Fisheries and Oceans Canada
Pêches et Océans Canada

Ecosystems and Oceans Science
Sciences des écosystèmes et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2024/079

Pacific Region

Migration Speed, Run Timing, and Migration Route for Interior Fraser Steelhead Trout

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December 2024

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044
ISBN 978-0-660-74464-3 Cat. No. Fs70-5/2024-079E-PDF

Correct citation for this publication:

Jenewein, B., Davis, B., Potapova, A., Wor, C., van Dam-Bates, P., and Hawkshaw, M. 2024. Migration Speed, Run Timing, and Migration Route for Interior Fraser Steelhead Trout. DFO Can. Sci. Advis. Sec. Res. Doc. 2024/079. vi + 34 p.

Aussi disponible en français :

Jenewein, B., Davis, B., Potapova, A., Wor, C., van Dam-Bates, P., et Hawkshaw, M. 2024. Vitesse de migration, période de montaison et itinéraire de migration de la truite arc-en-ciel du Fraser intérieur. Secr. can. des avis sci. du MPO. Doc. de rech. 2024/079. vi + 37 p.

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1. ABSTRACT

In this paper, we assess and validate the information available to inform key input parameters required for the development of future fishery planning models for Interior Fraser River Steelhead Trout, including migration speed, migration route, and run timing. This assessment includes the development and evaluation of models to estimate run timing of Interior Fraser River Steelhead Trout in the lower Fraser River. Our literature review revealed that relatively little is known about migration speed and migration route of Steelhead Trout in British Columbia, and even less is known specifically about Interior Fraser River Steelhead Trout. Migration speed is highly variable both within and among populations, but generally Steelhead Trout appear to migrate faster in marine waters than in rivers. The proportion of fish migrating along either side of Vancouver Island is not well-studied for most salmonids, but there is evidence that adult returning Steelhead Trout (and in particular, Interior Fraser River Steelhead Trout) are present on both sides. Despite knowing this, we have limited information to determine the relative proportions that take each route. Run timing of Interior Fraser Steelhead through the lower Fraser River is much better informed due to their incidental catch in Chinook and Chum-directed test fisheries at the Albion test fishery, which coincides with their fall migration. While the standard practice in estimating run timing of salmonids has been to use a normal distribution, here we present evidence that an alternative (asymmetric normal distribution) better captures the observed patterns in catch. This approach results in estimating that the majority (95%) of Interior Fraser River Steelhead Trout migrate through the lower Fraser River between September 8 and November 23, on average. The information presented in this paper is intended to support future work on a fishery planning model that estimates exposure of Interior Fraser River Steelhead Trout to fisheries throughout southern British Columbia. Given the uncertainty in modelled estimates of run-timing parameters, migration route around Vancouver Island, and migration speed throughout the migration corridor, it is strongly recommended that the future exposure model not use one value for each of these parameters; rather, a better understanding of the risk of fishery plans to Interior Fraser River Steelhead Trout would be obtained by drawing input parameters from a distribution and/or ensuring a sensitivity analysis is completed to understand how variation in these biological parameters may affect exposure estimates and subsequent management decisions.

2. INTRODUCTION

The Chilcotin and Thompson River Designatable Units (DUs) of Steelhead Trout (*Oncorhynchus mykiss*), major populations of the group often referred to as Interior Fraser River Steelhead Trout, have recently been assessed as Endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC 2020), and abundance of this aggregate is at historic low levels (Bison 2022). Fishing mortality was identified as one of several potential threats to these populations; therefore, quantitative information about the spatio-temporal distribution of these populations is required to design salmon fisheries to limit bycatch impacts on these populations. There is significant disagreement among First Nations, stakeholders, and various government agencies about the degree to which various salmon fisheries impact Interior Fraser River Steelhead Trout. Historical exploitation or fishery-dependent mortality patterns are scarce because monitoring programs for salmon fisheries are incomplete and tend to focus on estimating target species catch rather than rare-event bycatch, which includes Interior Fraser River Steelhead Trout. Consequently, estimates of catch of Interior Fraser River Steelhead Trout for use in conventional stock-assessment procedures are not available in most Canadian salmon fisheries.

Previous modeling work attempted to estimate the potential range of impacts of marine and freshwater fisheries on the Thompson River population of Steelhead Trout; however, an evaluation of that work concluded that the lack of reliable empirical data and the use of many subjective and undocumented assumptions precluded validation of the majority of parameter estimates and calculations used in those models (DFO 2006).

In this paper, we compile available information and estimate key input parameters required for the development of future fishery planning models, including migration speed, migration route (proportion of fish migrating through Johnstone Strait, rather than along the outer coast of Vancouver Island and through the Strait of Juan de Fuca), and run timing. A key part of this work is the evaluation of potential models to estimate run timing of Interior Fraser River Steelhead Trout in the lower Fraser River. These estimates are for an aggregated group of Interior Fraser River Steelhead Trout populations because the historical time series of catch data used here (Albion test fishery data 1983-2022) does not clearly differentiate the Thompson and Chilcotin populations from other Interior Fraser River Steelhead Trout. We evaluate and recommend a model identified through this work that explicitly accounts for uncertainty and provides measures of uncertainty for run-timing estimates.

Objectives:

1. Compile information on migration speed, diversion rate, and run timing of migrating Interior Fraser River Steelhead Trout and provide insights on information gaps;
2. Estimate historical run-timing parameters for Interior Fraser River Steelhead Trout based on the best available data, a test fishery in the lower Fraser River;
3. Evaluate the models developed for (2) by examining and identifying uncertainties in the data and modelling approach. This evaluation will include using simulation analyses to provide insight as to the reliability of the model given the data quality; and
4. Identify research needs to address data gaps and/or potential concerns.

3. LITERATURE REVIEW

3.1. MIGRATION SPEED

Published estimates of upstream Steelhead Trout migration speed are summarized in Table 1. The range of estimates in Table 1 show that migration speed is highly variable and affected by various factors such as the river system, freshwater or marine environment, population, time of day, and water temperature. Median and mean estimates range from 6.2 km/d to 36.6 km/d.

Limited data are available on Steelhead Trout migrating in the Fraser River. Renn et al. (2001) conducted a tagging study from 1996-1998 to monitor migration speed between telemetry stations positioned along the majority of the Fraser River Steelhead Trout migration route. The stations were placed from Barnston Island to Prince George and at the confluence with several spawning tributaries to the Fraser River, including Harrison, Nahatlatch, Bridge, Stein, Thompson, Nicola, Spius, Bonaparte, Deadman, and Chilcotin rivers (Figure 1). There are no migration speed estimates for the portion of the Fraser River between the mouth and Barnston Island (approximately 50 km upstream of the mouth), and estimates from Barnston Is. to Harrison River are based on data from very few (seven) tagged Steelhead Trout. As the fish migrate past Harrison River into the Fraser Canyon and approach their spawning grounds, it appears their migration may slow significantly to less than five km/d, though there was high variability among study years and sections of the river. This variability in migration speed could potentially be due to the interannual variability of river discharge, another factor known to influence Steelhead Trout migration speed (Spence 1989, English et al. 2006, Ruggerone 2006). This high variability in migration speed is also expected based on Steelhead Trout biology, as Steelhead Trout that enter freshwater several months prior to spawning (often referred to as “premature migration”) leave the ocean with larger fat stores compared to salmonids that migrate just prior to spawning, and hold in various locations along their migration route, depending on environmental conditions (Robards and Quinn 2002, High et al. 2006, Lamperth et al. 2016).

Migration rates of Interior Fraser River Steelhead Trout appear to be independent of water temperature when mean daily water temperatures exceed 7°C; below 7°C rates appear to decrease with colder water temperatures, except for the Chilcotin stock, which showed an increased migration rate with decreasing water temperatures (Renn et al. 2001). A telemetry study in the Skeena River showed that Steelhead Trout movement was significantly influenced by mean water temperature but in the opposite direction to the majority of Fraser River Steelhead Trout; with migration rate significantly decreasing above 6.5°C (Twardek et al. 2018). Similarly, in the Columbia and Snake rivers, Steelhead Trout migration rate slowed with increasing temperatures experienced during the summer, then increased as temperatures decreased in the fall (Keefer et al. 2004). However, the highest temperatures experienced during this study frequently exceeded the thermal limits of Steelhead Trout, above 21°C. Migration rates may be slower at higher temperatures due to fish staging in cold water refugia, such as tributaries (High 2006). High river temperatures near thermal limits are typically not experienced by adult Interior Fraser River Steelhead Trout as their migration in the river primarily occurs in the fall and early winter (Ministry of Environment, Lands and Parks (MELP) and DFO 1998).

Diel patterns of adult Steelhead Trout migration are both not well-understood and highly variable, with some populations traveling fastest at night in the open ocean (Walker et al. 2000), and some traveling fastest during the day in inland marine areas (Ruggerone et al. 1990). Diel movement is a behavioural response to various factors such as the presence of predators, competitors, or prey, and environmental conditions that impact the biophysical costs of movement (Keefer et al. 2013, Myers 2018). In most cases the presence or absence of these patterns shouldn't create problems when modelling adult Steelhead Trout movement because the parameter being estimated is typically net migration on a daily timestep, but it may be an important consideration when developing fine-scale management actions.

A potential alternative may be to employ a hypothesis about migration speed based on a similar co-migrating species for which there is tagging data, such as Chum Salmon. It has been observed, however, that Steelhead Trout migrate significantly slower than Sockeye, Chum, and Pink salmon on the high seas, but at similar speeds to Coho and Chinook salmon (Ogura 1990, 1991; Ogura and Ishida 1995), so care should be taken in using this approach. Furthermore, in freshwater, Steelhead Trout are known to slow their migration rates to conserve energy in response to challenging river conditions, unlike other species such as Chum and Sockeye salmon.

3.2. MIGRATION ROUTE AROUND VANCOUVER ISLAND

There is a desire to better understand the migratory route taken by Interior Fraser River Steelhead Trout to improve planning tools for salmon fisheries constrained by concerns about impacts to Interior Fraser River Steelhead Trout bycatch. The proportions of salmonids taking each migration route around Vancouver Island (i.e., along the western or eastern coast) have been studied almost exclusively for returning adult Fraser River Sockeye and Pink salmon, as these values are important for fisheries management (Putman et al. 2014; Folkes et al. 2018). To inform fisheries management decisions, Fisheries and Oceans Canada provides a pre-season forecast of these proportions for Fraser Sockeye and Pink salmon, while the Pacific Salmon Commission makes in-season estimates and predictions of the proportions based on test fishery catches in Johnstone Strait and the Strait of Juan de Fuca. This approach has not been applied to other Pacific Salmon species nor Steelhead Trout.

