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**Pre-season run size forecasts for  
Fraser River sockeye for 2006**

**Prévision présaison des remontes de  
saumon rouge du fleuve Fraser pour  
2006**

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## **Abstract**

Pre-season abundance forecasts are used for pre-season planning and during in-season assessments of run size for fishery management. Forecasts are produced annually by Fisheries and Oceans Canada (DFO). Forecasts of sockeye returns typically are made using a variety of models depending on data availability. In this year's assessment, a suite of biological and naïve models were assessed against standard performance measures. The biological models include models relating recruitment (and returns) to predictor variables (escapement, fry, smolts, and age-3 (jack) siblings in the case of Cultus Lake sockeye). We also investigate some environmental variables on model performance. These include Fraser River discharge, sea surface temperature (SST) data and the Pacific Decadal Oscillation index (PDO). Uncertainty in forecasts for 2006 is captured using Bayesian statistical inference. Nineteen stocks and four run timing groups were forecasted. Most of the forecasts are associated with large uncertainty. This is consistent with previous Fraser sockeye forecasts PSARC reviews and recent research on coast-wide salmon stocks ranging from Alaska to BC. Pre-season forecasts at the 50% probability level for all stocks totalled 17.4 million sockeye for 2006. By timing group, this includes 84,000 Early Stuart sockeye, 1.3 million Early Summer sockeye, 7.2 million Summer run and 8.8 million Late run sockeye.

## **Résumé**

Les gestionnaires des pêches utilisent des prévisions présaison des remontes pour effectuer la planification préalable à la saison et évaluer la remonte pendant la saison. Ces prévisions sont produites chaque année par Pêches et Océans Canada (MPO). Les prévisions des remontes de saumons rouges sont habituellement effectuées à l'aide de différents modèles, selon la disponibilité des données. Au cours de l'évaluation de cette année, nous avons examiné une série de modèles biologiques et naïfs par rapport à des mesures de rendement standard. Parmi les modèles biologiques figurent des modèles liant le recrutement (et les remontes) à des variables explicatives (échappées, alevins, saumoneaux et saumons d'un an en mer (âge 3) dans le cas du saumon rouge du lac Cultus). Nous avons également investigué l'effet de certaines variables environnementales sur le rendement du modèle. Parmi celles-ci figurent le débit du fleuve Fraser, des données sur la température à la surface de la mer et l'indice d'oscillation décennale du Pacifique. L'inférence statistique bayésienne nous permet de prendre en considération l'incertitude dans les prévisions pour 2006. Nous avons établi des prévisions pour dix-neuf stocks et quatre groupes à période de remonte différente. La plupart des prévisions sont marquées par de grandes incertitudes, une situation qui concorde avec les examens de prévisions antérieures sur le saumon rouge du fleuve Fraser effectués par le CEESP et avec des recherches récentes sur les stocks de saumons répartis le long de la côte, de l'Alaska à la Colombie-Britannique. Les prévisions présaison pour tous les stocks, à un niveau de probabilité de 50 %, totalisaient 17,4 millions de saumons rouges pour 2006. Par groupe de période de remonte, les chiffres sont de 84 000 pour les poissons de remonte hâtive de la Stuart, 1,3 millions pour les poissons de remonte hâtive d'été, 7,2 millions pour le groupe de remonte d'été et 8,8 millions pour les saumons rouges de remonte tardive.

## 1. Introduction

Pre-season abundance forecasts of returning adult sockeye are requested by resource managers. They are used for pre-season planning and during in-season assessments of run size for fishery management. Pre-season forecasts are most useful early in the summer fishing season before reliance on in-season run size estimates. Forecasts are produced by Fisheries and Oceans Canada (DFO) as agreed under the US-Canada Pacific Salmon Treaty. Forecasts have been reviewed annually and a series of reports are publicly available:

[http://www.dfo-mpo.gc.ca/csas/csas/Publications/Pub\\_Index\\_e.htm](http://www.dfo-mpo.gc.ca/csas/csas/Publications/Pub_Index_e.htm) .

