Catch Me if You Can: A Projection of Southeast Alaskan Coho Salmon Populations

Control Team 51

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Abstract

We model the future of the Coho salmon stock for five rivers in Southeast Alaska and generalize our findings to the entire region. To do so, we implement a combination of two standard quantitative fish dynamics models, the Ricker Model and the Baranov Catch Equation, adapted to mimic the Coho life cycle. Our model estimates salmon stocks based on the parameters of initial stock size, environmental conditions, and amount fished. We discuss the limitations of each model. From the model, we conclude that an unfavorable shift in either fishing or human-imposed environmental hazards will result in depletion of the salmon population. To mitigate this effect, we propose that the State of Alaska evaluate stricter environmental policies and establish a fishing quota system.

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1 Introduction: Ms. Jones always said "Reduce, Reuse, and Recycle"

In elementary school geology we all learn about the importance of conserving non-renewable resources–oil, water, coal–because when we use them all up, they will be gone forever. It is usually in the same lesson that we learn to recycle paper, because deforestation has depleted so much of the world's natural woodlands. But trees grow back; it just takes a long time, and the rate at which we log forests is faster than they can be replenished. In fact, it is the same with other "nonrenewable" resources: oil and coal will eventually compound again, though it may take thousands of years, and water will clean itself of pollutants. This brings about the question: **What constitutes a "nonrenewable" natural resource?**

From Webster's New Millennium Dictionary we take the definition:

nonrenewable resource: Any natural resource from the Earth that exists in limited supply and cannot be replaced if it is used up; also, any natural resource that cannot be replenished by natural means at the same rates that it is consumed.[1]

This definition is similar to the concept of *effectively nonrenewable* proposed by Barton, Reitan, Kieffer, and Palmer. Says Barton et al., "However, if the rate of resource consumption is high, even 'renewable' materials can become effectively nonrenewable."[4] Using this conception of nonrenewable, one could claim that with a rate of consumption greater than the rate of reproduction or replenishment, any resource could be considered nonrenewable. Certainly this is the case with our depleted woodlands.

Fish is a staple source of protein in the diets of nearly all coastal societies and plays a large role in the world economy. Both fish catch and fish consumption is project to increase drastically over the next 30 years.

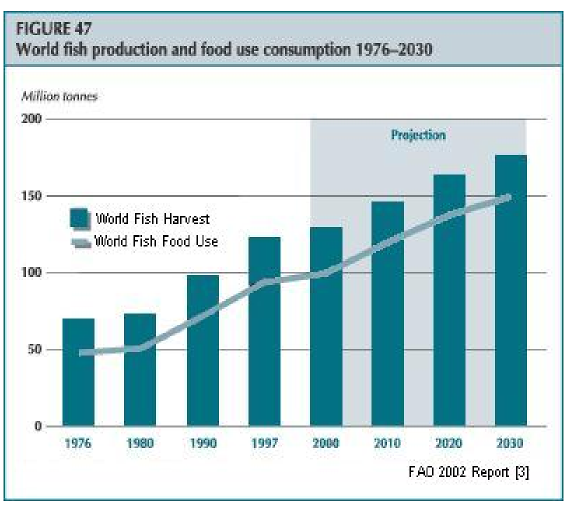


FIGURE 47
World fish production and food use consumption 1976–2030

Unfortunately, such increase is not necessarily a good thing for all parties involved. As demand has increased, overfishing has resulted in the endangerment of many species of fish. Making the problem worse is the loss of habitat that handicaps the fish in the reproduction/consumption battle. The real losers, however, will be the economies of the world when the results of this unintentional "tragedy of the commons" is felt.

In particular, we choose to inquire into **quantitative population dynamics** of the wild population of Southeast Alaskan Coho Salmon. While Coho populations in other parts of the Pacific have suffered in recent decades (with, for example, the Coho population of the Snake River in Washington having been declared extinct by the Fish and Wildlife Service [5]), the Coho population of the Southeastern Alaskan Peninsula have done comparably well for three reasons:

- **Favorable natural environment conditions.** Fluctuations in natural environment, especially current, water temperature and water level have a large effect on the prosperity of the species. Such conditions have favored Alaskan salmon over Pacific Northwest Salmon for approximately the past two decades. As a general rule, in the years before, during, and after El Niño, environment conditions tend to favor Alaskan salmon.
- **Low level of human imposed environmental hazards.** Human imposed environmental hazards such as a dams, polluted streams, and eroded river banks have the effect of not allowing salmon to reach suitable spawning grounds. Because Alaska is quite underdeveloped compared to other salmon habitats, these human imposed hazards have not greatly affected the fish population to date.
- **Close governmental controls protecting against overfishing.** Through treaties such as the Pacific Salmon Treaty between the U.S. Federal Government and the Canadian Government and through careful control by the Alaska Department of Fish and Game, agencies were proactive from an early stage about protecting Alaskan salmon.

However, we would hypothesize that an unfavorable shift in any of these areas without suitable compensation would translate into depletion of salmon population.

2 Objectives

- Construct a realistic model of the dynamics of the Coho Salmon Population accounting for both environmental conditions and amount harvested.
- Use the model to predict the future of the Coho population given various levels of fishing and future environmental trends.

- Use the model to calculate a maximum allowable annual harvest and still ensure enough salmon will spawn to replenish the population (herein termed "maximum sustainable yield").
- Create a fair and practical policy to allocate the available catch to the fishers of the region.
- To consider alternatives within the region to wild harvested salmon.

3 Terms

The terms defined here are specific concepts in ichthyology and quantitative fish dynamics. In several cases multiple terms may be found in the literature to express the same or similar concepts. We will define the term that we prefer and list alternate terms. In a few other cases we use a term slightly differently than it is used elsewhere.

Stock A countable population of fish sharing the same fishery and/or spawning area. We use this term interchangeably with fish population. Some literature attaches a more precise meaning to the term *Stock* as specifying fish of a certain maturity, but note that we *do not* attach any such connotation.

Smolt The number of fish in a given *stock* that survive until a level of maturity when they are prepared to begin migration to a marine habitat.

Run The group of fish in a fishery that survive until maturation and prepare to migrate back to their fresh water habitats to spawn. Referred to in data as *Run Size* for number of fish in a run.

Escapement The portion of a *run* that is not fished and survives to reach the spawning grounds or hatchery. Also sometimes *Spawning Population* or *Spawners*.

