Expected survival difference attributable to the Head of Old River Barrier

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Executive Summary

The difference in survival from the Head of Old River to Chipps Island expected from installing the Head of Old River Barrier (HORB) was estimated for various levels of Delta inflow at Vernalis. A preliminary generalized linear multinomial regression model was used to predict survival to Chipps Island as a function of inflow, migration route, and barrier status (installed vs uninstalled) using acoustic-telemetry data from the 6-Year Steelhead Survival Study (2011–2016). Predicted survival and the expected change in survival due to the barrier were estimated using fixed year effects for the years with Delta inflow <5,000 cfs (2012–2016), and then combined over years in a weighted average using weights equal to the proportion of observations from each year used in the regression model. The 95% confidence interval was estimated using the F-distribution and the estimate of total variance on the weighted average of year-specific barrier effects.

When the Head of Old River barrier is installed, the probability of total predicted survival from the Head of Old River to Chipps Island was estimated to range from 0.30 ($\widehat{SE}$ = 0.20) for a VNS flow of 319 cfs, to 0.67 ($\widehat{SE}$ = 0.20) for a VNS flow of 5,000 cfs (Figure 1). When the barrier was not installed, the estimated predicted survival ranged from 0.17 ($\widehat{SE}$ = 0.13; VNS = 319 cfs) to 0.50 ($\widehat{SE}$ = 0.24; VNS = 5,000 cfs) (Figure 1). The predicted difference in survival attributable to the barrier was estimated to

range from 0.13 ($\widehat{SE}$ = 0.08) for a VNS flow of 319 cfs to 0.19 ($\widehat{SE}$ = 0.08) for a VNS flow of 3,889 cfs (Figure 2). There was high uncertainty in the predicted survival estimates, both with and without the barrier, and moderate uncertainty about the predicted effect of the barrier on survival, indicated by the confidence bands shown in Figure 2 and Figure 3. Nevertheless, the predicted survival effect of the barrier (point estimate) was estimated to be positive for all values of Delta inflow, and for most values of inflow (i.e., ≥783 cfs), the confidence band excluded 0 and negative survival differences.

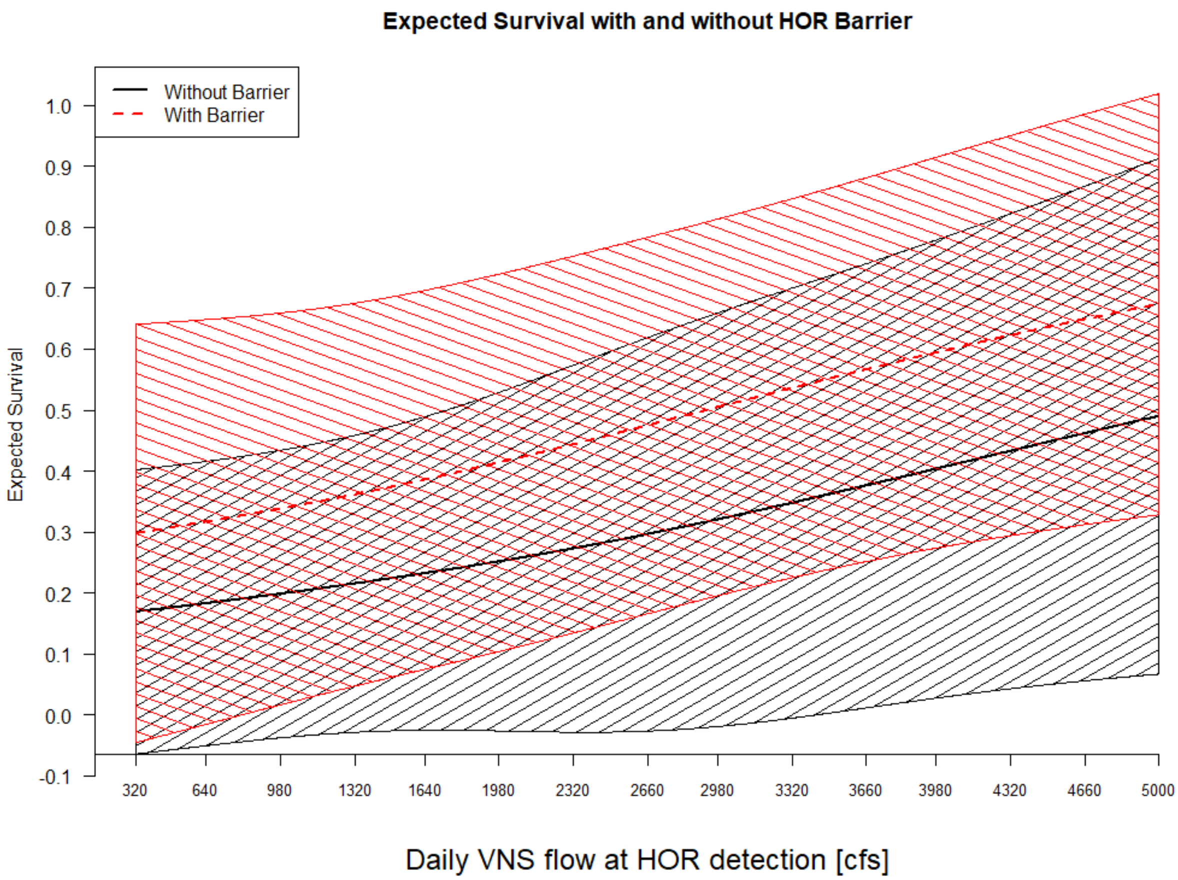

Figure 1. Predicted probability of survival from the head of Old River to Chipps Island with vs without the Head of Old River Barrier, as a function of Delta inflow at Vernalis (VNS), combined over 2012–2016. The shaded area is the 95% confidence band.