Forecasts of salmon returns are typically made using a variety of models depending on data availability. For all stocks the data include spawning escapement estimates that date back to the late 1940s. Nineteen stocks have paired escapement and recruitment data. A subset of stocks have juvenile abundance data in addition to escapement data. Several small populations only have escapement data. Data sources are described in Section 2. In this year's assessment, a suite of biological and naïve models are assessed against standard performance measures. The biological models include models relating recruitment (and returns) to predictor variables (escapement, fry, smolts, and age-3 (jack) siblings in the Case of Cultus Lake sockeye). We also investigate some environmental variables on model performance. These include Fraser River discharge, sea surface temperature (SST) data and the Pacific Decadal Oscillation index (PDO). Mueter et al. (2002) detected significant spatial covariation between coastal SST and the recruits-per-spawner survival index. Beamish et al. (2004) showed the PDO index significantly explained Fraser sockeye survival when data were aggregated by specific regimes compared to disaggregated data.

Uncertainty in forecasts for 2006 are captured using Bayesian statistical inference. The methodology is described in Section 3. Results of the analysis including 2006 forecasts are presented in Section 4. In keeping with past practice, forecasts are presented as distributions of age 4 + age 5 returns given data uncertainty. Finally, a discussion of results is presented in Section 5.

## 2. Data sources

Spawning escapement, fry, fall-fry, smolt and recruit estimates by stock are the primary data inputs. Most of these data were provided by the Pacific Salmon Commission in a Microsoft Access database. The spawning escapement data are estimates of the number of spawning females contributing to the spawning population based on sampling for potential egg deposition. These data are referred to as “effective females”. Total adult escapement data was used for Cultus Lake sockeye because estimates of effective females are poorly determined for that stock. Many of the nineteen stocks have paired escapement – recruitment for 53 years (brood years 1948-2000). Escapement data are available up to the 2002 brood year (2006 return year). Age 3, 4 and 5 recruits were used in the analysis.

Estimates of juvenile sockeye fry from Nadina, Gates and Weaver spawning channels are available beginning respectively in 1968, 1973 and 1965 (Roberta Cooke, Fisheries and Oceans Canada, personal communication). In addition to the estimates of channel fry production, each of these systems have historical estimates of stream (ie ‘wild’) fry production (Gates: 1968-1989; Nadina: 1973-1984; Weaver: 1951-1988, broken series). The PSC production database also maintains these same records for channel and stream fry production in these three systems. For years where estimates of both channel and stream fry emigration exist, the total fry production is the sum of both estimates. Total production in recent years lacking stream fry estimates, are estimated by summing channel production and the product of stream effective female escapement and average historical stream fry production per effective

female. Fry data for a maximum of three spawning locations (Forfar, Gluske and Kynoch creeks) in the Early Stuart timing group are available since 1990. (Keri Benner, Fisheries and Oceans Canada, personal communication). These data were expanded by the ratio of escapement in the sampled systems to the total Early Stuart escapement to estimate the total fry production for years that fry data are available.

Estimates of age-1 smolts for Chilko and Cultus sockeye were also used in the analysis. Chilko smolt data is available for most years starting in brood year 1949. Cultus smolts are available from brood year 1924 (Schubert et al. 2004) but recently have been estimated intermittently since the early 1950s with 28 years of data available in the 1951 and 2002 interval. Cultus sockeye smolt output has been supplemented by hatchery-reared smolts in recent years. Estimates of natural and hatchery survival rates have been estimated from marked-unmarked Cultus smolt-to-adult returns and assumed exploitation rates (Mike Bradford, Fisheries and Oceans Canada, personal communication). The data were used to estimate smolt survival rates in terms of natural smolt equivalents for years with hatchery supplementation (1999-2002 brood years). Estimates of jack returns to Cultus Lake sockeye in 2005 were derived from Sweltzer Creek fence counts. During August 18 to September 12 visual distinction between males, females, and jacks proved difficult. During that time period sockeye appeared to be smaller than usual and did not have well developed secondary sexual characteristics and small fish were often identified as females (Sue Grant, Fisheries and Oceans Canada, personal communication). After September 13 brood stock collection occurred and each fish was individually handled, secondary sexual characteristics were more developed, and scale analysis confirmed that the smaller fish were jacks rather than females. The August 18 - September 12 Cultus data were “corrected” by multiplying the total numbers of sockeye by the estimated proportions of males, females and jacks for the post September 12 period.