Recruitment The group out of those spawned by a given *escapement* that survive to a level of maturity when they are prepared to begin migration to a marine habitat. In our usage of the terms, this is **IDENTICAL** to the term *smolt*, but we specify that the *recruitment* from year x is produced from *escapement* of year x and then becomes the *smolt* for year $x + 1$. For example, the *recruitment* from 1995 in a single fishery are the same as the *smolt* for 1996.

Mortality The NUMBER of fish in a *stock* that die between the stage of being in the *smolt* and in the *escapement*.

Natural Mortality The NUMBER of fish that die as a result of any cause *other* than being fished.

Instantaneous Natural Mortality A **rate** calculation for natural mortality. Calculated as a solution to the differential equation given in the Baranov Catch Equation.

Exploitation Rate The PERCENT of the fish out of a *run* that are harvested. Also *Harvest Rate* or *Catch Percent*.

4 Southeast Alaskan Coho Salmon

Southeast Alaska is the region of coastline and offshore islands belonging to the United States bordering British Columbia. Sometimes the region is referred as the Alaska Panhandle, but we will call it Southeast Alaska Throughout. The primary industry of the region is salmon fishing, but tourism and logging also contribute. The group of several thousand islands making up the Alexander Archipelago off the shore offer protection to the inland coastal waters from large waves, making both an ideal environment for salmon and relatively easily navigable waters for fishing vessels.

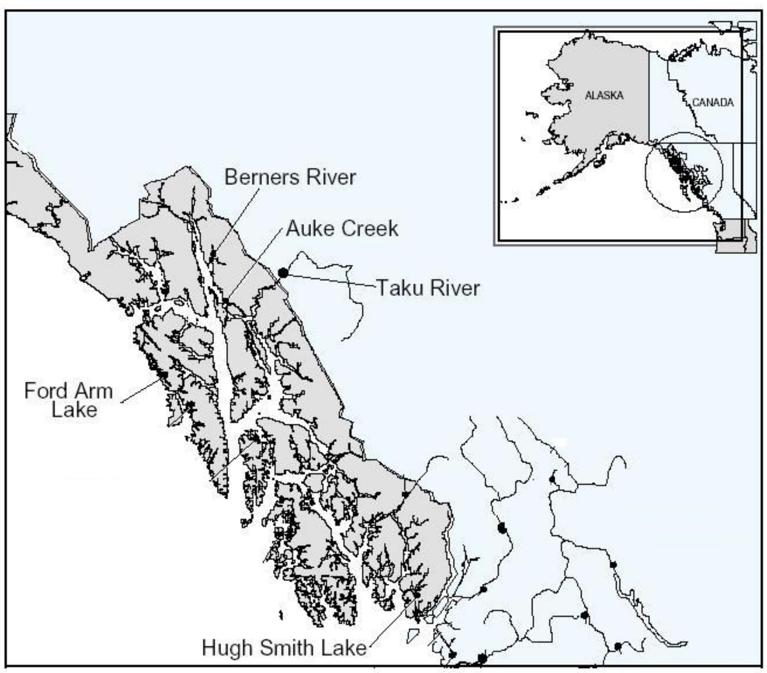


Figure 1: The Southeast Alaska region, with the rivers and lakes which we analyze [10].

4.1 The Importance of Fishing to Alaska and the Southeast

In 1994 commercial fishing produced $223.6 million in income for residents and employed 7,529 people, accounting for around 45% of the private sector employment. If the Southeast Alaska region was an a 51^{st} state, it would be the second largest seafood producer in the United States, a close second only to the remainder of Alaska[8]. As for the importance of Coho salmon in the region, in 2004 an estimated 2,755,000 Coho were fished in the region, over half the state-wide total of 5,066,000 Coho[9].

4.2 The Life Cycle of Coho Salmon

The life cycle of the Coho salmon lasts approximately three years. Mature salmon (the *escapement*) return to the same streams in which they themselves were spawned between July and November, depending in part on regional temperature. They are a semelparous species, meaning that they die after they spawn. Juvenile salmon (the *smolt*) make their way back to the ocean approximately twenty months after their embryos emerge from the gravel riverbeds in May or June. They spend eighteen months in the ocean before they prepare to return to their spawning streams. They are now the *run*, and it is during the beginning of this return trip to their spawning grounds that they are fished.[11]

Assumptions regarding the life cycle of the Coho:

- The life cycle lasts three years.
- Juvenile salmon, **smolts**, spend 3 years subject to natural mortality, assuming the natural mortality to be constant across freshwater and ocean over time.
- Salmon are subject to fishing mortality only once in their lifetime. The fisheries catch salmon on their way back to the spawning rivers, so this is a reasonable assumption.

4.3 Coho Salmon Data Sets

In order to construct our model, we use data sets from a 2003 paper, "Stock Status and Escapement Goals for Coho Salmon Stocks in Southeast Alaska" by Leon Shaul, Scott McPherson, Edgar Jones, and Kent Crabtree, a Special by the Alaska Department of Fish and Game[10]. The data used gives counts of the salmon stock from several different fisheries in the region: number of *smolt*, *catch size* by fishing method (troll, seine, gillnet, sport, etc.), and *escapement*. Also Shaul et. al use this data to calculate the other variables: *run size* (used interchangeably with *total return*), *exploitation rate* (referred to in other literature; we use this term interchangeably with *harvest rate*. These data are given by the formulas:

$$\text{run size} = \text{escapement} + \text{catch size}$$

$$\text{exploitation rate} = \frac{\text{total catch}}{\text{run size}}$$

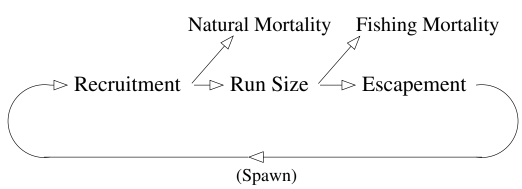
From the complete set of data we select five fisheries for which the most complete and regionally representative data is given. These are **Auke Creek**, **Berners River**, **Ford Arm Lake**, **Hugh Smith Lake**, and **Taku River**. Using data from these fisheries, we set parameters for our model, make future predictions for each river in the model, then, under the assumption that **over time, the behavior of the coho populations from these fisheries is roughly representative of behavior of the population from the entire region**, make predictions about future salmon populations from the region.

5 Developing a Model

5.1 Conceptual Model

We model Coho population as a feedback loop of a simplified life cycle: salmon spawn and die; the eggs hatch and grow into smolts; the juveniles mature into adults; the mature adults are subjected to fishing upon their return to spawning streams. The entire process takes three years. The number of salmon that become spawners for the next generation is then determined by environment and catch. Environment modulates both how many smolts survive prior to fishing, and the how many eggs survive to become smolts.

