{2} \left[\frac{1}{\sigma_{\ln y}} \ln\left(\frac{y}{\tilde{m}_y}\right)\right]^2\right\}$$

where $\tilde{m}_y$ is the median of the random variable Y and $\sigma_{\ln y}$ is the standard deviation. The median $\tilde{m}_y$ is defined as that value below which one-half of the probability mass lies.

In comparison to a normal distribution a lognormal distribution is skewed in shape. Depending on the value for $\sigma_{\ln y}$ this skewness can be more or less accentuated. Figure 2A illustrates some cases. The lognormal distribution is often used as a model where the observed data are found to be skewed. In order to verify a lognormal distribution governing some stages in the life cycle of sockeye salmon, more data than presently available are required to do a statistical analysis.

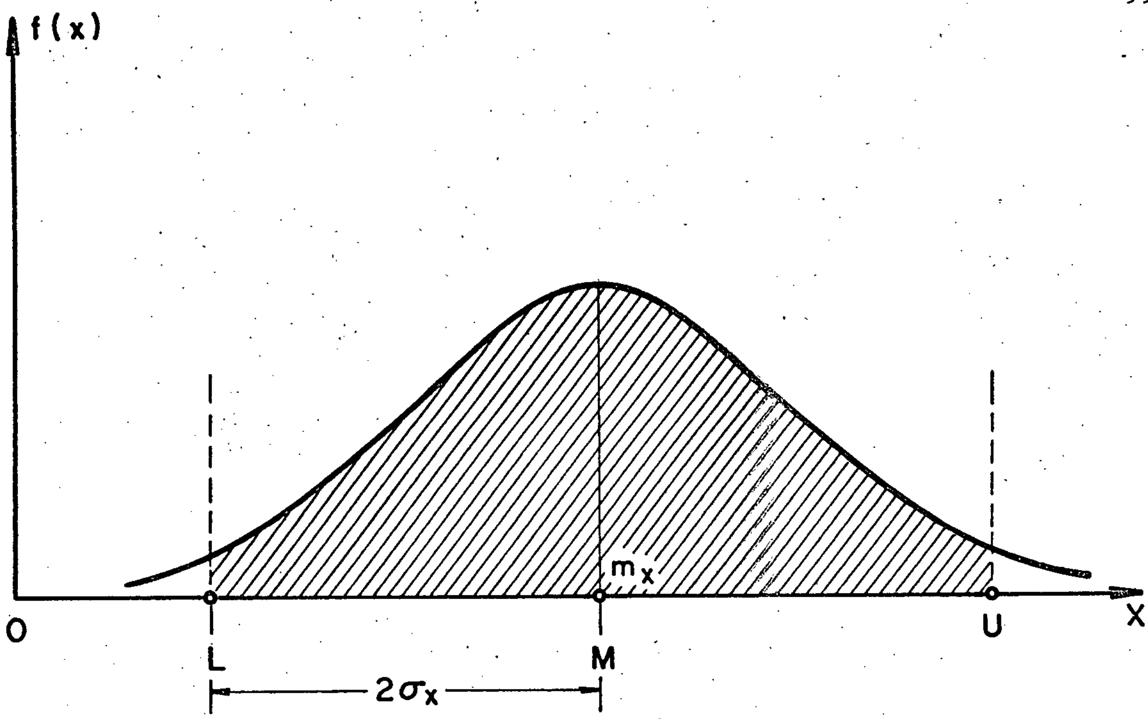


FIG. 1A NORMAL PROBABILITY DISTRIBUTION.