Mean spring-summer lighthouse SST data for April to July were derived from the data webpage of the Canadian Institute for Oceanographic Sciences website ([http://www-sci.pac.dfo-mpo.gc.ca/osap/data/SearchTools/Searchlighthouse\\_e.htm](http://www-sci.pac.dfo-mpo.gc.ca/osap/data/SearchTools/Searchlighthouse_e.htm)). The temperature data were sampled at lighthouse locations which we felt best likely represented conditions experienced by juveniles during their initial stages of migration in the marine environment in the juvenile ocean entry year. The two locations were Entrance Island (Strait of Georgia, proximate to Nanaimo) and Pine Island (NE corner of Vancouver Island).

Mean Winter (November-March) PDO indices were from

<http://jisao.washington.edu/pdo/PDO.latest>.

Mean April-June Fraser River discharge and peak discharge data at Hope BC in the juvenile ocean-entry-year were accessed at the “Archived Hydrometric Data” webpage of Environment Canada (<http://www.wsc.ec.gc.ca/hydat/H2O/>).

The complete set of data for each stock used in the analysis are listed in Appendices. Appendix Table 1 lists the biological data. Appendix Table 2 lists the environmental data.

### **3. Methods**

The methodology consists of the following steps:

- 1) choose candidate forecast models depending on data availability;
- 2) perform a retrospective analysis for each stock by sequentially forecasting abundance for years with observations of abundance;

- 3) evaluate model performance by comparing the retrospective forecasts with the abundance observations based standard performance criteria;
- 4) Identify the “best” forecast model from step 3 and present forecasts as posterior distributions of returns in 2006.

Several classes of forecast models were considered for each single stock analysis (Table 1). These include 1) naïve models that assume no underlying biological mechanism; 2) escapement-based models that assume a relationship between spawning escapement and adult recruitment; 3) juvenile-based models that theoretically eliminate some of the uncertainty in freshwater survival; 4) escapement or juvenile-based with covariates to assess potential environmental effects on forecast performance; and, 5) a jack-based sibling model for Cultus sockeye that theoretically eliminate some of the uncertainty in both freshwater and marine survival. Age-3 returns for other stocks are not usually available until the spring and jack models were not evaluated in this Working Paper. A mixed-effects (meta-population) model was also assessed using environmental covariates to assess common affects in mixed stock aggregates that potentially cannot be detected at the single stock level given stock-dependent residual noise.

The retrospective analysis compares recruitment (age-4 + age-5) resulting from each brood year escapement rather than the abundance in a given return year (different brood years). This was done to simplify the retrospective procedure for data restricted stocks where uncertainty and “holes” in the data series prevent a complete retrospective comparison of returns from adjacent return years. Abundance forecasts for 2006 however are based estimated age-4 returns from the 2002 brood and age-5 returns from the preceding (2001) brood year.

Effective female spawning escapement for 2001 (age-5 brood) and 2002 (age-4 brood) for populations without recruitment data were combined and reported in Table 3 as “miscellaneous” stocks. For the miscellaneous Late run, the forecast for Late Shuswap and non-Late Shuswap stocks are reported separately. Return forecasts were computed for miscellaneous stocks using the mean R/S for stocks with paired escapement and recruitment data within each timing group. Recruitment is then the product of brood escapement and the mean R/S. A forecast distribution was estimated using the mean and standard deviation for the R/S series. This is consistent with previous methods (i.e. Cass 1998).