Coho Life Cycle



Each class of salmon that return to spawn are considered stock and subjected to a standard escapement-recruitment model (Ricker, discussion below). From Ricker's model, we calculate the number of recruits that are available for fishing the next year. Natural mortality is computed using a version of Baranov's Catch Equation (see below), modified for a finite fishing season, and the returning salmon are the stock for the next year.

5.2 Ricker Model

Since we are interested in overall trends of the population of salmon over time, and not specific estimates of the number of recruits for any given year, we model recruitment based on a escapement-recruitment relationship, namely Ricker's model, rather than a Markov process. Ricker's model is preferable to similar stock-recruitment models (such as the Beverton-Holt model) for modeling Pacific salmon such as Coho[22].

Ricker's model (in one form) is given by the equation

$$R = Se^{a(1-S/b)}$$

where R is the recruitment, S is the stock, and a and b are parameters governing the shape of the curve. Biologically, a is proportional to reproductive capacity, while b is a measure of density-dependence. For a derivation, see Quinn and Deriso.

5.2.1 Implicit Assumptions and Limitations of the Ricker Model

- Ricker's model explicitly assumes that when there is no stock, there are no recruits. This means that the population is implicitly closed – there are no immigrations from other populations. This is a reasonable assumption in our case because every Coho salmon returns to its place of origin.
- Spawning stock size is inherently difficult to measure, and the escapement-recruitment analysis is extremely sensitive to errors in spawning stock size (Hilborn and Walters, Walters and Ludwig). Although our data is the official data used by the state of Alaska to determine fishing policy, Hilborn and Walters assert that the biases in the model, mainly underestimating the correllation between recruitment and stock size, have led to overfishing. In choosing a escapement-recruitment model, we may be falling subject to the same biases.

5.2.2 Estimating Parameters for the Ricker Model

For each of the five rivers, we fitted the Ricker curve to the data sets using a least squares approximation to find suitable values of a and b following the procedure described in Hilborn and Walters[22]. We begin by rewriting

$$R = Se^{a(1-S/b)}$$

as

$$log(\frac{R}{S}) = a - \frac{a}{b}S$$

and then treating the latter equation as a linear regression

$$y = b_0 + b_1 X + w$$

where $y = log(R/S)$ is the dependent variable, $b_0 = a$ is the intercept, $-a/b$ is the slope, and w the residual.

Values a and b derived from the data by applying the Least Squares Method

	a	b	σ
Auke	2.93	2970	1450
Berners	3.66	58600	61400
Ford	3.87	19900	27600
Hugh	4.42	4680	8700
Taku	3.28	745000	463000

5.3 Modified Baranov Catch Equation

We want to model mortality of fish until their return to spawning grounds. To do so, we use a simple deterministic model of fishing and modify it to account for the specifics of the Coho fisheries industry.

The standard Baranov Catch Equation is given by

$$C = \frac{F}{Z} N_0 (1 - e^{-Z\tau})$$

where C is the total catch, F is the instantaneous fishing mortality, N_0 is the initial population, $Z = F + M$, where M is the instantaneous natural mortality, and τ is the maximum age, which by assumption is three years.

This is the solution of the differential equation

$$dN/dt = -FN - MN$$
$$N(t) = N_0 e^{-Zt} [18]$$

5.3.1 Implicit Assumptions and Limitations of the Baranov Catch Equation

- Mortality during fishing season is solely due to catch and not to natural mortality.
- Natural mortality is constant over time. If we consider environmental variation to be random over time within bounds, then these environmental effects, averaged over time, result in the same error margin as those for a constant mortality model.
- Catch is proportional to stock. We assume that fisheries employ a risk-averse harvest strategy, mainly one in which catch is proportional to stock. This maximizes the logarithm of the catches [17]. This is equivalent to assuming that fisheries strive to sustain maximum profit over the long run.

5.3.2 Estimating Parameters for the Baranov Catch Equation

Coho are only subject to fishing once in their lives, so we can rewrite our expression for N as the number of fish left after natural mortality minus the number of fish caught. We make the simplifying assumption that no natural mortality occurs after fishing season, since salmon spawn relatively soon afterwards.

Thus for a limited fishing season, with $\tau = 3$ years (the duration of the Coho life cycle), we model the escapement as

$$\text{escapement} = (N_0 e^{-3M}) - C$$

The first term on the right-hand side gives the run size, where N_0 is the recruitment and M is the natural mortality value. We calculate M by solving for the formula

$$\text{Run} = N_0 e^{-3M}.$$

The solution is

$$M = -\frac{\ln(\frac{\text{Run}}{N_0})}{3}$$

We calculate C by averaging the percent of the total run caught, and assume that fisheries will strive to maintain this percent, following our third assumption. We take M to be the average of mortalities over time, and assume this also to be constant, neglecting environmental factors.

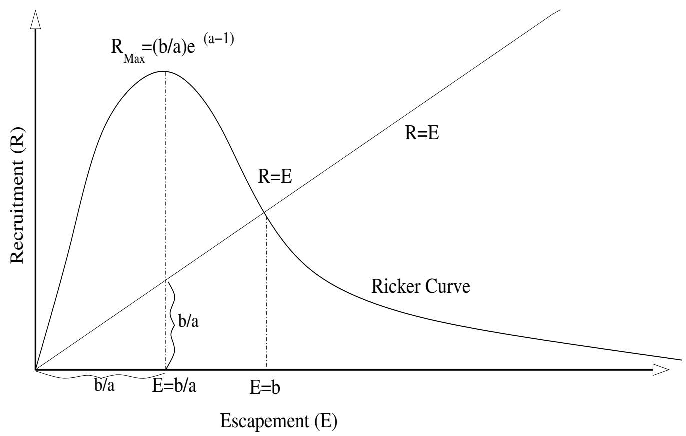
Values of M for the Modified Baranov Catch Equation

	Average Catch	M
Auke	548	0.5597
Berners	23200	0.6024
Ford	4910	0.7551
Hugh	2870	0.7093
Taku	88600	0.7136

‘

5.4 Using the Catch to obtain the MSY

There are two humanly modifiable variables in our model: human-imposed environmental change (i.e. dams, pollution, etc.) and yearly catch. The easiest to modify is catch. As we will show, it is possible to regulate the amount of catch so that it spawns the maximum recruitment over time. First, let us examine the qualities of the Ricker curve.