With no formal studies of Steelhead Trout migration route around Vancouver Island available, we can make limited inferences based on interception data in commercial and test fisheries. Steelhead Trout samples from commercial fisheries in Area 12/13 and Area 20 from 1977-1980 revealed Interior Fraser River Steelhead Trout populations are present along both migratory routes (Parkinson 1984). Further, when Steelhead Trout were sampled in the Nitinat Chum gill net fishery (Pacific Fishery Management Area 21) from 1994-1997, Fraser River (including Thompson River) populations were identified (Beacham et al. 1999). This finding is further evidence of Interior Fraser River Steelhead Trout migrating both through Johnstone Strait and the Juan de Fuca Strait, but does not assist in determining the proportion of Interior Fraser River Steelhead Trout populations that use each migratory route and how it may vary annually. It may be possible to estimate these proportions using previously-reported stock-specific catch information in Johnstone Strait and Juan de Fuca Strait, but further work must be done to account for catchability differences. Future work will likely need to continue to treat this parameter as unknown due to low Steelhead Trout catch rates and historical data possibly not being representative of current conditions. Recent genetic samples from commercial and test fisheries in Johnstone Strait and Juan de Fuca Strait are not available.

4. RUN-TIMING ANALYSIS METHODS

4.1. DATA SOURCES

4.1.1. Albion Test Fishery

The best data set we identified for estimating Interior Fraser River Steelhead Trout migration timing comes from the Albion test fishery, 60.4 km upstream from the mouth of the Fraser River

(Figure 1). This test fishery has been in operation since 1978 and provides an extensive dataset of Steelhead Trout interceptions. The target species of the test fishery are Chinook and Chum salmon; Steelhead Trout are bycatch and all catches of Steelhead Trout have been released since 2008. Catch lost to pinnipeds, which has become increasingly problematic, is not quantifiable.

On each day of test fishery operation, two sets are conducted near the high slack tide. The test fishery operates a Chum-directed gillnet (6.75” mesh) and a Chinook-directed gillnet (8” mesh) on approximately alternating days. As of October 20, the test fishery only operates the Chum-directed gillnet. This description reflects the most recent configuration of the test fishery, which has been in place since 2004, but there have been occasional minor changes in the exact dates fished by each net. In 1997 the test fishery operated a Chinook-directed multi-panel net (10 panels, two of each mesh size: 5”, 6”, 7”, 8”, 9”) on alternating days with the standard Chinook-directed single-panel net (8” mesh), and also operated the Chum-directed net every day. Since we are estimating catchability for each net configuration and there are relatively few multi-panel samples throughout the 40-year dataset, we chose to remove these data. Removing these observations did not affect our overall results significantly. See Gazey and Palermo (2000) for further details on the test fishery operation.

Only Steelhead Trout interception data from 1983-2022 (spawning years 1984-2023) were used in the analysis as the test fishing operations prior to this time were less consistent. Data from August 1 through December 1 of each year were selected as this period encompasses all the Steelhead Trout interceptions that are most likely to be returning adults (rather than outmigrating kelts in the spring). Data from December 2-16 in 1983 was excluded from the analysis as it was the only year in which the test fishery operated during this time period, and these few observations were found to drastically skew results. The test fishery has fished at the same drift location since its inception, starting just upstream of the old Albion ferry dock and ending approximately 1km upstream of Kanaka Creek (Figure 1).

It is important to note that full genetic analysis of the Steelhead Trout interception data is not available to accurately determine the origin of the catch. Consequently, some of the interceptions may be of lower Fraser River Coastal Winter populations (Coquitlam, Pitt, Chehalis, Chilliwack, and Coquihalla rivers, among others), which enter the Fraser River from November to April and overlap with the end of the return migration of Thompson and Chilcotin populations (MELP and DFO 1998). It is also possible that some of the interceptions between September 1 and November 20 are West Fraser populations (Bridge, Seton, Stein, Nahatlatch), which are not included as part of either the Thompson or Chilcotin Steelhead Trout DUs but overlap in return timing with them (MELP and DFO 1998). The Thompson and Chilcotin populations were historically relatively larger than the West Fraser populations but somewhat smaller than the Coastal Winter populations (MELP and DFO 1998).

4.1.2. Index of Return to the Albion Test Fishery

An index of the return of Steelhead Trout to the Albion test fishery was used in the run-timing models to scale the magnitude of the overall run-timing curve, and allowed us to estimate catchabilities for each fishery. We estimated the index of return by summing spawning escapements with catch and release mortality (where applicable) from fisheries upstream of the Albion test fishery (Table 2).

Spawning escapement estimates of Steelhead Trout in the Chilcotin and Thompson rivers and recreational fishery catch data of Thompson and Chilcotin Steelhead Trout were primarily obtained from Appendix 2 in COSEWIC (2020). Updated data for 2021-2023 were provided by R. Bison, (BC Ministry of Water, Land, and Resource Stewardship). The recreational fishery targeting Interior Fraser River Steelhead Trout has been closed since 2008 in the Chilcotin watershed, and since 2018 in all remaining Interior Fraser River Steelhead Trout watersheds. Spawning escapement estimation and recreational fishery creel survey methodologies are detailed in Johnston (2013).

Albion test fishery catch data (kept and released) were obtained from the Fisheries and Oceans Canada's Fishery Operations System. A 40% mortality rate was assumed for releases; this is lower than typically applied to gill net fisheries (60%), but is likely more accurate due to fishing methods that are designed to reduce mortality on bycatch, including the use of revival tanks and limited handling/air exposure (Hargreaves and Tovey 2001). As mentioned above, the catch data is not specific to Thompson and Chilcotin Steelhead Trout, but may also include catch of Coastal Winter and West Fraser Steelhead Trout.

Indigenous fishery catch data (kept and released) reported to and analyzed by DFO were obtained from DFO's catch monitoring staff. These data include catch records from 1983 to 2022 in the Fraser River mainstem upstream of Kanaka Creek (located at the downstream end of the Albion test fishery drift area), the Thompson River, and the Chilcotin River. As with the Albion test fishery dataset, these data will include catch of multiple Fraser River Steelhead Trout populations, not only Thompson and Chilcotin Steelhead Trout. Lillooet River catch is not included, as it is assumed these fish would be part of the Coastal Summer stock group (MELP and DFO 1998; Beacham et al. 1999, 2004). The catch from 1983 to 2003 was recorded as a total for Mission to Sawmill Creek, missing the component for Kanaka Creek to Mission that is recorded for 2004 to present. The annual catch for Kanaka Creek to Mission was therefore estimated for 1983 to 2003 based on the average percentage of Steelhead Trout encountered in this area for 2004 to 2022 (6.7%) multiplied by the number of Steelhead Trout caught annually in Mission to Sawmill Creek for each year from 1983 to 2003. This accounts for 956 total kept Steelhead Trout during this time period (average of 46 per year). Releases were separated by gear type and a gear-specific release mortality rate was applied: 5% for beach seine and fish wheel, 60% for gill net (drift and set), and 23% when gear type was indicated only as mixed (average mortality rate among the previous listed gear types).

Alternative estimates of Indigenous catch numbers from 1985-1989 are available from several studies that aimed to estimate numbers of Steelhead Trout harvested by commercial, Indigenous, and sport fisheries occurring from September through mid-November[1] (Stewart and Lewynsky 1988, Lewynsky 1988, Lewynsky 1989, Lewynsky 1990). These estimates were validated against DFO's fishery officer data collection reports, which suggested that DFO's estimates may have been biased low. The potential influence of these alternative estimates on the results of the run-timing estimates is explored as part of the sensitivity analysis in Section 4.5.3.

Other sources of Steelhead Trout interception data exist that may be useful for future related analyses (Appendix A).

4.2. RUN-TIMING MODELS

A common approach to estimating run timing is to fit a normal (or Gaussian) curve to indicators of daily abundance such as daily catch data. The mean and standard deviation of the normal

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[1] Lewynsky, V.A., Olmsted, W.R., Stewart, R.J., and Scott, K.J. 1987. Interception of fall-run steelhead trout by sport, commercial, and Indian food fisheries of the Fraser River. 1985. Prepared for Department of Fisheries and Oceans and B.C. Ministry of Environment by W.R. Olmsted and Assoc., North Vancouver, B.C., and Western Renewable Resources, 100 Mile House, B.C.

curve is usually reported as estimates of the annual 50% date (date when half of the return is expected to have passed a reference location) and spread of fish migration (Mundy 1979, Cave and Gazey 1994, Hilborn et al. 1999, Gazey and Palermo 2000, Bison 2021). This approach was taken in a recent analysis carried out by the Province of BC, also aimed at characterizing Interior Fraser Steelhead Trout run timing (Bison 2021). For a standard run-timing model, the normal distribution is well approximated to the discrete day, such that it describes the proportion of fish returning each day, and will sum to one over the entire run. Only in the case of a very short run-timing window might this condition be violated. However, the normal distribution forces an assumption of symmetry around the peak and has relatively short tails. Alternative parametric (or non-parametric, such as a smooth spline) curves may better approximate the proportion of fish returning each day but may need to be normalized so that the proportions sum to one. For example, Wilson et al. (2023) created a hierarchical modelling framework for estimating intra-annual patterns in phenology and temporal changes in run timing. They explored flexible alternatives to the normal distribution allowing for changes in both tail shape and symmetry. We explored using the R package developed as part of that work, but since our data set has two different catchability rates due to different nets used in the Chum and Chinook-directed sets of the Albion test fishery our data were not compatible with the models in that framework. This did, however, guide our exploration into using alternative distributions, further explained below.

Here, we present three run-timing models: the first model is similar to the one produced by Bison (2021), and the two other candidate models improve upon the first model by using a hierarchical framework and by accounting for greater variability of observed catch. The third model expands on the second by allowing an asymmetrical run-timing curve, rather than the generally-used normal curve. We compared the results, goodness of fit, and performance of each model to recommend a model structure to be used going forward. Since one of our candidate models does not follow a symmetrical normal curve, the estimates they produce cannot be directly compared by their means and standard deviations. Therefore, from these models we can calculate quantiles of Interior Fraser River Steelhead Trout passage, and from those, calculate the window of time necessary to encompass a set percentage of the run (i.e., the window that we expect the passage of X% of the Interior Fraser River Steelhead Trout run).

4.2.1. Independent Normal Curves, with Poisson Observation Error

We created a baseline model structure, mostly following what was described in Bison (2021). In this model, the normal run-timing curve for each year is independent (M_y, σ_y estimated independently across years). The expected abundance on a given year, *y*, and day, *d*, is therefore the product of the total yearly return (R_y) and the proportion of the run that migrates past a reference location on that day, as approximated by the normal curve:

$$\hat{A}_{y,d} = R_y * \alpha * \ e^{-\frac{\left(d-M_y\right)^2}{2\sigma_y^2}}$$

where α is the normalizing constant:

$$\alpha = \frac{1}{\sqrt{2\pi}\sigma_y}$$

In this model, we assume the observed catch on each day is Poisson distributed. Catchability changes with each net configuration ($m = 1$ for the Chum-directed net, $m = 2$ for Chinook-directed net), such that we observe fish at a rate equal to the product of gear-specific catchability (q_y^m) and expected daily abundance ($\hat{A}_{y,d}$):

$$C_{y,d}^{m} \sim Poisson\left(q_y^m * \hat{A}_{y,d}\right) \quad for\ m \in (1,2)$$

We used a hierarchical structure on catchability for each net configuration (Chum and Chinook), so that the model can “borrow” information across years, since we assume catchability of each net configuration would be similar across years. We estimated similar run-timing parameters to the Bison (2021) analysis, despite this difference. Because catchability, q, is constrained between 0 and 1, we use a logit transformation between the yearly catchability, and the “global” distribution of catchability across years (normal distribution with parameters μ_q and σ_q for each net configuration, m):

$$logit\left(q_y^m\right) \sim N\left(\mu_q^m, \sigma_q^m\right) \ for\ m \in (1,2)$$

Weakly informative priors were put on all parameters, the details of which can be found in Appendix B.