Introduction

The expected benefit in survival from the Head of Old River to Chipps Island from installing the barrier at the Head of Old River (HORB) was modeled as a function of Delta inflow at Vernalis using acoustic-telemetry data from the 6-Year Steelhead Survival Study (Buchanan 2018a,b,c, USBR 2018a,b,c). Estimates were based on a preliminary generalized linear multinomial regression model that used fixed year and route effects. The expected survival with and without the barrier and the expected change in survival due to the barrier were estimated using the year effects for the years with Delta inflow < 5,000 cfs (2012–2016), and then combined over years in a weighted average using weights equal to the proportion of observations from each year used in the regression model. Total survival to Chipps Island was estimated using a constant route selection probability based on barrier condition, estimated from the 6-Year Study data. For each estimate, the 95% confidence interval was estimated using the F-distribution and the estimate of total variance on the weighted average of year-specific barrier effects.

Methods

Denote total survival from the Head of Old River to Chipps Island as follows:

S_1 = total survival from the Head of Old River to Chipps Island without the barrier, and

S_2 = total survival from the Head of Old River to Chipps Island with the barrier.

Also define the survival difference attributable to the installation of the barrier as:

$$\delta = S_2 - S_1.$$

For each barrier condition, total survival was modeled as a weighted average of route-specific survival probabilities for the two primary migration routes: A = San Joaquin River route, and B = Old River route:

$$S_h = \psi_h S_{hA} + (1 - \psi_h) S_{hB} ,$$

where ψ_h is the probability of selecting route A for barrier status h, $h = 1, 2$.

Estimates of the predicted levels of S_{1A}, S_{1B}, S_{2A}, and S_{2B}, and consequently S_1, S_2, and δ, were derived for various levels of Delta inflow at Vernalis, based on analysis of six years of steelhead acoustic-telemetry data from the 6-Year Survival Study (Buchanan 2018a,b,c, USBR 2018a,b,c). The survival probabilities S_{1A}, S_{1B}, S_{2A}, and S_{2B} were modeled using a generalized linear regression model using multinomial errors, a logit link, and fixed effects of study year, barrier, route effects, and Delta inflow at Vernalis (x), using data from 2011–2016 from the 6-Year Study. Because the regression model included year effects, predictions of S_{1A}, S_{1B}, S_{2A}, and S_{2B} were estimated first for given year-specific models, defined by the unique intercept and slope parameters for the given year. The route-specific survival probability predictions were then combined across migration routes for a given barrier status, using fixed common route selection probabilities based on barrier status (i.e., ψ_1, ψ_2), estimated from all steelhead detections at the Head of Old River in 2012–2016 (0.95 when the barrier was installed, and 0.28 when the barrier was not installed). The resulting predictions of total survival to Chipps Island for a given barrier status (S_1 and S_2) were then compared to yield a prediction of the survival difference attributable to the barrier, δ. These year-specific estimates were then combined in weighted averages over years, with weights defined as the proportion of observations used in the regression that came from a given year. Confidence interval were defined using the law of total variance, prediction of a new observation from a regression model, and the F distribution with 21 and 1,494 degrees of freedom.

Using the fitted regression model, the expected survival probability with and without the barrier and expected difference in survival attributable to the barrier are $E\left(\hat{S}_1\right)$, $E\left(\hat{S}_2\right)$, and

$E\left(\hat{\delta}\right) = E\left(\hat{S}_2 \quad \hat{S}_1\right)$, where

$\hat{S}_1$ = modeled survival from the Head of Old River to Chipps Island without the barrier, and

$\hat{S}_2$ = modeled survival from the Head of Old River to Chipps Island with the barrier.

In particular, for Vernalis inflow value x_i, year y, and route r ($r = A, B$, for A = San Joaquin River route and B = Old River Route), define

$$\hat{S}_{1yiA} = \frac{\exp\left(\beta_0 + \tau_y + \beta_1 x_i + \beta_y x_i\right)}{1 + \exp\left(\beta_0 + \tau_y + \beta_1 x_i + \beta_y x_i\right)}$$

$$\hat{S}_{1yiB} = \frac{\exp\left(\beta_0 + \tau_y + \gamma + \beta_1 x_i + \beta_y x_i\right)}{1 + \exp\left(\beta_0 + \tau_y + \gamma + \beta_1 x_i + \beta_y x_i\right)}$$

$$\hat{S}_{2yiA} = \frac{\exp\left(\beta_0 + \tau_y + \mu_B + \beta_1 x_i + \beta_y x_i\right)}{1 + \exp\left(\beta_0 + \tau_y + \mu_B + \beta_1 x_i + \beta_y x_i\right)},$$

and

$$\hat{S}_{2yiB} = \frac{\exp\left(\beta_0 + \tau_y + \gamma + \mu_B + \phi + \beta_1 x_i + \beta_y x_i\right)}{1 + \exp\left(\beta_0 + \tau_y + \gamma + \mu_B + \phi + \beta_1 x_i + \beta_y x_i\right)},$$

where

β_0 = baseline intercept for 2011

τ_y = adjustment to intercept for year $y = 2012, \ldots, 2016$

γ = adjustment to intercept for the Old River route (route B)

μ_B = adjustment to the intercept for the Head of Old River barrier

ϕ = interaction effect on intercept between route effect and barrier effect (i.e., for Old River route when the barrier is present)

β_1 = baseline regression coefficient for Delta inflow at Vernalis

β_y = adjustment to coefficient for Delta inflow at Vernalis for year $y = 2012, \ldots, 2016$.

The estimated mean route-specific survival for parameter estimates $\hat{\beta}_0, \hat{\tau}_y, \hat{\gamma}, \hat{\mu}_B, \hat{\phi}, \hat{\beta}_1, \hat{\beta}_y$ is denoted $\hat{\hat{S}}_{2yir}$ with the barrier, and $\hat{\hat{S}}_{1yir}$ without the barrier $\left(r = A, B\right)$. The predicted total survival to Chipps Island is $\hat{\hat{S}}_{1yi} = \psi_1 \hat{\hat{S}}_{1yiA} + \left(1 - \psi_1\right)\hat{\hat{S}}_{1yiB}$ without the barrier, and $\hat{\hat{S}}_{2yi} = \psi_2 \hat{\hat{S}}_{2yiA} + \left(1 - \psi_2\right)\hat{\hat{S}}_{2yiB}$ with the barrier. The predicted expected change in survival due to the barrier is then $\hat{\delta} = \hat{\hat{S}}_{2yi} - \hat{\hat{S}}_{1yi}$.