The most interesting point is where $E = \frac{b}{a}$. If the abundance of Coho reaches this value, then we obtain the maximum number of recruits. This is commonly referred to as the Maximum Sustainable Yield (MSY). Furthermore, if

$$C = R_{\max} - (\text{Nat.Mort}) - \frac{b}{a},$$

then the next year's escapement will equal b/a. This produces a cycle that maximizes catch for a stable population. Written another way,

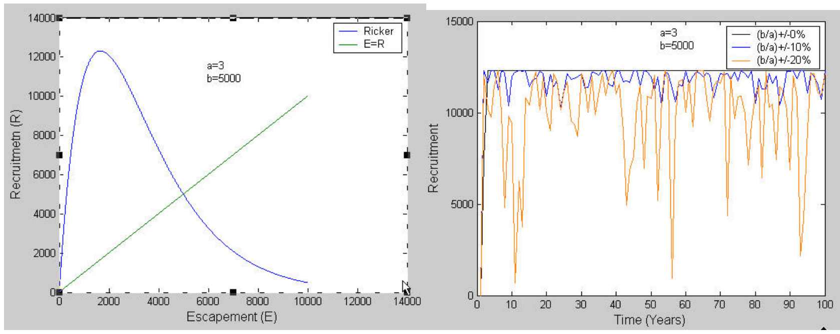
$$C = (C\%)\text{run},$$

where $C\% = \frac{C}{\text{run}}$. This form is used to compute the IFQ, as discussed later in the paper.

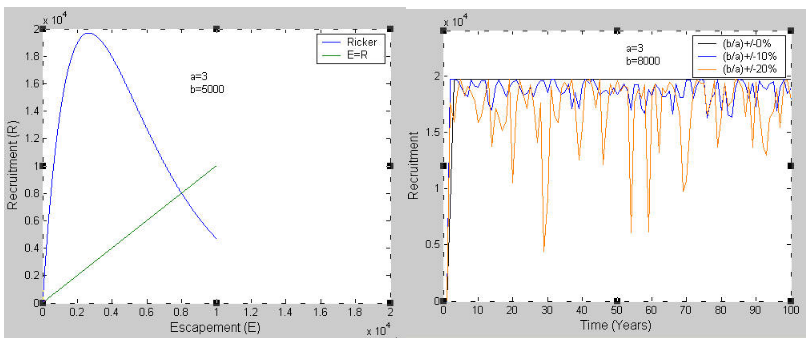
This is an ideal model. In reality there is uncertainty in the mortality, which effects the predicted value of C. This in turn creates uncertainty in the escapements about b/a. If the uncertainty is large enough, the model will become unstable and produce an oscillatory abundance from year to year, which increases the chance of extinguishing the Coho. Thus it is important to know more specifically what it means for an uncertainty to be large.

The uncertainty is dependant on many variables. The two most important are the concavity of Ricker curve at $E = b/a$ and the natural mortality of the Coho. However, as a first approximation, if the percentage error with respect to Escapement (i.e. b/a) is held constant between multiple Ricker plots, they produce approximately the same ratio of Recruitment to Max Recruitment. Thus if the percentage error is ϵ and $b' > b$, then the standard error, $\delta_{b'} = \epsilon(\text{Escapment}) = \epsilon(\frac{b'}{a})$, has the property that $\delta_{b'} > \delta_b$. This can be seen in the following graphs of Escapement versus Time.

Modeled Recruitment using the data



Ricker curve when $a = 3$ and $b = 8000$ (left), and the Recruitment with three different errors (right)



It is also worth noting what occurs when

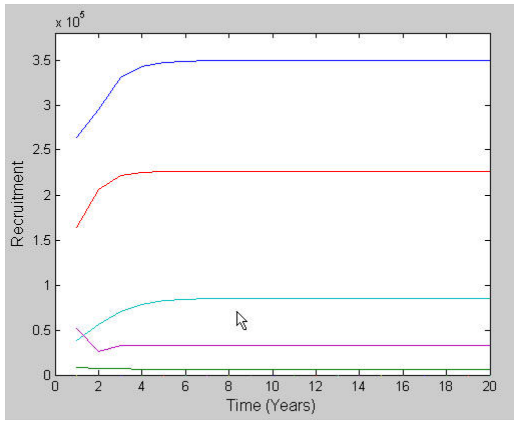
$$C > R_{\max} - (\text{Nat.Mort}) - a/b.$$

In this case, the recruitment and escapement will become oscillatory and there is no way to efficiently bring the value of escapement up unless C=0 for a duration of time until it once again reaches b/a.

What should be done if the Coho are initially less than $b/a - (nat.Mort)$? Among possible policies, the most direct is to make C=0 until it reaches this point of MSY.

6 Consequences of the Model

Predicted Recruitment assuming continuation of current catch and natural morality conditions



The book *Upstream*, a report by the National Research Council on the the status of salmon stocks in the Pacific Northwest, lists a number of reasons for the precipitous decline in fish population. Aside from fishing, the list is dominated human environmental interventions, such as forestry, industrial activities, urbanization, and dams[16]. Currently, these effects largely do not exist in Alaska.

Recall our original three hypotheses from the introduction about why Alaskan salmon did well compared to Pacific salmon: favorable natural environmental conditions, low level of human-imposed environmental hazards, and close governmental controls protecting against overfishing. Over the long term, human-imposed environmental conditions are the best predictor of salmon stock, because these are permanent stressors that will affect the stock over an extended if not indefinite period of time. Human-imposed environmental conditions include global warming, dams, foresting, and pollution of riverbeds. For year to year fluctuations in population, environmental conditions are a better predictor because they are more likely to vary from year to year – consider current, water temperature, or river height. Finally, we can consider fishing strictures also important in the long-term forecast of salmon stock, again maintaining the previous assumption of a constant exploitation rate.

How can we model the aforementioned and other environmental factors? We are interested in how the escapement-recruitment relationship (Ricker Model) and the natural mortality rate are modified by environment. However, there are numerous environmental variables, each with an unknown effect on the escapement-recruitment curve and natural mortality rate because the effect a single environmental variable cannot possibly be measured in isolation from the others.

Sticking to the assumption that current conditions are favorable, we test the model for different natural mortality rates over the current average, and see that the model is also sensitive to environmental change that increases mortality rate.

