NRC Research Press

ARTICLE

In-season assessment and management of salmon stocks using a Bayesian time–density model

Catherine G.J. Michielsens and Jim D. Cave

Abstract: We document a time–density model for in-season assessment of salmon stocks that integrates both relative and absolute indicators of abundance and incorporates preseason information on run size and migration timing using a Bayesian framework. We evaluate different data collection programs for Fraser River sockeye salmon (*Oncorhynchus nerka*) by examining the precision, bias, and timeliness of resulting run-size estimates with a retrospective analysis of 20 years of data. We quantify the run-size bias if migration was early versus late and evaluate the impact of run-size uncertainty on the ability to reach management objectives. In-season assessments greatly improve the accuracy and precision of run-size estimates compared with preseason forecasts. For the in-season assessment of Fraser River sockeye, catch-per-unit-effort (CPUE) data from seaward marine test fisheries, although less precise, were more informative at the peak marine migration than more precise terminal, in-river hydroacoustic data obtained on the same date due to the time lag associated with migration from the marine test fishing locations to the lower river. Throughout the season, the best fisheries management results were obtained by relying on in-season assessments using both marine CPUE data as well as marine reconstructed abundance estimates derived from in-river hydroacoustic estimates, thereby taking advantage of the benefits of both sources of information.

Résumé : Nous documentons un modèle temps–densité pour l'évaluation au cours de la saison de pêche de stocks de saumons, qui intègre des indicateurs d'abondance tant relatifs qu'absolus et incorpore de l'information sur les conditions précédant la saison relativement à la taille et au moment des migrations, en utilisant un cadre bayésien. Nous évaluons différents programmes de collecte de données pour le saumon sockeye (*Oncorhynchus nerka*) du fleuve Fraser en examinant la précision, le biais et l'opportunité des estimations de la taille des migrations en résultant par une analyse rétrospective de 20 années de données. Nous quantifions le biais associé à la taille de la migration selon qu'il s'agit d'une migration hâtive ou tardive et évaluons l'incidence de l'incertitude associée à la taille de la migration sur la capacité d'atteinte d'objectifs de gestion. Les évaluations en cours de saison améliorent considérablement l'exactitude et la précision des estimations de la taille des migrations par rapport aux prévisions avant la saison. Pour l'évaluation en cours de saison du saumon sockeye du fleuve Fraser, des données de la capture par unité d'effort (CPUE) pour des pêches expérimentales marines vers la mer, bien que moins précises, fournissent plus d'information durant le maximum de la migration marine que des données hydroacoustiques terminales plus précises obtenues dans le fleuve à la même date, mais qui contiennent de l'information sur une étape plus hâtive de la migration. Sur toute la durée de la saison, les meilleurs résultats en ce qui concerne la gestion des pêches sont obtenus en ayant recours aux évaluations en cours de saison qui reposent sur des données de CPUE marines et sur des estimations de l'abondance reconstituée dérivées d'estimations hydroacoustiques dans le fleuve, tirant ainsi parti des avantages qu'offrent les deux sources d'information. [Traduit par la Rédaction]

Introduction

Management of fisheries typically involves the assessment of the abundance of stocks using different types of information collected over varying periods of time. This information typically includes fishery-dependent as well as fishery-independent data. Historically, various statistical (frequentist) methods have been used to estimate abundance from these data (Ricker 1975). More recently, Bayesian methodology has been employed, allowing for objective approaches to combine results from multiple models and sources of information and to provide estimates of uncertainty of abundance (Fried and Hilborn 1988; Hyun et al. 2005). The assessment of uncertainty about stock abundance has become an important part of fisheries management, allowing for an objective decision process to evaluate the outcomes of various management actions (Rosenberg and Restrepo 1994). The quantification of uncertainty can also be used by managers to assess the contribution or value of scientific programs and fishery-dependent data.

For salmon stocks there is a marked difference in the uncertainty of assessments using preseason forecast methods based on stock–recruit data and in-season assessments using data collected during the migration of populations to their natal stream. While preseason abundance forecast estimates are important components of fisheries planning (PSC 2017), they are highly uncertain (Bocking and Peterman 1988; Subbey et al. 2014) and environmental changes have exacerbated the problem (Britten et al. 2016). In-season assessment methods that rely on information collected during the salmon migration to the spawning grounds provide more precise estimates of the total abundance of returning adults (Link and Peterman 1998). The data to support in-season assessments could include fisheries data (catch or catch-per-unit-effort, CPUE) collected when salmon migrate through different fisheries or abundance data collected when salmon are enumerated using

Received 24 May 2018. Accepted 15 August 2018.

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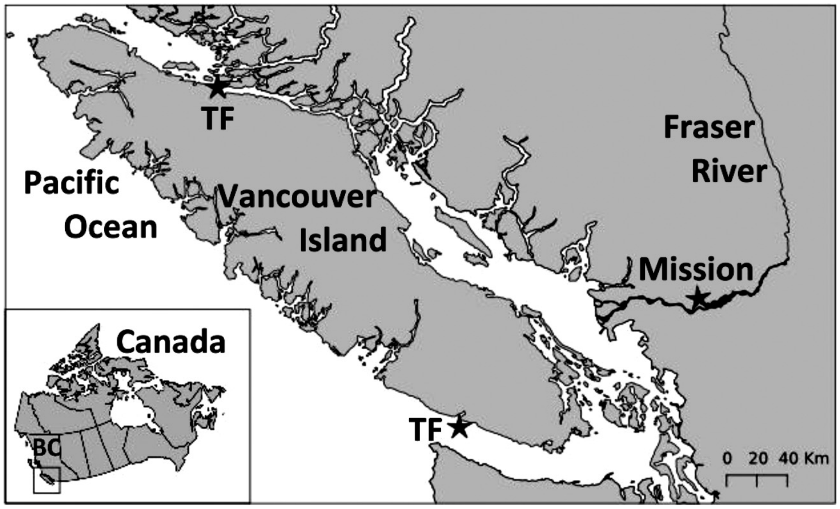
Published at www.nrcresearchpress.com/cjfas on 26 August 2018.

Fig. 1. Map indicating the location of the Fraser River, the site at Mission where hydroacoustic abundance estimates are generated and the seaward test fishing (TF) locations.



in-river hydroacoustics technology or at fences, fishways, or dams. In-season assessments of such data provide for rapid and continuous updates of estimates of total abundance (referred to as run-size estimates throughout this paper), allowing for more responsive in-season management to achieve spawning abundance goals and catch objectives (Woodey 1987; Carney and Adkison 2014). Real-time analyses of data combined with continuous reevaluations of assessments and management decisions can, however, lead to an expensive information collection program and management system. Given the many competing funding priorities, the relative contribution of the different data collection programs (e.g., hydroacoustics, test fisheries) to in-season assessments should be assessed. Benefits include improved accuracy and precision of derived run-size estimates as well as improved timeliness of those estimates.

The in-season assessment of salmon stocks relies on two main methods: regression models relating indicators of abundance (or cumulative abundance) on a given date with total run-size estimates obtained postseason (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; Brannian 1982; PSC 1995; Springborn et al. 1998). These time–density models of migration rely on the date of peak abundance as well as the shape of the migration as described by the spread and the degree of symmetry of the pattern of daily abundances over time. They can be fitted to abundance indices such as CPUE data from commercial or test fisheries as well as absolute estimates of abundance reconstructed from catch and real-time escapement data. One advantage of time–density models is that the timing of the migration becomes an estimated model parameter compared with a fixed input, as is the case for alternative in-season assessment models that rely on regression analyses using catch or CPUE data (PSC 1995; Ryall 1998). The main challenge with in-season assessments of salmon stocks is the simultaneous estimation of timing and total run size, as the peak catch or abundance dates can only be confirmed once more than 50% of the migration has passed. 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).

In this paper we describe a general time–density model developed in a Bayesian framework that can be used to provide in-season assessments of total run size and timing (including the associated uncertainty) for anadromous species that migrate past one or more assessment locations. We retrospectively evaluate the gains in the accuracy, precision, and timeliness of the run-size estimates when using relative and (or) absolute indices of abundance within the in-season assessment as compared with relying on preseason forecast estimates. In addition, we assess the bias in run-size estimates if the timing of the migration is early versus late and evaluate the impact of the run-size uncertainty on the ability to reach fisheries management objectives. These analyses were performed using data for sockeye salmon (*Oncorhynchus* nerka) returning to the Fraser River, the largest sockeye producing river in British Columbia, Canada (Fig. 1).