### 3.1. Naïve models

Eight naïve models were considered. The first model, “R1C”, simply forecasts abundance from the previous cycle year:

$$(1) \quad R_t = R_{t-4} + \varepsilon_t,$$

where  $R_t$  is the recruitment in the forecast year,  $R_{t-4}$  is the observed recruitment four years earlier and  $\varepsilon_t$  is the residual error with  $\varepsilon_t \sim N(0, \sigma^2)$ . The second naïve model, “R2C”, forecasts abundance based on the geometric mean in the previous two cycle line years:

$$(2) \quad R_t = \exp \left[ \frac{\log(R_{t-4}) + \log(R_{t-8})}{2} + \varepsilon_t \right].$$

Similarly, a third naïve model, “RAC”, uses the all-cycle line geometric mean abundance available in the data series to forecast abundance.

$$(3) \quad R_t = \exp \left[ \frac{\log(R_{t-4}) + \log(R_{t-8}) \dots + \log(R_{t-n})}{N} + \varepsilon_t \right]$$

where  $t-n$  is the first year in the series of cycle years and  $N$  is the number of years of data within each cycle line. The fourth naïve model, “TSA”, forecasts abundance using the geometric mean recruitment for all cycle lines of the stock.

Four additional naïve models were considered, each with the same structure as the previous four models. These latter four models produce estimates of recruits-per-spawner (like last cycle, like last two cycles, cycle average, time series average) which are then multiplied against the brood escapement to produce a recruitment forecast. Means and standard deviations for the recruitment rates are estimated in log transformed space.

### 3.2. Biological models

Bayes posterior parameter distributions for the biological models were estimated using BUGS (Bayesian software Using Gibbs Sampling) (<http://www.mrc-bsu.cam.ac.uk/bugs/welcome.shtml>). The R statistical software and the BRugs library were used to automate the analysis

(<http://www.biostat.umn.edu/~brad/software/BRugs/>).

BUGS model formulation for each class of forecast model is presented in Appendix 3. In each trial the MCMC burn-in length was set to 1000 samples from the posterior distribution. This was adequate based on the Gelman Rubin statistical test. A further 10,000 posterior samples were then used for parameter estimation.

Two escapement-based models were considered. The Ricker model (Ricker 1954) of the form:

$$(4) \quad \log(R_t / S_t) = a - bS_t + \varepsilon_t$$

and a power model

$$(5) \quad \log(R_t) = a + b \log(S_t) + \varepsilon_t$$

are based on the relationship between recruits  $R_t$  and spawning escapement  $S_t$ . Prior distributions for  $a$  and  $b$  are  $Normal(\mu, \sigma^2)$ . We assumed non-informative prior distributions  $a, b \sim Normal(0, 1e6)$  (i.e. a normal distribution with large variance) and allowed the model to estimate the parameters from the data. For stocks with escapement data extending back to the 1950s, the performance of the Ricker and power models were also evaluated for data restricted to each cycle line.

Juvenile data are available for 8 of the 19 stocks. Fry (Early Stuart, Stellako, Nadina, Gates, Weaver), in-lake fall-fry (Quesnel and Shuswap) or smolt data (Chilko and Cultus) were used in a power model for forecast adult abundance.

Annual estimates of spring Fraser River discharge measured at Hope and spring SST measured data in the juvenile ocean-entry year were added to equation (4) and (5). When included in a Ricker model for example:

$$(7) \quad \log(R_t / S_t) = a - bS_t + \gamma X_{t+2} + \varepsilon_t,$$

$\gamma$  represents the added effect of variable  $X_{t+2}$  in addition to spawning escapement  $S_t$  on recruitment variation.

The final biological model is a sibling model that includes priors for modelling smolt-to-adult survival and age-3 jack proportions. The priors were based on the historical distribution of smolt survival rates and jack proportions. Jack abundance estimates in 2005 were only available for Cultus Lake sockeye at the time forecasts were requested. For all other stocks, jack data are not usually available until February or March of the forecast year. The joint posterior distribution for smolt survival  $s_s$  and jack proportion  $p_3$  given the smolt  $N_t$  and jack  $E_{3,t}$  abundance for brood year  $t$  is

$$(8) \quad \Pr(s_s, p_3 \mid N_t, E_{3,t}) \propto \text{Beta}(\alpha_s, \beta_s) \text{Beta}(\alpha_3, \beta_3) \text{Poisson}(N_t s_s p_3)$$

where  $s_s$  is beta distributed with prior parameters  $\alpha_s$  and  $\beta_s$ . Parameter  $p_3$  is beta distributed with parameters  $\alpha_3$  and  $\beta_3$  estimated from age-3 proportion data