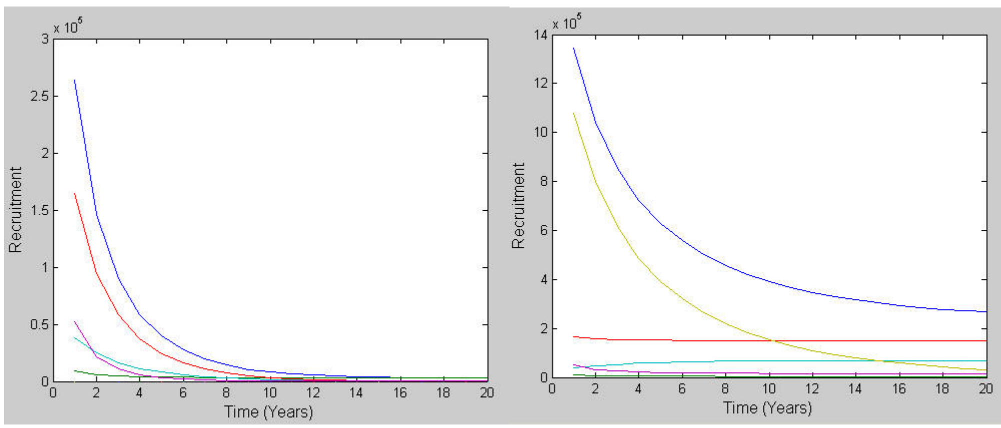
We then explore the effect of introducing negative generic environmental effects of various orders of magnitude (without trying to specify by what or to what degree the environment is being altered).

The figure below left shows what the model predicts with a 15% higher catch rate. Recall the Baranov Catch Equation:

$$\text{escapement} = (N_0 e^{-3M}) - C$$

Environment can affect stock through increasing the natural mortality rate. Here we increase the mortality rate by 25% and show that it results in depletion of the population (Figure below right)

Modeled Recruitment with a 15% higher catch rate (left) and a 25% higher natural mortality rate (right)

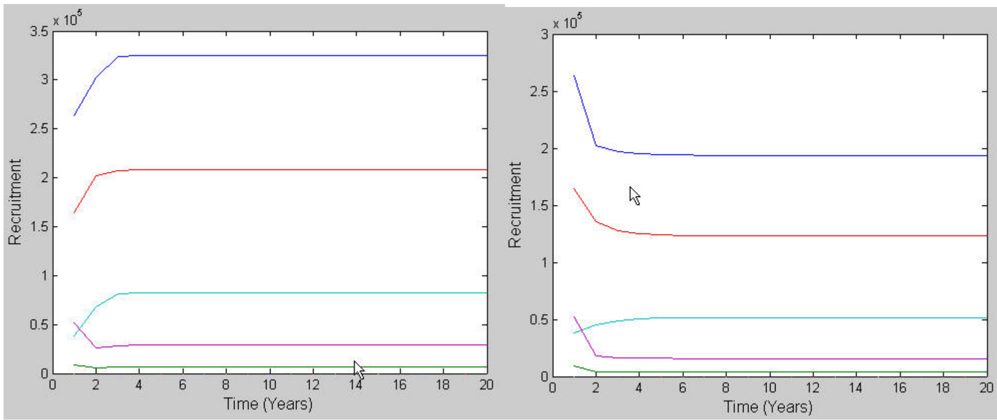


We have said previously that current conditions are favorable for Alaskan Coho. We thus take a and b values over the past twenty years to encapsulate favorable environmental conditions. Environmental variables effect Ricker's model in the following extension suggested by Chen and Irvine:

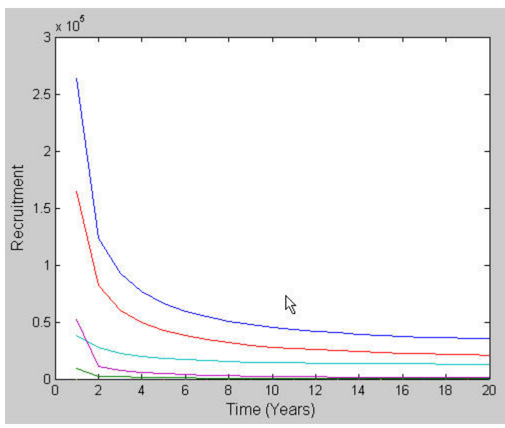
$$R = Se^{a - \frac{a}{b}S + env}[23]$$

The following three graphs are the predicted recruitment for three different values of environment.

Modeled Recruitment with an environmental factor of .1 (left) and .5 on the right



Modeled Recruitment with an environmental factor of 1



Ricker's model is extremely sensitive to negative environmental effects. We thus conclude that the fate of the salmon stock is dependent on mitigating these negative environmental factors, although we cannot say which ones are most germane.

Our model predicts that any one of three factors – increased exploitation rate, increased natural mortality, or unfavorable environmental change in the Ricker model – can extinguish the population on the order of twenty years. (See figures above) There are two levels at which environmental change affects the model: first, in the natural mortality rate, and second, in the exponent of the Ricker model.

If the fisheries maintain their current catch rate, we then predict that human-imposed environmental conditions will determine the future of salmon stocks.

7 Policy Recommendations

While we have seen that under current conditions Southeast Alaskan Coho Salmon runs are not in serious danger and could even be considered to be thriving, we also note from the ever so slight adjustments to environmental constants in the Ricker Model that any negative shift in environment could be devastating to fish populations. Thus we see two areas in which Alaskan lawmakers should effect policy in order to ensure the preservation of Southeastern Coho salmon:

- Ensure the protection of the environment and in particular salmon freshwater habits by limiting development around the Southeastern rivers and the Alexander Archipelago.
- Enact a well advised Individual Fishing Quota (IFQ) system now, before it is needed so that if conditions deem one necessary, it is already in place and functional.

7.1 Preserving Salmon Habitats

In salmon and many other respects, Alaska holds the advantage over other regions such as the Pacific Northwest and British Columbia in that Alaska boasts a vast abundance of resources, but without a dense population or harmful urban centers. As an example, while Southeastern Alaska alone harvested more salmon in 2004 than the states of Washington, Oregon, and California combined[12], but the entire state's population, 648,818 people[6], is only slightly larger than the 570,426 who live in Seattle proper[7], Washington's largest city.