For a given year-specific model

The regression model uses year effects, which essentially define year-specific models via the combination of the baseline intercept for 2011 (β_0) and the year-specific adjustments for 2012 through 2016 (τ_y for year y), and the baseline slope associated with Delta inflow for 2011 (β_1) and the year-specific adjustments to the slope for 2012 through 2016 (β_y for year y). For a selected year y from 2012–2016, the expected predictions of survival with and without the barrier, and the expected predicted difference in survival with and without the barrier, are functions of the year effect, route selection probabilities $\underset{\sim}{\psi} = (\psi_1, \psi_2)$, Delta inflow, and the estimates of parameters $\underset{\sim}{\theta}$ = $(\beta_0, \tau_y, \gamma, \mu_B, \phi, \beta_1, \beta_y)$:

$$E\left(\hat{\hat{S}}_{hyi} \middle| y, \underset{\sim}{\psi}, x_i, \underset{\sim}{\theta}\right) = E\left[g_{S_h}\left(\underset{\sim}{\hat{\theta}}, \underset{\sim}{\psi}\right) \middle| y, \underset{\sim}{\psi}, x_i, \underset{\sim}{\theta}\right]$$

and

$$E\left(\hat{\delta} \mid y, x_i, \underset{\sim}{\theta}\right) = E\left(\hat{\hat{S}}_{2yi} \quad \hat{\hat{S}}_{1yi} \middle| y, \underset{\sim}{\psi}, x_i, \underset{\sim}{\theta}\right) \quad E\left[g_{\delta}\left(\underset{\sim}{\hat{\theta}}, \underset{\sim}{\psi}\right) \middle| y, \underset{\sim}{\psi}, x_i, \underset{\sim}{\theta}\right].$$

for functions g_{S_h} (for $h = 1, 2$) and $g_d = g_{S_2} \quad g_{S_1}$.

Using the Delta Method (Seber 2002),

$$E\left(\hat{\hat{S}}_h \middle| y, \underset{\sim}{\psi}, x_i, \underset{\sim}{\theta}\right) = g_{S_h}\left(\underset{\sim}{\hat{\theta}}, \underset{\sim}{\psi}\right) \quad b_{S_h yi}$$

and

$$E\left(\hat{\delta} \middle| y, \underset{\sim}{\psi}, x_i, \underset{\sim}{\theta}\right) = g_{S_2}\left(\underset{\sim}{\hat{\theta}}, \underset{\sim}{\psi}\right) - g_{S_1}\left(\underset{\sim}{\hat{\theta}}, \underset{\sim}{\psi}\right) + b_{\delta yi}$$

where

$$b_{S_h yi} \approx \sum_{j,k} \frac{1}{2}\left(\frac{\partial^2 g_{S_h}}{\partial \theta_j \partial \theta_k}\right) Cov\left(\hat{\theta}_j, \hat{\theta}_k\right) \text{ and } b_{\delta yi} \approx \sum_{j,k} \frac{1}{2}\left(\frac{\partial^2 g_{\delta}}{\partial \theta_j \partial \theta_k}\right) Cov\left(\hat{\theta}_j, \hat{\theta}_k\right),$$

for $\theta = \beta_0, \tau_y, \gamma, \mu_B, \phi, \beta_1, \beta_y$ and $h = 1, 2$. The necessary partial derivatives are defined in the Appendix.

Conditional on year y, route selection probability ψ_h , and the value of Delta inflow (x_i), the prediction error about the survival estimate for barrier status $h = 1, 2$, $S_h - \hat{\hat{S}}_h$, has two sources of variance: (1) variance due to estimation error of the regression coefficients, and (2) variance of the sampling distribution of S_h about its mean. Component (1) is estimated using the Delta Method and the estimated overdispersion parameter for the regression model ($\hat{\sigma}^2$ = mean error deviance):

$$\hat{V}_{\hat{S}_h} = \widehat{Var}\left(\hat{S}_h \middle| y, \psi_h, x_i, \underset{\sim}{\theta}\right) \approx \hat{\sigma}^2 \sum_{j,k} \left(\frac{\partial g_{S_h}}{\partial \theta_j}\right)\left(\frac{\partial g_{S_h}}{\partial \theta_k}\right)\Bigg|_{\theta=\hat{\theta}} \widehat{Cov}\left(\hat{\theta}_j, \hat{\theta}_k\right)$$

for $\theta = \beta_0, \tau_y, \gamma, \mu_B, \phi, \beta_1, \beta_y$ and $h = 1,2$. The mean error deviance for the selected model is $\hat{\sigma}^2$ = 4.92.

Component (2) of the year-specific variance is estimated from applying the Delta Method to the multinomial data counts that yield the survival estimate, with and without the barrier. In particular, define n_{11}, n_{10}, n_{01} to be the counts of the possible detection histories at the two telemetry lines at Chipps Island (dual array), or collectively at Chipps Island and Benicia Bridge, where “1” = detection and “0” = no detection, and define P_1 and P_2 to be either the conditional detection probabilities at the two telemetry lines at Chipps Island; if Benicia Bridge was monitored, then P_1 = conditional detection probability at Chipps Island and P_2 = joint probability of surviving from Chipps Island to Benicia Bridge and detection at Benicia Bridge. In each case, P_1 and P_2 are conditional on survival to Chipps Island. Then,

$$Var\left(S_h \middle| \hat{S}_h, y, \psi_h, x_i, \underset{\sim}{\theta}\right) = Var\left(S_h \middle| \hat{\hat{S}}_h, y, \psi_h, x_i, \underset{\sim}{\hat{\theta}}\right) = \sigma^2_{S_h yi\theta}$$

where $\sigma^2_{S_h yi\theta}$ is estimated by Delta Method according to:

$$\hat{\sigma}^2_{S_h iy\theta} = \sum_{j,k} \left(\frac{\partial \hat{S}_h}{\partial n_j}\right)\left(\frac{\partial \hat{S}_h}{\partial n_k}\right) \widehat{Cov}\left(n_j, n_k \middle| S_h, P_1, P_2\right)$$

for n_j, n_k in $\left(n_{11h}, n_{10h}, n_{01h}\right)$, $\hat{S}_h = \frac{\left(n_{11} + n_{10}\right)_h \left(n_{11} + n_{01}\right)_h}{N n_{11,h}}$, and $h = 1,2$. The partial derivatives and covariance factors in the above equation were estimated using the predicted survival probability from the regression model, annual observed estimates of detection probabilities (P_1 and P_2), and the total number of observations available for Delta inflow ≤5,000 cfs.