4.2.2. Hierarchical Normal Curves, with Negative Binomial Observation Error

The results of the first model showed that the normal run-timing parameters were quite variable across years, and in some years (especially in years with few non-zero observations) the model estimated unrealistic run-timing. For example, in 2019 the model estimated a 95% window of run-timing spanning from mid-July to mid-January, and in 2008 estimated that run-timing peaks in early September, and is 97.5% finished by November 5, both of which we know to be unreasonable (see Figures 2 and 3). Results from the independent model showed a lack of clear directional trend in run-timing across years (Figure 3), and additional analyses found that models that allowed an annual trend in run-timing weren’t useful for this exercise. For these reasons, we chose to put a hierarchical structure on run-timing parameters across years, such that each year’s timing parameters are drawn from “global” distributions for mean (M_y) and spread (σ_y):

$$M_y \sim N(\mu_M, \sigma_M),$$

$$\sigma_y \sim N(\mu_\sigma, \epsilon_\sigma).$$

This helps to keep each year’s estimates reasonable, and is also convenient in that we estimate a “global” run-timing distribution, from which we can glean average timing in a way that balances the amount of information in each year of data (i.e., years with higher abundance, and therefore more non-zero observations are more influential), rather than averaging across years that we know are returning unreasonable estimates due to the low Steelhead Trout detection.

Additionally, results from the first model indicated that the Poisson observation model was not adequately capturing the variability in catch data (i.e., overdispersion; see section 4.3). Therefore, we replaced the Poisson distribution with a negative binomial distribution, with probability parameter p_m and dispersion parameter, r, to model the observation error in catch for each net configuration, m.

$$C^m \sim NB(p_m, r) \ for\ m \in (1,2).$$

Where

$$p_m = \frac{r}{r + q_y^m * \hat{A}_{y,d}} \ \ for\ m \in (1,2).$$

The dispersion parameter, r is assumed to be constant across the two fisheries. Details of prior specification can be found in Appendix B.

4.2.3. Hierarchical Asymmetric Normal Curves, with Negative Binomial Observation Error

In our exploration of candidate run-timing models, and inspecting non-parametric run-timing curves (that account for differential catchability between the two test fisheries, in similar ways to the above models) we observed what appeared to be asymmetry in the run-timing distribution. These findings led us to fit an asymmetric (or two-piece) normal distribution for run-timing. This model allows for a different standard deviation on each side of the mode (σ_{y-} and σ_{y+}), such that:

$$\hat{A}_{y,d} = \begin{cases} R_y * \alpha * e^{-\frac{(d-M_y)^2}{2\sigma_{y-}^2}} & \text{if } d < M_y \\ R_y * \alpha * e^{-\frac{(d-M_y)^2}{2\sigma_{y+}^2}} & \text{if } d > M_y \end{cases}$$

where α is a normalizing constant:

$$\alpha = \frac{\sqrt{2}}{\sqrt{\pi}(\sigma_{y+} + \sigma_{y-})}.$$

All other elements of the model remain the same as the above model, except that here we have two “global” distributions for the spread parameter, σ_{ys}, with $s \in (-,+)$ indicating each side (left, right) of the asymmetric normal distribution:

$$\sigma_{ys} \sim N(\mu_{\sigma s}, \epsilon_{\sigma s}) \quad for\ s \in (-,+)$$

All models were fit in a Bayesian context, using JAGS (Plummer 2003) to run MCMC, fit through R (R Core Team, 2023), using the R2jags package (Su and Yajima 2022). Convergence was assessed using Gelman-Rubin statistics (all parameters < 1.01) and visual trace plot inspection. All data and code can be found on Zenodo.

4.3. MODEL VALIDATION AND COMPARISON

Posterior predictive checks are often used in Bayesian analysis to check for model suitability. This check generally involves simulating new observations, creating posterior predictive distributions based on the estimated model parameters, and then seeing whether or not the true observed values are captured within the distribution. For discrete distributions such as the Poisson or negative binomial, typical residuals are challenging to interpret for model checking purposes. Instead, we generate residuals similar to randomized quantile residuals (Dunn and Smyth 1996) using the DHARMa package in R (Hartig 2022). The DHARMa residuals are calculated by simulating the posterior predictive distribution to calculate a simulation-based cumulative density function for each observed data point. The residual is then defined based on where the observed data point falls on the function, resulting in a residual that is continuous and constrained from zero to one (zero indicating all simulated values were above the observed value, one indicating the opposite). Observed data that are well fitted by the model fall close to the median (0.5). These residuals can then be interpreted similarly to conventional residuals from a linear model (right panels of Figure 4).

We used a Q-Q plot to check the distributional assumption of the model (e.g., Poisson or negative binomial) and a standard residual plot to ensure there were no observable residual trends, which indicates that the model assumptions were met (Figure 4). The DHARMa package also provides three formal tests for model suitability (see text on top of left figure panels in Figure 4). A Kolmogorov-Smirnov (KS) test is used to check whether the assumed distribution (i.e., Poisson or negative binomial) is appropriate. An overdispersion test compares the observed residual variance to the simulated model residual variance. An outlier test flags when true observations fall outside the distribution of simulated values and provides a simulation-based hypothesis test on whether true observations fall outside the distribution of simulated values.

4.4. RUN-TIMING ESTIMATION RESULTS

4.4.1. Model Convergence and Suitability

All three models converged using three chains of 20,000 iterations with the first 5,000 iterations discarded as “burn-in”, in order to minimize the effect of starting values on results. All key parameters had Gelman-Rubin statistics <1.01 and chains that passed visual inspection for convergence. For convenience, daily abundance estimates were obtained using chains that were thinned by a factor of five, meaning that each parameter had a total of 9,000 iterations (3,000*3 chains). Simulation-based diagnostics were carried out using a random draw of 1,000 iterations.

Inspecting DHARMa outputs (Figure 4) revealed poor model fit for the independent Poisson model, indicated by flags in tests for suitable distribution, overdispersion, and outliers. Residual plots with several outliers (residual values of one) indicate that the model is underpredicting high catch values (see cluster of red stars in Figure 4B, right panel). This finding was confirmed by inspecting posterior predictive distributions and observed values, which showed that the posterior predictive distribution does not capture high catch values observed in some years, a common result due to overdispersion. Changing the observation model to a negative binomial and changing the structure of the run-timing parameters to being hierarchical across years rather than independent, eliminated these problems (see Figure 4, panels A and B). All diagnostics indicated good model fit for both the hierarchical normal and the hierarchical asymmetric normal models when using the negative binomial.

To formally compare the models, we calculated the deviance information criterion (DIC; Spiegelhalter et al. 2002) for each of the three models (Table 3 – Differences in deviance information criterion values (ΔDIC) and effective number of parameters (Δ-pD) for the three models presented). DIC is a generalization of the Akaike information criterion (AIC; Akaike 1973) that can be used for hierarchical models. Both metrics balance model fit with model complexity (the number of parameters) to identify the most parsimonious model. Since the number of estimated parameters isn’t concretely defined in hierarchical models, the effective number of parameters (pD) is estimated based on how correlated the random effects are (here, each year’s run-timing parameters and catchabilities).

4.4.2. Model Estimates

The hierarchical normal model estimated a global peak date (μ_M) of October 11 (95% CI: Oct. 8-13), and global spread parameter (μ_σ) of 19 days (18-21), whereas the asymmetric normal distribution estimated a higher spread parameter for the right side of the distribution than the left, with $\mu_{\sigma-}$=13 days (12-15) and $\mu_{\sigma+}$ = 25 days (22-28). This heavier right tail pulls the mean date earlier, to October 2 (Sep. 29-Oct. 6); however, since this distribution is asymmetrical, the mean and date when 50% of abundance has passed are not the same – the 50% date of Oct 10 (Oct. 6-13) is within one day of the mean/mode/median of the hierarchical normal model (Oct. 11: Oct. 8-13).

To make the indication of spread of these models directly comparable to each other, and to the independent Poisson model (which we are retaining for comparison purposes, despite its poor model suitability), we calculated “windows” that we would expect to encompass given percentages of the total run. For the hierarchical models, the global mean and standard deviations were used to calculate the median posterior run quantiles. For the independent Poisson model, since we don’t have a global run-timing distribution, we calculated the posterior median run quantile across all years, and then took the median of the posterior as a point estimate for each aggregate quantile.

For each model, we calculated migration windows that would capture 95%, 90%, and 80% of the run migrating past the Albion site (see Table 4 and Figure 3). For the hierarchical asymmetric normal, the lengths of these windows were 77 days, 64 days, and 51 days, respectively. For the hierarchical normal model, the lengths of the 95% and 90% windows were the same as the asymmetric normal, while the 80% window was one day shorter, at 50. However, these windows were shifted between 2 and 5 days earlier in the year, when compared to the asymmetric normal (Table 4). The windows for the independent Poisson were longer than those of the other two models, with lengths of 81 days, 67 days, and 53 days for the 95%, 90%, and 80% windows, respectively. The windows were centered on the same date as the hierarchical normal model (Oct 10), but were two days wider on either end (Table 4). This result makes sense, since the independent Poisson model is independently estimating years with few non-zero observations, which allows for wildly different run-timing estimates than those years with many detections. This approach inherently increases the variability in these estimates, when compared to those estimated hierarchically.

As an indicator of performance, we used the 95% windows to compare what proportion of the catch observations were being captured by each model. The 95% windows estimated by the asymmetric normal and the independent Poisson both captured 97% of the catch observations over the 40 years of data, while the hierarchical normal captured 96%. Across years, the asymmetric normal typically missed between one and nine individual fish per year while the other two models missed up to 14 individuals in a given year. Although the windows for the asymmetric normal were the shortest amongst the three models, it still performed as well as, or better than, the other models in terms of capturing the dates of observed Steelhead Trout catch.

When we compare DIC for our three models, the independent Poisson model is identified as the least parsimonious and the hierarchical normal model is a close second behind the asymmetric normal model, which has the lowest DIC value despite having the highest effective number of parameters.

Based on good model suitability, indicated by the DHARMa residual analysis, good performance in capturing the timing of observed catches, and having the best DIC, the hierarchical asymmetric normal model is recommended as our best tool for characterizing Interior Fraser River Steelhead Trout run-timing in the lower Fraser River. Going forward, we suggest that this model be used in the development of a fisheries planning tool attempting to minimize Interior Fraser River Steelhead Trout exposure to fisheries..

4.5. SENSITIVITY ANALYSIS

For our sensitivity analysis we explored four scenarios that confronted different sources of uncertainty, to understand their potential impacts on parameter estimates. We explored the potential effects of over- and under-estimating return estimates, the effect of years of data where we have few observations of Steelhead Trout, and finally, the effect of varying the duration of the sampling window, which also incorporated some alternative catch estimates from early in the time series.