$$(9) \quad p_3 = \frac{R_3}{R_3 + R_4 + R_5}.$$

The likelihood function is Poisson with an expected value equal to the predicted jack abundance based on smolt abundance  $N_t$ , smolt survival  $s_s$ , and the age-3 proportion  $p_3$ . A posterior forecast for the total return (age-4 plus age-5) is

$$(10) \quad R_t = N_{t-1} s_t (1 - p_{t,3}).$$

A version of this model was used to forecast 2005 Cultus Lake sockeye returns (Wood and Parken 2005). Equation (8) includes the additional prior for jack proportions and therefore admits added uncertainty in the historical jack proportion that was fixed in the 2005 forecast.

The proportion of age 4+5 returns  $R_{4+5}$  in 2006 for all models was estimated from:

$$(6) \quad R_{4+5} = p_4 R_t + (1 - p_4) R_{t-1}$$

where  $p_4$  is the estimated proportion of recruits  $R_t$  returning at age-4 in 2006 and  $R_{t-1}$  recruits from the previous brood returning at age-5 in 2006. In the biological models, the prior distribution of  $p_4$  is beta distributed with parameters estimated from the historical data series. In the naïve models  $p_4$  is the historical mean.

Table 1. List of candidate models and data requirements.

<i>Model Name</i>	<i>Model Type</i>	<i>Model Method</i>	<i>Data Applied</i>			
			<i>Returns</i>	<i>Escpamement &amp; Adult Recruitment</i>	<i>Juvenile Estimates</i>	<i>Environmental</i>
R1C	Naïve	Same returns as 4 years previous	X			
R2C	Naïve	Average of returns 4 & 8 years previous	X			
RAC	Naïve	Average returns on cycle line	X			
TAC	Naïve	Time Series Average Return	X			
Power	Biological	Power function combining all cycles		X		
Power-cyc	Biological	Power function based on 1 cycle line		X		
Ricker	Biological	Ricker function combining all cycles		X		
Ricker-cyc	Biological	Ricker function based on 1 cycle line		X		
Power-fry	Biological				X	
Smolt-Jack	Biological	Bayesian			X	
Ricker-disc	Biological & Environmental	Multiple regression		X		Average spring Fraser discharge
Ricker-peak	Biological & Environmental	Multiple regression		X		Peak spring Fraser discharge
Ricker-ei Ricker-pi	Biological & Environmental	Multiple regression		X		Average spring-summer Lighthouse SST
Ricker-PDO	Biological & Environmental	Multiple regression		X		Winter Pacific Decadal Oscillation Index

### 3.3. The retrospective analysis

Forecast performance for candidate models was evaluated in a retrospective analysis by comparing forecast recruitment to estimated (observed) recruitment for years that data are available. In this way only data that would have been available for a given past forecast year is used in the analysis. Most model inputs were initialized with data from the first half of the data series. We then sequentially forecast subsequent years for all years in the second half of the series with paired data points of predictor and recruitment variables. Cycle-line models have at most 12 paired data points and were initialized

with available data for 1948 to 1990 in an attempt to reduce the error resulting from low sample sizes in the retrospective analysis.

For stocks with juvenile data or juvenile-jack data, the retrospective analysis occurred in a two-step process. We first compared the performance of juvenile (and the juvenile-jack model in the case of Cultus sockeye) against the theoretically less informative escapement-based and the naïve models. In these tests, the performance assessment only included years with juvenile data. Typically, the series of juvenile data is shorter than the escapement and naïve data series. For example, for Early Stuart sockeye, there are 11 years of paired fry and recruit data (1990-2000) to retrospectively compute forecast error and compared model performance. The model was initialized using 1990-1994 paired fry-recruit data. Forecast error was then sequentially computed for each subsequent year starting in 1995 and ending in 2000; the last year with available fry-recruitment data. Beginning in 1995, only forecast data available from 1990 to 1994 was used in the retrospective analysis. A forecast was then projected for 1995 and the median recruitment forecast was compared to the observed recruits in the 1995 brood. The model was updated with data from 1990 to 1995 and the median forecast for 1996 was computed and compared to the observed recruits in 1996. This procedure was continued to obtain 6 years of paired forecast and observed recruit data points (1995-2000) from which to compute the performance measures. Accordingly, all other candidate naïve and escapement models were initialized using all the available data from the first year in the respective data series (1948 for Early Stuart) to 1994 and forecast error was computed for 1995. As with the fry-based model, this procedure continued in annual time steps for the remaining five years of paired data points. This process was repeated for all other candidate models to compute performance measures consistently for the same six years. The “best” model was then selected from among all the candidate naïve and biological models.