Thus,

$$\widehat{Var}\left(S_h - \hat{\hat{S}}_h \middle| y, \psi_h, x_i, \underset{\sim}{\theta} \right) = \hat{\sigma}^2_{S_h yi\theta} + \hat{V}_{\hat{S}_h}.$$

Likewise, $\widehat{Var}\left(\delta - \hat{\delta} \middle| y, \underset{\sim}{\psi}, x_i, \underset{\sim}{\theta} \right) = \hat{\sigma}^2_{S_1 yi\theta} + \hat{\sigma}^2_{S_2 yi\theta} + \hat{V}_{\hat{\delta}}$ where

$$\hat{V}_{\hat{\delta}} = \widehat{Var}\left(\hat{\delta} \middle| y, \underset{\sim}{\psi}, x_i, \underset{\sim}{\theta} \right) \approx \hat{\sigma}^2 \sum_{j,k} \left(\frac{\partial g_\delta}{\partial \theta_j} \right) \left(\frac{\partial g_\delta}{\partial \theta_k} \right) \Bigg|_{\theta = \hat{\theta}} \widehat{Cov}\left(\hat{\theta}_j, \hat{\theta}_k \right)$$

for $\theta = \beta_0, \tau_y, \gamma, \mu_B, \phi, \beta_1, \beta_y$.

Combined across year-specific models

The estimate of the survival effect of the barrier depends on two steps: select the year that is used in the year-specific model, and estimate the survival and barrier effect predictions for that year. A multiyear estimate of survival and the survival effect of the barrier must combine the year-specific estimates defined above by accounting for the contributions of these two steps.

The predicted survival estimated for a given barrier status (h), route selection probability ψ_h, and Delta inflow level x_i is defined based on the following decomposition:

$$\begin{aligned} E\left(\hat{\hat{S}}_h \middle| x_i, \psi_h, \underset{\sim}{\theta} \right) &= E_Y \left[E_R \left(\hat{\hat{S}}_h \middle| y, \psi_h, x_i, \underset{\sim}{\theta} \right) \right] \\ &= \sum_y f_y E_R \left(\hat{\hat{S}}_h \middle| y, \psi_h, x_i, \underset{\sim}{\theta} \right) \\ &\approx \sum_y \hat{f}_y \hat{E}_R \left(\hat{\hat{S}}_h \middle| y, \psi_h, x_i, \underset{\sim}{\hat{\theta}} \right) \end{aligned}$$

for year-specific weights f_y, where R represents the regression model, and Y represents the year. The weights f_y were defined by the overall proportion of observations in the inflow range ≤5,000 cfs that came from year y:

$$\hat{f}_y = \frac{\text{Number of observations of Inflow} \leq 5000 \text{ cfs from year } y}{\text{Total number of observations of Inflow} \leq 5000 \text{ cfs}}.$$

The variance for $\hat{\hat{S}}_h$ is derived using the law of total variance and is decomposed over the year selection process and the regression model as follows:

$$Var\left(\hat{\hat{S}}_h \middle| x_i, \psi_h, \underset{\sim}{\theta}\right) = E_Y\left[Var_R\left(\hat{\hat{S}}_h \middle| y, \psi_h, x_i, \underset{\sim}{\theta}\right)\right] + Var_Y\left[E_R\left(\hat{\hat{S}}_h \middle| y, \psi_h, x_i, \underset{\sim}{\theta}\right)\right]$$

where

$$\begin{aligned} E_Y\left[Var_R\left(\hat{\hat{S}}_h \middle| y, \psi_h, x_i, \underset{\sim}{\theta}\right)\right] &= \sum_y f_y Var\left(S_h - \hat{\hat{S}}_h \middle| y, \psi_h, x_i, \underset{\sim}{\theta}\right) \\ &\approx \sum_y f_y \left(\sigma^2_{S_h yi\theta} + V_{\hat{S}_h}\right) \end{aligned}$$

and

$$\begin{aligned} Var_Y\left[E_R\left(\hat{\hat{S}}_h \middle| y, \psi_h, x_i, \underset{\sim}{\theta}\right)\right] &= E_Y\left(\left[E_R\left(\hat{\hat{S}}_h \middle| y, \psi_h, x_i, \underset{\sim}{\theta}\right)\right]^2\right) - \left(E_Y\left[E_R\left(\hat{\hat{S}}_h \middle| y, \psi_h, x_i, \underset{\sim}{\theta}\right)\right]\right)^2 \\ &= \sum_y f_y \left(\left[E_R\left(\hat{\hat{S}}_h \middle| y, \psi_h, x_i, \underset{\sim}{\theta}\right)\right]^2\right) - \left(\sum_y f_y E_R\left(\hat{\hat{S}}_h \middle| y, \psi_h, x_i, \underset{\sim}{\theta}\right)\right)^2 \end{aligned}$$

The total variance of $\hat{\hat{S}}_h$ is estimated by

$$\begin{aligned} \widehat{Var}\left(\hat{\hat{S}}_h \middle| x_i, \psi_h, \underset{\sim}{\theta}\right) = \sum_y \hat{f}_y \left(\hat{\sigma}^2_{S_h yi\theta} \quad \hat{V}_{\hat{S}_h}\right) + \qquad + \\ \sum_y \hat{f}_y \left[\hat{\hat{S}}_{hyi} + \hat{b}_{S_h yi}\right]^2 - \left(\sum_y \hat{f}_y \left[\hat{\hat{S}}_{hyi} + \hat{b}_{S_h yi}\right]\right)^2 \end{aligned}$$