4.5.1. Uncertainty in Index of Return

Our estimates of the index of return to Albion are uncertain due to the potential for under-reporting of catches in fisheries upstream of the Albion test fishery (observed in commercial fisheries elsewhere; Bijsterveld et al. 2002, J.O. Thomas and Associates Ltd. 2010) and variability in release mortality from gill nets depending on fishing and handling techniques (Hargreaves and Tovey 2001). However, since the goal of this modelling exercise is primarily to estimate the window of time during which the majority of Interior Fraser River Steelhead Trout are migrating through the lower Fraser River (not the expected daily abundance), these uncertainties are fairly inconsequential. The main purpose of including an index of return is to scale the relative catchabilities between the two test fisheries (see Figure 5). To test the influence of uncertainty in annual return index on the estimated run-timing window, we re-ran our recommended model (hierarchical asymmetric normal) with a dataset where we have increased and decreased our return estimates by 50%. We found that even these drastic alterations of the return data had very little effect on the run-timing windows (Table). It is likely that we are underestimating rather than overestimating the return, but increasing our return estimates by 50% did not change the windows. Decreasing the return by 50% narrowed the window by one day at either end.

In a second suite of analyses, adjustments were made to years when there may have been a bias in the estimates of Indigenous catch. We altered our annual return data set to account for alternative reports of Indigenous catch numbers from the 1980s, which suggest that DFO's estimates may have been biased low[1] (Stewart and Lewynsky 1988, Lewynsky 1988, Lewynsky 1989, Lewynsky 1990), and potential under-reporting that may have continued after changes to the catch monitoring program were implemented in the 1990s. This approach included increasing Indigenous catch numbers from 1984 to 1996 to either directly match the Lewynsky reports, or presume a similar level of bias was present in prior and some subsequent years, tapering off over time as catch monitoring methods were improved. The time series matches the one used for the main analysis from 1997 onwards. With these adjustments it was found that the median date shifted earlier by one day, but that the 95% migration window was unchanged. These results indicate that these timing windows are likely robust to underlying uncertainties in our index of return time series.

4.5.2. Effects of Low Detection in Low-Abundance Years

As highlighted in Figure 1, both total annual return and the number of non-zero observations has declined drastically over time. Bison (2021) carried out a simulation analysis (assuming normal run-timing, and a Poisson observation process) to illustrate that years of low return had estimates of spread (σ_y in our model) that tended to be biased low and were very uncertain. Bison (2021) found a slight declining trend in spread over years that was shown by simulation to be potentially caused by lower abundance in recent years. They estimated a 'bias correction factor', that was then applied to estimates of spread, which varied with yearly return (more correction when abundance was low). In that same analysis, these data quality issues were further ameliorated by removing three years (1993, 2008, and 2019) from the estimation of average mean and spread that were deemed to not have enough information to estimate run timing.

Figure 3 (bottom row) demonstrates how widely the estimated run-timing curves can vary when estimated independently for each year, and Table 3 – Differences in deviance information criterion values (ΔDIC) and effective number of parameters (Δ-pD) for the three models presented shows how run-timing windows become wider, when averaging across these disparate run-timing curves. Interestingly, simply by putting a hierarchical structure on catchability, q, but keeping all other aspects of the model the same, our independent Poisson model gave an overall mean estimate of spread (21.5) closer to the corrected value in the Bison 2021 report (21) than the uncorrected value (19). This results indicates that sharing information on catchability across years may help constrain run-timing estimates to more reasonable values and help eliminate potential "bias" from low abundance and/or low detection years. Following these results, we didn't believe we had any reason to incorporate a bias correction in our models.

By placing a hierarchical structure on run-timing parameters, we believe we have reduced or eliminated this bias caused by (or perhaps better described as a sensitivity to) low detection years giving unreasonable estimates, since we are sharing information across years and thereby constraining yearly run-timing curves to more realistic shapes. To test how sensitive our recommended model is to varying detection levels, we ran it with a trimmed data set, which only included years with 15 or more non-zero observations. Bison (2021) identified a minimum return of 1,000 Steelhead Trout to eliminate the perceived bias in spread. There seems to be a natural break at our cut-off of 15 non-zero observations, which also happens to align well with having a return of 1,000 or more. An additional three years (1997, 2006, 2008) had returns of more than 1,000 Steelhead Trout but catches were low (< 15 non-zero observations). In 1997 we had to remove half of the observations from the Chinook test fishery because a different (multi-panel) net was used, which is why we have a low number of detections (18 Steelhead Trout caught over 12 days) despite fairly high abundance (return = 2,276). By running the model only with years of higher abundance and a larger number of catch observations we can evaluate whether or not the resulting migration windows could be biased when including all of the data. We found that the hierarchical asymmetric normal showed no discernable difference in run-timing estimates when using only higher abundance/higher catch observation years (Table), showing that our model is robust to varying abundance and data quality across years.

4.5.3. Effects of Sampling Window Duration and Potential Catch-Estimation Bias Early in the Time Series

Finally, we included one more scenario that evaluates the sensitivity of our results to the window of data used. In this scenario, the hierarchical asymmetric normal model was run with the test fishing data trimmed to a shorter period (August 20 to November 20) to increase the likelihood that the sampled Steelhead Trout were from Interior Fraser River populations, and not other earlier- or later-timed populations such as Coastal Summers or Winters (see Section 4.1.1). The results show that the 5th percentile of the run-timing window (start of the 90% window) was shifted earlier by one day but no other quantiles were affected.

5. DISCUSSION

This analysis highlights the value of hierarchical (also known as mixed-effects) modelling in scenarios where the number of observations is highly variable across various groupings (in this case years), and there is no expected directional trend in the data. By essentially "borrowing" information across years, we have the flexibility to capture variability over time, while learning more from those years with higher numbers of observations. This approach reduces the need to subjectively remove years with unsatisfactory data resolution, which improves transparency and reproducibility.

Despite suggesting a different modelling approach to Bison (2021), the results weren't drastically different. The estimated median migration date past the Albion test fishing site aligned with that analysis. The only difference is that our suggested approach results in a shorter 95% window (77 days, vs "at least 84 days" described in Bison 2021) that is shifted slightly later. While shortening the window may seem non-precautionary, we found that performance (in terms of proportion of observed catch within that window) was no worse with the asymmetric normal model than the independent Poisson model (both windows captured 97% of observed catch over 40 years).

Our results align with the telemetry study by Renn et al. (2001), which observed Interior Fraser River Steelhead Trout populations migrating through the lower Fraser River within the window of time estimated by our model, between mid-September and mid-November, peaking approximately the third week of October. An important consideration is their results further differentiated the Thompson and Chilcotin populations, suggesting the Chilcotin Steelhead Trout migrate earlier and over a shorter duration than the Thompson Steelhead Trout, which were observed throughout the whole migration period. This difference was also observed by Parkinson (1984). It is unclear to what extent a difference in contribution of Thompson versus Chilcotin Steelhead Trout could shift migration timing over time.

Although the index of return to the Albion test fishery doesn't have a significant impact on run-timing, it does dictate the estimated catchability the model produces. The index of return is uncertain for several reasons, including that there is no differentiation between Interior Fraser River Steelhead Trout populations and other Fraser River populations, no accounting for natural mortality, incomplete collection of spawner time series for all Interior Fraser River Steelhead Trout populations, and high likelihood of missing or incomplete catch records (underestimation of catch). It is also possible that the release mortality rates used are incorrect, as the typically-used rates are based on mortality estimates from Sockeye and Coho salmon. However, our sensitivity analysis suggests that the impact of error in these estimates on the run-timing parameters is minimal. Decreasing the index of return decreased our 95% window by one day on either end, while increasing the index of return by 50% did not change the results at all. These considerations become important if others wish to use this index of return for purposes such as gleaning status, or assessing absolute catchability.

As described in Section 4.5.2, Bison (2021) raised concerns that reduced numbers of non-zero observations in recent years may be biasing our estimates of run-timing spread. While we found that our model structure seemed to correct this issue, the hierarchical structure cannot elucidate any recent patterns we may be missing. Answering more in-depth questions about how migration timing could be changing with climate (if timing is driven by environmental cues), reduced population size (if timing is driven by density/social cues; see Berdahl et al. 2017), or by changing relative proportions of component populations with overlapping, but different, run-timing, are likely precluded by the low numbers of Steelhead Trout bycatch in this test fishery in recent years. Steelhead Trout abundance has become so low that we have observed less than 20 days with Steelhead Trout catch in each of the past 10 years. Although preliminary analysis did not show significant changes in run-timing over the time series, these questions are outside the scope of this work, which was to characterize historical run-timing. Due to degrading data quality over time, if we wish to hone in on those types of questions, more directed sampling methods or approaches such as acoustic tagging would likely be required.

Despite having a relatively useful data set to inform run timing compared to migration speed and route, there are still several sources of uncertainty. Firstly, the Albion test fishery data is only a snapshot of adult Interior Fraser River Steelhead Trout migration timing, so it may not be representative of run timing in areas further upstream or in marine waters. Knowing that migration speeds are highly variable across space and time means that transposing the run timing at the Albion test fishery to other locations will be quite uncertain. Other data that could be used to corroborate estimates of run timing for other locations include observations further up-river, Steelhead Trout interceptions in marine test fisheries, and fish wheel tagging projects upstream of the Albion test fishery (Appendix A).

Additionally, while the goal of this analysis is to infer the run timing of Thompson River and Chilcotin River Steelhead Trout, other Interior Fraser River Steelhead Trout populations are also likely captured in this data set. The estimated run-timing curve is expected to consist of several overlapping run-timing curves for component populations of Interior Fraser River Steelhead Trout. The protracted right tail of our run-timing curve, while seemingly performing better than the usual symmetric normal curve, could be due to observing later-returning Steelhead Trout populations, such as the Coastal Winter populations that spawn in tributaries to the lower Fraser River (e.g., Coquitlam, Pitt, Chehalis, Chilliwack, and Coquihalla rivers, among others) or other Interior Summer stocks in the West Fraser (Bridge, Seton, Stein, and Nahatlatch rivers). While our lack of genetic data makes parsing out these individual stocks impossible, it does raise more questions about whether the observed run timing could be driven by relative abundances of its component populations. Sensitivity analyses showed that trimming the time series to a period that is expected to exclude most of these earlier- and later-returning fish did not affect the estimated timing windows, but we cannot be sure they would have all been removed without finer scale information. As mentioned above, any in-depth analysis to try and tease these factors apart would require additional targeted data beyond what is currently available in this test fishery database.

While our model seemed to easily estimate values for each species-specific net configuration, the data are not evenly-distributed throughout the season, with the Chum test fishery carrying on much later in the season. The Chum-directed test fishery (which uses a smaller gillnet mesh size) also has higher catchability than the Chinook test fishery (Figure 5), suggesting that our asymmetric tails could be at least partially influenced by the higher catchability of the later-occurring fishery. However, there is a fair amount of overlap in these two data sets (Figure 1), which should help the model discern the relative catchabilities and should ameliorate any case of run-timing shape being confounded with net configuration/catchability.