Overall, if the theoretically superior juvenile or juvenile-sibling model out performed the escapement or naïve models, then the retrospective analysis was terminated and the “best” model was determined to be the juvenile-based model. If the escapement or naïve models proved superior then a second set of retrospective analyses were performed that excluded the juvenile or juvenile-jack models. This second step occurred to compare model performance over the longer time series of escapement and naïve model data.

### 3.4. Performance measures

We used three quantitative measures of model performance, referred to as *performance measures* (PM's) (Haeseker et al, 2005):

1. Mean raw error (MRE)
2. Mean absolute error (MAE)
3. Root mean square error (RMSE)

Each of these is a measure of the variability between the forecasted and observed recruitment. MRE is the average, across all forecasted years, of the difference between forecasted and observed recruitment.

$$\text{Mean Raw Error} = \frac{\sum_{t=1}^n (\hat{R}_t - R_t)}{n}$$

A value of zero is the best possible result for MRE, but as Haeseker et al (2005) indicate, large positive errors can be offset by large negative errors leading to a mean close to zero. This issue is addressed by

use of the MAE measure, whereby the absolute value of the differences is calculated before the average is taken.

$$\text{Mean Absolute Error} = \frac{\sum_{t=1}^n |\hat{R}_t - R_t|}{n}$$

RMSE was the measure used in previous Fraser sockeye forecast papers (Cass, 1998). The RMSE criterion is appropriate for minimizing extreme high or low forecast errors and is calculated as:

$$\text{RMSE} = \sqrt{\frac{\sum_{t=1}^n (\hat{R}_t - R_t)^2}{n}}$$

If all three PM's of a single model were close to zero, this would suggest it is the best choice. Thus an averaging of the model's rank placement was calculated. Each forecast model was ranked by it's placement within each performance measure (ie rank=1 for PM closest to zero etc, separately for each stock). Thus, each model would have three values of ranked placement, one for each PM. The average of the overall rank was used to gauge each model's overall placement, and to indicate which model should be chosen for forecasting 2006 returns. The model with the best average rank was judged to be the 'best' forecast. We choose to exclude the MRE in the calculation of the mean rank and therefore in the "best" model selection process. MRE is a measure of positive-negative deviation. In order to rank the absolute value of the MRE is needed. That step negates the usefulness MRE compared to the MAE criteria.

Haeseker et al. (2005) used the RMSE estimate as an indicator of forecast error. As Haeseker et al. point out, the model with the lowest RMSE would have the narrowest confidence intervals around the forecast and the model with the lowest RMSE estimate would also have the lowest variance. The RMSE calculation has a form similar to that for estimating the standard deviation of a sample ( $\sigma$ ) and was used here to estimate forecast distributions for stock with best performing naive model assuming log-normal error where:

$$\sigma = \sqrt{\frac{\sum_{t=1}^n (\log(\hat{R}_t) - \log(R_t))^2}{n}}$$

The amount of variation in observed recruits explained by the model can also be used to judge model performance relative to the amount of error explained by a particular forecast model (Haeseker et al. 2005). This is based on the multiple R-Squared statistic of a linear regression of observed versus forecast abundance from the retrospective analysis. This additional measure was computed for the "best" performing model to assess the overall amount of variation explained by the best performing model.