Likewise, the estimated survival effect of the barrier is estimated as

$$\hat{E}\left(\hat{\delta} \middle| x_i, \underset{\sim}{\psi}, \underset{\sim}{\theta}\right) = \sum_y \hat{f}_y \left(\hat{\hat{S}}_{2yi} \quad \hat{\hat{S}}_{1yi} \quad \hat{b}_{\delta yi}\right)$$

and the variance of $\hat{\delta}$ is estimated by:

$$\widehat{Var}\left(\hat{\delta} \middle| x_i, \underset{\sim}{\psi}, \underset{\sim}{\theta}\right) = \sum_{y} \hat{f}_y \left(\hat{\sigma}^2_{S_1 yi\theta} + \hat{\sigma}^2_{S_2 yi\theta} + \hat{V}_{\hat{\delta}}\right) + \sum_{y} \hat{f}_y \left[\hat{\hat{S}}_{2yi} - \hat{\hat{S}}_{1yi} + \hat{b}_{\delta yi}\right]^2 - \left(\sum_{y} \hat{f}_y \left[\hat{\hat{S}}_{2yi} - \hat{\hat{S}}_{1yi} + \hat{b}_{\delta yi}\right]\right)^2.$$

Results

When the Head of Old River barrier is installed, the probability of total predicted survival from the Head of Old River to Chipps Island was estimated to range from 0.30 ($\widehat{SE}$ = 0.20) for a VNS flow of 319 cfs, to 0.67 ($\widehat{SE}$ = 0.20) for a VNS flow of 5,000 cfs (Figure 2, Table A1). When the barrier was not installed, the estimated predicted survival ranged from 0.17 ($\widehat{SE}$ = 0.13; VNS = 319 cfs) to 0.50 ($\widehat{SE}$ = 0.24; VNS = 5,000 cfs) (Figure 2, Table A1). The predicted difference in survival attributable to the barrier was estimated to range from 0.13 ($\widehat{SE}$ = 0.08) for a VNS flow of 319 cfs to 0.19 ($\widehat{SE}$ = 0.08) for a VNS flow of 3,889 cfs (Figure 3, Table A1). There was high uncertainty in the predicted survival estimates, both with and without the barrier, and moderate uncertainty about the predicted effect of the barrier on survival, indicated by the confidence bands shown in Figure 2 and Figure 3. Nevertheless, the predicted survival effect of the barrier (point estimate) was estimated to be positive for all values of Delta inflow, and for most values of inflow (i.e., ≥783 cfs), the confidence band excluded 0 and negative survival differences (Figure 3).

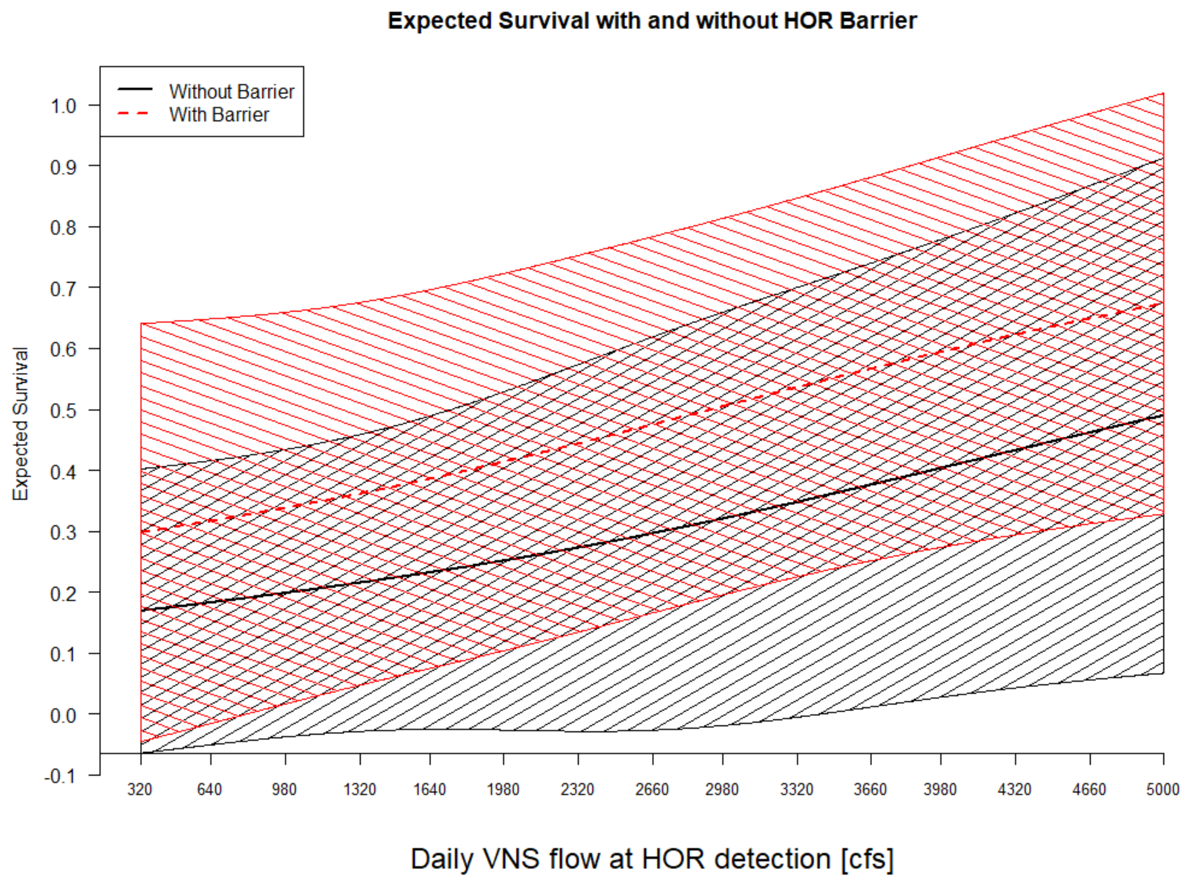

Figure 3. Predicted probability of survival from the head of Old River to Chipps Island with vs without the Head of Old River Barrier, as a function of Delta inflow at Vernalis (VNS), combined over 2012–2016. The shaded area is the 95% confidence band.