The run-timing curve characterized by these data may not reflect future potential run timing for several reasons. First, the Steelhead Trout observed at the Albion test fishery would have had to pass through several marine and freshwater fisheries prior to being observed there. This means that catches of Steelhead Trout at the test fishery are potentially skewed by the timing and intensity of fishing that these fish were subjected to before they reached the test fishery site. As fisheries downstream and in the marine waters change over time, this could impact the observed timing of Steelhead Trout at the test fishery. Additionally, observed catches are translated to run timing via an annually estimated catchability parameter. However, it is likely that catchability of Steelhead Trout varies within each year, affected by environmental conditions and the abundance of co-migrating stocks. For example, if flow is high, fish may migrate along the edges of the river and may be less likely to be caught in the test fishery. It is also possible that when co-migrating stocks are in very high abundance, the net could become saturated with fish, and Steelhead Trout could be less likely to be caught. Catchability could also vary with variation in the abundance of predators. Furthermore, if co-migrating stocks have significantly different average body sizes, they would be expected to have different catchabilities – meaning catchability could vary as these finer resolution populations move through the area. Similar to our discussion above of detecting changes in run-timing, detecting changes and/or trends in catchability due to these factors is hampered by low estimation in recent years, and outside the scope of this exercise. The estimates of catchability provided here are incidental to the main goal of estimating run-timing, and should be viewed as yearly indices of catchability, and not reliable estimates of the catchability of every set in a given year. Although residual analyses did not indicate the need for additional parameters to capture effects of other factors on catch, such as environmental covariates or downstream catch, these effects could be explored in future work.

6. CONCLUSIONS

1. The literature review revealed that relatively little is known about migration speed and migration route of Steelhead Trout in British Columbia, and even less is known specifically about Interior Fraser River Steelhead Trout. Migration speed is highly variable both within and among populations, but generally Steelhead Trout appear to migrate faster in marine waters than in rivers. The proportion of fish migrating along either side of Vancouver Island is not well-studied for most salmonids, but there is evidence that Steelhead Trout (and in particular, Interior Fraser River Steelhead Trout) migrate along both routes.
2. While the standard practice in estimating run timing of salmonids has been to use a normal distribution, here we present evidence that an alternative run-timing distribution (the asymmetric normal) captures the observed patterns in catch. Additionally, this model performs as well as, or better than, modelling approaches using the normal curve, in terms of the number of catch observations captured within the 95% timing window. This results in estimating the majority (95%) of Interior Fraser River Steelhead Trout migrate through the lower Fraser River between September 8 and November 23, with a median date of October 10.
3. The Albion test fishery data are currently the best available information on Steelhead Trout interceptions in the Fraser River and provides a long (40-year) and mostly consistently-sampled time-series. Despite this fact, the available observations of Steelhead Trout have declined significantly in recent years, driven largely by extremely low returns of Steelhead Trout. Although this hampers our ability to discern any recent changes in run timing, we found our hierarchical modelling approach was robust to uncertainty and well-suited to the data, based on simulation analysis.. While this modelling approach appears adequate for capturing the patterns seen in these data, more targeted data collection would be required to confront more specific questions about recent changes in run timing and stock-specific migration timing.

7. RECOMMENDATIONS FOR FUTURE WORK

The information presented in this paper is intended to support future work on a fisheries planning model that would estimate exposure of adult Interior Fraser River Steelhead Trout to fisheries throughout southern British Columbia. Given the uncertainty in the proportion of Steelhead Trout migrating around either side of Vancouver Island, migration speeds throughout the migration corridor, and modelled estimates of run-timing parameters, it is strongly recommended that the future exposure model not use one value for each of these parameters. Rather, a better understanding of the risk of fishery plans to Interior Fraser River Steelhead Trout would be obtained by drawing input parameters from a distribution and/or ensuring a sensitivity analysis is completed to understand how variation in these biological parameters may affect exposure estimates and subsequent management decisions.

Future research on Interior Fraser River Steelhead Trout will be complicated by the low abundance of these populations and the need to minimize any potential harm in support of conservation efforts. When feasible, key areas for future research may include:

1. Non-lethal genetic sampling of Steelhead Trout intercepted in fisheries, which could be facilitated through collaborations with Indigenous groups and recreational fishers;
2. Genetic analysis of historical Steelhead Trout samples from various fisheries and projects that may still reside in archives; and

3. As tagging technology advances and becomes safer for fish, there may be an opportunity to develop a tagging program to answer questions about migration speed and route. This research is not recommended until Interior Fraser River Steelhead Trout populations recover to a level where they are less at risk.

In the meantime, the development of future fishery planning models will use assumptions of migration route and speed, and attempts will be made to validate these assumptions using data from fisheries in other areas and from the spawning grounds.

8. TABLES

Table 1. Published estimates of upstream adult Steelhead Trout migration speed (adapted from Myers 2018). Literature review was conducted over several years and aimed to be as comprehensive as possible. Myers 2018 provided a critical starting point, and additional search was conducted using some or all of the following terms in common search engines: Steelhead, run timing, migration, migration speed, Fraser River, Thompson Steelhead, Chilcotin Steelhead, Pacific, British Columbia. The references section of relevant literature were also examined for potential additional resources. Locations marked with an asterisk (*) indicate the system requires dam passage, so migration rates may be impacted by fallbacks. N = sample size (number of fish). N/A = not applicable.

Location	Timing of Tagging	N	Marine speed	Freshwater speed	Source
Fraser River: Barnston to Harrison	September to November	7	N/A	17.8 km/d (1996 average)	Renn et al. 2001
Fraser River: Harrison to Hope	September to November	43	N/A	4.3 km/d (1996 average)	Renn et al. 2001
Fraser River: Hope to Nahatlatch	September to November, February to May	24	N/A	4.8 km/d (1996 average)	Renn et al. 2001
Fraser River: Nahatlatch to Lytton	September to November, February to May	19	N/A	3.8 km/d (1996 average)	Renn et al. 2001
Fraser River: Harrison to Hope	September to November, February to May	3	N/A	4.2 km/d (1997 average)	Renn et al. 2001
Fraser River: Hope to Nahatlatch	September to November, February to May	2	N/A	16.7 km/d (1997 average)	Renn et al. 2001
Fraser River: Nahatlatch to Stein	September to November, February to May	2	N/A	24.7 km/d (1997 average)	Renn et al. 2001
Fraser River: Stein to Bridge	September to November, February to May	2	N/A	14.5 km/d (1997 average)	Renn et al. 2001
Fraser River: Bridge to Chilcotin	September to November, February to May	1	N/A	16.9 km/d (1997 average)	Renn et al. 2001
Fraser River: Harrison to Hope	September to November	14	N/A	7.6 km/d (1998 average)	Renn et al. 2001
Fraser River: Hope to Nahatlatch	September to November, February to May	45	N/A	9.4 km/d (1998 average)	Renn et al. 2001
Fraser River: Nahatlatch to Lytton	September to November, February to May	47	N/A	15.2 km/d (1998 average)	Renn et al. 2001
Fraser River: Lytton to Bridge	September to November, February to May	1	N/A	16.1 km/d (1998 average)	Renn et al. 2001
Skeena River	July to September	25	8 km/d average (range 3.7 – 33.7)	10.4-20.2 km/d (median, range 1.5 to 32, variable by river reach)	Spence 1989

Location	Timing of Tagging	N	Marine speed	Freshwater speed	Source
Lower Columbia River*	June to November	1,485	N/A	24 km/d median (4-8 km/d in summer)	Keefer et al. 2004
mid-Columbia River*	July to October	1,672	N/A	36.6 km/d (median)	English et al. 2006
Skeena River	July to September	255	6.2 km/d (median among stocks)	11.9-15.9 km/d (median, variable by year and reach)	English et al. 2006
Snake River*	June to November	1,103	N/A	10-20 km/d (median) (n = 19)	Keefer et al. 2004
High seas/coastal North Pacific Ocean	January to September (varies annually)	12	33 km/d	N/A	Burgner et al. 1992
High seas/coastal Central Gulf of Alaska	May to July	1	25.9 km/d	N/A	Walker et al. 2000
Dean and Fisher channels to Dean River mouth (Inland marine)	July to August	19	17.2 km/d (1987 average) (range 6.5 – 42.0)	N/A	Ruggerone et al. 1990
Dean and Fisher channels to Dean River mouth (Inland marine)	July to August	6	18.0 km/d (1988 average) (range 9.6 – 24.0)	N/A	Ruggerone et al. 1990

Table 2. Estimated index of return to the Albion test fishery. Total spawners and recreational catch (kept + estimated release mortality) for Thompson and Chilcotin stocks (COSEWIC, 2020); data updates for 2021-2023 provided by R. Bison, BC Ministry of Water, Land, and Resource Stewardship. Albion test fishery data provided by Fisheries and Oceans Canada. Average number of days with non-zero Steelhead Trout catch is 28 across the time series (1984-2023). Compilation of catch and release mortality data for Indigenous fisheries upstream of the Albion test fishery provided by Fisheries and Oceans Canada. Test and Indigenous fishery catch may include other Fraser River Steelhead Trout populations aside from Thompson and Chilcotin.

Brood Year	Spawners	Recreational Fishery Catch	Albion Test Fishery (August 1 to December 1)					Indigenous Salmon Fisheries Upstream of Albion		Sum (Index of Return)
			Kept Catch	Release Mortalities	Total Fishing Days	Total Non-Zero Steelhead Trout Catch Days	Proportion Non-Zero Steelhead Trout Catch Days	Kept Catch	Release Mortalities	
1984	2,253	880	47	0	89	30	0.34	295	0	3,474
1985	6,659	1,393	331	0	86	62	0.72	5,787	0	14,171
1986	4,322	1,195	264	0	76	55	0.72	712	0	6,494
1987	4,008	112	166	1	82	44	0.54	3,102	0	7,389
1988	3,842	573	44	0	123	29	0.24	1,771	0	6,231
1989	2,280	354	57	27	129	67	0.52	2,158	0	4,876
1990	1,603	115	84	0	128	43	0.34	495	0	2,297
1991	1,666	82	79	1	125	37	0.30	239	0	2,067
1992	1,442	70	71	0	149	45	0.30	180	0	1,763
1993	4,506	170	148	0	151	81	0.54	109	0	4,932
1994	3,577	134	56	0	145	38	0.26	114	0	3,881
1995	3,420	140	81	3	163	41	0.25	0	0	3,644
1996	1,538	74	79	0	161	84	0.52	156	0	1,847
1997	4,373	119	54	64	97	12	0.12	151	0	4,761
1998	2,142	100	14	6	101	32	0.32	13	0	2,276
1999	3,264	55	0	22	105	28	0.27	5	12	3,359
2000	2,239	40	14	8	104	35	0.34	0	3	2,303
2001	3,068	43	25	26	104	38	0.37	38	19	3,220
2002	4,274	83	26	19	107	32	0.30	9	5	4,417
2003	2,397	42	25	10	117	21	0.18	44	0	2,518
2004	1,204	25	1	10	103	17	0.17	5	0	1,245
2005	2,824	28	0	10	98	26	0.27	25	15	2,903
2006	2,212	34	0	19	93	15	0.16	14	21	2,300
2007	1,114	20	3	6	105	21	0.20	7	2	1,153

Brood Year	Spawners	Recreational Fishery Catch	Albion Test Fishery (August 1 to December 1)					Indigenous Salmon Fisheries Upstream of Albion		Sum (Index of Return)
			Kept Catch	Release Mortalities	Total Fishing Days	Total Non-Zero Steelhead Trout Catch Days	Proportion Non-Zero Steelhead Trout Catch Days	Kept Catch	Release Mortalities	
2008	1,318	19	1	12	106	12	0.11	15	13	1,377
2009	1,040	0	0	5	99	14	0.14	20	1	1,066
2010	734	20	1	8	95	15	0.16	5	2	770
2011	894	0	0	7	104	24	0.23	22	3	926
2012	1,307	28	0	12	106	23	0.22	17	22	1,387
2013	1,464	34	0	14	92	19	0.21	5	6	1,523
2014	2,255	23	0	14	83	18	0.22	16	12	2,321
2015	1,268	14	0	9	93	13	0.14	10	14	1,314
2016	494	2	0	6	94	9	0.10	0	4	506
2017	447	1	0	4	91	5	0.05	4	3	460
2018	227	1	0	2	95	5	0.05	0	1	231
2019	360	0	0	2	93	4	0.04	21	3	387
2020	295	0	0	2	91	5	0.05	0	5	302
2021	222	0	0	2	91	2	0.02	2	2	228
2022	123	0	0	1	92	9	0.10	0	1	125
2023	505	0	0	4	93	7	0.08	7	8	524

Table 3. Differences in deviance information criterion values (ΔDIC) and effective number of parameters (Δ-pD) for the three models presented.

