Fraser River Sockeye Spawning Initiative (FRSSI)

A Review for the Cohen Commission

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Fraser River Sockeye Spawning Initiative (FRSSI)

Executive Summary

The Fraser River is the greatest producer of sockeye salmon in British Columbia, with more than 150 spawning populations. In recent years the average abundance dropped significantly and several individual stocks have declined severely in abundance, constraining harvest opportunities in both mixed-stock and terminal fisheries.

Fisheries and Oceans Canada (DFO) developed the *Rebuilding Plan* in 1987 to increase Fraser sockeye production. This plan appeared to be a success in building the stocks until the productivity began to decline in the mid 1990's. In addition, by 1995, late run sockeye had begun migrating into the river earlier than normal and in some years have experienced particularly severe in-river mortality.

DFO initiated a review of the rebuilding strategy prior to the 2003 fishing season to address the growing concern about its appropriateness during a time of reduced productivity and dwindling abundance. The mandate of the review process was to incorporate new information, integrate emerging policies such as the *Wild Salmon Policy* (WSP), and establish a formal framework for setting escapement targets. In addition, there were new and emerging technologies and methodologies for analyzing the historical data and projecting consequences of different strategies. The *Fraser River Sockeye Spawning Initiative* (FRSSI) was the result.

The FRSSI is a process to develop guidelines for setting annual escapement and exploitation targets for Fraser sockeye stocks. FRSSI was piloted in 2006 and spawning escapement targets for the 2007 through 2010 seasons were set using the FRSSI. The annual management cycle for Fraser River sockeye has integrated FRSSI. The intent is to have a full review of FRSSI after one cycle, four years, of implementation. This should occur after the 2010 season.

Introduction

This paper was written from the perspective of a participant in the technical working group that helped develop the analytic tools used in FRSSI. The intent is to focus on the data and the analytic tools. The results of FRSSI, the total allowable mortality rules (TAM rules), are a result of a set of assumptions and constraints placed on the analysis, some as a consequence of the uncertainties and deficiencies in the data and analysis, and others as an expression of the current policies and approaches to fisheries management.

There are several papers referred to in this paper that describes the model and its results. This paper is not intended as an exhaustive review of these reports. Instead, it provides perspective from someone who was a direct participant in the development of the tool. Some information is been drawn from the other reports that were based upon the efforts of the technical working group.

Brief Overview of the History of Setting Spawning Targets

The Fraser River is the greatest producer of sockeye salmon in British Columbia, with more than 150 spawning populations. Many of the sockeye populations have recovered from very low levels in the early 1900s and historical evidence suggests that the Fraser River may have the potential to produce substantially larger sockeye runs than observed in recent decades.

Average annual abundance has increased from less than 7 million in the 1950s to 12 million in the 1990s, and 1993 saw a record return of 23 million fish; 2010 may have exceeded this by as much as 10 million fish. In recent years, however, average abundance has dropped significantly and several individual stocks have declined severely in abundance, constraining harvest opportunities in both mixed-stock and terminal fisheries.

Fisheries and Oceans Canada (DFO) developed the *Rebuilding Plan* in 1987 to increase Fraser sockeye production. A steady increase in total spawning escapement occurred over almost 20 years of implementation, accompanied by declining abundance and production observed since the mid-1990s. There has been a significant reduction in the overall expectation rate. The shift towards increased escapement, and reduced exploitation rate, was partly driven by the rebuilding objective and partly by harvest constraints imposed to protect weak stocks such as Cultus Lake sockeye within mixed-stock fisheries. Additional concerns over potential in-river mortality due to behavioural changes and detrimental environmental conditions have resulted in more reductions to exploitation rates.

By 1995, late run sockeye had begun migrating into the river earlier than normal and in some years experienced particularly severe in-river mortality. With the exception of 2002 when Late run, sockeye delayed their migration into the River and experiencing less en route mortality. Significant spawning escapements occurred in 2002, particularly to the Adams River.

DFO initiated a review of the rebuilding strategy prior to the 2003 fishing season to address the growing concern about its appropriateness during a time of reduced productivity and dwindling abundance. The mandate of the review process was to incorporate new information, integrate emerging policies such as the *Wild Salmon Policy* (WSP), and establish a formal framework for setting escapement targets. In addition, there were new and emerging technologies and methodologies for analyzing the historical data and projecting consequences of different strategies. The *Fraser River Sockeye Spawning Initiative* (FRSSI) was the result. It is a participatory process to develop guidelines for setting annual escapement and exploitation targets for Fraser sockeye stocks. Underlying the process was the FRSSI model.

Pestal et al. (2008) summarized escapement planning for Fraser River sockeye since the mid-1980s. Implementation details are documented in the annual reports of the Fraser River Panel (e.g. PSC 2006).

Following the signing of the Pacific Salmon Treaty in 1985, the "*Rebuilding Plan*" was designed to increase annual escapements incrementally from historical levels. A DFO task force identified *Interim Escapement Goals* between escapements observed at the time and the optimal escapements estimated at that time. In addition, the rebuilding plan attempted to test the basis for cyclic dominance in some of the stocks while maintaining cyclic management to others.

A basic premise of the rebuilding plan was to increase escapements each year, beyond brood year levels, to maintain an increasing rebuilding trajectory towards interim escapement targets. In periods of high or increasing survival, these escapement targets can be met with little short-term losses in harvests. To meet rebuilding targets during years of low survival and abundance exploitation rates were reduced to meet escapement targets.

An implementation plan was developed which identified:

- Lower bounds for annual target escapement designed to maintain escapements above brood year levels for Early Summer, Summer and Late Run aggregates.
- Lower bound for annual target escapement on the Early Stuart aggregate fixed at 66,000

spawners and then revised to 75,000 spawners through consultations.

- Upper bounds for annual target escapement for all aggregates were based on a 65 - 70% exploitation rate ceiling.

This implementation plan guided escapement management from 1987 to 2002, but sockeye abundance did not respond. Productivity has declined significantly over the past few years although there was a substantial upturn in 2010. In addition, harvest opportunities on abundant and productive stocks have been constrained by management considerations for less productive or less abundant stocks intercepted in the same fisheries (e.g. Interior Fraser Coho, steelhead). Because of these factors, there was a shift from large catches and higher exploitation rates to smaller catches and large spawning escapements. Larger total abundances may have been achieved from the increased escapements of the 1990s and early 2000s if productivity had remained similar to the levels observed in the 1970s and 1980s. Spawner levels and resulting returns would have been much lower for many of the Fraser River sockeye stocks if pre-1987 exploitation patterns had been maintained in the face of reduced productivity.

General support for the rebuilding plan also declined, by the early 2000s, due to a decline in catch, difficulty of accommodating multiple objectives, and the constraints of a strict rebuilding schedule (Cass et al. 2000, Pestal et al. 2008).

Brief History of FRSSI Process

The FRSSI is a process to develop guidelines for setting annual escapement and exploitation targets for Fraser sockeye stocks. DFO used a participatory planning process for incorporating new information, using newer methodologies and responding to and incorporating emerging policies (i.e. *Wild Salmon Policy*).

New Bayesian approaches to the historical stock recruitment analysis formed the basis of the technical groundwork on stock/recruitment models. Forward-looking simulations use these stock/recruitment models. The analytic approach and the simulation model were refined over three years and a series of workshops, that then saw the FRSSI model and process used as a pilot implementation of the integrated management processes envisioned under the *Wild Salmon Policy* (WSP).

The data analysis and simulation model have evolved with ongoing research over the past decade. Changes include assumptions about spawner-recruit relationships (e.g. delayed density effects, the Larkin model), the range of strategies that can be explored (e.g. allowable mortality rules), mixed-stock simulations (i.e. 19 stocks in 4 management groups), and additional biological mechanisms (e.g. environmental management adjustments, pre-spawn mortality, future patterns in productivity).