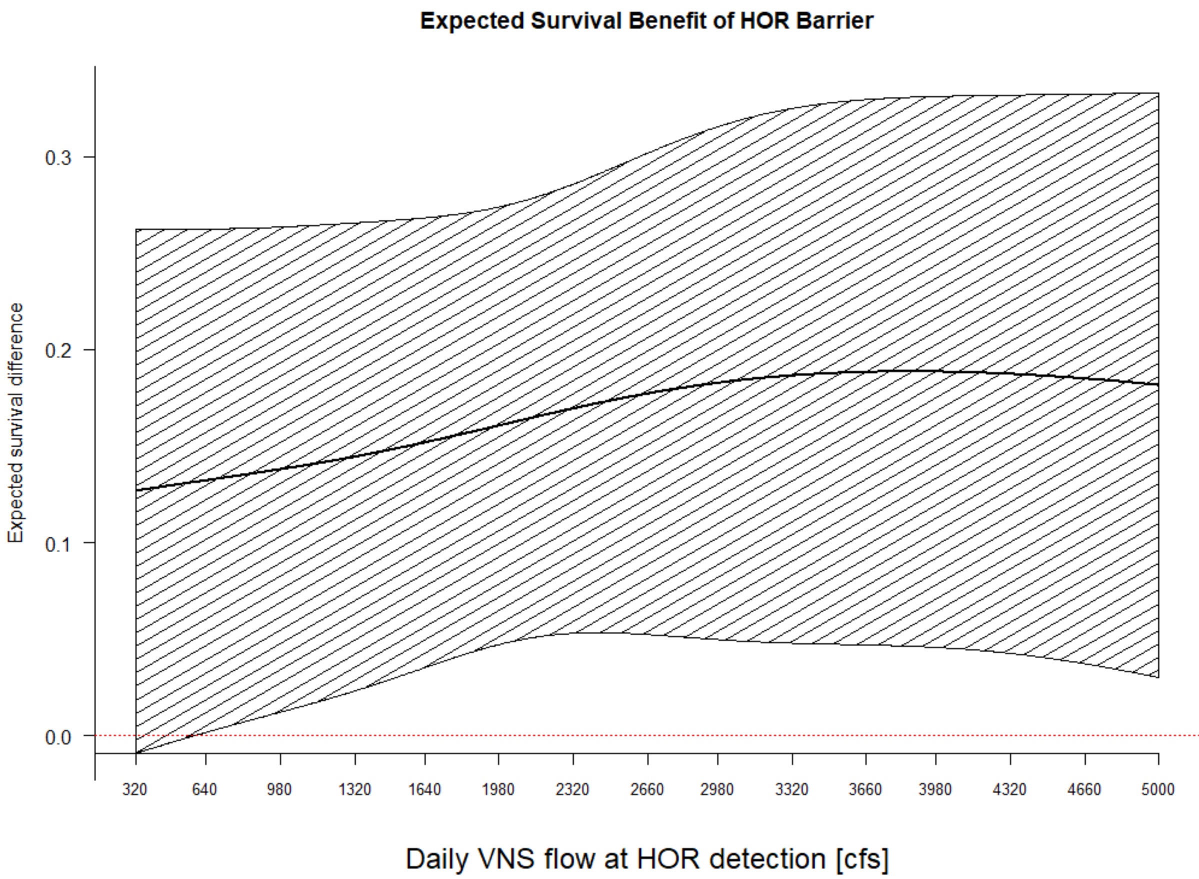

Figure 4. Predicted difference in survival from the head of Old River to Chipps Island with vs without the Head of Old River Barrier, as a function of Delta inflow at Vernalis (VNS), combined over 2012–2016. The solid black line is the predicted survival difference, the dashed red line indicates no difference in the survival, and the shaded area is the 95% confidence band.

Discussion

There are some limitations of the predictions provided here, based on the underlying survival model. The predicted survival benefit of the barrier is based on the observed data from 2011–2016, and is based on a preliminary regression model of survival as a function of Delta inflow that uses year effects. The wide variability in the year effects (primarily intercept) and the limited data available in any one year contribute to the wide uncertainty about the predictions. Only the scale of year effects actually estimated from the available data were considered; a new year may have a very different year effect, leading to different survival levels with and without the barrier. Additionally, a different weighting of the year-specific estimates would result in different survival predictions.

The estimates of total survival and the survival benefit of the barrier are also based on assumed values of the route selection probability at the Head of Old River based on the barrier status, and do not account for uncertainty in the route selection probability estimates. The assumed route selection probabilities (0.95 with the barrier, and 0.28 without the barrier) were based on the overall frequency of route use among the five years of the 6-Year Study when Delta inflow was <5,000 cfs (2012–2016). The prediction results are at least moderately sensitive to the route selection probability assumed, and the predicted benefit of installing the barrier can be higher or lower, depending on how effective the barrier is assumed to be at guiding fish away from Old River. In general, the lower the assumed barrier effectiveness, the smaller the predicted survival benefit of installing the barrier. When the barrier is assumed to be 100% effective at keeping fish out of Old River, the predicted total survival change due to the barrier was as high as 0.20; the difference between this estimate and the maximum estimate without the route effect (0.19) was well within the 95% confidence band. A more complete analysis is needed to model the route selection probability as a function of Delta inflow and barrier status.

List of References

Buchanan, R. A. (2018a). 2014 Six-Year Acoustic Telemetry and Steelhead Study: Statistical Methods and Results. Technical report to the U.S. Bureau of Reclamation. Available online at http://www.cbr.washington.edu/papers.

Buchanan, R. A. (2018b). 2015 Six-Year Acoustic Telemetry and Steelhead Study: Statistical Methods and Results. Technical report to the U.S. Bureau of Reclamation. Available online at http://www.cbr.washington.edu/papers.

Buchanan, R. A. (2018c). 2016 Six-Year Acoustic Telemetry and Steelhead Study: Statistical Methods and Results. Technical report to the U.S. Bureau of Reclamation. Available online at http://www.cbr.washington.edu/papers.

Seber, G. A. F. (2002). The estimation of animal abundance. Second edition. Blackburn Press, Caldwell, New Jersey.

U.S. Bureau of Reclamation (USBR) (2018a). NMFS Biological Opinion RPA IV.2.2: 2011 Six-Year Acoustic Telemetry Steelhead Study. Contributions by Buchanan, R., J. Israel, P. Brandes. E. Buttermore. Reclamation Bay-Delta Office, Mid-Pacific Region, Sacramento, CA. FINAL REPORT May 14, 2018, 144p.