Model	**Δ DIC**	**Δ pD**
Hierarchical Asymmetric Normal	0	35.2
Hierarchical Normal	25.5	16.7
Independent Normal	202.3	0

Table 4. Quantiles of average run-timing distributions past the Albion test fishing location (and associated 95% CIs to the right of each), across the three models presented. Models are presented in order from best to worst fitting based on delta DIC values from Table 3.

Model	**Run-timing Distribution Quantiles**													
	2.5%		5%		10%		50%		90%		95%		97.5%	
Hierarchical Asymmetric Normal	8-Sep	5-Sep	13-Sep	9-Sep	18-Sep	15-Sep	10-Oct	6-Oct	7-Nov	2-Nov	15-Nov	10-Nov	23-Nov	17-Nov
		11-Sep		16-Sep		21-Sep		13-Oct		12-Nov		22-Nov		30-Nov
Hierarchical Normal	3-Sep	29-Aug	9-Sep	5-Sep	16-Sep	12-Sep	11-Oct	8-Oct	4-Nov	1-Nov	11-Nov	8-Nov	18-Nov	14-Nov
		7-Sep		12-Sep		19-Sep		13-Oct		8-Nov		15-Nov		22-Nov
Independent Normal	1-Sep	28-Aug	8-Sep	4-Sep	15-Sep	11-Sep	10-Oct	7-Oct	6-Nov	3-Nov	13-Nov	11-Nov	20-Nov	17-Nov
		5-Sep		11-Sep		17-Sep		12-Oct		8-Nov		16-Nov		23-Nov

Table 5. Results of sensitivity analysis showing quantiles of average run timing across sensitivity analysis scenarios. Model form is the same across all models. Second and third rows show results of increasing and decreasing the index of return by 50%, and the fourth row shows estimates when using years with less than 15 non-zero observations (n=13).

Model	**Run-timing Distribution Quantiles**						
	2.5%	5%	10%	50%	90%	95%	97.5%
Hierarchical Asymmetric Normal	8-Sep	13-Sep	18-Sep	10-Oct	7-Nov	15-Nov	23-Nov
Increase Return 50%	8-Sep	13-Sep	18-Sep	10-Oct	7-Nov	16-Nov	23-Nov
Decrease Return 50%	9-Sep	14-Sep	19-Sep	10-Oct	7-Nov	15-Nov	22-Nov
Adjusted catch	8-Sep	13-Sep	18-Sep	9-Oct	7-Nov	15-Nov	23-Nov
Remove Low Years	8-Sep	13-Sep	18-Sep	10-Oct	7-Nov	15-Nov	23-Nov
Truncated data	8-Sep	12-Sep	18-Sep	10-Oct	7-Nov	15-Nov	23-Nov

9. FIGURES

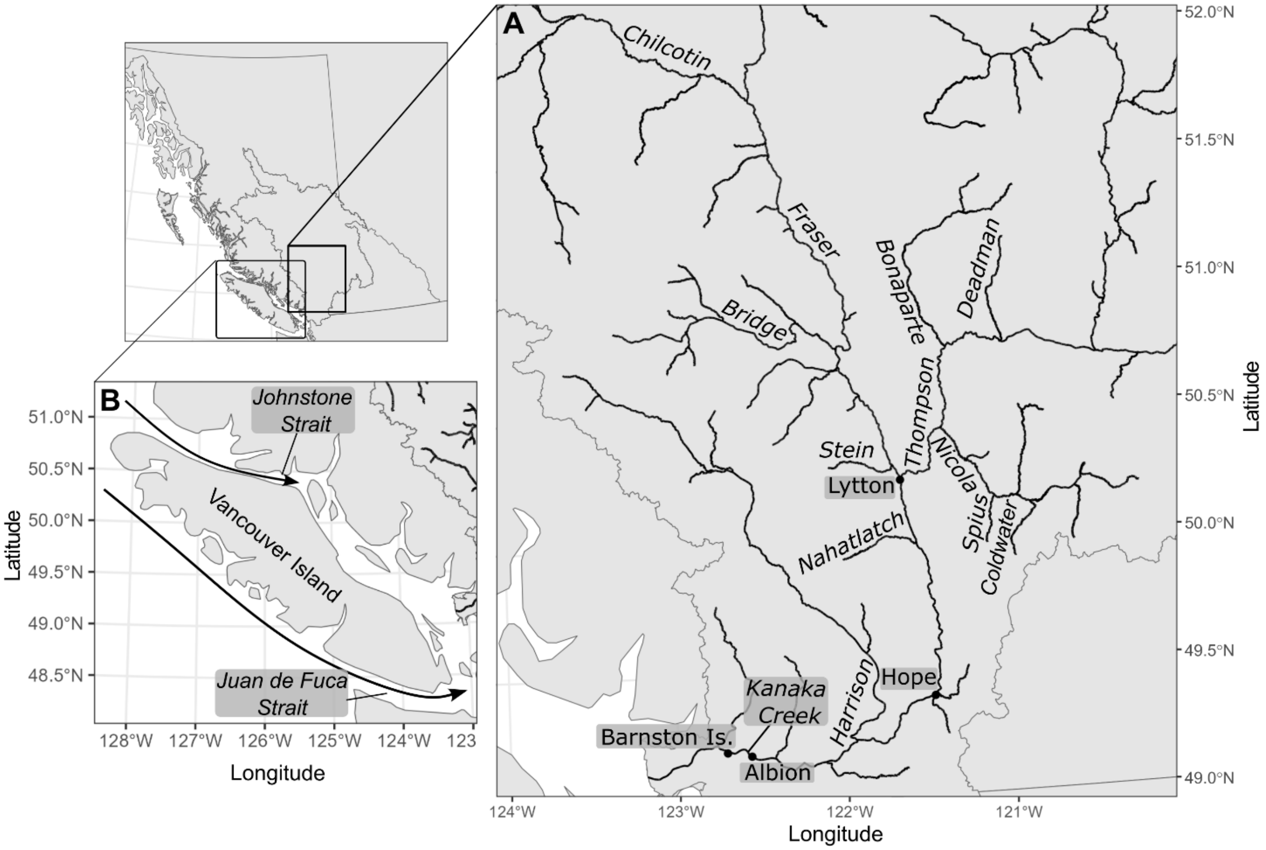

Figure 1. Map of freshwater and marine areas relevant to Interior Fraser River Steelhead Trout. Panel A depicts a subset of the Fraser River watershed with place names and rivers used in migration speed studies and test fishery data collection. Panel B depicts Vancouver Island with two possible marine migration routes used by Steelhead Trout.

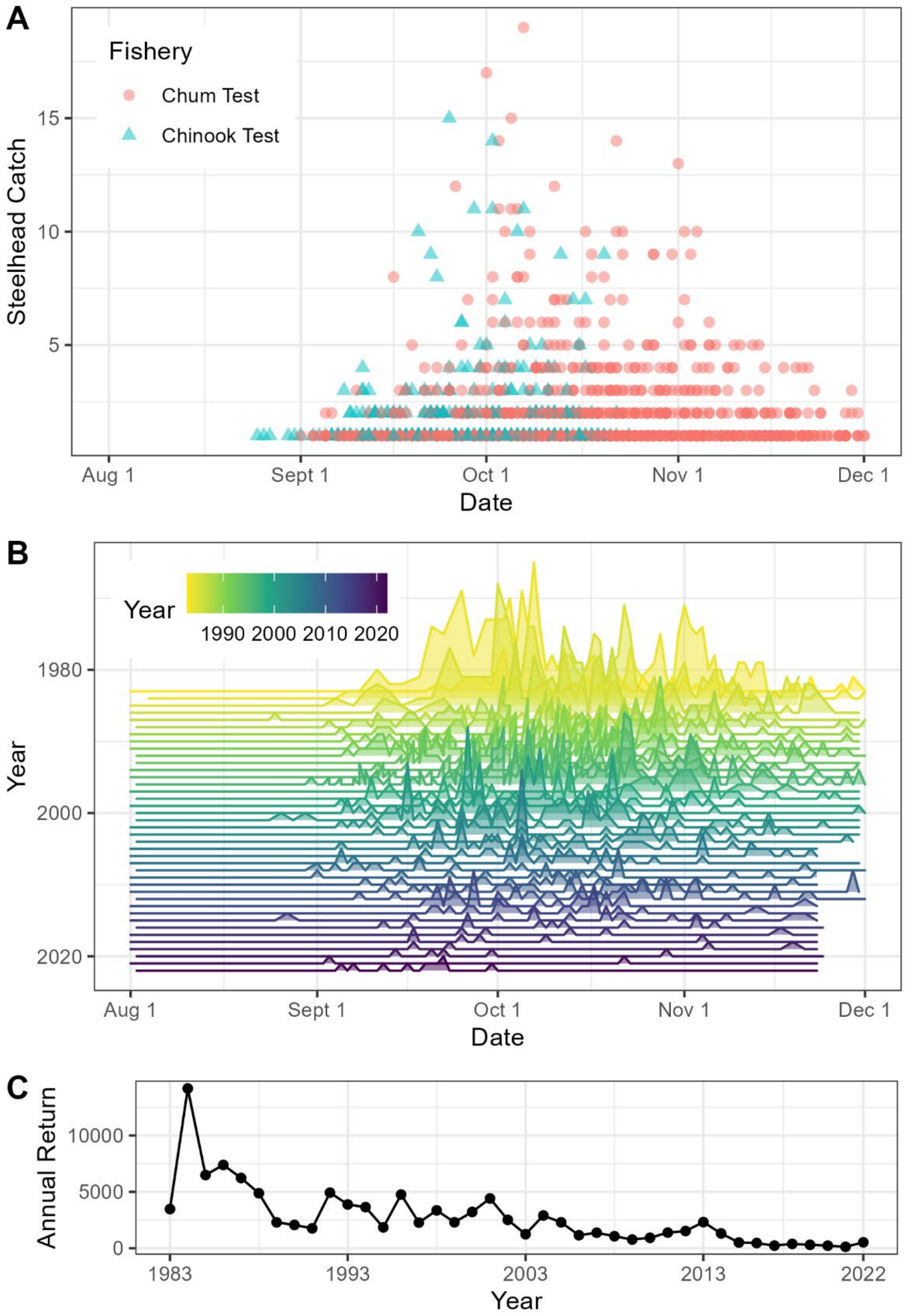

Figure 2. Data used for model fits. Panel A shows daily catch data for the nets targeting Chum and Chinook. Panel B shows a ridgeline plot of daily catch data for each year, with each line colored by year. Ridgelines are drawn on a vertical scale of 10 fish per grid box. On average, there were 108 days of test fishing per year. Panel C shows total annual return for Interior Fraser River Steelhead Trout for each year.