The 2006 season was used to pilot the preliminary results from FRSSI, as a part of a Wild Salmon Policy pilot. Based on the results of that pilot, spawning escapement targets for the 2007 through 2010 seasons were set using the FRSSI. The annual management cycle for Fraser River sockeye has integrated FRSSI. The intent is to have a full review of FRSSI after one cycle, four years, of implementation. This should occur after the 2010 season.

First Nation and Stakeholder Input into Model Development

One of the objectives in the FRSSI process was to make it as participatory as possible. The development of FRSSI involved holding many workshops that engaged fishers, representatives of fishing organizations, First Nations participants as well as representatives from environmental group NGOs. These were important meetings; however, it was difficult to communicate the analytic approaches to both the data analysis and simulation modeling. While the discussion about the overarching policy issues was useful and informative it was hard for the participants to fully grasp and understand the details of the analysis. Unfortunately, there are many important facets to this sockeye issue that rest at the detailed level. Therefore, it is important for everyone to have a good understanding of the details of the analysis to ensure there is a common language and framework to discuss the other issues.

The workshops were not as successful as hoped, in enabling the participants to understand fully the basis for the analysis. Of particular concern would be the First Nations participation. While there were technical staffs of First Nations participating in the workshops they were not in a position to provide guidance on the policy issues. As some of the policy issues rest on the technical details, it is difficult to engage the current generation of First Nations leadership or many of the other non-technical participants. While the approaches used to communicate the material were state-of-the-art there needs to be more research and effort in communicating with harvesters, particularly First Nations, and managers/technicians on some of these important issues.

FRSSI has been the subject of much criticism. The criticisms range from it being too constraining at-large abundances (the current 60% mortality maximum) to not being conservative enough in the face of changing (mostly reduced) productivity. While all of the criticisms deserve close attention and discussion, it is important to remember that FRSSI is a process not an answer. The process tries to mobilize the historical data set in such a way as to provide a framework for looking at alternative futures. As a process and a tool, it represents the existing historical data well. It has the capacity to explore a wide range of options and to do so in a systematic way. Much of the criticism about FRSSI is misdirected at the analytic tool; it should be directed at, and the debate should be about, the uses of the tool.

This paper tries to explain and describe FRSSI as a tool. It may be that many of the conclusions that have been drawn from the use of FRSSI more reflect the positions of the users and questions asked of the tool than the ability of the tool to act as a structure for dialogue around important policy issues and uncertainties.

The FRISSI Data Analysis and Models

The data analysis and models in FRSSI are state-of-the-art approaches to the types of problems that have extremely variable dynamics and large uncertainties in the data. The Bayesian data analysis provides not just single point estimates but generates distributions, called posterior distributions, of the key parameters used in the forward simulation models. The simulation models using these distributions of parameters can reflect the wide range of possible outcomes. These distributions can reflect the probabilities of different outcomes and associated risks.

The FRSSI process uses a sample of 500 different parameter sets, in the model, to simulate forward for 48 years. All of these parameter sets are consistent with the historical data. We have only observed one realization or trajectory. We can only hope that this history is somewhere near the average possible trajectory but it is just one of many possible histories dependent on its own random events.

The modelling framework developed for FRSSI attempts to be consistent with the biological principles outlined in the WSP. For example, the sockeye stocks included in the simulation model are generally lake-based and can be associated with conservation units. Evaluations can be based on the performance of individual stocks, not just management groups. Unfortunately, there are only 19 stocks with sufficient escapement and return data to allow incorporation into the simulation model. This presents an ongoing challenge for the operational aspects of the *Wild Salmon Policy*, and a coast-wide approach is under development for incorporating CUs with insufficient data into the planning and implementation of fisheries (Mark Saunders, pers. comm.). In addition, there is a CSAS paper scheduled for review in the fall of 2010, on Fraser Sockeye benchmarks. Once these benchmarks are available, the status of the stocks can be evaluated formally.

The Data Set

The historical data set on Fraser sockeye run sizes, catches and spawning escapements is one of the longest most comprehensive data sets of its kind for any wild animal. There are relatively good records dating back to near the beginning of last century. There is a comprehensive and well-documented data set from the middle of the last century. While there have been many challenges to gathering the data it remains a great resource for fisheries scientists to develop and test methodologies. Many students of fisheries population dynamics and harvest management have studied these data sets. New and innovative methodologies have been developed using these data and are now being used throughout the world on other fish and wildlife populations.

There have been several changes and advances in the methodologies for collecting and recording these data (i.e. DNA). These changes have presented challenges to maintaining the consistency of these data sets. There has been a high degree of rigor employed by the various agencies and scientists over the years to maintain records of these changes. This record makes it possible to use this large historical data set to guide current and future management with a high degree of confidence - at least as confident as any other data set in the world.

"Modeled Stocks"

The stocks that are represented in the FRSSI model are the same 19 stocks for which forecasts are prepared each year. They are aggregated into the management groups. Once the TAM rule is determined for a management group it is adjusted each year for the expected portion of miscellaneous stocks that are to be included in that management group.

Table 1: Modeled Stocks, Miscellaneous Stocks and Management Groups

Management Group	Modeled Stocks	Miscellaneous Stocks
Early Stuart	Early Stuart	
Early Summer	Bowron Fennel Gates Nadina Pitt Raft Scotch Seymour	Early Shuswap, South Thompson North Thompson tributaries North Thompson River Nahatlach River & Lake Chilliwack Lake, Dolly Varden Creek
Summer	Chilko Late Stuart Quesnel Stellako	
Late	Cultus Harrison Late Shuswap Portage Weaver Birkenhead	Misc. non-Shuswap (Harrison Lake)

The modeled stocks represent populations that have a long history of stock and recruitment data. These have been collected long before the Wild Salmon Policy was conceived or developed. Therefore, there is not a one-to-one correspondence between the modeled stocks in FRSSI and the conservation units of the Wild Salmon Policy. The Table 2 indicates the conservation units, which are associated with the modeled stocks. In some cases, the model stocks are made up of more than one conservation unit, such as Early Stuart. In other cases, several modeled stocks belong to the same conservation unit, such as Raft and Fennel or Scotch and Seymour. Some miscellaneous stocks are difficult to associate with conservation units and some of the smaller conservation units are difficult to associate with the modeled stock. Several of the river-type sockeye conservation units have this characteristic.

The inconsistencies between the modeled stocks and conservation units will remain a challenge for some time. It is unlikely there will be adequate population data on some individual conservation units, particularly if they are part of a group the makes up a modeled stock, to apply the FRSSI tools in the near future. In the meantime, there is a need for a method to reconcile and associate the modeled stocks with conservation units, both for the purposes of stock management and the implementation of the Wild Salmon Policy. Some of these methods will likely be on a case-by-case basis that reflects the circumstances and state of knowledge of the stocks and conservation units.