## 4. Results

Nineteen stocks were forecasted. The performance of each stock is listed in Appendix Table 4. A survey across stocks suggests that there is no universally optimal forecast model. The breakdown of optimal model by category is presented in Table 2

**Table 2. Summary of the best performing forecast model by model category.**

<i>Model Category</i>	<i>Number of Stocks Optimally Forecasted</i>
Naïve	7 of 19 stocks
Biological Escapement	12 of 19 stocks
Biological Escapement by cycle	1 of 10
Biological Juvenile	4 of 8
Biological Juvenile – jack	1 of 1
Biological & Environmental	1 of 10

Biological models outperformed naïve models by 13:19. Biological models that included juveniles out-performed other model by 4:8. Biological models that included an environmental component perform worse than biological models that consider only stock (or fry) and recruitment. Of the 10 stocks considered to have sufficient data (1950-present) to fit a Ricker cycle-line model only 1 (Seymour) performed best.

Biological models rely on the historical range of escapement and recruitment to confidently fit a relationship. Escapements beyond the range historically experienced can lead to highly uncertain forecasts. In 2002 escapement to Late Shuswap was 1.6 times the historic high, while Harrison escapement was the highest on record. We did not consider escapement-based models in the performance evaluation for these stocks

A summary of the results for each of the major timing groups (Early, Stuart, Early Summer, Summer and Late runs) and stocks within each group are presented below. Return forecasts at the 10%, 25%, 50%, 75% and 90% probability of achieving the specified run size along with mean returns are presented in Table 3. The “best” forecast for 2006 returns is discussed in the context of historical returns. For each of the 19 stock-specific forecasts, the trends in spawning escapement, recruits-per-spawner and return time series are shown in Figures 1, 2 and 3, respectively. In Figure 1, escapement is represented by estimates of effective female spawners. For these plots, only the natural stream spawners are considered, not channel escapement. Channel escapement was excluded to allow for a comparison to the estimated 12 year rate of change line. Rate of change was derived from a linear fit to 12 generational average data points represented by escapement during 1990-2004.

### 4.1. Early Stuart Sockeye

Despite the limited data series (1990-present) and the potential measurement uncertainty in the expansion from the three index spawning systems to the total system, the highest ranked forecast of the seven candidate models is the fry-based model. The model only explained 25% of the variation in recruitment but ranked the highest in all performance measures (Appendix Table 4).

## 5. Discussion

One of the data choices made in this analysis is the method of pooling data. Data inputs were aggregated by cycle-line and by pooling the entire data series. Restricting models to cycle-line years theoretically should out perform alternative models based on data for the entire data series if the relationship between returns and predictor the variable varies among the four cycle lines. The performance of cyclic escapement-based models was an overall poor performer. The retrospective analysis could be a biased test due to small sample sizes or because we cannot detect a difference in productivity among cycles.

We tested whether productivity estimated by  $\log(R/S)$  and/or stocks density effects estimated by a Ricker model can be better explained by data aggregated by cycle line data. We used classical analysis of variance (ANOVA) to answer the specific questions:

- 1) Does cycle line productivity expressed as  $\log(R/S)$  in the absence of density dependence explain more of the variation in productivity compared to data aggregated across the entire data series?
- 2) Do distinct Ricker models for each cycle better explain the stock-recruitment relationship compared to a common Ricker model fit to the entire data series?

For Question 1, suppose that  $\log(R/S)_i$  varies randomly around a mean level  $\mu_i$  within each cycle  $i$ :

$\log(R_{it}/S_{it}) = \mu_i + \varepsilon_{it}$ . We tested the null hypothesis

$$H_0: \mu_1 = \mu_2 = \mu_3 = \mu_4$$

Was tested against the alternative

$H_1: \mu_1 \neq \mu_2 \neq \mu_3 \neq \mu_4$ . For all 19 stocks, without exception, we could not reject  $H_0$  for a common productivity in favour of statistically different productivities among cycle lines (F-test;  $P < 0.05$ ).

For Question 2, we tested whether the Ricker  $a$  or  $b$  parameters varies among cycle lines. Here the null hypothesis

$$H_0: a_1 = a_2 = a_3 = a_4$$

$$b_1 = b_2 = b_3 = b_4$$

was tested against the alternative

$$H_1: a_1 \neq a_2 \neq a_3 \neq a_4$$

$$b_1 \neq b_2 \neq b_3 \neq b_4.$$

We could not reject the null hypothesis for a common Ricker model for any of the non-cyclic stocks (F-test;  $P < 0.05$ ) but could reject  $H_0$  for the highly cyclic stocks. On the basis of the ANOVA tests, aggregating data for the entire data series for at least the non-cyclic stocks appears justified. We acknowledge, however, that alternative data treatments (and models) are potentially tenable particularly for cyclic populations given the complexity of the dynamics in cyclic populations.

