# Run size assessment: In-season time-density model

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## Summary

The in-season assessment of Fraser River sockeye salmon relies on the Bayesian implementation of a time-density model to estimate run size and associated run timing. This model is fit to available catch-per-unit-effort (CPUE) data from gill net test fisheries in statistical fishing Areas 12 and 20, purse seine data in Areas 12, 13 and 20 (Chapter B2), and reconstructed daily abundance estimates derived from hydroacoustic data collected at Mission (Chapter B10) and seaward catches. The model relies on prior probability distributions of run size, timing, standard deviation (or spread), diversion rate, and test fishery catchability based on pre-season forecasts or historical observations (Chapters A1 and A2). Updated posterior distributions are produced by the model for timing, abundance, diversion, and sometimes spread, but the catchability priors are not updated. Instead, the daily catchabilities are assumed to be fixed but uncertain inputs, based initially on historical estimates, and later on in-season observations as they become available (Chapter B4). Early in-season, the model tends to underestimate the number of days for the salmon to pass through marine areas, and therefore the standard deviation of the migration (spread) is also considered a fixed but uncertain parameter. If necessary, this assumption can be relaxed after the peak of the run has been observed. The model is applied to stock aggregates which share similar migration timing and fall within the same management groups. For stocks that delay their upstream migration, only marine CPUE are used to assess the run, resulting in larger run size uncertainty in comparison to stocks that also rely on marine reconstructed data.

## Introduction

The Fraser River Panel is responsible for the in-season management of Fraser River sockeye stocks, as stipulated by the Pacific Salmon Treaty between Canada and the United States (PSC in-season). Under the terms of the Treaty, Commission staff are responsible for providing the Panel and Technical Committee with in-season updates of run size. Historically, two different methods had been relied upon for the in-season assessment of salmon stocks: regression models relating indicators of abundance (or cumulative abundance) on a given date with total run-size estimates obtained post-season (Fried and Hilborn 1988, Ryall 1998) and time-density (or cumulative time-density) models that estimate the proportion of the migration on a given date (Walters and Buckingham 1975, PSC 1995, Springborn et al. 1998). These time-density models rely on the date of peak abundance as well as the shape of the daily abundance profile over time. They can be fit to abundance indices such as catch-per-unit-effort (CPUE) data from commercial or test fisheries, as well as absolute estimates of abundance reconstructed from catch and real-time escapement data.

While time-density models have the advantage that the timing of the migration is an estimated model parameter compared to a fixed input as is the case for alternative in-season assessment models that rely on regression analyses using catch or CPUE (PSC 1995; Ryall 1998), the simultaneous estimation of timing and run size can also pose some challenges. The peak of the run can only be confirmed once more than 50% of the migration has been observed. Consequently, prior to the peak, runs that are small and early or late and large may be indistinguishable (Adkison and Cunningham 2015). The integration of all available sources of data and information within the assessments is therefore important to ensure timely in-season management decisions. Bayesian methods offer an ideal platform for such analyses while also accounting for the uncertainty in the resulting estimates (Fried and Hilborn 1988; Hyun et al. 2005). This document describes a general time-density model developed in a Bayesian framework for the in-season assessment of run size and timing for Fraser River sockeye salmon.

## Data

The in-season assessment of Fraser River sockeye stocks relies on four types of data: Lower Fraser River daily abundance estimates from the hydroacoustic program at Mission, catches seaward of the hydroacoustics program, test fishing catch and effort, and stock identification data (Woodey 1987). The reduced allowable exploitation of Fraser River sockeye in recent years has increased the reliance on test fishing CPUE information rather than commercial data as an index of abundance. The main marine test fisheries for in-season assessments are the gill net and purse seine test fisheries in DFO statistical Areas 12 and 13 (Johnstone Strait), and Area 20 (Juan de Fuca Strait). The combined CPUE data from these two Straits provide time series of relative daily abundance. Reconstructed estimates of daily absolute abundance in the same areas are derived through backward reconstruction methods (Starr and Hilborn 1988) using upstream daily passage estimates by the Mission hydroacoustics program in combination with seaward catches (Chapter B18). Both the CPUE and the reconstructed data are multiplied by stock proportion estimates (Chapter B17) to produce multiple timeseries resolved at finer stock resolutions. Separate models are then parameterized for stock aggregates within each management group that have distinctly different migration timing, catchability, or migration behaviour (e.g. delay or non-delay). To simplify the model description within this report, stock indices have been omitted from the model equations.

In-season, the marine CPUE data are considered early indicators of the expected daily abundance at Mission 6-days later, as it takes Fraser sockeye approximately 6-days to travel from the marine test fishery locations to the hydroacoustic site at Mission. Therefore, in-season, there is a 6-day lag between CPUE and reconstructed timeseries. In addition, reconstructed marine abundance estimates are only available for stocks that do not delay their upstream migration into the Fraser River due to the violation of basic reconstruction assumptions (Chapter B18). For stock like Harrison and delaying Late run stocks, only marine CPUE data can be used to assess these stocks, resulting in larger run size uncertainty.