And as we have seen this advantage is felt in the robustness of Coho salmon stocks; as we have seen Alaska's are doing quite well, while Washington's are nearly extinct. The lesson to be learned from this is to be sure that Alaska's freshwater preserves do not become blocked by dams or polluted. As stated above, without further research it is impossible to pinpoint exactly which environmental factors are the most important to control, but we can say that controlling the environment is of paramount importance to the sustainability of Coho salmon stocks. Thus we urge Alaskan policy makers to:

- **Discourage any development which may have adverse effects on freshwater and marine salmon habitat until further research identifies which environmental factors are most crucial**

7.2 Individual Fishing Quotas (IFQs)

An Individual Fishing Quota is an amount of the annual harvest of a particular fish out of a particular fishery that is allocated to a single fisherman or vessel for a season. In their limited implementation IFQs have been shown to be the most effective policy for controlling fish populations [19][20][21]. A 1996 study of IFQs in the Organization for Economic Cooperation and Development (OECD) found that IFQs had brought stability to fish populations in all 13 fisheries for which data was available *and* 23 out of 24 fisheries managed by IFQs had experienced increased profitability [19].

7.2.1 Implementing an IFQ System

There are two philosophies on when it is appropriate to implement an IFQ. First of all, to implement an IFQ system **there must be a predictable run size**, which the Southeast Coho population certainly have. Then a **proactive** stance would be to implement an IFQ system given this alone, regardless of quality of the stock. The advantage to this scenario is that even if fish populations are thriving, the IFQ will ensure that this will continue by acting as an early alarm and hopefully an antivirus for economic and industrial disaster, should the fish populations decrease for any reason. The disadvantage to this system is that implementing an IFQ system often has initial costs, but these should be accounted for over the long term (see **Advantages to IFQs**).

A **reactive** stance would be to only implement an IFQ system when the fish population becomes in trouble. The advantage of this is that the fish population may be fine for an extended period of time and this avoids the costs and bureaucratic hassles of establishing an IFQ. However, the disadvantage is that bringing a population back after it has been overfished is much harder than simply never letting it be overfished and there is much less room for error in establishing the quotas.

- Due to the importance of the fishing industry to Alaska and the devastation that could occur if the runs dies out, we recommend that an IFQ policy should go into affect immediately to control Southeast Alaska's Coho salmon population.

7.2.2 Establishing Total Allowable Catch (TAC)

We make the assertion that **the Total Allowable Catch should be the value that gives the Maximum Sustainable Yield (MSY) for the system (Optimal Exploitation Rate).** Using the algorithm given for calculating the Optimal Exploitation Rate, we calculate this independently for each of the five river systems (under the condition that current environmental trends continue). These rates are the values in the first column of the table below. Then we use the assumption that Coho salmon stocks from these five river systems are roughly representative of stocks from entire region (see **Section 4.2**) to calculate a Optimal Exploitation Rate for the region. To do this we first take the average of the run size for each river or lake (data in second column of table), then use this to calculate a weighted average of the Optimal Exploitation Rate according to the formula:

$$\text{Regional Optimal Exploitation} = \frac{\sum\left[(\text{Optimal Exploit})_i \cdot (\text{Aver Run Size})_i\right]}{\sum\left[(\text{Average Run Size})_i\right]}$$

where the i subscripts indicate a river or lake and we are taking the sum over each of the 5 systems.

	Optimal Catch Percentage	Run Size Average
Auke	0.21	1295
Berners	0.54	31441
Ford	0.36	8077
Hugh	0.74	4174
Taku	0.42	173113
TOTAL	0.44	218099

Catch Percentage found by applying the MSY model

Thus we take .44 to be the Optimal Exploitation Rate for Coho Salmon in the Southeast Alaska region. In the literature, there is great deal of debate over choosing an appropriate Total Allowable Catch. We propose the following to compute Regional TAC using Regional Run Size:

$$\text{TAC} = \text{Run Size} \cdot \text{Optimal Exploitation Rate}$$

Many think that TAC should be some figure less than the Optimal Exploitation Rate as a safeguard against overfishing, being that this is the most compelling argument for IFQs to begin with. Such logic seems valid in fisheries where the stock is severely threatened and IFQs are being implemented as a sort of last resort effort to save the population. However, in the instance of the Southeast Coho, this is currently not the case, and one of the advantages of implementing an IFQ structure now while the stock is strong is that if the TAC is slightly off, the thriving fish population will be able to handle it without devastation, and the TAC can be adjusted for the following year. In the interests of maximum fish harvests, this solution is superior to the alternative of setting a lower TAC.

7.2.3 Allocating Catch Shares

Allocating catch shares has been the recurring sticking point in implementing IFQ systems regardless of fishery location, type of fish being harvested, or method of allocation. One can understand why; assuming each business catches its allocation, raw market share is largely decided by one's allocation. However, as IFQs have become more common and more studied, allocation has evolved and presents a few systems that are the most fair and leave fishing businesses the most appeased.

Allocations should be made as a **percentage** of the TAC. Thus exact number or poundage of fish each business is allocated will vary slightly year to year so that exactly the Maximum Sustainable Yield is taken each year. However such variance should be small in the case of a nearly-constant run size (the goal product of the quota system).

Dividing allocation shares amongst fishing businesses.

In order to preserve market dynamics and not give unfair advantages small or fading businesses, **75% of the shares should be divided based on previous catch history over the past decade**. To do this we use an adaptation of the 'Adjusted Preferred Method' [19] employed with a high level of success in South Australia fisheries. In this method each business desiring shares is assigned a **catch history index** calculated by:

- The *Average* of the business's catch over the previous three years is weighted as 40% of the index score.
- The *Average* of the catch over the three years previous to that is weighted as 30% of the index score.
- The *Average* of the catch over the four years previous to that is weighted as 20% of the index score.
- The *Average* of the businesses highest three catches over the ten year period is weighted as 10% of the index score.

With this formulation the index score has property that:

- the index reflects catch history over an extended, ten year period.
- more weight is given to recent catch to avoid favoring fading businesses.
- consideration is given to high catches, as these likely represent the maximum capabilities of the company.

Using these indexes, as stated above, 75% of the shares will be offered to businesses proportional to the ratio of the businesses index to the sum of all indexes.

In order to leave an opportunity for small businesses to grow and new businesses to enter the market, **the remaining 25% of the shares, and any shares refused by businesses will be sold to any company in a closed-bid auction setting.** Companies will presumably choose to purchase shares based on individual investment/return decisions, and such a model helps maintain the element of free-market capitalistic economy in a largely deterministic system.

Ensuring proper use of allocated market shares.