U.S. Bureau of Reclamation (USBR) (2018b). NMFS Biological Opinion RPA IV.2.2: 2012 Six-Year Acoustic Telemetry Steelhead Study. Contributions by Buchanan, P. Brandes, R., J. Israel, E. Buttermore. Reclamation Bay-Delta Office, Mid-Pacific Region, Sacramento, CA. FINAL REPORT May 16, 2018, 172p.

U.S. Bureau of Reclamation (USBR) (2018c). NMFS Biological Opinion RPA IV.2.2: 2013 Six-Year Acoustic Telemetry Steelhead Study. Contributions by: R. Buchanan, P. Brandes, J. Israel, and E. Buttermore. U.S. Bureau of Reclamation. Bay-Delta Office, Mid-Pacific Region, Sacramento, CA. FINAL REPORT. June 2018, 213 pp.

Appendix

Partial Derivatives for Delta Method

The necessary first order partial derivatives are as follows, for year $y = 2012,\ldots,2016$ and Delta inflow value x_i :

$$\frac{\partial S_{1yiA}}{\partial \theta_j} = \begin{cases} \hat{S}_{1yiA}\left(1-\hat{S}_{1yiA}\right) & \text{for } \theta_j = \beta_0, \tau_y \\ x_i \hat{S}_{1yiA}\left(1-\hat{S}_{1yiA}\right) & \text{for } \theta_j = \beta_1, \beta_y \end{cases}$$

$$\frac{\partial S_{1yiB}}{\partial \theta_j} = \begin{cases} \hat{S}_{1yiB}\left(1-\hat{S}_{1yiB}\right) & \text{for } \theta_j = \beta_0, \tau_y, \gamma \\ x_i \hat{S}_{1yiB}\left(1-\hat{S}_{1yiB}\right) & \text{for } \theta_j = \beta_1, \beta_y \end{cases}$$

$$\frac{\partial S_{2yiA}}{\partial \theta_j} = \begin{cases} \hat{S}_{2yiA}\left(1-\hat{S}_{2yiA}\right) & \text{for } \theta_j = \beta_0, \tau_y, \mu_B \\ x_i \hat{S}_{2yiA}\left(1-\hat{S}_{2yiA}\right) & \text{for } \theta_j = \beta_1, \beta_y \end{cases}$$

$$\frac{\partial S_{2yiB}}{\partial \theta_j} = \begin{cases} \hat{S}_{2yiB}\left(1-\hat{S}_{2yiB}\right) & \text{for } \theta_j = \beta_0, \tau_y, \gamma, \mu_B, \phi \\ x_i \hat{S}_{2yiB}\left(1-\hat{S}_{2yiB}\right) & \text{for } \theta_j = \beta_1, \beta_y \end{cases}$$

$$\frac{\partial g_{S_h}}{\partial \theta_j} = \psi_h \frac{\partial S_{hA}}{\partial \theta_j} + (1-\psi_h)\frac{\partial S_{hB}}{\partial \theta_j} \quad \text{for } h = 1,2$$

and

$$\frac{\partial g_{\delta}}{\partial \theta_j} = \psi_2 \frac{\partial S_{2A}}{\partial \theta_j} + (1-\psi_2)\frac{\partial S_{2B}}{\partial \theta_j} - \psi_1 \frac{\partial S_{1A}}{\partial \theta_j} - (1-\psi_1)\frac{\partial S_{1B}}{\partial \theta_j} \quad \text{for } \theta_j = \beta_0, \tau_y, \gamma, \mu_B, \phi, \beta_1, \beta_y .$$

The necessary second order partial derivatives are:

$$\frac{\partial^2 S_{1yiA}}{\partial \theta_j \partial \theta_k} = \begin{cases} \hat{S}_{1yiA}\left(1-\hat{S}_{1yiA}\right)\left(1-2\hat{S}_{1yiA}\right) & \text{for } \theta_j, \theta_k = \beta_0, \tau_y \\ x_i \hat{S}_{1yiA}\left(1-\hat{S}_{1yiA}\right)\left(1-2\hat{S}_{1yiA}\right) & \text{for } \theta_j = \beta_0, \tau_y \text{ and } \theta_k = \beta_1, \beta_y \text{ and vice versa} \\ x_i^2 \hat{S}_{1yiA}\left(1-\hat{S}_{1yiA}\right)\left(1-2\hat{S}_{1yiA}\right) & \text{for } \theta_j, \theta_k = \beta_1, \beta_y \end{cases}$$

$$\frac{\partial^2 S_{1yiB}}{\partial\theta_j\partial\theta_k}=\begin{cases}\hat{S}_{1yiB}\left(1-\hat{S}_{1yiB}\right)\left(1-2\hat{S}_{1yiB}\right) & \text{for } \theta_j,\theta_k=\beta_0,\tau_y,\gamma \\ x_i\hat{S}_{1yiB}\left(1-\hat{S}_{1yiB}\right)\left(1-2\hat{S}_{1yiB}\right) & \text{for } \theta_j=\beta_0,\tau_y,\gamma \text{ and } \theta_k=\beta_1,\beta_y \text{ and vice versa} \\ x_i^2\hat{S}_{1yiB}\left(1-\hat{S}_{1yiB}\right)\left(1-2\hat{S}_{1yiB}\right) & \text{for } \theta_j,\theta_k=\beta_1,\beta_y\end{cases}$$

$$\frac{\partial^2 S_{2yiA}}{\partial\theta_j\partial\theta_k}=\begin{cases}\hat{S}_{2yiA}\left(1-\hat{S}_{2yiA}\right)\left(1-2\hat{S}_{2yiA}\right) & \text{for } \theta_j,\theta_k=\beta_0,\tau_y,\mu_B \\ x_i\hat{S}_{2yiA}\left(1-\hat{S}_{2yiA}\right)\left(1-2\hat{S}_{2yiA}\right) & \text{for } \theta_j=\beta_0,\tau_y,\mu_B \text{ and } \theta_k=\beta_1,\beta_y \text{ and vice versa} \\ x_i^2\hat{S}_{2yiA}\left(1-\hat{S}_{2yiA}\right)\left(1-2\hat{S}_{2yiA}\right) & \text{for } \theta_j,\theta_k=\beta_1,\beta_y\end{cases}$$