The intensive management regime for Fraser River sockeye provides a useful case study to retrospectively evaluate the value of different in-season assessment data due to the extensive degree of monitoring of Fraser River sockeye as compared with other major sockeye producing systems (Rand et al. 2007). In addition, extensive time series (1998–2017) of stock-specific marine test fishing CPUE data and in-river hydroacoustic data analysed retrospectively allowed more general conclusions to be drawn. However, the recent low returns of sockeye salmon within the Fraser River have raised concern regarding the utility of the expensive in-season assessment and management program. The results presented in this paper can be used directly to help inform decisions regarding the funding of different data collection programs in support of Fraser River sockeye assessments.

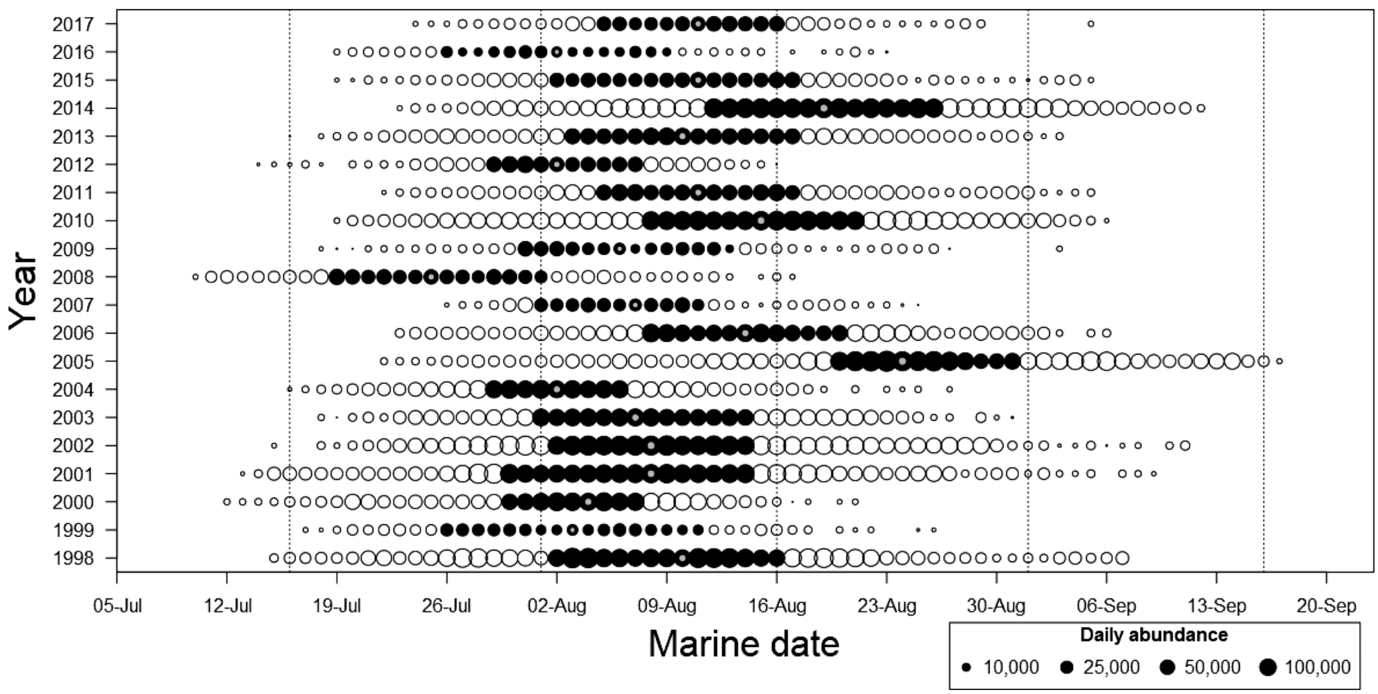
Materials and methods

Fraser River sockeye data to support in-season assessment and management

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 2017). The Panel meets every 3–4 days during the sockeye migration to evaluate the available information, assess the run size and timing of the different Fraser sockeye stocks, and agree on fisheries openings in Panel waters (Woodey 2000).

The in-season assessment of Fraser River sockeye stocks is based on four sources of information: catch data from commercial and other fisheries, test fishing catch and effort, stock identification,

Fig. 2. Time series of daily abundance of Summer-run sockeye returning to the Fraser River in 1998–2017. These estimates have been reconstructed based on upstream daily passage estimates from a hydroacoustic program at Mission and seaward catches. The solid circles represent the middle 50% of the distribution of daily abundances, while the open circles represent the lower and the upper 25% of the daily abundances. The marine migration date (the date when 50% of the run has migrated through the marine areas) is represented by the grey circle. The vertical lines indicate the start and middle of each month.



and hydroacoustics information collected in-river (Woodey 1987). The reduced exploitation of Fraser River sockeye in recent years has increased the reliance on test fishing CPUE information rather than on commercial data as an index of abundance. For this paper, we restrict our analyses to the last 20 years of data (1998–2017) when a structured purse seine test fishery was operational in Canadian Pacific Fishery Management Area 20 (Juan de Fuca Strait) and Area 12 (Johnstone Strait). The combined CPUE data from these two test fisheries provide a time series of relative daily abundances (Putman et al. 2014).

Estimates of daily marine abundance are derived through backward reconstruction methods (Starr and Hilborn 1988; Cave and Gazey 1994; PSC 1995) using upstream daily passage estimates from a hydroacoustics program at Mission, British Columbia (Xie et al. 2005) and seaward catches. These estimates provide a time series of absolute daily marine abundances and will hereinafter be referred to as reconstructed abundance estimates. For in-season management purposes, the sum of the reconstructed abundance estimates is assumed to represent the true total run size of the stocks (PSC 2017). Only data on Summer-run stocks have been included in the analyses by applying the relevant stock ID information derived from analyses of scale information (pre-2002) and microsatellite DNA (2002–onward) to the reconstructed marine abundance estimates and CPUE data (PSC 2017). Similar analyses conducted on Early Stuart, Early Summer-run, and Late-run stocks are not reported in this paper. The time series of daily abundance of Summer-run sockeye returning to the Fraser River in 1998–2017 is presented in Fig. 2.

To replicate the in-season assessment approach for Fraser River sockeye, only data up to the date prior to the assessment date were included in the analysis (Fig. 3). Marine CPUE data are considered early indicators of the expected daily abundance at Mission 6 days later, as it takes Fraser sockeye 6 days to travel from the marine test fishing locations to the hydroacoustic site at Mission. In-season, reconstructed marine abundance estimates based on Mission hydroacoustic data are therefore not available for the last 6 days (Fig. 3).

In-season time–density model

A time–density function can be used to represent the daily salmon migration past a geographical reference location (Mundy 1979; Cave and Gazey 1994; Springborn et al. 1998; Gazey and Palermo 2000). For the assessment of Fraser sockeye, we assume the geographical reference location is in the marine area. The daily abundance of salmon (N_t) passing this marine assessment location on a given day t can be represented as

$$(1) \qquad N_t = R \cdot f(t)$$

where $f(t)$ is the time–density function of migrating salmon (i.e., the daily proportion of the total run size), and R 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):