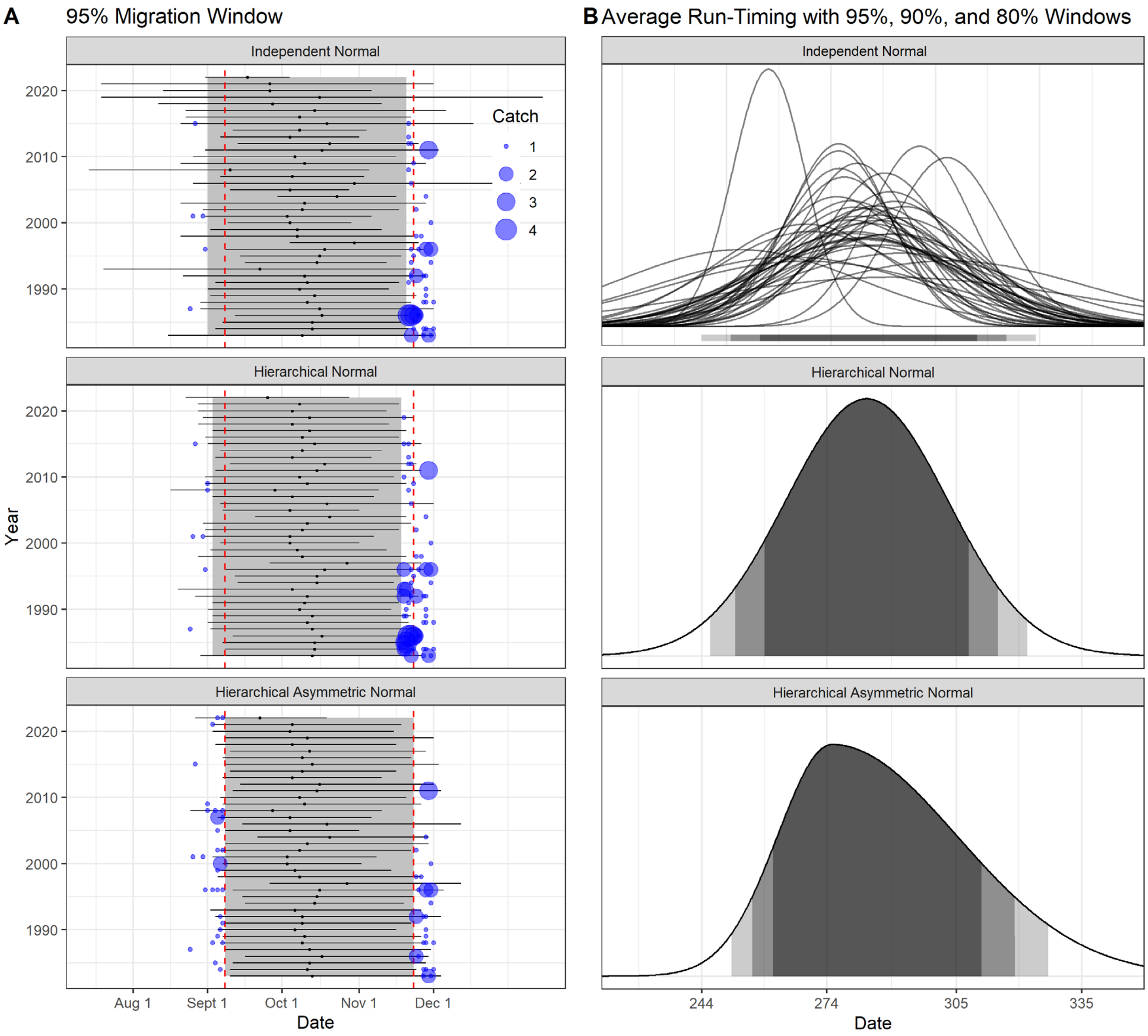

Figure 3. Run-timing estimates for the three models considered in the study. Panel A shows 50% date (black point) and the 95% window for each year, for each model presented. Grey box indicates average 95% window across years. Blue circles indicate catches that occurred outside of this average 95% window. To help visualize differences, red dashed lines indicate bounds of average 95% window for the hierarchical asymmetric normal model. Panel B shows estimated global run-timing distribution, shading shows 80%, 90% and 95% windows. For the independent Poisson model, we don't have a global run-timing distribution; however, we show the run-timing curves for each year. Shaded bar at the bottom indicates average 80%, 90%, and 95% windows across years. Note that we are presenting the independent Poisson model purely for comparison, even though the model does not seem well-suited to the data, as indicated by the model validation exercise (Figure 4).

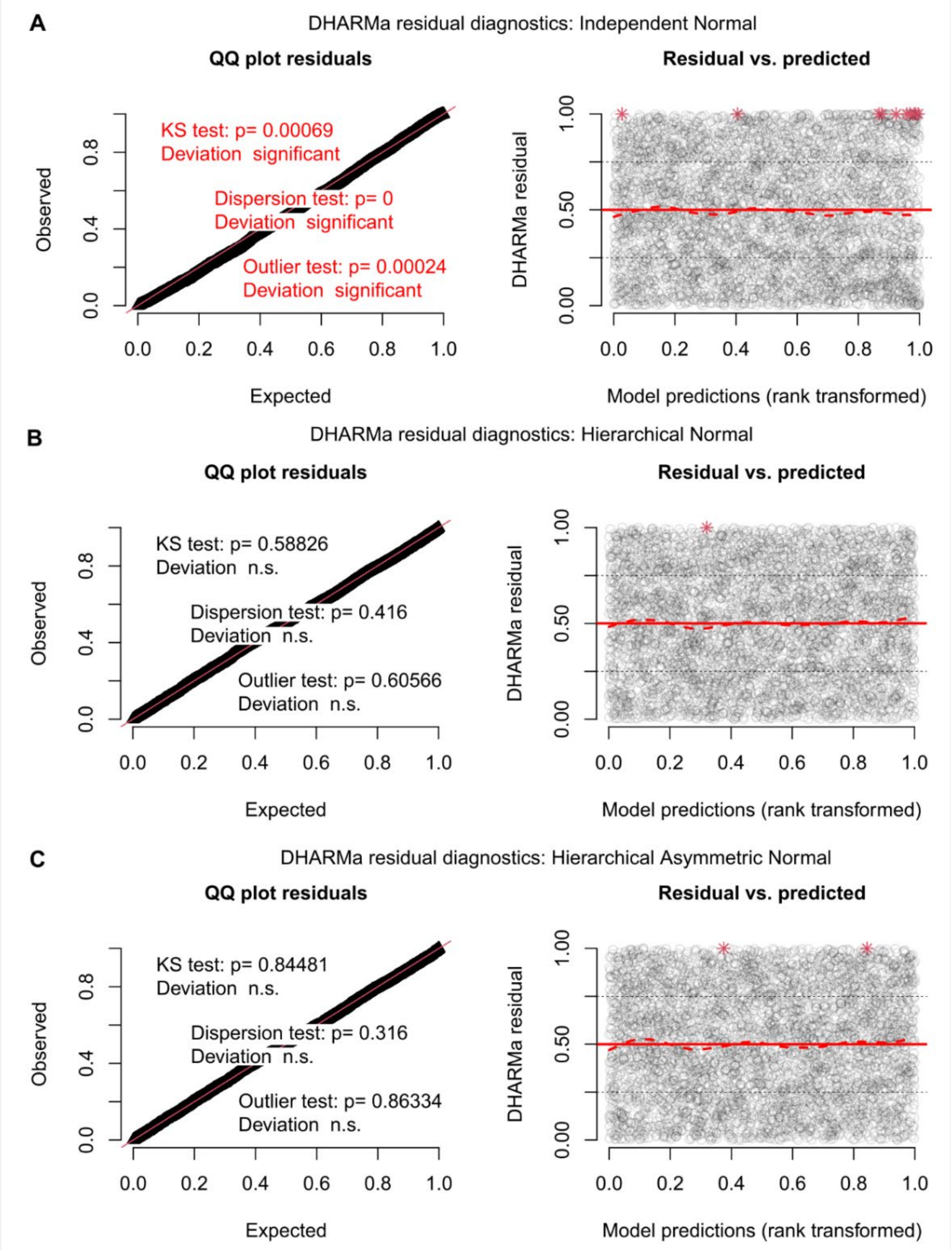

Figure 4. Residual diagnostic plots generated by the DHARMa package in R. Left panels show Q-Q plots for each model, with observed data plotted against model predictions, and test results for distribution suitability (KS test), dispersion, and outliers overlaid on the plot. Significant test results for the independent Poisson model are highlighted in red (not significant = n.s.). Right panels show randomized quantile residuals plotted against model predictions. The dashed red line is a smoothed spline fit to the median trendline and the solid red line is the expected shape of this line. Outliers are indicated with red stars.

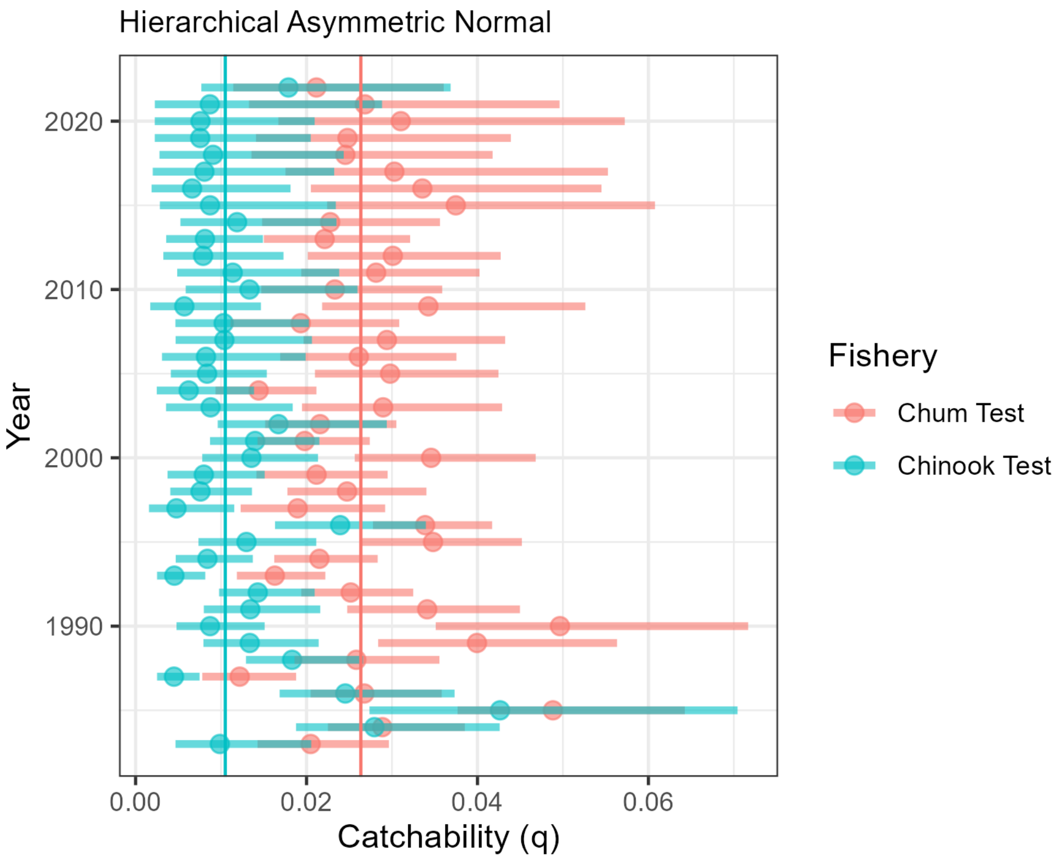

Figure 5. Annual catchability parameter estimates from the hierarchical asymmetric normal model, with median and 95% credible intervals for each fishery. Vertical lines indicate the median of the estimated global catchability parameter for each fishery.