$$\frac{\partial^2 S_{2yiB}}{\partial\theta_j\partial\theta_k}=\begin{cases}\hat{S}_{2yiB}\left(1-\hat{S}_{2yiB}\right)\left(1-2\hat{S}_{2yiB}\right) & \text{for } \theta_j,\theta_k=\beta_0,\tau_y,\gamma,\mu_B,\phi \\ x_i\hat{S}_{2yiB}\left(1-\hat{S}_{2yiB}\right)\left(1-2\hat{S}_{2yiB}\right) & \text{for } \theta_j=\beta_0,\tau_y,\gamma,\mu_B,\phi \text{ and } \theta_k=\beta_1,\beta_y \text{ and vice versa} \\ x_i^2\hat{S}_{2yiB}\left(1-\hat{S}_{2yiB}\right)\left(1-2\hat{S}_{2yiB}\right) & \text{for } \theta_j,\theta_k=\beta_1,\beta_y\end{cases}$$

$$\frac{\partial^2 g_{S_h}}{\partial\theta_j\partial\theta_k}=\psi_h\frac{\partial^2 S_{hA}}{\partial\theta_j\partial\theta_k}+\left(1-\psi_h\right)\frac{\partial^2 S_{hB}}{\partial\theta_j\partial\theta_k} \text{ for } h=1,2$$

and

$$\frac{\partial^2 g_\delta}{\partial\theta_j\partial\theta_k}=\frac{\partial^2 g_{S_2}}{\partial\theta_j\partial\theta_k}-\frac{\partial^2 g_{S_1}}{\partial\theta_j\partial\theta_k}.$$

Tabular Results

Table A1. Predicted survival from the Head of Old River to Chipps Island when the Head of Old River barrier is not installed ($\hat{S}_1$ *) and when it is installed (* $\hat{S}_2$ *), and the difference in survival with vs without the barrier* $\left(\hat{\delta} = \hat{S}_1 \quad \hat{S}_2\right)$*, as a function of Delta inflow at Vernalis, and 95% confidence band limits. Values of* $\delta > 0$ *indicate higher survival to Chipps Island in the presence of the barrier.*

VNS (cfs)	$\hat{S}_1 \left(\widehat{SE}\right)$	$CI\left(\hat{S}_1\right)$	$\hat{S}_2 \left(\widehat{SE}\right)$	$CI\left(\hat{S}_2\right)$	$\hat{\delta} \left(\widehat{SE}\right)$	$CI\left(\hat{\delta}\right)$
319	0.17 (0.13)	(-0.07, -0.07)	0.30 (0.20)	(-0.05, -0.05)	0.13 (0.08)	(-0.01, -0.01)
549	0.18 (0.13)	(-0.06, -0.06)	0.31 (0.19)	(-0.03, -0.03)	0.13 (0.07)	(0.00, 0.00)
783	0.19 (0.13)	(-0.05, -0.05)	0.33 (0.19)	(0.00, 0.00)	0.14 (0.07)	(0.01, 0.01)
1,017	0.20 (0.13)	(-0.04, -0.04)	0.34 (0.18)	(0.02, 0.02)	0.14 (0.07)	(0.02, 0.02)
1,251	0.21 (0.14)	(-0.03, -0.03)	0.36 (0.18)	(0.04, 0.04)	0.14 (0.07)	(0.02, 0.02)
1,486	0.22 (0.14)	(-0.03, -0.03)	0.37 (0.18)	(0.06, 0.06)	0.15 (0.07)	(0.03, 0.03)
1,720	0.24 (0.15)	(-0.03, -0.03)	0.39 (0.18)	(0.08, 0.08)	0.16 (0.07)	(0.04, 0.04)
1,954	0.25 (0.16)	(-0.03, -0.03)	0.41 (0.18)	(0.10, 0.10)	0.16 (0.06)	(0.05, 0.05)
2,189	0.26 (0.17)	(-0.03, -0.03)	0.43 (0.18)	(0.12, 0.12)	0.17 (0.06)	(0.05, 0.05)
2,423	0.28 (0.18)	(-0.03, -0.03)	0.45 (0.18)	(0.14, 0.14)	0.17 (0.07)	(0.06, 0.06)
2,657	0.30 (0.18)	(-0.03, -0.03)	0.47 (0.18)	(0.16, 0.16)	0.18 (0.07)	(0.05, 0.05)
2,891	0.31 (0.19)	(-0.02, -0.02)	0.50 (0.18)	(0.18, 0.18)	0.18 (0.07)	(0.05, 0.05)
3,126	0.33 (0.20)	(-0.02, -0.02)	0.52 (0.18)	(0.21, 0.21)	0.19 (0.08)	(0.05, 0.05)
3,360	0.35 (0.20)	(-0.01, -0.01)	0.54 (0.18)	(0.23, 0.23)	0.19 (0.08)	(0.05, 0.05)
3,594	0.37 (0.21)	(0.00, 0.00)	0.56 (0.18)	(0.24, 0.24)	0.19 (0.08)	(0.05, 0.05)
3,829	0.39 (0.21)	(0.02, 0.02)	0.58 (0.18)	(0.26, 0.26)	0.19 (0.08)	(0.05, 0.05)
4,063	0.41 (0.22)	(0.03, 0.03)	0.60 (0.18)	(0.28, 0.28)	0.19 (0.08)	(0.04, 0.04)
4,297	0.43 (0.22)	(0.04, 0.04)	0.62 (0.19)	(0.29, 0.29)	0.19 (0.08)	(0.04, 0.04)
4,531	0.45 (0.23)	(0.05, 0.05)	0.64 (0.19)	(0.30, 0.30)	0.19 (0.08)	(0.04, 0.04)
4,766	0.47 (0.23)	(0.06, 0.06)	0.66 (0.19)	(0.31, 0.31)	0.19 (0.08)	(0.04, 0.04)
5,000	0.49 (0.24)	(0.06, 0.06)	0.67 (0.20)	(0.33, 0.33)	0.18 (0.09)	(0.03, 0.03)