To avoid share hoarding and to keep large companies from monopolizing the market by sucking up large numbers of shares, and to ensure that the TAC is caught and Coho populations stay balanced, **a fine should be assessed to large numbers of unfished shares** according to the following model:

- a fine equal to **10%** of the market value of any unfished shares totalling more than 10% of the businesses's total allocation.

- a fine equal to **25%** of the market value of any unfished shares totalling more than 20% of the businesses's total allocation.

If it becomes apparent that such fines are not sufficient to ensure integrity, the policy may be amended to increase fines.

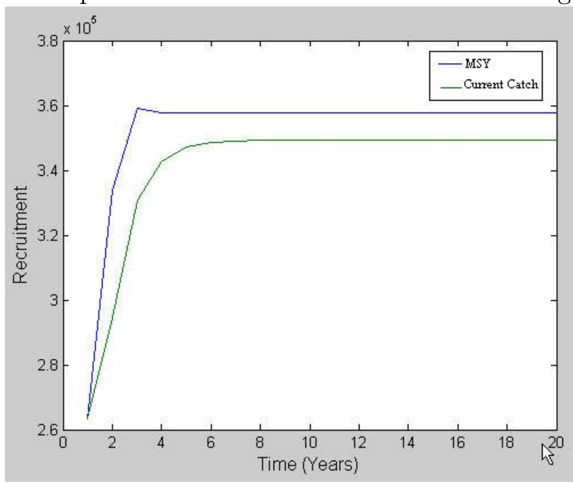
Transferability of shares.

Also to maintain a free and evolving market, **shares may be bought, sold, rented, leased or otherwise transferred**, but the business maintaining ownership of the share shall be responsible to see that the share is fished. Also to a avoid the 'Windfall Effect' of initially allocated shares being sold for high profit margins, **no shares may be transferred until after the completion of the first season under the quotas** and **shares may only be sold for 90% of their market value for the first five years**.

7.2.4 Advantages to IFQs

- **Conservation** IFQs are the best way to ensure that the Total Allowable Catch is not exceeded and that fish populations reproduce at an optimal rate.
- **Conservation** By assigning quotas as percent IFQs are easily adjustable to account for annual changes in environmental conditions.
- **Conservation** Unlike simple TAC quotas, IFQs are assigned by regions, safeguarding against area-specific stock depletion.
- **Fleet Safety** Because each fisherman has his a specific quota for the whole season, it is not so imperative to take the catch as early or quick as possible, so fishing vessels can chose to only fish in ideal conditions and when catch will be good. Repeatedly, this has been found to decrease careless environmental harm (such as lost gear) and help coastal commercial economies because fisherman may choose to take weekends, holidays, or bad weather days off and spend more time in coastal cities and towns[19].
- **Economic** Empirically catch values have been shown to increase after the implementation of an IFQ system. This could be the result of market stabilization and predictability effected by the quota system[19].
- **Economic** Since the IFQ system is designed so that the catch will give the Maximum Sustainable Yield each year, under the IFQ system, an optimally large harvest will be taken, while also ensuring the fish stock for the subsequent year will be high. Environment factors held constant, catch is positively correlated with catch size, so having an optimal stock will imply an optimal catch over an extended period of time. Without the IFQ, catch is taken, but it is unlikely that the subsequent stock will be at its optimal level. (See Figure below.) The result is that even in a thriving system, the costs of an IFQ system will be offset by added profits from an optimal catch.

Graph of Escapement from the MSY model and the original data



8 Alternatives and Technology

The main alternative to wild Coho, and wild salmon in general, is farmed salmon. Farmed salmon have much higher levels of a contaminant known as PCB, primarily because their feed (aquaculture) consists of meal and fish oil made from small wild fish. [13]. Studies conducted by the Environmental Protection Agency conclude that PCBs are likely responsible for myriad negative health effects, including cancer, stinted brain development, immune deficiency, and decreased birth weight and conception rates[14]. In addition to adverse health effects, farmed salmon have a deleterious impact on the population of wild salmon. Pens of farmed salmon generate waste that then burdens the local ecosystem. The high densities of fish in the pens promote disease, which sometimes carries over into the wild population. In addition, accidentally released farmed salmon could interbreed with, and potentially overcome, wild populations. [15].

At the moment, farmed salmon are not a substitute. This is not to say that they could not become one. In the event of poor future environmental conditions, it may be necessary to severely reduce fishing wild salmon, in which case an improved farmed salmon industry would be able to fulfil demand for salmon. Such an industry would limit its environmental impact and alter its aquaculture policy to reduce PCBs in the farmed salmon it produces.

Hatcheries are the classic example of a technology introduced to increase or replace salmon populations. Over a hundred years ago, hatcheries were introduced with the assumption that the ocean could support an unlimited number of salmon, and that the hatchery could improve on nature by producing more salmon. This turned out not to be the case:

> Hatcheries have resulted in reduced genetic diversity within and between salmon populations, increased the effects of mixed-population fisheries on depleted natural populations, altered behavior of fish, caused ecological problems by eliminating the nutritive contributions of carcasses of spawning salmon from streams, and displaced the remnants of wild runs.[16]

The committee goes on to say that the reason for this failure stems from the fact that hatcheries have carried the burden of population substitution, rather than being used as research laboratories. They suggest that hatcheries could, in fact, provide invaluable data on the life history of salmon.

8.1 Research Policy Recommendations

Our model indicates that human-imposed environmental damage and overfishing is responsible for declining salmon stock. In order to mitigate the exhaustion of salmon, we propose a three-fold research policy:

- First, a study of which environmental factors are most relevant to salmon stock. We would like to know, for example, whether water pollution or deforestation causes greater reduction of stock from year to year. In particular, we propose a cross-study of salmon tagged from hatcheries in areas subject to different environmental conditions over time.
- Second, a study of an improved salmon farm. This would include comparisons of aquacultures, pen designs, and appropriate waste-management systems.
- Third, better data on spawning, recruitment, and natural mortality rates would much improve our chance of determining how best to protect salmon. We propose a study on implanting small computer chips (similar to those used in house pets) into pre-juvenile salmon, with an accompanying computer tracking system, giving data on location over the life-span.