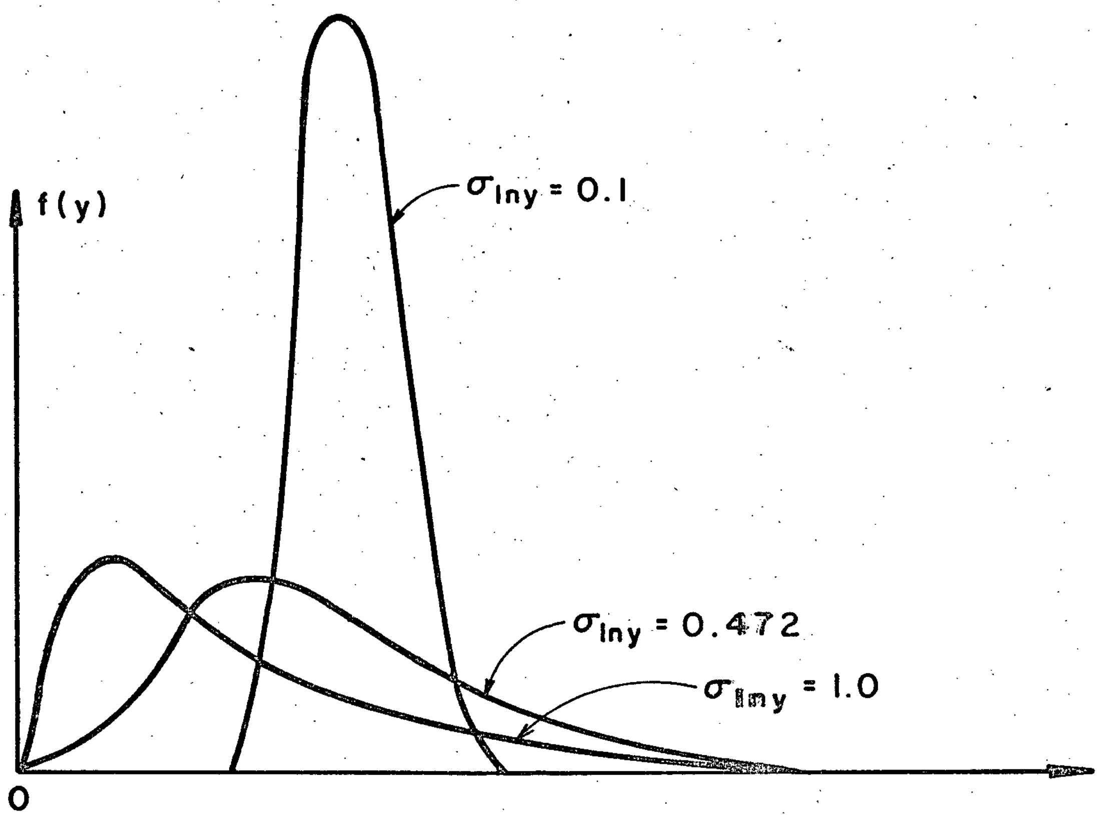
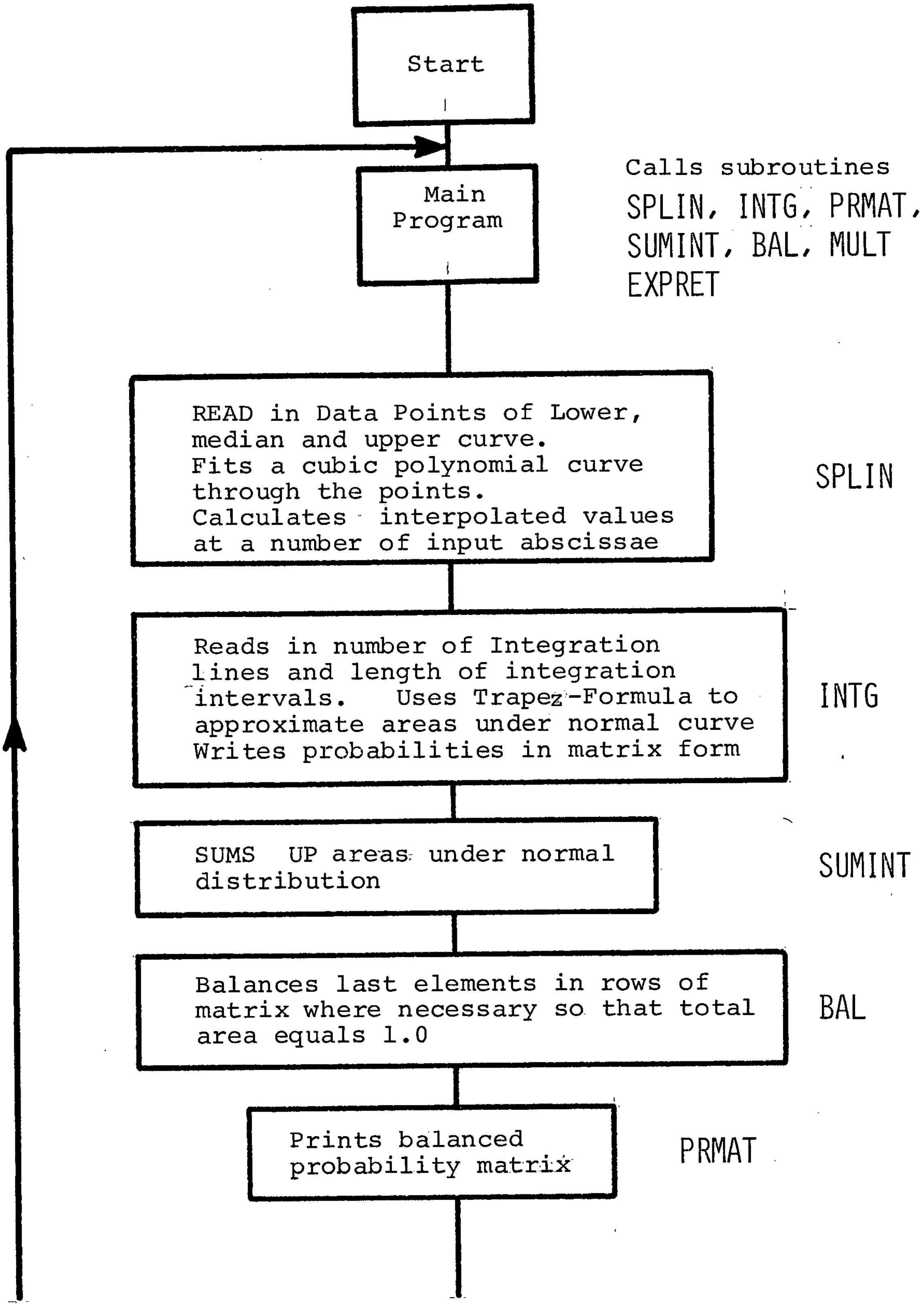
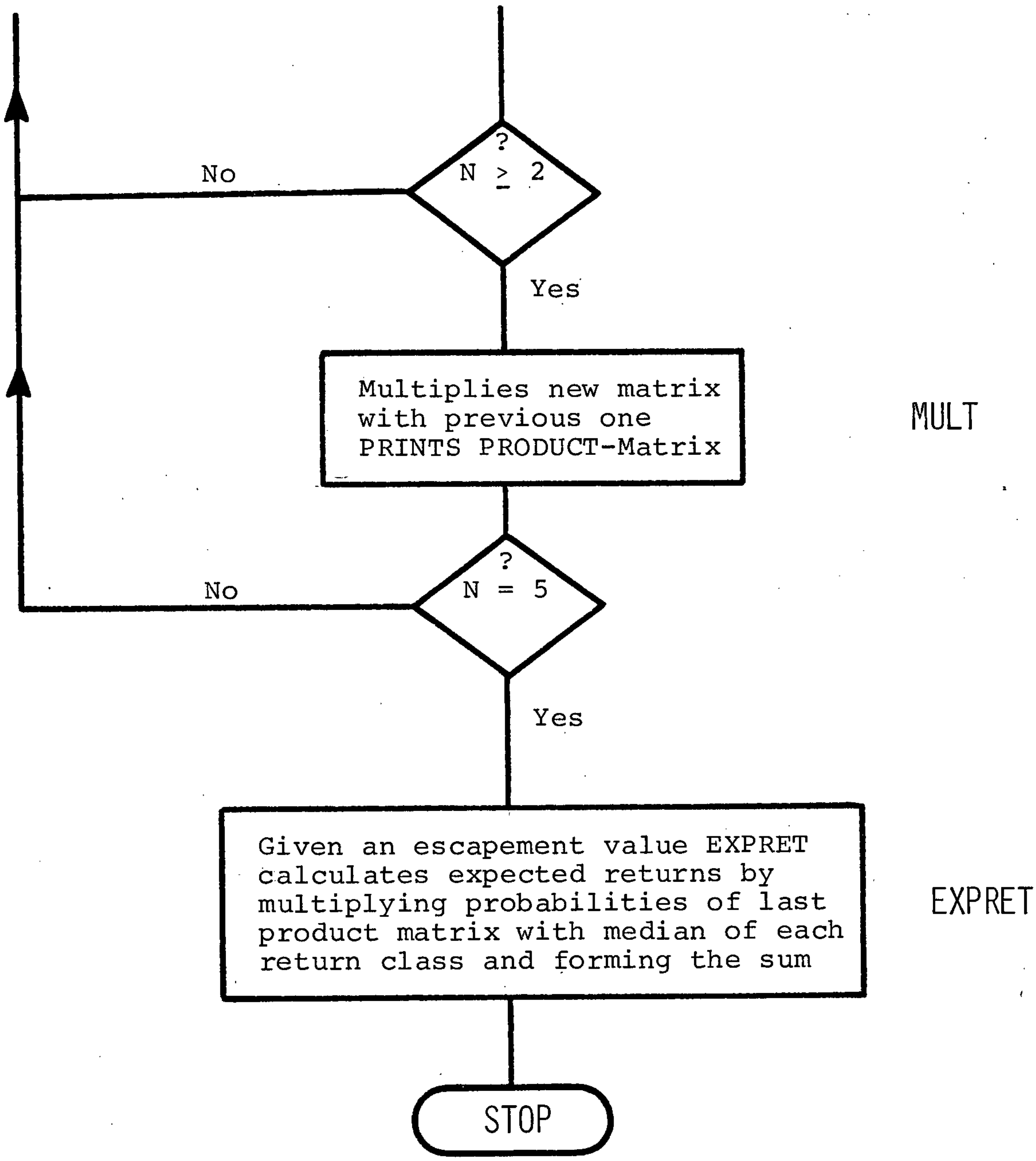


FIG. 2A LOGNORMAL PROBABILITY DISTRIBUTIONS FOR DIFFERENT STANDARD DEVIATION VALUES. (After Benjamin and Cornell.)

Appendix 2

Flow Chart of the model




No
?
N ≥ 2
Yes
Multiplies new matrix with previous one PRINTS PRODUCT-Matrix
MULT
No
?
N = 5
Yes
Given an escapement value EXPRET calculates expected returns by multiplying probabilities of last product matrix with median of each return class and forming the sum
EXPRET
STOP