Table 2: Modeled and Miscellaneous Stocks, Conservation Units and Management Groups

Mgmt. Group	CU label	CU Type	# of Lakes	# of Sites	# of Esc Obs.	Freshwater Adaptive Zone	Stock
Early Stuart	Stuart-EStu	lake	1	2	13	Middle Fraser	Early Stuart
	Takla/Trembleur-Estu	lake	2	42	70	Middle Fraser	Early Stuart
Early Summer	Anderson-ES	lake	1	2	59	Middle Fraser	Gates
	Bowron-ES	lake	1	2-3	70	Upper Fraser	Bowron
	Chilko-ES	lake	1	1	19	Middle Fraser	Chilko
	Chilliwack-ES	lake	1	2	36	Lower Fraser	Early Summer Miscellaneous
	Francois-ES	lake	1	3-4	67	Middle Fraser	Nadina
	Fraser-ES	lake	1	2	43	Middle Fraser	Early Summer Miscellaneous
	Indian/Kruger-ES	lake	3	1	3	Upper Fraser	Unknown
	Kamloops-ES	lake	2	9	70	N Thompson	Raft, Fennel, ES Miscellaneous
	Nadina-ES	lake	1	1	2	Middle Fraser	Nadina
	Nahatlatch-ES	lake	1	2	33	Fraser Canyon	Early Summer Miscellaneous
	Pitt-ES	lake	1	2	69	Lower Fraser	Pitt
	Shuswap Complex	lake	8	21-27	66	S Thompson	Scotch, Seymour, ES Misc.
	Taseko-ES	lake	1	1 - 2	43	Middle Fraser	Early Summer Miscellaneous
Summer	Chilko-S	lake	1	3	70	Middle Fraser	Chilko
	Francois-S	lake	1	3	9	Middle Fraser	Stellako
	Fraser-S	lake	1	1	70	Middle Fraser	Stellako
	Mckinley-S	lake	1	1	19	Middle Fraser	Quesnel
	Quesnel-S	lake	4	51-66	67	Middle Fraser	Quesnel
	Stuart-S	lake	1	5	64	Middle Fraser	Late Stuart
	Takla/Trembleur-S	lake	2	4 - 5	67	Middle Fraser	Late Stuart
Late	Cultus-L	lake	1	1	70	Lower Fraser	Cultus
	Harrison (D/S)-L	lake	1	6 - 8	68	Lower Fraser	Misc. non-Shuswap
	Harrison (U/S)-L	lake	1	4	70	Lower Fraser	Weaver
	Kamloops-L	lake	1	1	48	S Thompson	Misc. Shuswap
	Kawkawa-L	lake	1	1 - 2	8	Fraser Canyon	Unknown
	Lillooet-L	lake	1	8	70	Lillooet	Birkenhead
	Seton-L	lake	1	1	60	Middle Fraser	Portage
	Shuswap Complex	lake	1	44-58	70	S Thompson	Late Shuswap, Misc. Shuswap
River	Fraser Canyon	river	-	6	10	Fraser Canyon	Unknown
	Lower Fraser	river	-	5	70	Lower Fraser	Harrison
	Middle Fraser	river	-	8 - 10	36	Middle Fraser	Stellako, Quesnel
	Thompson	river	-	2	4	N&S Thompson	Unknown
	Upper Fraser	river	-	1	1	Upper Fraser	Unknown
	Widgeon	river	-	1	65	Lower Fraser	Misc. non-Shuswap

Stock and Recruitment Models

One of the main underlying assumptions of the FRSSI analysis is that the number of recruits, adult fish returning to and passing through the marine fishing areas, is determined in large measure by the number of spawners that produced them. Different management strategies are assumed to show measurable differences in the flow of benefits from those management actions.

While there is a high degree of variability and uncertainty about the relationship between recruits to the number of spawners, if there were no relationship then there would be no need to have spawning escapement strategies or targets. For some marine fish species, recruitment is statistically unrelated to the adult spawning population and appears more related to environmental factors. For most salmon stocks, there is at least some statistical relation between the number of spawners and the number of resulting recruits. Therefore, it is important to try to develop spawning escapement strategies and the corresponding harvest strategies that improve the flow of benefits from alternative strategies. FRSSI attempts to do this by using so-called stock and recruitment models.

Ricker Model

Many mathematical models have been used to approximate the process of recruitment in fisheries science. For salmon, Bill Ricker of the Pacific biological Station developed the most commonly used model during the 1950s. The Ricker model is a classic stock/recruitment model used to describe the dynamic behaviour of salmon populations.

The model assumes that when there are very few spawners there is no negative interaction due to crowding or over-spawn (that may result when subsequent spawners disturb fertilized eggs from earlier arriving spawners) and there is maximum productivity of recruits per spawner. The recruits per spawner are assumed to be at a maximum at low spawner densities (the slope of the line is maximum near zero).

As spawning density increases, the negative interactions between spawners decrease the productivity of each individual spawner, resulting in a decrease in recruits per spawner. Due to limited carrying capacity or negative interaction between spawners, total recruitment reaches a maximum at an intermediate spawning number. At even higher spawning numbers, the total recruitment declines from the maximum until theoretically it may approach zero.

The shape of the mathematical model proposed by Ricker can reflect over spawning, a case where too many spawners could result in a decline of population sizes. For the Ricker model, the theoretical maximum sustainable yield is reached at a spawning level less than the level that would produce maximum recruitment.

Statistical techniques have been developed to estimate the parameters of the Ricker model. There are three parameters to be estimated:

1. One is the productivity parameter or the intrinsic rate of increase (or maximum recruits per spawner). This is the slope of the function near zero spawners, where there is assumed to be no negative interactions between spawners.
2. The second parameter relates to the carrying capacity for the population. It is expressed as either spawning level for maximum recruitment or the spawning level of maximum sustainable yield.
3. The third parameter is an estimate of the variation or variance of probability distribution that represents the variability in the environment and/or measurement.

With estimates of these three parameters, the model can simulate or project the response of populations to varying harvest and/or other mortality regimes. The estimation of these parameters and simulation forward is the basis for the FRSSI model.

Cycles and "Cyclic Dominance"

Some Fraser sockeye demonstrate cycles in abundance. These cycles are associated with their age structure. Fraser sockeye predominately return his four-year-old fish. Therefore, there are four-year cycles. In other sockeye populations, such as on the Skeena River, there is a mix of four-year-olds and five-year-olds. Therefore, there is little or no discernible cycle. Further north in Alaska there are stocks that are predominately five-year-olds, which cycle with five-year periodicity.

There has been a debate among fisheries scientist for decades about the biological mechanisms for the interaction between the cycles and whether these interactions maintain cycles. There are hypotheses that cycles are a manifestation of biological interactions between cycle lines. If there is a biological mechanism that creates and maintains these cycles then harvesting and spawning strategies should consider these interactions. Other hypotheses suggest that the cycles are simply a series of random highs and lows in abundance that are maintained through time by the independent population dynamics. The cycles may have been maintained through time by fishing patterns. If there is no biological interaction between cycles then the stocks should be managed according to the overall population dynamics associated with the particular population.

Larkin Model – Delayed Density Dependence

An extension to the Ricker model has been proposed to include cycle line interaction, the Larkin model or delayed density dependence model. This model extends the basic Ricker expression by including the effects of spawning abundance of the other three recent years. If the coefficients associated with the three most recent population sizes are set to zero then this model simplifies to the standard Ricker model.

Various levels of the three interaction terms or parameters result in varying degrees of cycle line interaction and may result in different cyclic patterns. Some sets of coefficients suggest the best harvesting strategy is to maintain cycles, varying the harvest pressure on the cycle lines. This situation is similar to a farm where crops are grown in one year and the ground is fallowed the next, due to negative interactions left in the ground like disease.

The mechanisms represented by this delayed density dependence model are not well understood. Hypotheses include such things as: overgrazing of food supplies that carries over to the following year, the stimulation of predators that are present in subsequent years and affect the success of spawning, or even disease vectors that are transmitted from adults and juveniles of different broods.

The latest version of the FRSSI model includes the use of the Larkin or delayed density dependent versions. Some researchers have suggested that the recent decline in productivity of Fraser sockeye is due to a management regime that attempts to increase the spawning abundance across all cycle lines. In addition, delayed density dependence suggests higher exploitation rates than do the standard Ricker models. The FRSSI model has the capacity to explore implications of these alternative hypotheses.

Stationary Productivity

A common approach in parameter estimation and simulation modeling, like FRSSI, is to assume that some of the basic parameters are stationary. They do not change much over the 40 to 50 year period of record or the time horizon of the simulations. While there is a great deal of uncertainty about the true value of the parameters, such as the intrinsic productivity, carrying capacity or environmental variability, these parameters are assumed to remain constant for the period of analysis, both historical and the projected. This assumes that the models capture and replicate all of the dynamics of the population as reflected in historical data. However, the models are just models, mathematical abstractions programmed into computers. They can mimic but they cannot fully capture all the complexities of the real world. There is a great deal of year-to-year variability; the variability is assumed not to be time-dependent and there are no correlations from one year to the next. Each year's deviation from the average is independent of other years.