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9 Raw Data Supplement

Year	AukeSmolt	AukeSurv	AukeMortal	AukeRun	AukeCatch	AukeCatPer	AukeEscap	AukeRecr
1980	8789	9.88	90.12	868	170	19.59	698	10714
1981	10714	9.11	90.89	976	330	33.81	646	6967
1982	6967	10.61	89.39	739	292	39.51	447	6849
1983	6849	18.09	81.91	1239	545	43.99	694	6901
1984	6901	15.87	84.13	1095	444	40.55	651	6838
1985	6838	24.61	75.39	1683	741	44.03	942	5852
1986	5852	16.64	83.36	974	520	53.39	454	5617
1987	5617	20.99	79.01	1179	511	43.34	668	7041
1988	7041	17.06	82.94	1201	445	37.05	756	7685
1989	7685	14.39	85.61	1106	604	54.61	502	7011
1990	7011	21.14	78.86	1482	785	52.97	697	5137
1991	5137	22.95	77.05	1179	371	31.47	808	5690
1992	5690	32.95	67.05	1875	855	45.60	1020	6596
1993	6596	24.09	75.91	1589	730	45.94	859	8647
1994	8647	35.33	64.67	3055	1618	52.96	1437	7495
1995	7495	10.94	89.06	820	360	43.90	460	4884
1996	4884	23.36	76.64	1141	626	54.86	515	3934
1997	3934	19.24	80.76	757	148	19.55	609	6111
1998	6111	23.12	76.88	1413	551	39.00	862	7420
1999	7420	19.34	80.66	1435	590	41.11	845	5233
2000	5233	18.52	81.48	969	286	29.51	683	4969
2001	4969	28.30	71.70	1406	541	38.48	865	5980
2002	5980	26.76	73.24	1600	424	26.50	1176	

Year	BernSmolt	BernSurv	BernMort	BernRun	BernCatch	BernCatPer	BernEscap	BernRecr
1990	164356	20.57	79.42637	33814	22764	67.32	11050	141154
1991	141154	24.91	75.08962	35162	23632	67.21	11530	187715
1992	187715	24.43	75.57467	45850	30550	66.63	15300	326126
1993	326126	15.21	84.79299	49594	33924	68.40	15670	255431
1994	255431	28.86	71.13584	73728	57808	78.41	15920	181503
1995	181503	15.87	84.13249	28800	23855	82.83	4945	194019
1996	194019	12.27	87.73316	23800	17750	74.58	6050	133629
1997	133629	11.56	88.44413	15442	5392	34.92	10050	139959
1998	139959	16.98	83.0236	23760	16958	71.37	6802	252199
1999	252199	12.92	87.08044	32583	22663	69.55	9920	183023
2000	183023	11.83	88.16815	21655	11005	50.82	10650	268468
2001	268468	11.90	88.10026	31947	12657	39.62	19290	264772
2002	264772	18.92	81.0841	50084	22384	44.69	27700	-

Year	FordSmolt	FordSurv	FordMort	FordRun	FordCatch	FordCatPer	FordEscap	FordRecr
1985	38509	12.37	87.63406	4762	2438	51.20	2324	46422
1986	46422	8.85	91.15075	4108	2562	62.37	1546	73272
1987	73272	4.41	95.59313	3229	1535	47.54	1694	88649
1988	88649	6.72	93.27573	5961	2933	49.20	3028	43354
1989	43354	14.16	85.83983	6139	3962	64.54	2177	55803
1990	55803	9.46	90.54352	5277	3087	58.50	2190	56284
1991	56284	10.70	89.29891	6023	3262	54.16	2761	61724
1992	61724	15.08	84.92159	9307	5460	58.67	3847	57401
1993	57401	22.11	77.88714	12693	8491	66.90	4202	83686
1994	83686	13.73	86.26772	11492	8264	71.91	3228	134640
1995	134640	5.56	94.43702	7490	5045	67.36	2445	91843
1996	91843	6.51	93.48889	5980	3480	58.19	2500	66528
1997	66528	15.36	84.63654	10221	5256	51.42	4965	80567
1998	80567	19.88	80.11841	16018	8969	55.99	7049	132607
1999	132607	7.52	92.47626	9977	6379	63.94	3598	62444
2000	62444	12.89	87.10845	8050	5763	71.59	2287	106531
2001	106531	8.24	91.76108	8777	6599	75.19	2178	102010
2002	102010	14.83	85.17498	15123	8014	52.99	7109	

Year	HughSmolt	HughSurv	HughMort	HughRun	HughCatch	HughCatPer	HughEscap	HughRecr
1984	51789	7.74	92.25704	4010	2602	64.89	1408	32104
1985	32104	7.51	92.48692	2412	1509	62.56	903	23499
1986	23499	19.04	80.96089	4474	2691	60.15	1783	21878
1987	21878	10.71	89.28604	2344	1226	52.30	1118	36218
1988	36218	4.22	95.77558	1530	1017	66.47	513	23336
1989	23336	10.39	89.61262	2424	1991	82.14	433	26620
1990	26620	17.25	82.74606	4593	3723	81.06	870	32925
1991	32925	17.41	82.59377	5731	3905	68.14	1826	23326
1992	23326	20.96	79.03627	4890	3464	70.84	1426	32853
1993	32853	12.99	87.0088	4268	3438	80.55	830	48433
1994	48433	19.51	80.48851	9450	7697	81.45	1753	49288
1995	49288	13.70	86.2989	6753	4972	73.63	1781	22413
1996	22413	17.47	82.53246	3915	2957	75.53	958	32294
1997	32294	8.21	91.78795	2652	1920	72.40	732	37898
1998	37898	11.40	88.60362	4319	3381	78.28	938	29830
1999	29830	14.01	85.99397	4178	2932	70.18	1246	19902
2000	19902	6.60	93.39765	1314	714	54.34	600	23343
2001	23343	13.46	86.53986	3142	1562	49.71	1580	36531
2002	36531	14.47	85.53284	5285	1994	37.73	3291	-

Year	TakuSmolt	TakuSurv	TakuMort	TakuRun	TakuCatch	TakuCatPer	TakuEscap	TakuRecr
1993	1510032	14.03	85.97056	211849	102392	48.33	109457	1475874
1994	1475874	23.01	76.98692	339644	243301	71.63	96343	1525330
1995	1525330	11.87	88.1324	181020	125310	69.22	55710	986489
1996	986489	9.55	90.44946	94215	49580	52.62	44635	759763
1997	759763	6.69	93.30568	50861	18516	36.41	32345	853662
1998	853662	14.04	85.96166	119840	58458	48.78	61382	1184195
1999	1184195	9.90	90.10256	117205	56361	48.09	60844	1387399
2000	1387399	8.09	91.91083	112229	47529	42.35	64700	1720387
2001	1720387	9.12	90.87938	156910	52450	33.43	104460	2292949
2002	2292949	13.24	86.7588	303614	83825	27.61	219789	-