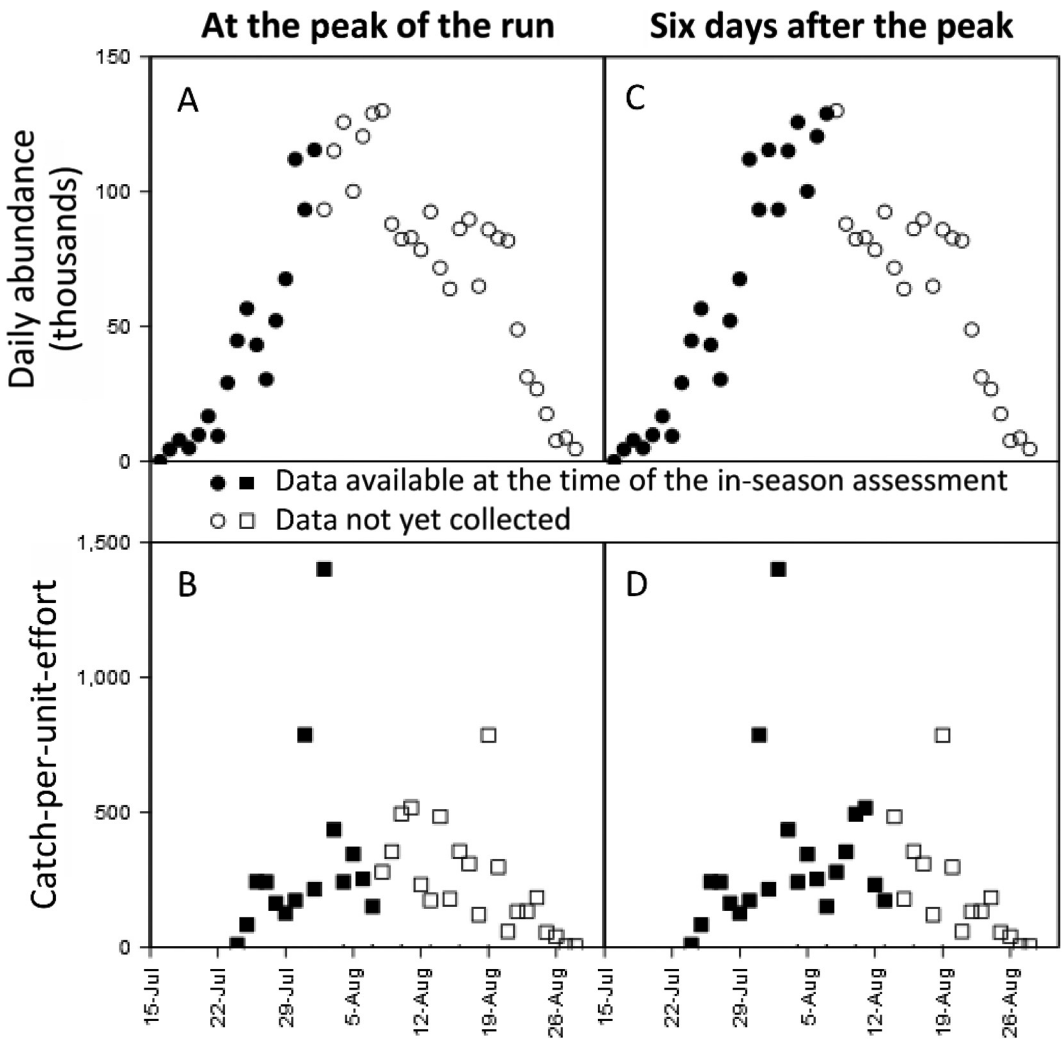
$$(2) \qquad f(t\,|\,T, S) = \frac{1}{S\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-T}{S}\right)}$$

where T is the mean timing of the salmon migration, and S is the standard deviation. Reconstructed daily marine abundances (N_t^{obs}) deviate from the daily abundances predicted by the time–density model (N_t):

$$(3) \qquad N_t^{\mathrm{obs}} = N_t + v_t$$

with $v_t \sim \mathrm{N}(0, \sigma_v^2)$ reflecting the deviation. Based on the salmon abundance available on a given day (N_t), the associated CPUE by the purse seine test fishery on that day (I_t) is given by

Fig. 3. Illustration of 2003 in-season data available to estimate the total abundance of Summer-run sockeye returning to the Fraser River at the peak migration date within marine areas (A, B) and 6 days later (C, D). Data include reconstructed daily marine abundance estimates based on in-river hydroacoustic estimates and seaward catches (reconstructed abundance data; A, C) and daily CPUE data collected through test fishing (B, D). Because the marine test fishing areas are located 6 days seaward of the in-river hydroacoustic site, the time series of CPUE data available for in-season assessment contains six more observations compared with the hydroacoustic-based abundance time series.



(4) $I_t = q \cdot N_t$

where I represents the predicted index of abundance, and q represents the catchability coefficient (the proportion of the daily abundance taken by one unit of effort). The observed CPUE data differ from the model predictions assuming lognormal residual errors:

(5) $I_t^{\text{obs}} = I_t \cdot e^{w_t}$

with $w_t \sim N(0, \sigma_w^2)$. An overview of the different symbols used to describe the above in-season model can be found in Table 1.

Bayesian implementation incorporating prior knowledge

The time–density model described above requires the simultaneous estimation of total run size (R), timing of the migration (T), the standard deviation of the migration (S), the catchability coefficient (q), as well as the variances of the two residual error terms (σ_v^2 and σ_w^2). Additional information is available to formulate informative prior probability distributions for run size and timing, which can be incorporated using a Bayesian estimation approach (Gelman et al. 1995). During the last 20 years, different methodologies have been used to produce preseason forecasts. To achieve some consistency throughout the years, we based the prior probability distributions for run size and timing used in this paper on the historical median forecasts (Table 2) in combination with the average coefficient of variation based on the most recent forecast methodologies. For run size, the most recent forecast methodology relies on a retrospective analysis of both biological and nonparametric Bayesian stock–recruitment models to identify the best performing model for each stock (Grant et al. 2010). For timing, the current forecast methodology relies on multivariate models using current velocity and sea surface temperature (DFO 2016). For run size (N), we assumed a lognormal prior probability distribution and for timing (T) a normal distribution (Table 3). The standard deviation of the migration (S) indicates the time it takes for the run to migrate past the reference location. The normal prior probability distribution for this parameter has been derived using the mean and variance across 20 years of historical data, excluding the assessment year. Similarly, the normal prior probability distribution for the inverse of the catchability coefficient (q^{-1}) was derived through an hierarchical analysis of historical daily estimates of CPUE and reconstructed abundance excluding

Table 1. List of symbols used within the Bayesian time–density model.

Symbol	Description
Parameter	
R	Total annual run size or total recruitment available to coastal fisheries
T	Timing of the migration (date when 50% has migrated past the marine geographical reference location)
S	Standard deviation (dispersion) of the migration indicating the time it takes for the run to migrate past the geographical reference location
q	Catchability coefficient (proportion of the stock taken by one unit of effort)
σ_v^2	Variance of the error around marine abundance estimates
σ_w^2	Variance of the error around the index of abundance
Variable	
N	Model-predicted marine abundance estimates
I	Model-predicted index of abundance
Data	
N^{obs}	Reconstructed marine abundance based on in-river hydroacoustic data plus seaward catch
I^{obs}	Index of abundance (e.g., test fishing catch-per-unit-effort (CPUE) data)
Index	
t	Day of the year

Table 2. Historical values (1998–2017) of the median forecasts of run size and timing, as well as comparison of the forecasts against post-season estimates (percent run size error and days timing error) for Summer-run Fraser River sockeye.

	Run-size forecast		Timing forecast	
Year	Median estimate (million)	Percent error (%)	Median estimate	Error (days)
Average	2.9	MPE: 158% MAPE: 165%	8 Aug.	MPE: –4 MAPE: 4
1998	6.7	25	9 Aug.	–1
1999	5.3	217	4 Aug.	–2
2000	2.8	16	5 Aug.	1
2001	1.2	132	2 Aug.	–6
2002	9.0	37	9 Aug.	1
2003	3.4	22	7 Aug.	0
2004	3.6	52	7 Aug.	5
2005	11.2	115	8 Aug.	–16
2006	6.9	180	14 Aug.	0
2007	3.4	436	6 Aug.	–1
2008	1.8	72	21 July	–4
2009	9.0	1172	5 Aug.	–1
2010	2.7	–48	5 Aug.	–10
2011	2.6	51	31 July	–11
2012	1.5	42	1 Aug.	–1
2013	3.6	75	3 Aug.	–7
2014	5.2	–22	10 Aug.	–9
2015	3.3	139	7 Aug.	–4
2016	1.5	236	3 Aug.	1
2017	3.2	218	6 Aug.	–6

Note: Forecasting methods vary across the time series (Grant et al. 2010; DFO 2016).

estimates of the assessment year. The resulting posterior predictive distribution for this parameter accounts for both the variability in catchability within a year as well as between years (PSC 2017). Uninformative gamma distributions were used as prior probability distributions for the residual error terms (σ_v^2 and σ_w^2; Table 3).

Table 3. Probability density functions (pdfs) of the Bayesian time–density model and the parameter values of the prior pdfs used to assess Summer-run Fraser River sockeye.