The data from recent years of Fraser sockeye suggest that there may be time trends in the underlying parameters such as productivity. These trends in the basic parameters may represent major changes in the environment, such as climate change. Harvesting strategies or TAM Rules that do not assume that there are underlying trends in productivity may not be the most appropriate. It would be helpful to account for these trends and predict them, in developing our management strategies or TAM rules. Unfortunately, we do not currently understand the behaviour of these trends well enough to predict them or even to use them in a prescriptive model like FRSSI. We can, however, assume different future scenarios of these changes and test sensitivity of TAM rules to these possible futures.

Non-Stationary Productivity (Kalman Filters)

A new approach, being researched for use in FRSSI, is to represent trends in basic parameters, such as productivity, using Kalman filters in the model. Kalman filters are used in engineering for designing control systems such as the cruise control on your car. They simply estimate the rate of change of the underlying parameters and project that such changes will continue. These Kalman filters are useful while the trends are continuing but are not very good at projecting when the trends will shift or reverse.

The FRSSI model now has the capacity to estimate and calculate the Kalman filters on the basic productivity parameters of either the Ricker or the Larkin model. This addition will be useful in exploring alternative futures and the effects of different harvesting strategies on those possible future scenarios.

Parameter Estimation (Fitting the Models to the Data)

FRSSI uses modern Bayesian data analysis to estimate parameters for the stock/recruitment models. A Markov Chain Monte Carlo (MCMC) method is used to generate a large sample of possible parameter sets (intrinsic productivity, carrying capacity and environmental variability - Ricker model; cycle line interaction parameters - Larkin model). Parameter sets that are more likely to generate model outcomes that are consistent with observations are represented more frequently in the sample. Parameter sets that are less likely to generate model outcomes similar to the historical data are represented less frequently in the sample. Therefore, the sample parameter sets capture the probability distribution of likely models that are consistent with the data. The sample parameter sets can then be used to simulate forward in time to project the outcomes of different management strategies in the context of the probability distributions that represent both the uncertainty in the model fits as well as the variation around the model projections.

Some important characteristics of these distributions are that the parameters may co-vary with one another. For example, a particular historical data set of stock and recruitment may be as likely to have arisen from high productivity low carrying capacity model as from a large carrying capacity but less productive. These co-variations have important implications for assessing alternate management strategies.

Harvesting/Mortality Model

The FRSSI process currently produces Total Allowable Mortality (TAM) rules. TAM rules include both harvest mortality and en route mortality. En route mortality is usually defined as the difference between the estimates of adult sockeye entering the River and the estimates of sockeye that arrive at the spawning ground, once known harvests are accounted for.

The TAM rule may call for zero mortality at low abundance; however, en route mortality is still calculated. In addition, there is a provision for a minimum harvest rate to reflect incidental catch of a management group with no allowable harvest during a fishery targeted on other management groups.

Mixed Stock Harvesting

The current FRSSI model represents only mixed stock fishing. It does not currently have the capacity to account for a combination of mixed stock and near terminal or, as sometimes called, known stock fisheries.

In the marine areas, many of the stocks are mixed together and fished together. When the fish are in the river, some stocks start to peel off into their tributaries, such as the Harrison River, and so fisheries upstream of these confluences represent fishing on more "known" stocks or separate stocks.

There is always some degree of mixing even in the upper reaches of the river, until the stocks are at or very near the spawning grounds. As stocks approach their spawning grounds, they are more separated from other stocks. Therefore more controlled or known harvest rate could be applied to these individual stocks. All else being equal, if one were to manage each stock individually and harvest it to its individual needs and productivity then one would likely be able to produce the maximum catch from the mix of stocks. If stocks are fished together in mixed fisheries, it is difficult to set the exploitation to the productivity and available harvest of each individual stock.

Mixed vs. "Known Stock" Harvests or Both

While the FRSSI model does not have the capacity to combine mixed stock and known stock fisheries in the same scenario it does provide for the exploration of sensitivities of mixed versus known stock fisheries. By using the simulation model to test fisheries strategies on individual stocks then summing and comparing them to the results of fishing strategies on the aggregates of stocks, or management groups that would be present in mixed stock areas. Then comparing these two calculations (the sum of the individual strategies and the mixed stock fisheries strategies) one can see how sensitive or what issues are at play when comparing mixed stock to known stock fishing. A better appreciation for the potential trade-offs between, and mixtures of, mixed stocks and known stock fisheries would assist the dialogue around the appropriate fishing regimes.

Management Imprecision or "Error"

In the development of the FRSSI model, the concept of management imprecision or error has been considered. It is not realistic to expect to be able to implement a particular exploitation rate or a mortality rate precisely. Furthermore, the FRSSI model works on aggregates or management groups and these management groups are overlapped in time and area. There are mechanisms in FRSSI to reflect both these overlaps in timing as well as the imprecision in management.

Management takes place on a day-to-day basis within the season. The FRSSI model assumes a long-term perspective (40 – 50 years) on an annual time step. The degree to which the day-to-day management is represented in this longer-term view is a matter of approximation and abstraction. More research and experimentation will be needed to improve the representation of overlaps and management imprecision the FRSSI process.

Many aspects of Fraser sockeye management are approximated in the FRSSI model all of them should be subject to sensitivity analysis to see how important they are to the modeled outcomes. The ideal outcome would be a management regime/TAM Rule that produces the same stream of benefits and risks regardless of the type or degree of realistic management imprecision. The search for these robust management regimes is time-consuming and is a subject of ongoing research.

Objectives

The FRSSI process is intended to try to find management regimes or approaches that are better than alternatives. In order to compare one regime to another one requires a set of indicators to compare performance of these alternatives. Throughout the development of FRSSI and in the workshops, many performance measures or indicators have been proposed. They fall into three general classes:

1. Yield, the sustainable catch that can be taken from stock or management group;
2. Variability of the catch. For example there is an interest in having a stable and reliable supply of salmon for First Nations food fisheries; and
3. Conservation, the performance of management regimes in regards to risks for conservation.

While simulating forward in time the computer model calculates and accumulates various measures that relate to one of these general classes: yield, stability or conservation. The metrics that are used for these performance measures include:

1. Averages or totals– for example the catch or average catch over the 40 to 50 years and;
2. The possibility, probability or frequency of an indicator's value falling below or above a benchmark e.g. spawning abundance falling below a lower benchmark (Wild Salmon Policy benchmark).

Performance evaluation

The goal of the FRSSI process is to try to find a balance between the objectives of (1) ensuring spawner abundance and production for individual stocks, and (2) accessing the catch-related benefits. However, there are many nuances to be considered when interpreting the simulation results. Early on in the FRSSI development process, the "best" balance was found by optimizing a value function with user-supplied weighting. This approach proved cumbersome and too obscure for many participants. Later the process moved to the current approach of interactive exploration of alternative scenarios with the help of visual tools and graphs. Over the course of more than a dozen workshops, the list of potentially interesting variations of performance measures grew steadily to over 300.

Currently the following subset is used:

- Proportion of simulated years where the 4yr running average of spawner abundance falls below a stock-specific benchmark.
- Proportion of simulated years where catch for an aggregate falls below a benchmark.

The notions of low escapement and low catch can be quantified in many different ways, and even the Wild Salmon Policy offers a range of potential benchmark definitions that should be explored on a case-by-case basis (pages 17 and 18 of DFO 2005). Methods for determining WSP benchmarks for conservation units have been finalized (Holt et al 2009, Holt 2009), but the resulting benchmarks for the 19 stocks of Fraser sockeye are still under development.