10. ACKNOWLEDGEMENTS

We'd like to acknowledge Karen Rickards for her work conducting literature review related to this work. We appreciate the insightful conversations with Rob Bison that provided helpful background and context.

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APPENDIX A. OTHER POTENTIAL DATA SOURCES TO OBSERVE STEELHEAD TROUT MIGRATION PATTERNS

Listed below in Table A1 are other potential data sources that could be used to observe Steelhead Trout migration patterns, including validating estimates of run timing for areas upstream and downstream of the Albion test fishery. Data utility may be limited depending on the timing of observations and availability of genetic stock identification information. If the opportunity arises, there may also be a benefit to looking for biological samples from Steelhead Trout collected during these fisheries (e.g., scales, tissues) and conducting genetic stock identification analysis on them.

Table A1. Other potential data sources that may be used in future studies to observe Steelhead Trout migration patterns. Detailed maps of Pacific Salmon Commission (PSC) test fishing locations are available on the PSC website.

Data Source	**Location**
Johnstone Strait Chum Test Fishery (DFO)	Pacific Fishery Management Areas 12 and 13
Juan de Fuca Chum Test Fishery (DFO)	Pacific Fishery Management Area 20-5
Marine Gillnet and Seine Test Fisheries (PSC)	Pacific Fishery Management Areas 12 and 20
Gulf Troll Test Fishery (PSC)	Offshore west from Steveston, BC
Cottonwood Test Fishery (PSC)	Fraser River near Tilbury Island (Delta), BC
Whonnock Test Fishery (PSC)	Fraser River near Whonnock (Maple Ridge), BC
Qualark Test Fishery (PSC/DFO)	Fraser River near Yale, BC
Indigenous fishwheel catch (DFO)	Fraser River near Matsqui and Yale, BC
Spawning ground arrival timing (Province of BC)	Thompson River and Chilcotin River, BC

APPENDIX B. MODEL SPECIFICATION DETAILS

Prior Specification

A weakly informative prior was placed on mean date M_y, or the global mean of M_y (μ_M) in the hierarchical models:

Independent, Normal, Poisson model:

$$M_y \sim N(280, 40)$$

Hierarchical Models:

$$\mu_M \sim N(280, 40)$$

Day-of-year 280 (October 7) was chosen by visually examining the raw data (Figure 1) to estimate an approximate center of the data. We use a standard deviation of 40 days around this mean, to ensure we capture all plausible mean dates.

We put a half-t distribution on standard deviation around the mean date, σ_y^2, which is accomplished by putting a scaled gamma distribution on precision, in the JAGS code. This is suggested as a prior form for variance/precision parameters in the JAGS manual (Plummer 2017). Similarly, in the hierarchical models, we use this same prior for the global mean of σ_y^2 (μ_σ^2) in the hierarchical normal model, and the global means for the variance parameters for either side of the asymmetric normal.

Independent, normal, Poisson model:

$$\sigma_y^2 \sim half\text{-}t(15, 2)$$

Hierarchical, normal, negative binomial model:

$$\mu_\sigma^2 \sim half\text{-}t(15, 2)$$

Hierarchical, asymmetric normal, negative binomial model:

$$\mu_{\sigma s}^2 \sim half\text{-}t(15, 2) \text{ for } s \in (-, +)$$

For the variance parameters around global means of run-timing parameters, we use the same prior, with a lower magnitude, since we expect the spread in these values to be smaller.

Independent, normal, Poisson model:

$$\sigma_M^2 \sim half\text{-}t(7.5, 2)$$

Hierarchical, normal, negative binomial model:

$$\epsilon_\sigma^2 \sim half\text{-}t(7.5, 2)$$

Hierarchical, asymmetric normal, negative binomial model:

$$\epsilon_{\sigma s}^2 \sim half\text{-}t(7.5, 2) \text{ for } s \in (-, +)$$

We used a simple, uniform, prior on negative binomial r parameter, for the two negative binomial models:

$$r \sim unif(0,1)$$

For catchability, q, since it is bounded between 0 and 1, we use a logit transformation and model the global distribution of logit(q) as normally distributed (see Section 0). Therefore, our priors are on the scale of logit(q). Weakly informative priors were chosen based on the knowledge that catchability would be roughly bounded between 0 and 0.05.

$$\mu_q^m \sim N\left(-3, \frac{1}{\sqrt{0.8}}\right) \text{ for } m \in (1,2)$$

Note that variance on normal distributions in JAGS are defined in terms of precision ($\tau = 1/\sigma^2$), which is why we are expressing it in this way (since $\sigma = 1/\sqrt{\tau}$).

For variance around μ_q for each fishery, σ_q^2, we use the same prior shape as the other variance parameters above:

$$\left(\sigma_q^m\right)^2 \sim half\text{-}t(15, 2) \text{ for } m \in (1,2)$$

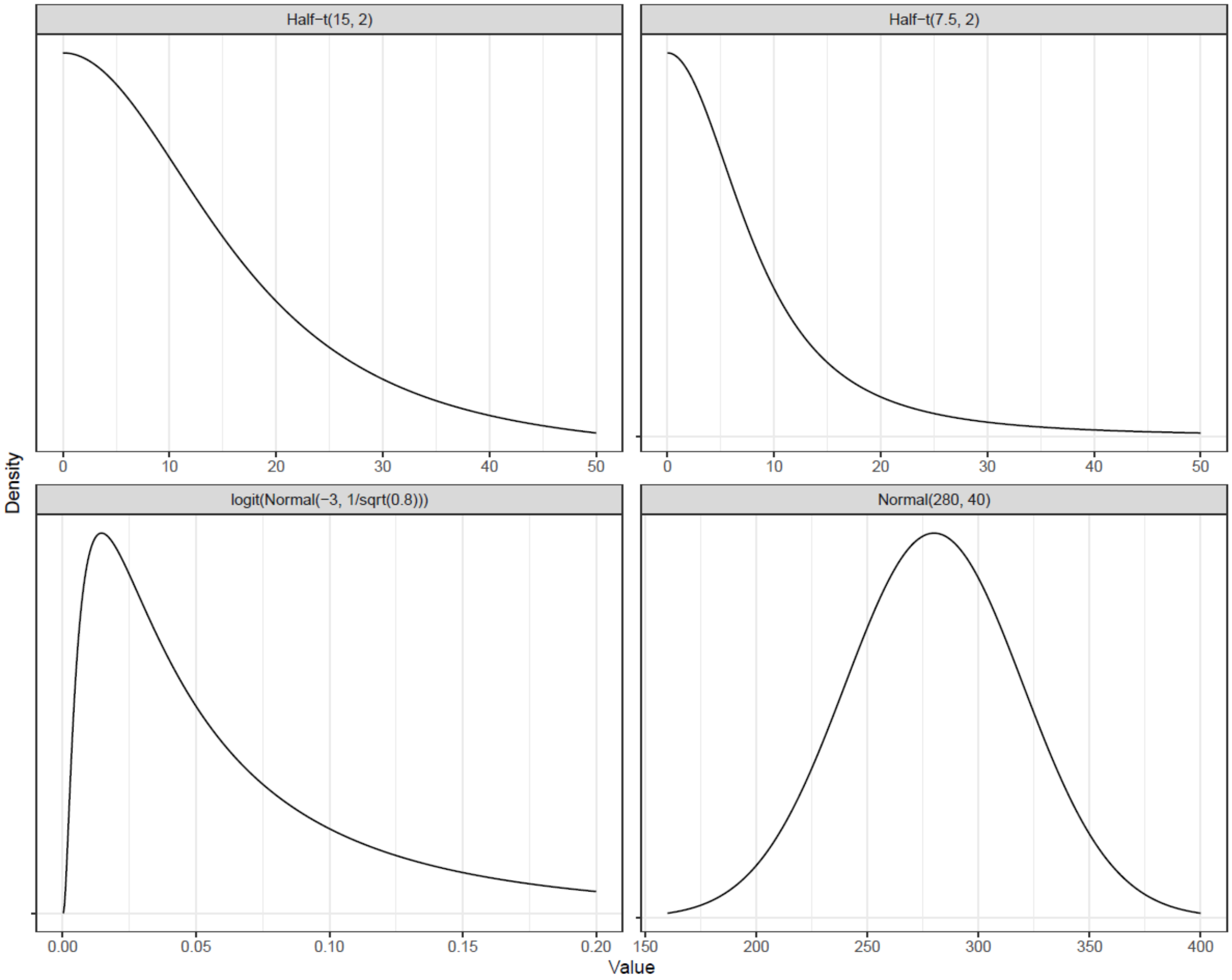

Figure B1. Priors used in model specification.Omitted uniform(0,1) since it is easily comprehended. Note for the normal(280, 40) put on mean migration date, that day of year 200 corresponds to July 19, and day of year 350 corresponds to December 15.

APPENDIX C. ANNUAL RUN-TIMING ESTIMATES

Year	Run-timing Distribution Quantiles (Day of Year)		
	2.5%	50%	97.5%
1983	253	286	338
1984	253	284	328
1985	254	285	332
1986	259	290	333
1987	251	285	334
1988	249	282	331
1989	250	283	330
1990	248	279	320
1991	251	282	326
1992	247	282	338
1993	245	279	330
1994	259	287	323
1995	258	288	327
1996	254	289	339
1997	269	300	346
1998	248	281	330
1999	249	279	318
2000	250	276	306
2001	246	276	312
2002	249	281	326
2003	251	284	333
2004	264	293	333
2005	251	277	305
2006	258	292	346
2007	248	277	310
2008	237	270	314
2009	250	283	330
2010	249	281	324
2011	254	288	338
2012	257	289	335
2013	250	278	314
2014	253	282	320
2015	251	286	337
2016	250	282	326
2017	253	285	332
2018	247	278	320
2019	251	284	335
2020	246	277	319
2021	246	278	322
2022	239	265	292