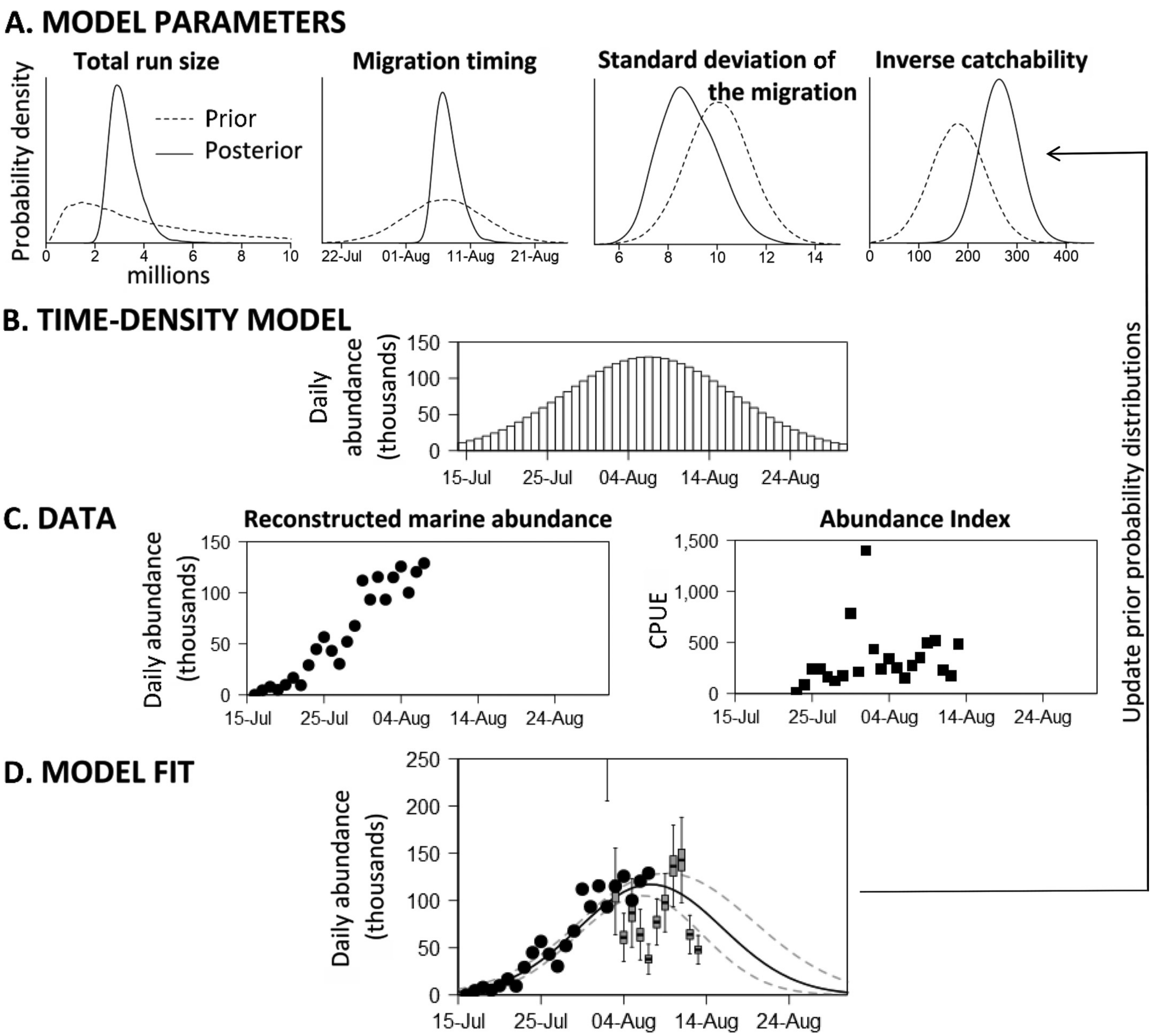
Prior probability density function	Parameter values for Summer-run Fraser River sockeye
$R \sim \text{Lognormal}(\ln(m), 1/\ln(1 + \text{CV}^2))$	Median (m) reported in Table 2 and CV = 1.2
$T \sim \text{Normal}(\mu, 1/(\mu \times \text{CV})^2)$	Mean (μ) reported in Table 2, converted in number of days since 15 June and CV = 0.11
$S \sim \text{Normal}(\mu, 1/(\mu \times \text{CV})^2)$	Mean (μ) = 10 and CV = 0.13
$q^{-1} \sim \text{Normal}(\mu, 1/(\mu \times \text{CV})^2)\, I\,(0.001,)$	Inverse q (q^{-1}), with mean (μ) = 180 and CV = 0.6 (PSC 2017)
$1/\sigma_v^2 = \tau_N \sim \text{Gamma}(0.001, 0.001)$	Mean = 1, variance = 1000
$1/\sigma_w^2 = \tau_I \sim \text{Gamma}(0.001, 0.001)$	Mean = 1, variance = 1000

A graphical overview of the Bayesian time–density model as described above can be found in Fig. 4. This model was developed and run in WinBUGS 1.4 (Spiegelhalter et al. 2003), and the code can be found in Appendix A. To remove the impact of initial Markov chain Monte Carlo samples and to ensure convergence, we evaluated all model results using Gelman–Rubin's convergence diagnostics (Gelman and Rubin 1992; Best et al. 1995) as well as Monte Carlo error statistics (Spiegelhalter et al. 2003). We assume the reported statistics of the posterior probability distributions represent the true underlying distributions. The model takes several minutes to run on a standard computer, making it a reasonable approach for in-season assessments.

Value of in-season data and assessments

The intensive in-season management regime for Fraser River sockeye requires continuous run-size assessment updates, but this comes at a price. In 2009 and 2010, both the hydroacoustics program and the marine test fishing program as described in this paper each cost about CAN$12 500 per day when taking into account the full costs, including salaries and genetic stock identification. Given the costly nature of in-season data collection and assessment programs, it is important to understand their value in terms of their impact on the accuracy, precision, and timeliness of in-season run-size estimates as well as subsequent management decisions (Hansen and Jones 2008). Using the Bayesian time–density model retrospectively, we first illustrated the value of in-season assessments graphically for 1 year (2003, an average year in terms of run size and timing), before presenting results across all years (1998–2017). The model was run at various times during the salmon migration: 3 days before the peak or date when 50% of the migration passed the marine reference location; at the peak of the migration; and 3, 6, 9, and 12 days afterwards. Four scenarios, based on different in-season data collection programs (Table 4) were evaluated retrospectively. Under these scenarios, in-season assessments relied on (1) reconstructed abundance estimates derived from data by the hydroacoustics program, (2) CPUE data collected by the marine test fishing program, (3) a combination of reconstructed abundance and CPUE data, and (4) abundance estimates from a hypothetical marine hydroacoustics program. The fourth scenario simulates the replacement of the expensive marine test fishing program designed to collect CPUE with a marine hydroacoustic program in combination with a less expensive test fishing program designed to collect information on stock identification. The value of more precise and unbiased daily marine daily abundance estimates was explored by assuming that the current marine daily abundance estimates based on in-river hydroacoustics had been obtained 6 days earlier in the marine environment. Results of the value of marine hydroacoustic data for in-season assessment reflected a best-case scenario, as the analyses assumed that the quality of estimates using marine hydroacoustic

Fig. 4. Graphical overview of the Bayesian time–density model when applied for the in-season assessment of Summer-run sockeye returning to the Fraser River. Prior probability distributions (A) based on preseason forecasts of run size, migration timing, and standard deviation of the migration allow to predict the daily abundance of salmon assuming a normal distribution of migrating salmon over time (B). Daily estimates of absolute reconstructed marine abundance 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 (D). 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 are 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 variance parameters have been omitted.



techniques would match the quality of estimates using in-river hydroacoustics.

To evaluate the value of the four different data collection programs at various times during the season and across all years, we ran the Bayesian time–density model retrospectively and compared the median in-season run-size estimates ($\hat{R}$) against the observed postseason run size (R). Potential biases in the assessment results were explored using mean percent error (MPE) as defined by

$$\text{MPE} = \frac{100}{n}\sum_{y=1}^{n}\frac{\hat{R}_y - R_y}{R_y} \tag{6}$$

while the precision was described by the mean absolute percent error (MAPE):

$$\text{MAPE} = \frac{100}{n}\sum_{y=1}^{n}\left|\frac{\hat{R}_y - R_y}{R_y}\right| \tag{7}$$

In addition, the in-season assessment data were divided into years with earlier and later than average timing and analysed retrospectively to quantify the associated bias. To test the hypothesis that the run size is overestimated when the migration is early and

Table 4. Overview of the in-season data collection and run-size assessment scenarios evaluated within this paper.