## Methods

The following model description assumes that all timeseries have been offset in order to align with a single geographical reference location associated with the Area 20 purse seine test fishing site (Chapter B18). Date indices corresponding to data from all other locations are adjusted accordingly based on the relative difference in assumed fish migration time between Area 20 and Mission, and the migration time between the location of interest and Mission. For example, it takes approximately 7-days for sockeye to migrate from the Area 12 purse seine test fishing site to Mission, making the corresponding Area 20 date for the CPUE data of the purse seine test fishery in Area 12 one day later than the actual date. All dates mentioned in the description of the time-density model below refer to Area 20 dates.

### In-season time-density model

The in-season time-density model to assess the run size and timing of different Fraser River sockeye groups relies on a time-density function to represent the daily salmon migration past the marine test fishing locations (Mundy 1979, Cave and Gazey 1994, Springborn et al. 1998). Two different versions of the time-density model are used depending on the available test fishing data and the associated quality. The marine gill net data are of lower quality as a relative index of abundance compared to the purse seine data given the substantially lower catchability of sockeye salmon by gill nets versus purse seines, i.e., they catch a much smaller proportion of the run. The marine gill net data are however essential for the assessment of early-timed, low abundance stocks for which the cost of running expensive purse seine test fisheries would be prohibitive. Given the high variability in the individual gill net CPUE time-series for the Area 12 and 20, the two time-series are combined into a total CPUE time-series to assess the combined abundance migrating through marine areas. In cases where purse seine CPUE data are available, a more detailed version of the model assesses the abundance in both approaches separately. The following paragraphs will first describe the model using marine gill net data, followed by a description of a more complex model version incorporating data from both gear types.

The daily abundance of salmon (*Nd*) passing the marine reference locations on a given day *d* can be represented as:

where *f(d)* is the time-density function of migrating salmon, i.e., the daily proportion of the total run size and *N* is the total run size or the total recruitment of salmon, available to coastal fisheries. For Fraser sockeye, we assume a normal distribution of migrating salmon over time (Gilhousen 1960, Cave and Gazey 1994):

where *T* is the mean timing of the salmon migration and *S* is the standard deviation. Reconstructed daily marine abundances () deviate from the daily abundances predicted by the time-density model (*Nd*):

with reflecting the deviation. Based on the salmon abundance available on a given day (*Nd*), the associated CPUE by the gill net (*GN*) test fishery on that day (*Id,GN*) is given by:

where *q* represents the catchability coefficient, i.e., the proportion of the daily abundance taken as catch by one unit of effort. The observed CPUE data differ from the model predictions assuming lognormal residual errors:

with .

In cases when purse seine test fishery data are available in addition to gill net data, the time-density model is expanded to include daily abundance estimates in Johnstone as well as Juan de Fuca Strait:

1. *and*

where *Nd,a* is the daily abundance on a given day *d* in area *a* (*A12* or *A20)*, and *D* is the (northern) diversion rate, i.e. the proportion of the run migrating through Johnstone Strait (*A12*) (Chapter A2). For gill net test fisheries, it is assumed that the sockeye catchability is the same in Johnstone Strait versus Juan de Fuca Strait. Therefore the Gill net CPUE on a given day (*Id,GN*) is:

1. .

For purse seine test fisheries, it is assumed that the catchability depends on the relative width of the area swept or sampled, i.e., the width of the migratory channel at the test fishing site in relation to the size of the fishing net. Because the relative width of the area swept in Juan de Fuca Strait is 2.2 times larger than in Johnstone Strait, it is assumed that the sockeye catchability of the purse seine test fishery in Area 12 is 2.2 times greater than in Area 20. Similarly, the catchability in Area 13 is assumed to be 1.5 times greater than in Area 12, or 3.3 times greater than in Area 20. The purse seine CPUE on a given day in the Area 12, 20 and 13 (*Id,PS,a*) is therefore respectively:

1. *,*
2. *, and*

where *Cd,A12* is the total catch taken between Area 12 and 13 on a given day. The observed CPUE data for the different test fisheries (*f*) differ from the model predictions assuming lognormal residual errors:

with . Reconstructed daily marine abundances () deviate from the daily abundances (*Nd*) predicted by the time-density model:

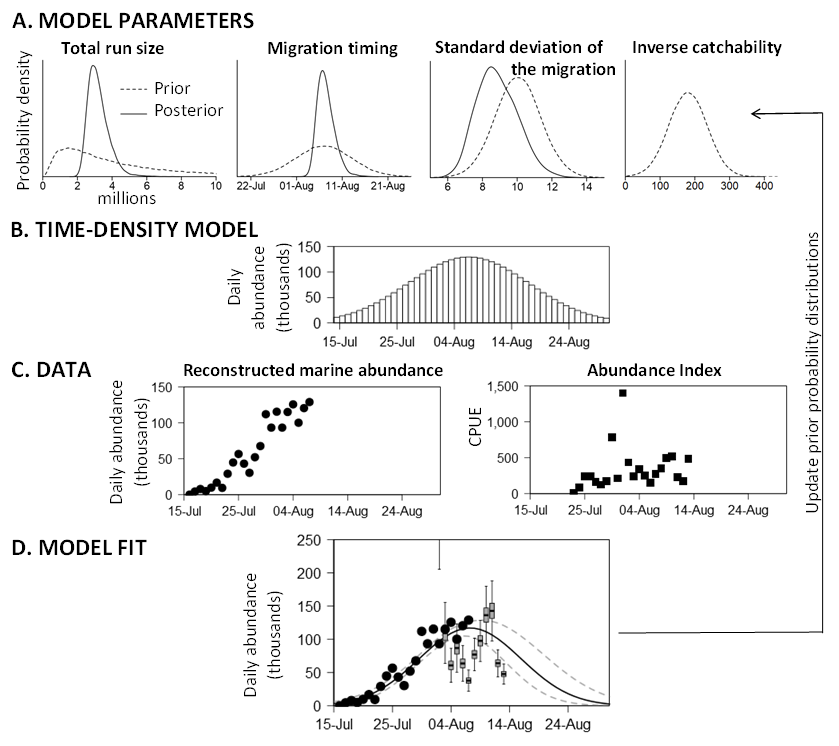
with reflecting the deviation. For stocks that delay their upstream migration, reconstructed daily abundance estimates will not be available.

### Bayesian implementation incorporating prior knowledge

The time-density model described above requires the simultaneous estimation of total run size (*N*), timing of the migration (*T*), the diversion rate (D), and the variances of the residual error terms ( and ). For several of the model parameters, additional information is available to formulate informative prior probability distributions which can be incorporated using a Bayesian estimation approach (Gelman et al. 1995). The prior probability distributions for run size, timing and diversion rate are based on the pre-season forecasts (Chapters A1 and A2). The assumed distributions for run size, timing and diversion rates are respectively a lognormal, normal and beta distribution (Table 1). The normal prior probability distribution for the standard deviation of the migration (*S*) is based on historical data. Because early in-season, the model tends to underestimate the spread of the migration (i.e. the number of days it takes for the 95% of the run to pass through the marine test fishing areas), this model parameter is considered fixed but uncertain by default. However, this model parameter can be estimated if in-season data clearly indicates a strong deviation from historical standard deviations.

For the catchability coefficient (*q*), a normal prior probability distribution is assumed for the inverse of the catchability coefficient (*q-1*), i.e., the expansion line. At the start of the season, the prior probability distributions for the gill net and purse seine expansion lines are based on historical data, but later in the season, these distributions are based on in-season observations (Chapter B4). Unlike other prior probability distributions, these distributions for expansion lines are not further updated by the model. Uninformative gamma distributions are used as priors for the residual error terms ( and ).

Figure 1 provides a graphical overview of the Bayesian time-density model as described above. This model was developed and is run in WinBUGS 1.4 (Spiegelhalter et al. 2003) and called from the statistical software package R (R Core Team 2013). All the model results undergo diagnostics to remove the impact of initial MCMC samples, to eliminate the negative impact of autocorrelation within the MCMC chains and to ensure convergence (Best et al. 1995). We assume the reported statistics of the posterior probability distributions represent the true underlying distributions.



**Figure 1.** Graphical overview of the Bayesian time-density model when applied for the in-season assessment of Fraser River sockeye. Prior probability distributions (A) based on preseason forecasts of run size, migration timing and standard deviation of the migration allow the prediction of the daily abundance of salmon assuming a normal distribution of migrating salmon over time (B). Reconstructed daily marine abundance estimates and marine test fishery CPUE data are collected and updated continuously throughout the salmon migration (C) and the model predicted daily abundance estimates are fitted to these data. Relative abundance estimates such as CPUE data however require an additional model parameter, in this case a catchability estimate. The uncertainty in daily abundance estimates derived from CPUE data is therefore represented using boxplots. Comparing the model predictions against the data allows the model to derive the posterior probability distributions of the model parameters (A). To simplify this figure, the probability distribution for the diversion rate and the variance parameters have been omitted.

**Table 1.** Probability density functions (pdfs) of the Bayesian time-density model and the parameter values of the prior pdfs used to assess Fraser River sockeye salmon.

|  |  |
| --- | --- |
| Prior probability density function | Parameter values for Fraser River sockeye |
| R ~ Lognormal(ln(m), 1 / ln(1 + CV2)) | Median and CV derived from the run size forecast |
| T ~ Normal(µ, 1 / (µ \* CV)2) | Mean and CV derived from the timing forecast |
| S ~ Normal(µ, 1 / (µ \* CV)2) | Mean and CV derived from historical data |
| D ~ Beta(µ \* η, (1 - µ) \* η) | Mean derived from the diversion rate forecast, η = 20 |
| q-1 ~ Normal(µ, 1 / (µ \* CV)2) | Mean and CV based on historical data, later on in-season data |
| 1 / = τN ~ Gamma(0.001,0.001) | Mean = 1, variance = 1000 |
| 1 / = τI ~ Gamma(0.001,0.001) | Mean = 1, variance = 1000 |

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