Pending the completion of the WSP, interim benchmarks, developed during the 2006 planning process, are used. Workshop participants reviewed alternative approaches for setting biological benchmarks and settled on a robust combination using the smallest and largest value resulting from five different definitions of low escapement (Table 3). These benchmarks are based on a combination of population dynamics (e.g. 20% of the escapement that maximizes run size) and past observations (e.g. smallest observed 4yr average escapement). Benchmarks for identifying low catch for each management group are based directly on feedback received from workshop participants: Early Stuart – 15,000; Early Summer – 100,000; Summer – 600,000; Late – 300,000.

Benchmarks

Benchmarks are specific levels of a performance measure that are meaningful to a broader audience. Benchmarks are used in the FRSSI model to assist in evaluating performance of scenarios and spawning regimes (TAM rules). Performance can then be assessed based upon the frequency with which populations, catches or other indicators fall above or below the benchmark when simulating forward with the 500 sample parameter sets. Choosing an appropriate benchmark may be as much of an art as a science. While FRSSI was being developed, implementation of the Wild Salmon Policy was also underway. Definition of benchmarks is an important aspect of the Wild Salmon Policy. Those WSP benchmarks for Fraser Sockeye are not available yet.

A variety of benchmarks for various types of indicators was examined through the FRSSI research. They included benchmarks for catch, benchmarks for variation in catch and benchmarks for spawning escapements. The technical working group examined a wide variety of indicators against benchmarks. After this review, it appears that the most informative measures needed are ones related to low catch and low escapement. Total average yield and catch variation were highly correlated with low catch performance measures.

The biological benchmarks were derived based on approaches consistent with what is being considered for the Wild Salmon Policy. These include the spawning abundance from which, on average, one would expect the population to recover to spawning levels that produce maximum recruitment within one or two generations without fishing. The other indicators that were used and compared were the four-year average minimum escapement observed over the historic period.

From the set of production benchmarks (spawning levels from which recovery is possible within one or two generations) and the minimum spawning observed benchmark, two benchmarks were selected: one that was the smallest (BM1) of all those numbers and one that was the largest (BM2).

Table 3: Conservation Benchmarks used in FRSSI

	Escapement Summary (up to 2004)					Production BM Range for 4 alternative definitions		Potential Conservation Reference Point Smallest observed	Low Escapement BM Lowest and highest of Production BM and Conservation RP	
Stock	Smallest	25p	Median	25p	Largest	Min	Max	4 yr. average	BM 1	BM 2
E. Stuart	1,500	21,000	39,500	122,900	688,000	24,100	50,300	10,200	10,200	50,300
Bowron	800	3,100	6,800	13,300	35,000	2,500	4,900	3,000	2,500	4,900
Fennell	<100	1,400	5,700	9,100	32,300	1,100	2,200	500	500	2,200
Gates	<100	2,000	4,700	8,400	86,300	1,100	3,500	1,500	1,100	3,500
Nadina	1,000	2,400	5,900	14,300	173,800	2,000	5,700	5,800	2,000	5,800
Pitt	3,600	12,700	18,000	36,500	131,500	3,400	6,800	11,200	3,400	11,200
Raft	500	2,600	6,100	8,700	66,300	2,500	5,200	2,600	2,500	5,200
Scotch	100	2,200	4,600	14,800	101,300	900	4,000	2,200	900	4,000
Seymour	1,300	5,700	13,400	44,600	272,000	9,500	19,000	9,100	9,100	19,000
Total	7,300	32,100	65,200	149,700	898,500	23,000	51,300	35,900	22,000	55,800
Chilko	17,300	109,600	239,900	544,400	1,037,700	66,400	132,900	164,500	66,400	164,500
Late Stuart	<100	5,700	21,600	157,100	1,363,800	39,100	78,300	29,500	29,500	78,300
Quesnel	<100	300	8,500	263,000	3,062,200	41,100	154,500	7,800	7,800	154,500
Stellako	15,800	42,100	79,300	138,000	371,600	22,700	45,400	37,000	22,700	45,400
Total	33,100	157,700	349,300	1,102,500	5,835,300	169,300	411,100	238,800	126,400	442,700
Birkenhead	11,900	30,700	48,900	78,600	335,600	19,700	39,300	23,200	19,700	39,300
Cultus	100	1,900	10,300	17,600	47,800	3,700	7,300	1,900	1,900	7,300
Harrison	300	3,800	8,200	17,100	45,600	2,000	4,100	3,600	2,000	4,100
Portage	<100	1,100	3,600	8,200	31,300	100	1,200	1,300	100	1,300
Weaver	3,200	16,700	34,700	45,400	267,300	8,600	17,800	14,500	8,600	17,800
L. Shuswap	600	3,600	12,800	1,133,400	5,216,800	111,100	222,100	320,500	111,100	320,500
Total	4,200	27,100	69,600	1,221,700	5,608,800	125,500	252,500	341,800	123,700	351,000

Assess Risks – Frequency of Occurrences

In FRSSI, risk assessment forms a part of the process of producing performance measures. Most of the performance measures are described as the frequency, of simulated results, that result in a particular indicator being more or less than a benchmark. For example how many times does the population fall below a low spawning level benchmark in the course of the simulations. With the appropriate choice of indicators and benchmarks, the model can be used to assess the risk (the frequency or probability of crossing the benchmark) of various TAM Rules.

Simulations

The model simulates a group of stocks into the future and tracks the performance of different escapement strategies or TAM Rules. The model simulates stock-specific abundance and total mortality under uncertain and variable conditions. It does not include any explicit in-season management mechanisms; however, it does approximate the management of overlaps between Management Groups. The escapement strategy (TAM Rule) is applied on an annual basis; all stocks within a management group are exposed to the same exploitation rate and en route mortality. Catches are not taken in specific areas or fisheries; they are calculated as the remainder for the TAM after en route mortality is deducted, except where minimum exploitation rates are set.

Each simulated scenario is based on several important assumptions about the biology and behaviour of Fraser sockeye stocks. For each stock, these assumptions include:

- Characteristics of the spawner-recruit model (e.g. spawning capacity, annual variability, cyclic interaction).
- Level of accuracy in implementing allowable mortality rates.
- Amount of non-harvest mortality during up-river migration.

The conceptual structure for a more detailed in-season management model is currently being developed. It is hoped that this new model will be able to simulate individual stocks or conservation units, each with their own timing, moving through a sequence of fishing areas.

The Simulation Process

The simulation process begins with the generation of a set of sample parameters, fit to the data. If it is the Ricker model, there are three parameters: productivity, carrying capacity and the variance in the error term or environmental variation. The Larkin model includes three additional parameters representing the interaction terms with the other cycles or years. The sample currently includes 500 sets of these parameters for each model stock. For each modeled stock (each of the 500 sets of parameters) the simulation model projects forward 48 years using the most recent spawning data as a seed to the future projections and a test candidate set of assumptions and harvest strategies (TAM Rules).

In each year of the simulation, recruitment is calculated based on the production from previous years and the expected age structure return to previous years. While most Fraser sockeye return as four-year-olds, some return as five-year-olds or even three-year-olds. The simulation model accounts for this variable age structure. The production from a spawning is calculated with the particular stock/recruitment model parameter set (Ricker or Larkin) and each year the productivity and carrying capacity parameters are used. An error term is generated from a normal or lognormal distribution using a pseudo-random number generator and the variance parameter, and then applied to the recruitment to simulate environmental variability.

The current model generates one trajectory, 48 years of population sizes, for each modeled stock (parameter set), drawing a single error term (environmental variability) for each year. Another approach would be to generate several trajectories for each parameter set using a sample of replicate trajectories reflecting the influence of variability around each set of productivity, carrying capacity and interaction parameters. Error terms would be drawn randomly using the assumed error structure and the variance parameter in the set. This process would increase the number of calculations and the time it takes to run each parameter set. However, it may represent the variability more realistically. The degree to which this increase in calculations affects the results should be examined using sensitivity analysis.