A. Value of in-season information
In-season data collection scenario
1. Reconstructed marine abundance estimates based on hydroacoustic data collected in-river
2. Marine test fishing CPUE data
3. Both reconstructed marine abundance estimates and marine test fishing CPUE data
4. Hypothetical marine abundance estimates based on marine hydroacoustics
B. Implication of run size bias and precision on fisheries management
Run-size assessment scenario
1. Preseason forecast estimate based on historical stock–recruitment data
2. In-season estimate based on reconstructed marine abundance
3. In-season estimate based on marine test fishery CPUE data
4. Both reconstructed marine abundance estimates and marine test fishing CPUE data

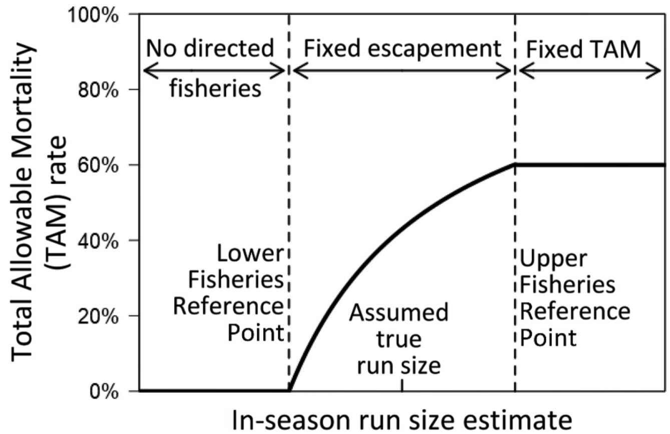
underestimated when late, we performed a one-sided two-sample t test on the yearly estimates of the MPE at the peak of the migration. In the case of a directional run-size bias, we evaluated retrospectively whether preseason timing forecast estimates could be used to reduce the bias. Based on the preseason timing forecast (early or later than average; Table 2), a bias correction, equal to the MPE, was applied to the in-season run-size estimate. The resulting bias-corrected in-season run-size estimates were subsequently compared against the observed postseason estimates. We performed a one-sided two-sample t test to test the hypothesis that the bias correction would reduce the average run-size error.

Implications for fisheries management

Run-size uncertainty and the value of reducing that uncertainty remain academic concepts unless we can evaluate the implications for fisheries management. We therefore extended our analyses to evaluate the impact of differences in run-size bias and precision on the ability to reach management objectives. The primary objectives that guide the Fraser River Panel's in-season fisheries management decisions are to achieve spawning escapement (SET) and catch targets. The SETs are derived through the Fraser River Sockeye Spawning Initiative (FRSSI) by evaluating the long-term performance of different escapement strategies under a wide range of alternative biological assumptions and future states of nature while taking into account social and economic considerations (DFO 2011; Holt and Irvine 2013). The resulting management strategy relies on the application of a total allowable mortality (TAM) rule (Fig. 5), defined by a lower and upper fishery reference point (DFO 2017). In the case of run-size estimates above the upper fishery reference point, the TAM rate is kept fixed. Between the lower and upper fishery reference points, a fixed escapement target, equal to the lower fishery reference point, is assumed. When the run size is below the lower fishery reference point, no directed fisheries are allowed; only incidental harvest, directed at co-migrating stocks, is permitted.

We evaluated the impact of different assessment methods and the bias and precision of associated run-size estimates on the achievement of management objectives. This was achieved by comparing potential escapement and catches assuming perfect run-size knowledge against escapement and catch estimates based on median in-season run-size estimates. Four scenarios based on different assessment and data collection programs were evaluated retrospectively: (1) a preseason assessment based on historic stock–recruitment data and in-season assessments using (2) reconstructed abundance estimates, (3) marine test fishery data, and (4) a combination of both. To standardize results across

Fig. 5. Harvest rule for the management of Summer-run sockeye in the Fraser River (DFO 2017), which is dependent on the in-season run-size estimate. Below the lower fishery reference point, only incidental harvest (<10%), directed at co-migrating stocks, is permitted. Between the lower and upper fishery reference points, escapement is kept fixed and equal to the lower fishery reference point.



years, we assumed the observed run size for each year fell in the middle between the lower and upper fishery reference points and that the upper fishery feference point was 2.5 times larger than the lower fishery reference point (DFO 2017; Fig. 5). In addition, we assumed that the TAM rule referred only to fishing mortality and a TAM rate of 60% was implemented when the run size exceeded the upper fishery reference point. Assuming no implementation error, catches were based on estimates of total allowable catch (TAC, the difference between the estimated run size and SET) but could not exceed 80% of the available abundance, a practical limit based on the available fleet size and other socioeconomic constraints (DFO 2017; PSC 2017).

Fisheries decisions based on the preseason run-size forecast assumed that the derived SET and TAC were not adjusted in-season. The resulting catch equaled the total TAC unless catches were restricted by the total available abundance and spawning escapement was the difference between the observed run size and the total catch. Fisheries management based on in-season run-size estimates allowed for continuous adjustments of the SET and the proportion of the run size available for harvest. For this analysis, we assumed that the run size would be updated every 3 days, starting 3 days before the peak of the migration. To properly simulate in-season conditions, we used the model-predicted peak migration date. After each run-size update, the SET, TAC, catch-to-date, and remaining TAC were adjusted. Catches in the 3 days following the assessment equaled the total remaining TAC unless catches were restricted by the available abundance. Before the start of the in-season assessments, we assumed that there was no available TAC but that 20% of the daily abundance was caught by fisheries directed at earlier time co-migrating stocks.

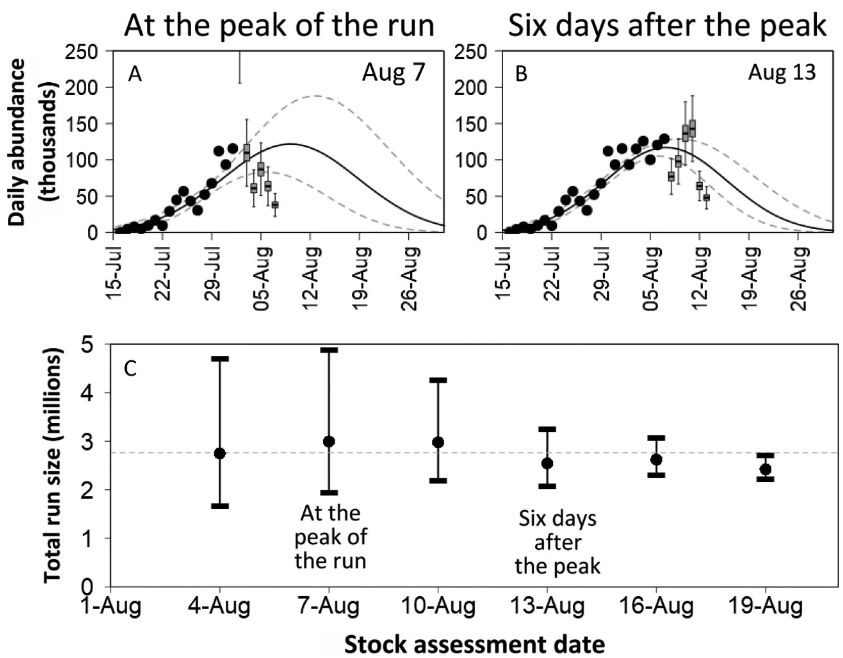
Sensitivity analyses allowed us to evaluate the impact of the assumption that the observed run size for each year fell in the middle between the lower and upper fishery reference points. For those additional analyses, we assumed the observed run size fell on the lower fishery reference point or on the upper fishery reference point.

Results

In-season assessment using a Bayesian time–density model

To illustrate the functioning of the Bayesian time–density model (Fig. 4) and the impact of the accumulation of in-season information on the uncertainty in the run size (Fig. 6), we will first

Fig. 6. Illustration for 2003 of the in-season application of the Bayesian time–density model to assess the total abundance for Summer-run Fraser River sockeye using data available at the peak marine migration and 6 days later. The model is fitted to reconstructed marine daily abundance estimates based on hydroacoustic data (circles) as well as abundance estimates based on marine test fishing CPUE data (boxplots; A and B). The boxplots represent the uncertainty around the CPUE-based abundance estimates due to the uncertain catchability estimate. The uncertainty in the resulting estimates of total abundance depends on the amount of data and precision of available information and decreases over time as more data accumulate (C). Results in all three panels are presented in terms of the median and the 80% probability interval.