Most of the forecasts presented here are associated with large uncertainty. This is consistent with previous Fraser sockeye forecasts PSARC reviews and recent research on coast-wide salmon stocks ranging from Alaska to BC (Haeseker et al. 2005; Randall Perterman, Simon Fraser University, personal communication).

A recent study of forecasting model performance with 16 Fraser sockeye stocks, but excluding juvenile models, suggests naïve models were the best performers for the majority (10:6) (Personal communication, Steve Haeseker, U.S. Fish & Wildlife Service, Vancouver, Washington). Further, within the naïve group, the R1C model (i.e. like last generation) was the most common (7 of 10 cases). The differences in the choice of candidate models between the two studies could explain the different strengths of biological versus naïve model. Nevertheless, it is clear that no single model performs optimally across stocks and data sets. The best performing model is often stock dependent and varies according to performance criteria. Even for the best performing model assessed here, the recruitment variation among stocks explained by models spans a large range (3-83%) from extremely uncertain to informative.

Notwithstanding the Bayesian smolt-jack model used for Cultus sockeye, our choice of models was less inclusive compared to Haeseker (2005). We did not include a mixed-effects model that potentially increases parameter precision and inference about environmental effects. Nor did we consider Kalman filter models. Peterman et al (2003) applied a Kalman filtering technique to reconstruct historical productivity changes in Bristol Bay sockeye. Their work showed large swings in productivity for most of the stocks on a scale of 5-10 years. All studies to date indicated that all the test models are highly uncertain.

Our choice of biological data for Fraser River sockeye was more inclusive than other multi-stock studies in that we included a full suite of juvenile data. The performance of juvenile-based models was however also mixed. We selected environmental data that has been linked to salmon survival patterns in other studies. These include coastal SST (Mueter et al. 2002) and winter PDO (Beamish et al. 2004). Consistent with other studies, there was no noticeable improvement in forecast performance explained by the selected environmental variables including the addition of Fraser River discharge data. Admittedly our treatment of environmental effects is cursory. We recommend a more exhaustive assessment of hierarchical Bayesian mixed-stock effects model (Su et al. 2004), for example, to more fully consider environment/climate impacts.

Coast-wide high abundances of sockeye jack returns, including to the Fraser River in 2005, and large trawl catches of Fraser sockeye juveniles from the 2002 brood in Strait of Georgia (Dick Beamish, Fisheries and Oceans Canada, personal communication) have been reported. Qualitatively, these perhaps are suggestive of above average survival of the brood. On the other hand, the warm ocean conditions of the past few years (Anon. 2005) ([http://www.pac.dfo-mpo.gc.ca/sci/psarc/OSRs/2004OSR\\_e.htm](http://www.pac.dfo-mpo.gc.ca/sci/psarc/OSRs/2004OSR_e.htm)) and the anomalously late migratory timing and small body size of returning adults in 2005 perhaps are indicative of large-scale negative oceanographic effects. Whether these signals are short-term or indicative of long-term climate change impacts are unknown. There is consensus among members of the North Pacific Science Organization (PICES) that 1998 marked the change to another climate regime in the North Pacific (<http://www.pices.int/publications/brochures/PICES%20Advisory%20Report.pdf>). Again, the short-term and long-term impact of that event on Fraser sockeye productivity and returns is unknown. The impact of global warming on the productivity of salmon, such as Fraser sockeye, that geographically are at the southern limit of the species range will increase forecast uncertainty. It is important to note that jack-based (sibling) regression forecasts of Fraser sockeye have not performed well in the past. The high ranking of the retrospective performance of the Bayesian smolt-jack model for Cultus Lake sockeye is encouraging but was not very informative in terms of the 2006 forecast compared to the next-best smolt model. Unfortunately, because sibling model perform poorly, the impacts of oceanographic factors on early life stages cannot reliably be estimated using the standard data sets and forecast models.