Figure 1, reproduced from Pestal et. al. (2008) illustrates an annual planning cycle with the use of the FRSSI model.

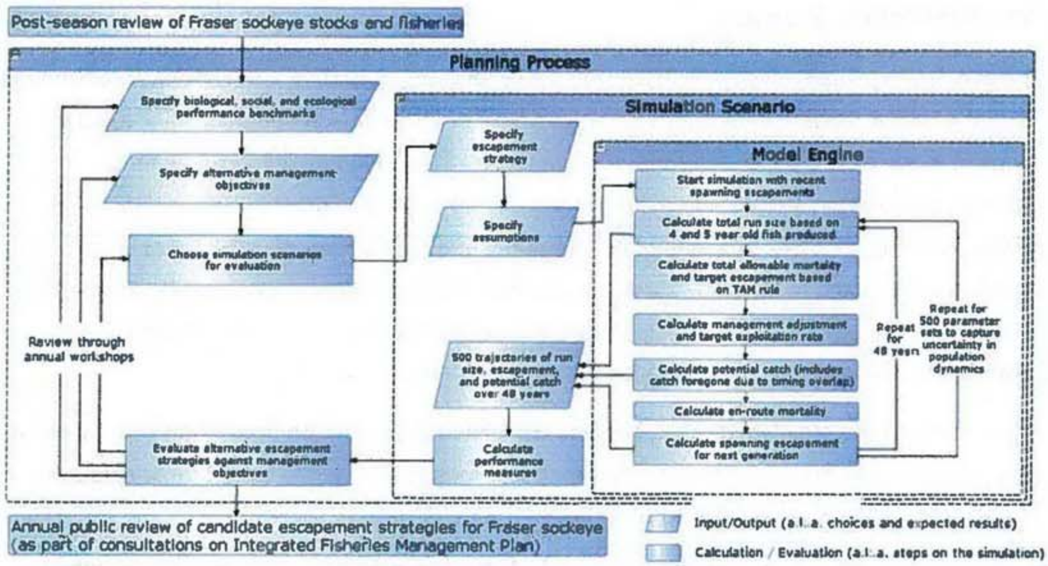

Figure 1: Idealized Annual Planning Cycle

Sensitivity Analysis

Sensitivity analysis is used in simulation modeling to test the relative effects of various assumptions on the projected outcomes. In the FRSSI model, there are several key assumptions and sensitivity analysis has been done for many of them. It is a long and arduous task to run all of the sensitivity analyses for all the assumptions and uncertainties. It requires a systematic definition of the variety of assumptions and the uncertainty in the characterization of those assumptions. There has been a significant amount of sensitivity analysis but there is still a need for research on how to test effectively and systematically all possible combinations and permutations of assumptions and uncertainties.

Scenarios – Combinations and Permutations

With all the alternative possible assumptions and harvest strategies, the number of combinations and permutations is daunting. The number of scenarios is almost endless. Furthermore each time there is a change the model structure, change to some of the assumptions or an update in the data sensitivity analysis is required. With all the possible combinations and permutations, this has proven difficult. Further review of the need for sensitivity analysis, on all combinations and permutations of assumptions and uncertainties every time there is a change or update the model, should be undertaken. It would be important to determine if all the sensitivity analyses need to be redone, there may only be a subset of scenarios that are necessary and informative.

Communication of the Results

The annual cycle of data analysis and model review, are bracketed by two phases of public consultation, the *post-season review* in the fall and *pre-season planning* in the spring. Both of these consultations use a combination of formal advisory processes (e.g. *Integrated Harvest Planning Committee),* bilateral meetings with First Nations, and in the past town hall style public meetings (e.g. in coastal communities). Each year, the FRSSI model is used to examine a range of alternative escapement strategies for each management group. A shortlist of 3 to 5 options for each management group is selected based on pre-season expectations for each alternative and a summary of simulation results. These options are then presented for review during the annual pre-season consultations (e.g. draft Integrated Fisheries

Management Plan, annual technical memo). Occasionally, additional options are added to the options list based on feedback generated during the review process. One option is then included in the final management plan.

One of the major challenges with FRSSI has been communication about the nature of the model and results to the broad community of First Nations and other stakeholders such as fishers. The volume of information contained in the FRSSI process is large. The analytic approach is state-of-the-art and it is difficult to explain, in an understandable way, to audiences who are not mathematically or otherwise technically inclined.

Extensive use has been made of graphs and interactive worksheets that allow users to explore the volume of output from the model in a systematic way. However, to date it does not appear that many, other than the core technical working group responsible for FRSSI, have used this facility. It would be useful to have more hands-on workshops with those who are interested in FRSSI and who are affected by the decisions that flow from it. The audience needs a better appreciation of what is in FRSSI and what is not. The analytic framework and the model can be used to explore a wide variety of alternatives. To date, not all of the possibilities have been examined, it is still a work in progress. It may never be "finished" as new research, data and tools appear.

Some of the criticism of FRSSI arises because of the small set of alternatives that have been fully explored. If the model were widely available and accessible then some critics might be able to explore other alternatives that have not been part of the formal presentation of FRSSI. If the broader audience were able to work and explore the model, it would help them to engage in the deeper debate about the underlying assumptions and policy issues. Then the criticism and debate could be about the analysis and the output not so much on the analytic framework.

Simplification and Digestibility without Losing Important Complexities

In an attempt to communicate some of the output there have been some significant simplifications in the analysis related FRSSI. One of the most striking is simplification of the shape of the TAM rule. There are many possible other alternative shapes and assumptions about a TAM rule.

Early in the process, the TAM rule shape provided for an unexpected result. The shape of the Rule suggested that the spawning escapement target should increase as a run size decreased. When this result was apparent, the response was to simplify the possible TAM rule shapes. An alternative would have been to examine the reasons for this result. It could have been that the model was suggesting that it is better to be aggressive in rebuilding the stock (increase the spawning target) the smaller the run sizes. The closer the population size gets the lower benchmark the more aggressive and quicker one should try to rebuild the run. The current shape of the TAM rule does not provide for this solution.

Total Allowable Mortality (TAM) Rules

One of the key characteristics of the TAM rule is a maximum allowable mortality rate. Current maximum is 60%. This number was not a direct result of the FRSSI model and analysis. It was set in an attempt to account for populations of species or stocks that are not represented in the model. Of particular concern are those stocks and populations that are small and/or weak and difficult to detect. It is hoped that the maximum mortality rate will avoid or minimize collateral damage to these small and/or weak populations when the larger Management Groups are in higher and healthy abundance. This maximum mortality rate should be examined and thoroughly evaluated.

The current TAM rule shape, employed in FRSSI, can be determined by with a single parameter. The parameter is the run size at which mortality rate begins to decrease or the so-called cutback point. For run sizes between the cutback point and the so-called no fishing point, the result of the TAM rule is a fixed escapement target. The mortality rate declines with the run size to maintain a fixed escapement.

The no fishing point is a bit of a misnomer. The combination of en route mortality and the TAM rule may mean that there is no fishing at run sizes above the so-called no-fishing point. In addition, the FRSSI model provides for a minimum exploitation rate. This aspect was developed to reflect the practice of having fisheries directed on other Management Groups that would result in some exploitation on the stock of concern, when the plan or rule would suggest no fishing or exploitation. For example, a minimum exploitation rate of 20% is set for late runs in years when they are managed to a maximum exploitation of 20%.

The simplification of the TAM rule to a single parameter allows for the display of response of performance measures to alternate TAM rules on a two dimensional graph. In this format, the output can demonstrate whether a particular performance measure or indicator is sensitive to the alternate TAM rules. Examples of this are shown from the 2009 analysis (Figures 2 – 5). In most cases, the options that were prepared for the Integrated Fisheries Management Plan represent cutback points for the TAM rules where there is a slight inflection or change in the performance indicator. For example for Early Stuart all three indicators: low catch, low escapement and low escapement averaged over four years have a slight inflection at approximately 400,000 spawners. Some of the other options have been provided for illustration purposes.