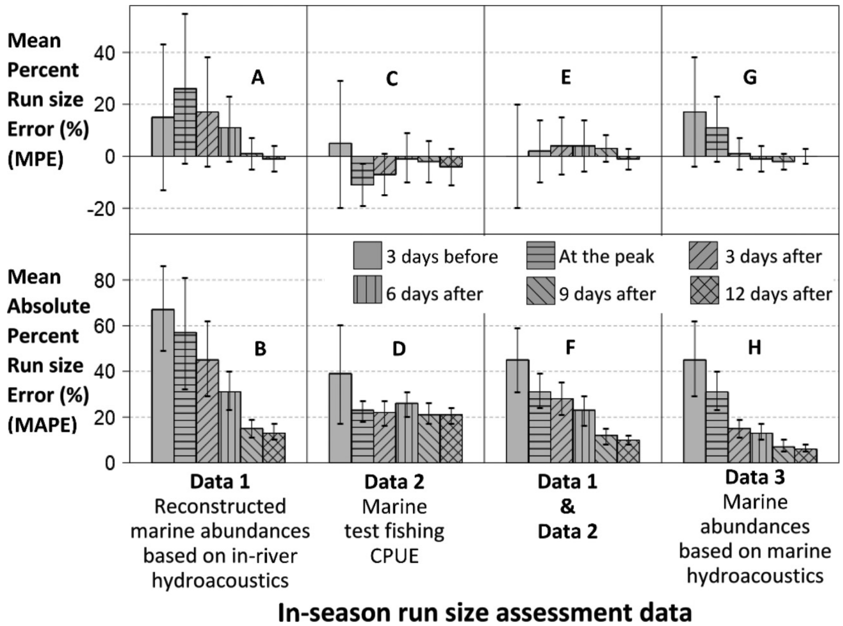
discuss the results of this model for one individual year (2003, an average year in terms of run size and migration timing; PSC 2007). In this year-specific example, the in-season assessment model was fitted to both reconstructed abundance estimates and the last 12 days of available marine test fishing CPUE data. Of those 12 days of CPUE data, the first 6 days were used in conjunction with the matching reconstructed daily abundance estimates to update the prior probability distribution for the catchability coefficient. The resulting distribution for the catchability coefficient was used to derive the CPUE-based daily abundance estimates for the last 6 days, for which matching reconstructed abundance estimates were not yet available. These CPUE-based abundance estimates were represented as boxplots in Figs. 6A and 6B to highlight the uncertainty around these estimates.

Results indicated that the run-size uncertainty was not only a function of the amount of data and of the precision of available information but was also influenced by the timing of the assessment relative to the peak migration date; assessments early in the migration were typically less certain than assessments at later dates when more data had been collected. For example, prior to the 2003 season, the median run-size forecast was 3.4 million (80% probability interval (PI): 1.0–11.3 million). When running the Bayesian time–density model at the peak of the migration, the run-size uncertainty was almost half of the preseason forecast (80% PI: 1.9 to 4.9 million; Fig. 6A). At this point, the reconstructed abundance estimates based on in-river hydroacoustic data still indicated an increasing trend (Fig. 3A). However, the marine test fishing CPUE data (Fig. 3B), and especially the last 6 days of data (Fig. 6A), indicated a declining trend in daily abundance estimates, which could support the conclusion that the peak of the migration had passed. Although the CPUE data indicated a smaller run with earlier timing, the resulting median run-size estimate was still 8% higher than the observed run size because of the additional prior information on run size, timing, and spread of the migration incorporated within the Bayesian time–density model (Fig. 6A). Six days later, both the reconstructed abundance estimates (Fig. 3C) and the CPUE data (Fig. 3D) had plateaued. These trends in both sources of information, in combination with the informative prior on the spread of the migration, increased the probability that the peak of the migration had passed while decreasing the probability of further increases in daily abundance estimates, and the resulting run-size estimate were more certain (80% PI: 2.1–3.2 million; Fig. 6B). Running the time–density model later in the season, when additional data confirmed the peak of the migration further reduced the run-size uncertainty as reflected by the narrower probability intervals (Fig. 6C).

Value of in-season data and assessments

The value of the test fishing and hydroacoustic programs, under the four different scenarios described in the methods section, was evaluated retrospectively using the Bayesian time–density model at different times during the season for 20 years of available data (Fig. 7). The evaluation criteria were timely improvements in run-size accuracy and precision. Assessments based solely on reconstructed abundance estimates (scenario 1, Figs. 7A, 7B) were negatively impacted by the late availability of marine estimates derived from data provided by the in-river hydroacoustic program and provided less certain run-size estimates early in the migration than assessments incorporating CPUE data (scenarios 2 and 3, Figs. 7D, 7F). Although abundance estimates based on hydroacoustic data were more precise, only after the peak of the migration was observed in-river (6 days after the peak had been observed in marine areas) did the run-size uncertainty decline to 30%. In addition, before the peak of the migration was observed, the model tended to overestimate the run size (MPE > 15%; Fig. 7A) due to the increasing trend in daily abundance estimates. A marine test fishing program (scenario 2) provided an earlier indication of run size, but unless these data were used in combination

Fig. 7. In-season run-size error when fitting the normal time–density model to different types of data: marine reconstructed abundance estimates based on hydroacoustic data collected in-river plus seaward catches (A, B), CPUE data collected in marine areas by a test fishery (C, D), both data sets combined (E, F), and hypothetical marine abundance estimates based on marine hydroacoustics (G, H). The run-size error is expressed in terms of the mean percent error (A, C, E, G) and the mean absolute percent error (B, D, F, H) and is calculated when 50% of the run migrates past the marine reference location (at the peak), as well as 3 days earlier and 3, 6, 9, and 12 days later. For Fraser River sockeye, the marine reference location is located approximately 6 days seaward of the hydroacoustic site at Mission, British Columbia.



with reconstructed abundance estimates and the preseason catchability estimate was updated in-season, the average run-size error did not decrease below 20% (Fig. 7D). Deviation of the annual catchability coefficients from the historical average resulted in run-size errors that persisted throughout the season regardless of the amount of in-season CPUE data. In addition, the larger variability in CPUE data on occasion resulted in spurious indications of declining trends in relative abundance, causing the Bayesian time–density model to underestimate the run size (MPE < –15%; Fig. 7C). When fitting the Bayesian time–density model to both the marine CPUE data and reconstructed daily abundance estimates (scenario 3), the catchability coefficient was updated in-season, resulting in smaller run-size errors once the majority of the migrating salmon had entered the river and further reductions as more in-season data became available (Fig. 7F). Most importantly, using both time series decreased the bias in the run-size estimates (MPE < 5%; Fig. 7E).

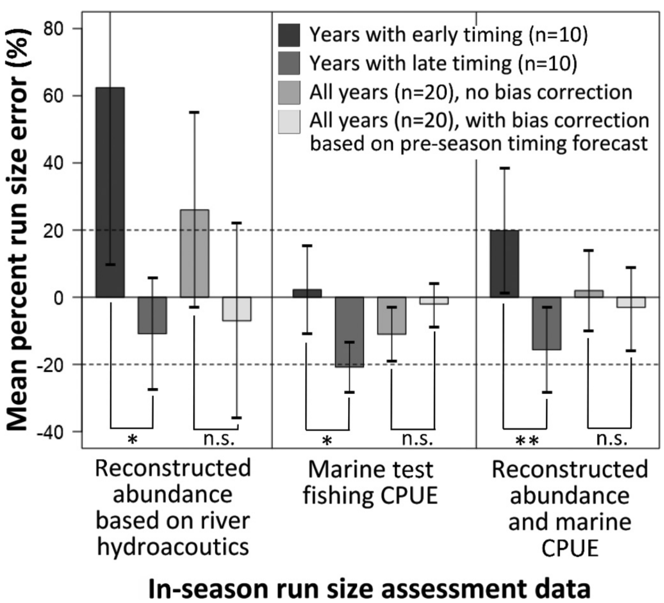
The above results indicate that marine data collection programs resulted in timelier estimates of run size. Given the variability of the marine CPUE data and the uncertainty around the derived marine abundance estimates, we examined the value of relocating the in-river hydroacoustic program to marine assessment areas (scenario 4), assuming the same accuracy and precision of derived daily abundance estimates. In this scenario, the average run-size error before or at the peak of the migration (Fig. 7H) was similar to the run-size error when relying on marine test fishery data in combination with in-river-based daily abundance estimates (Fig. 7F). Improving the quality of the marine data reduced the run-size error after the peak migration date, but only by 10%, as the improved precision in marine abundance estimates did not improve the estimation of the migration left to come, seaward of the marine data collection site.