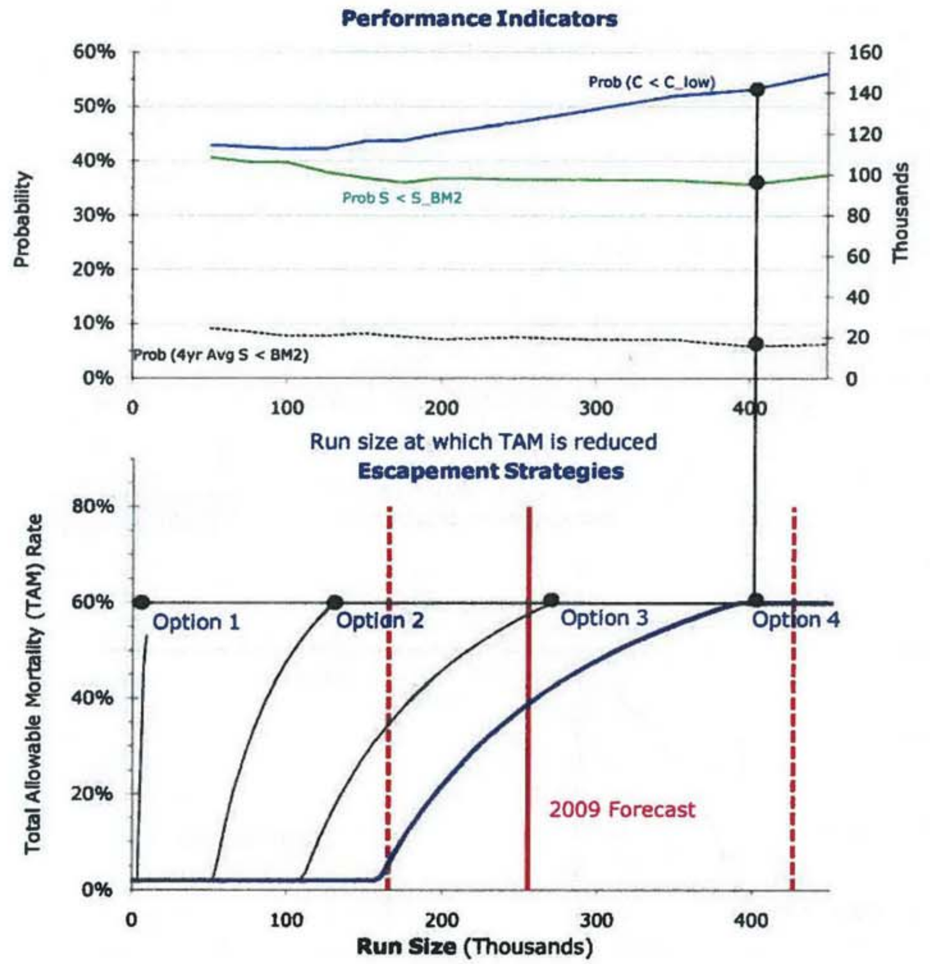

Figure 2: Early Stuart 2009 FRSSI Options

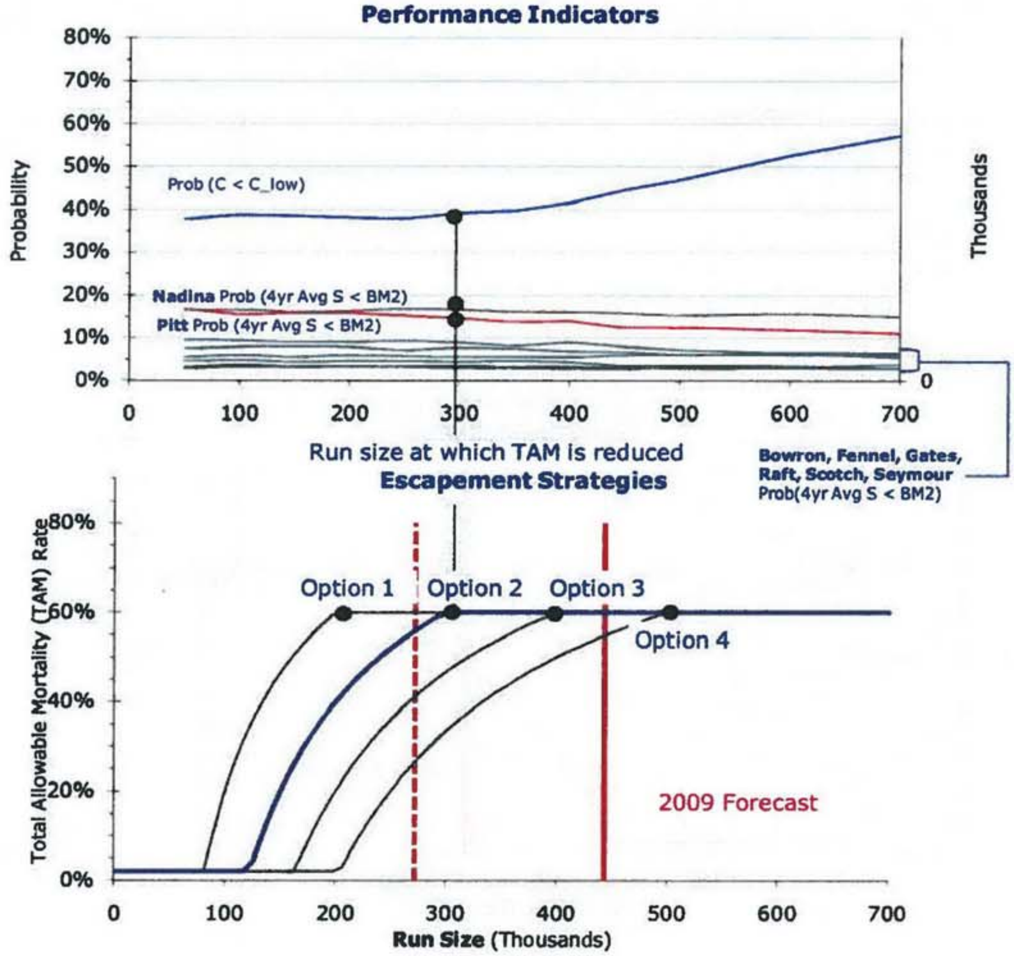

Figure 3: Early Summer 2009 FRSSI Options

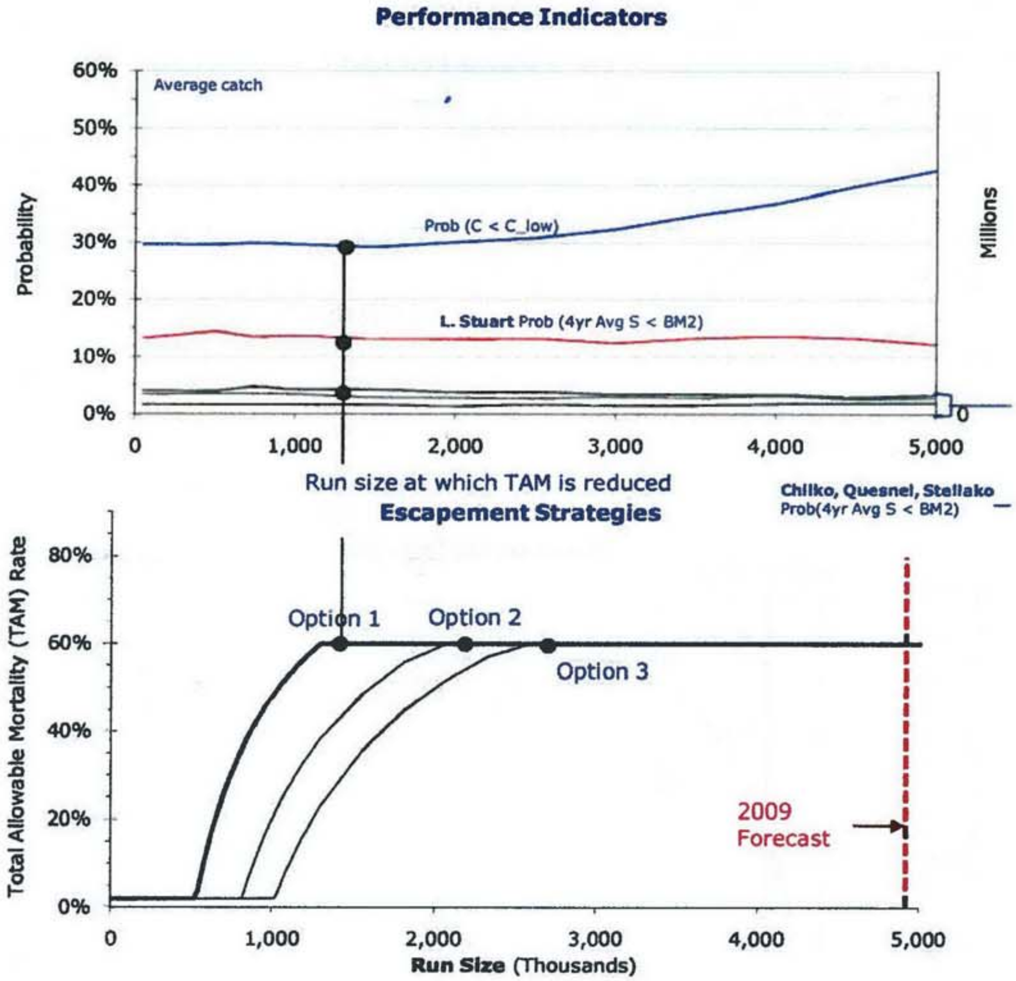

Figure 4: Summer Run 2009 FRSSI Options

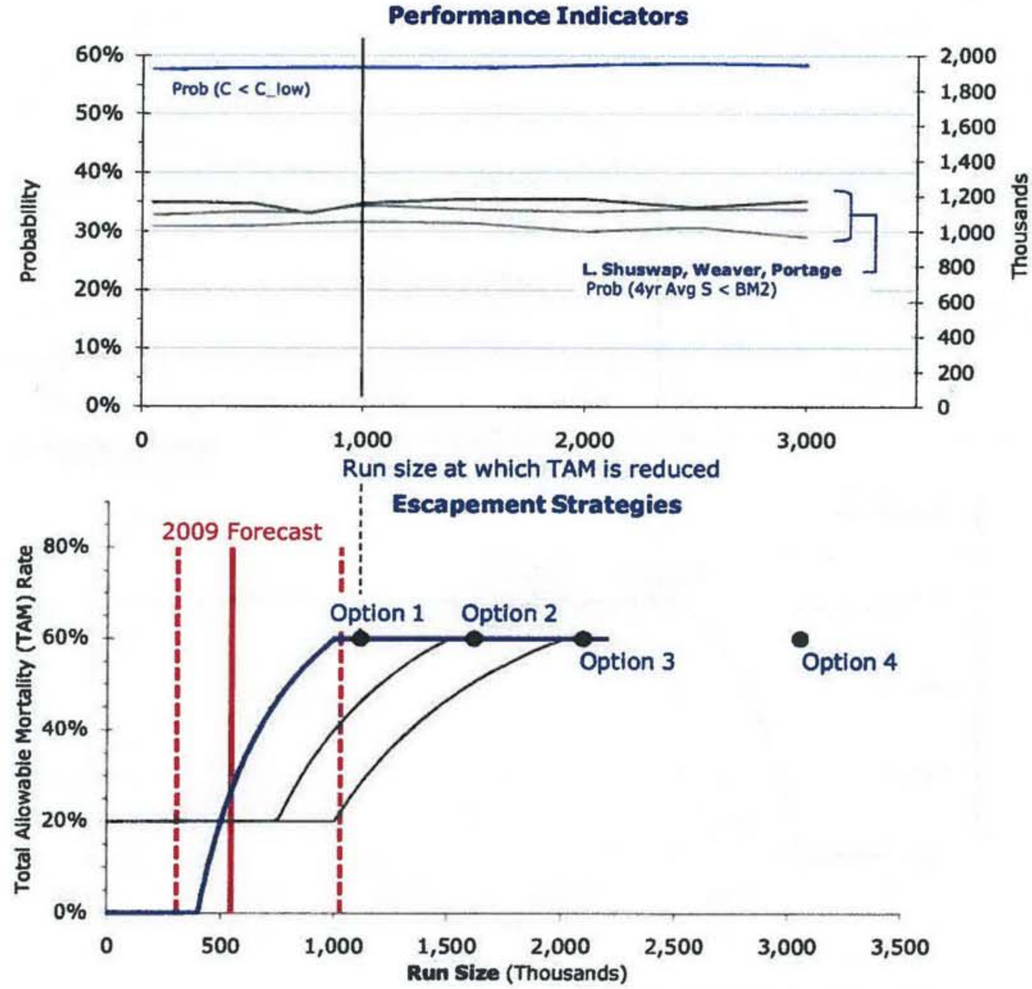

Figure 5: Late Run 2009 FRSSI Options

Discussion and Conclusions

The data analysis and models in FRSSI are state-of-the-art. The Bayesian data analysis provides distributions of the key parameters that are used in the forward simulation model. The simulation models using these distributions of parameters can reflect the wide range of possible outcomes and associated risks.

The historical data set on Fraser sockeye run sizes, catches and spawning escapements is one of the longest most comprehensive data sets of its kind for any wild animal. The data from recent years suggests that there may be a trend in the underlying parameters such as productivity. Harvesting strategies or TAM Rules that do not assume that there are underlying trends in productivity's may not be the most appropriate. We should not ignore the historical data but use it as a frame of reference to explore possible futures and debate appropriate actions. It would be helpful to account for these trends in productivity and predict them. Unfortunately, we do not understand the behaviour of these trends well enough to predict them or even to use them in a prescriptive way in a model like FRSSI. We can only assume future scenarios and test the modeled sensitivity of TAM rules to these possible futures.

The latest version of the FRSSI model includes the use of the Larkin or delayed density dependent versions. Some researchers have suggested that the recent decline in productivity of Fraser sockeye is due to a management regime that attempts to increase the spawning abundance across all cycle lines. In addition, delayed density dependence suggests higher exploitation rates than do the standard Ricker models. The FRSSI model has the capacity to explore implications of these alternative hypotheses as well as to assess the number of years and observations it might take to have some certainty about the best model and exploitation rate range.

There needs to be a better understanding of the potential trade-offs between mixed stocks and known stock fisheries. The FRSSI process can assist in bettering our understanding and can assist the dialogue around the appropriate fishing regimes that utilize mixed and known stock fisheries to generate benefits and avoid risks.

There is a need for more research and experimentation to improve the representation of overlaps and management imprecision the FRSSI model. A good result would be to find a management regime, or TAM Rule, that produces similar benefits and risks regardless of the type or degree of realistic management imprecision.

The conceptual structure for a more detailed in-season management model is currently being developed elsewhere (SFU). This new model is being designed to simulate individual stocks or conservation units, each with their own timing, as they move through a sequence of fishing areas.

There has been a considerable amount of sensitivity analysis but there is still a need for significantly more. It would be useful to test systematically all possible combinations and permutations of assumptions and uncertainties efficiently and effectively. It would also be helpful to determine if all the sensitivity analysis needs to be redone whenever changes are made to the model and/or data.

Hands-on workshops with those who are interested in FRSSI and who are affected by the decisions that flow from it would help in broadening the understanding of the tools available in the FRSSI model. The audience needs a better appreciation of what is in FRSSI and what is not.

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