Across years, there was a statistically significant relationship between timing and run size, with later timed runs being larger than runs with early timing ($p = 0.0096$). In addition, the timing of the migration was found to have a statistically significant impact on the bias of the estimated run size (Fig. 8). When running in-season assessments at the peak of the migration, the model on average overestimated the run size of early timed runs and underestimated late timed runs. The difference in average run-size error between salmon runs with early and late migration timing was statistically significant for each of the different assessment scenarios. For early timed runs, the average bias in the run size was most pronounced when relying solely on in-river hydroacoustic data (MPE = 62%). The average bias disappeared when relying on marine CPUE data within the assessment (MPE = 2%) or decreased substantially when combining both data sets (MPE = 20%). For runs characterized by a late migration timing, the in-season run-size model on average underestimated the run size by –11% when using hydroacoustic data, –20% when using marine CPUE data, and –16% when using both data sets. While it is possible to use the MPE to adjust the run-size estimates depending on the preseason timing forecast (early or later than average timing), when implemented retrospectively, the historic timing forecast estimates (Table 2) were not precise enough to improve in-season run-size errors. For the three different data collection scenarios, the MPE of the run size when implementing the bias correction was not significantly different from the MPE of the run-size estimates without bias correction (Fig. 8).

Implications for fisheries management

The impact of the accuracy, precision, and timeliness of run-size estimates on the ability to reach management objectives was evaluated for four different assessment scenarios by comparing escapement estimates based on median run-size estimates against SET estimates assuming perfect run-size knowledge (Fig. 9). Under the first scenario, the preseason run-size forecasts based on historic stock–recruitment data were used to derive SETs. Owing to the substantial positive bias in preseason run-size forecasts in the last 20 years (MPE = 158%; Table 2), subsequent TAC estimates were much larger than available abundances, but because catches were restricted to 80% of the available abundance, the resulting escapement reached 35% of the escapement target for most of the years (first boxplot, Fig. 9). For example, assuming the observed run size

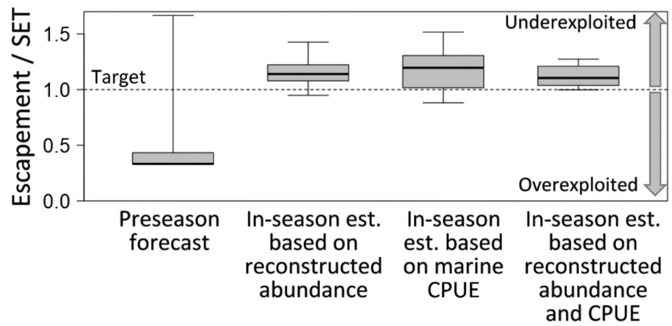
Fig. 8. In-season run-size error (mean percent error, MPE) based on the Bayesian time–density model when predicting the run size at the peak of the marine migration (when 50% of the run has migrated through the marine assessment areas). The run-size errors associated to the use of three different in-season data scenarios have been evaluated (Table 4, A1–3). Results indicate the run-size error when the run is earlier or later timed than average and whether there is a statistically significant difference between the MPE depending on the timing of the run (n.s., not significant; *, $p < 0.05$; and **, $p < 0.025$). Based on preseason timing forecast estimates (early or later than average; Table 2), a bias correction, equal to the MPE, was applied to the in-season run-size estimate. The resulting MPE of bias-corrected in-season run-size estimates are compared against the MPE of run-size estimates without bias correction. The MPE for early and late timed stocks is used in combination with the preseason timing forecast (Table 2) to adjust the in-season run size. The resulting MPE of the adjusted run size based on timing forecast estimates is compared against the MPE without adjustment.



is 1 million and this estimate falls in the middle of the lower and upper fisheries reference points (Fig. 5), the resulting SET is 570 000. Therefore, a catch of 80% of the total run size (800 000 sockeye) results in an escapement of 200 000 sockeye, which represents 35% of the 570 000 escapement target.

Fisheries management decisions based on in-season assessment outperformed management based on preseason run-size estimates due to the smaller run-size error (Fig. 9). In-season fisheries management decisions based on assessments using both test fishing CPUE data and reconstructed abundance estimates where sufficiently precise to reach the SET for all years included in the retrospective analysis and the foregone catch was lower compared with assessments relying on one data set only. When assessed using reconstructed abundance based on hydroacoustics, run-size estimates were more uncertain around the peak of the marine migration. Nonetheless, the SET was not reached in only 1 year (5% of all years) thanks to the high precision of run-size estimates later in the season, after the peak of the migration had been observed at Mission. When relying on marine test fisheries only, there was no in-season confirmation of the run size, and as a result, in five of the years (25%), the SET was not met. In addition, if the SET was reached, resulting catches were on average 19% lower compared with catches based on in-season assessments using both data sets. Sensitivity analyses with different run-size estimates relative to the lower and upper fishery reference points revealed consistent relative differences between different assessment scenarios in their ability to reach the SET. However, across assessment scenarios it was more likely that the SET was not reached if the observed run size equaled the lower fishery reference point than if the observed run size equaled the upper fishery reference point.

Fig. 9. Impact of run-size bias and precision on the achievement of management objectives under four different assessment scenarios for Fraser River sockeye: (1) preseason run-size assessment based on historic stock–recruitment data; and in-season run-size assessment using (2) reconstructed abundance estimates, (3) marine test fishery data, or (4) both. Spawning escapement targets (SET) were derived using the total allowable mortality rule (DFO 2011), creating a direct inverse relationship between the ability to reach escapement and catch objectives. Overexploitation results in not reaching escapement targets and underexploitation in exceeding escapement targets.



Discussion

This paper presents a time–density model for the in-season assessment of salmon stocks. A key assumption of the time–density model we describe above is that daily abundance estimates follow a symmetrical normal distribution. This assumption allows estimation of the abundance seaward of the data collection programs once the peak migration has been observed, but deviations from this assumption will cause the model to over- or underestimate the run size. For example, if the distribution of daily abundance estimates is skewed to the left and abundances decline dramatically after the peak migration date, the time–density model will overestimate the run size when assessed prior to observing that sharp decline. The probability to over- or underestimate the run size is also influenced by the timing of the stocks, with early timed stocks more likely to be overestimated and later timed stocks more likely to be underestimated when assessed at their peak migration date. While it is possible to use the estimated MPE to adjust run-size estimates depending on the preseason timing forecast (early or later than average timing), when implemented retrospectively, the historical timing forecast estimates were not precise enough to improve in-season run-size estimates.

The time–density model can be fitted to both absolute as well as relative indicates of abundance. In this paper, the application of the model for the in-season assessment of Fraser River sockeye illustrates the use of reconstructed marine abundances estimates based on in-river hydroacoustic data and seaward catches as well as marine test fishing CPUE data. Since the in-season management of Fraser River sockeye assumes marine reconstructed abundances are known without error, the same assumption was made within this paper. In reality, the accuracy of the total run-size estimate is dependent on four sources of error: (*i*) the precision of the total salmon abundance estimate generated by the hydroacoustics program at Mission, (*ii*) the accuracy of species composition estimates used to partition the estimate of total salmon into sockeye and other co-migrating salmon species, (*iii*) the error in stock identification, and (*iv*) catch reporting errors. Of these four sources of error, the precision of total salmon abundance estimates (Xie and Martens 2014) and stock identification estimates (PSC 2017) were both estimated to be 5%. An evaluation of the precision of species composition estimates is difficult to quantify, as methods vary within years and from year to year depending on the species mixture at any given time (PSC 2017). Species composition is particularly challenging on odd-numbered years when pink salmon (*Oncorhynchus gorbuscha*) are present in the Fraser River (PSC 2017). The potential impact of species composition errors on the total run size can be illustrated using the in-season assessment results of 2005 when postseason analyses revealed the total number of salmon to be overestimated by 50% (PSC 2009). Finally, there is uncertainty around reported catches seaward of Mission (Bijsterveld et al. 2002). The impact of uncertainty as well as bias in catch estimates will depend on the run size and the amount of catch taken, as well as on the types of fisheries reporting the catches.

The time–density model presented in this paper has been applied to the in-season assessment of other sockeye stocks as well as other salmon species (PSC 2017). The flexible framework allows for a variety of different fisheries-dependent and -independent time series to be used (e.g., Ballard lock counts for the assessment of Lake Washington sockeye). The types of available data will not only depend on the presence of a suitable data collection program but also on the timeliness of the available data. In the case of Late-run sockeye, the in-river hydroacoustics data collected at Mission are less useful for in-season assessment because of the delay in their migration into the river (Lapointe et al. 2003). In-season assessments of delaying late-run stocks are therefore solely based on marine test fishing CPUE. In addition, management regimes for other stocks may require less intensive in-season assessments than those described above for Fraser River sockeye. For example, the in-season management of Fraser River chum salmon (*Oncorhynchus keta*; Gazey and Palermo 2000) relies on the in-season assessment of marine and in-river test fishing CPUE data and is considerably less costly than the program used for Fraser River sockeye.

The Bayesian implementation of the time–density model allows for the incorporation of additional knowledge and information into the in-season assessment through the use of informative prior probability distributions for the run size, timing, and standard deviation (dispersion) of the migration and the catchability coefficient. The use of informative prior probability distributions forms an important part of the in-season assessment method, as the data available in-season may not always be informative enough to update the prior probability distributions. For example, when fitting the Bayesian time–density model to marine CPUE data only, there would be insufficient information in the data to update the distribution of the catchability coefficient. Instead, the uncertainty around the catchability coefficient as reflected by the prior probability distribution will directly impact the run-size uncertainty. Similarly, when assessed at the peak migration date, the data will contain limited information about the standard deviation of the migration. The assumed prior probability distribution for the standard deviation of the run will therefore have a major impact on the run size but this impact diminishes as more in-season information about the duration of the run becomes available.

For the assessment of Fraser River sockeye salmon, the prior probability distributions for the run size and timing are based on the peer-reviewed preseason forecasts generated prior to the salmon season. These forecasted distributions have been long established inputs within the preseason fisheries management planning process and are well understood and debated by the technical individuals and other representatives involved in the management process. In the case of our described model, we believe that their use as priors provides both an intuitive as well as a computationally advantageous approach for the in-season estimation of total abundance and timing. While it would be helpful to have more accurate and precise preseason information on both variables, gains in these areas are difficult to achieve (Grant et al. 2010; DFO 2016). In addition, more accurate preseason forecasts may not substantially change in-season results, which are strongly influenced by the in-season data, especially once the peak migration date is apparent in the data. For example, in 2009, the median preseason forecast for Summer-run sockeye was 8.7 million (2.9–32 million 80% PI), while 6 days after the peak migration date, the in-season run-size estimate was 881 000 (720 000 – 1.1 million 80% PI), and the actual number of returning sockeye estimated postseason was 675 000 (PSC 2015*a*). The following year in 2010, the median preseason forecast for Summer-run sockeye was 2.6 million (1–7 million 80% PI), and the median in-season estimate at the peak of the migration was 3.3. million (2.5–4.4 million 80% PI; PSC 2015*b*). Six days after the peak migration date, the in-season median run-size estimate had increased to 5.1 million (4.3–6.1 million 80% PI) as compared with an actual return of 5.8 million. Although in both years actual returns were considerably different from forecasted preseason, information from the in-season hydroacoustic and test fishing programs allowed for in-season updates of the run-size and timing estimates and adjustment of fisheries catches. As a result, based on postseason estimates, 92% of the summer-run SET was reached in 2009 and 84% of the summer-run TAC was caught in 2010.

The retrospective analyses of the Bayesian time–density model demonstrated that the in-season assessment programs for Fraser River sockeye greatly improved the accuracy and precision of run-size estimates compared with preseason forecasts. For the period 1998–2017, historic preseason run-size forecasts based on stock–recruitment data tended to be highly uncertain (MAPE = 165%) and biased high (MPE = 158%; Table 2). In comparison, in-season assessments reduced the average run-size error (MAPE < 70%) and greatly decreased biases (MPE < 30%). The improvements in run-size error depended on the timing of the in-season assessments in relation to the peak migration date and the quality of the data and information used for the assessment. The marine CPUE information at the peak of the migration, 6 days seaward of Mission, had a greater influence on the run-size error than the more accurate and precise hydroacoustic data reflecting an earlier stage of the migration. In addition, the run-size uncertainty was primarily due to the uncertain abundance seaward of the test fishing areas, rather than due to uncertain daily abundance estimates derived from the test fishing CPUE data. As the main objective of the marine assessments is to provide an early indication of the trend in daily abundance estimates, relative indictors of abundance seemed to work equally well as absolute indicators of abundance around the peak migration.

This paper also evaluated whether in-season assessments could be improved by replacing marine CPUE data with more precise data such as marine daily abundance estimates based on marine hydroacoustics. Such estimates could potentially improve total run-size estimates by an average of 10% 3–6 days after the peak migration. These results, however, assume the daily abundance estimates based on marine hydroacoustics would reach the same accuracy and precision as the estimates derived from in-river hydroacoustic data, which is unlikely given that the sampling area in the marine environment is much larger and more variable than in the river. For example, a marine hydroacoustic program would be challenged by highly variable tidal currents, and the more diverse marine environment would complicate the separation of sockeye targets from other hydroacoustic targets, including other fish species, nekton, and debris (Vagle et al. 2008). In addition, a marine hydroacoustic program would still require an accompanying test fishing program to obtain samples for the identification of the stocks present in the area. While the expensive purse seine test fishery designed to collect CPUE data might potentially be replaced by a less expensive sampling program using smaller mesh seine or trawl gear (Levy et al. 1991), the overall cost of a marine hydroacoustic program could still be substantial given the cost of the current in-river hydroacoustic program and the fact that such a program would need to be run in both Johnstone Strait and Juan de Fuca Strait.

Reduced bias and improved precision of run-size estimates based on in-season information as compared with historical stock–recruitment information has a clear and substantial impact on the achievement of management objectives. Over the 20-year time period studied, TAC estimates based on preseason forecasts were larger than available abundances for most years. This would have resulted in overexploitation of the salmon run if management decisions had been based on those preseason estimates. By comparison, the in-season programs, regardless of the collected data, provided more accurate and precise run-size estimates. In addition, reductions in run-size error as the season progressed further improved the ability to achieve the two competing management objectives: to reach spawning escapement targets and to achieve catch objectives.

For in-season management, the timeliness of information is crucial. Although it takes about 2 months for Summer-run sockeye to transit an area, approximately 50% of the abundance passes in a 2-week window around the peak migration date. This restricts the availability of fish to marine fisheries, as there will only be a small window of time in which most of the fish can be caught. Throughout the migration, the assessments based on in-season information from the test fishing and (or) hydroacoustics program differed in terms of the accuracy and precision of resulting run-size estimates. While daily abundance estimates derived from in-river hydroacoustic data were more precise than abundance estimates derived from marine test fishing CPUE data, these daily estimates provided little indication of expected abundances seaward of the hydroacoustic site. Marine test fishing CPUE data in combination with catchability estimates provided more uncertain daily abundance estimates but could provide these estimates 6 days earlier than the in-river hydroacoustic system. Overall, the best fisheries management outcomes were obtained by combining the marine CPUE data with marine reconstructed abundance estimates within the Bayesian time–density model, thereby taking advantage of the benefits that each of the two data sets had to offer (i.e., timeliness and precision).

Acknowledgements

The authors are grateful to Carl Walters and Bill Gazey for their guidance and feedback at the start of this project and to Mike Lapointe for the useful discussions over the years that forced us to clarify our thinking. We thank two anonymous reviewers and Merran Hague for valuable comments on the paper.

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Appendix A. WinBUGS code for a Bayesian time–density model

```
model{
  R ~ dlnorm(log_mu_R, tau_R) #Total annual run size (thousands)
  T ~ dnorm(mu_T, tau_T) #Timing estimate
  S ~ dnorm(mu_S, tau_S) #Standard deviation of the migration
  inv_q ~ dnorm(mu_inv_q, tau_inv_q)I(0.001,) #Inverse catchability estimate
  tau_N ~ dgamma(0.01, 0.001) #Precision of the predicted daily abundance estimates
  tau_I ~ dgamma(0.01, 0.001) #Precision of the predicted CPUE estimates
  for (t in 1 : n){ #For n days
    #Daily proportion of the total annual run size
    P[t] <- (1 / (S * pow(6.283, 0.5))) * exp(-pow((t - T), 2) / (2 * pow(S ,2)))
    N[t] <- P[t] * R #Model predicted daily abundance (thousands)
    N_obs[t] ~ dnorm(N[t], tau_N) #Likelihood function for the reconstructed daily marine abundances
    I[t] <- abs(N[t] * 1000 / inv_q) #Model predicted daily CPUE (Note that abundances are converted from thousands to individual fish)
    log_I[t] <- log(I[t]) #Log-transformation
    I_obs[t] ~ dlnorm(log_I[t], tau_I) #Likelihood function for the daily CPUE data
  }
}
```