Estimates of Wenatchee Steelhead Spawners

Spawn Years 1987-2022

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1 Goal

The current method of estimating spawners in the Wenatchee subbasin involves using a PIT-tag based escapement model (DABOM) to estimate tributary spawners (Waterhouse et al. 2020) and adjust the observed redd counts in the mainstem Wenatchee from two observers with a redd observer error model and a Gaussian area-under-the-curve method, as described in Murdoch et al. (2018). These adjusted redd counts are combined with redd counts in tributaries below the PIT tag arrays. The PIT tags observed moving into the mainstem (or the tributaries) are used to calculate a fish / redd estimate (males/females + 1 (Murdoch et al. 2009)) and the proportion of hatchery fish on the spawning grounds (pHOS), both of which are used to translate estimates of redds into estimates of hatchery and natural origin spawners. This method has been utilized from spawn year 2014 until the present.

From 2011-2013, the exact same methods were used, except observer error was estimated with the one-observer net error model from Murdoch et al. (2018), because redd surveys in the Wenatchee during that time used a one-observer methodology.

From 2004-2010, estimates of spawners come mainly from redd surveys, which are adjusted using the one-observer net error model from Murdoch et al. (2018). Estimates of fish / redd and pHOS come from fish sampled at Dryden dam or from broodstock collection. There were three tributaries (Mission, Chumstick and Chiwaukum) that were not part of the redd sampling frame. However, when PIT tag arrays were placed in those tributaries after 2011, some steelhead spawning was observed. Therefore, for 2004-2010, we expanded the estimate of hatchery and natural origin spawners by the mean proportion of overall Wenatchee spawners in those tributaries from 2011 on.

This results in a complete time series from 2004-2022 of estimates of hatchery and natural origin spawners, with associated standard errors. We believe these estimates to be unbiased, based on Murdoch et al. (2018) and Waterhouse et al. (2020).

There is another time series of estimates, from 1987 - 2021, using older methods based on dam counts at the mainstem dams on the Upper Columbia. The goal of this work is to establish a relationship between the two time-series, and use that relationship to "adjust" the older time-series, from 1987-2003, to better match the more recent time-series.

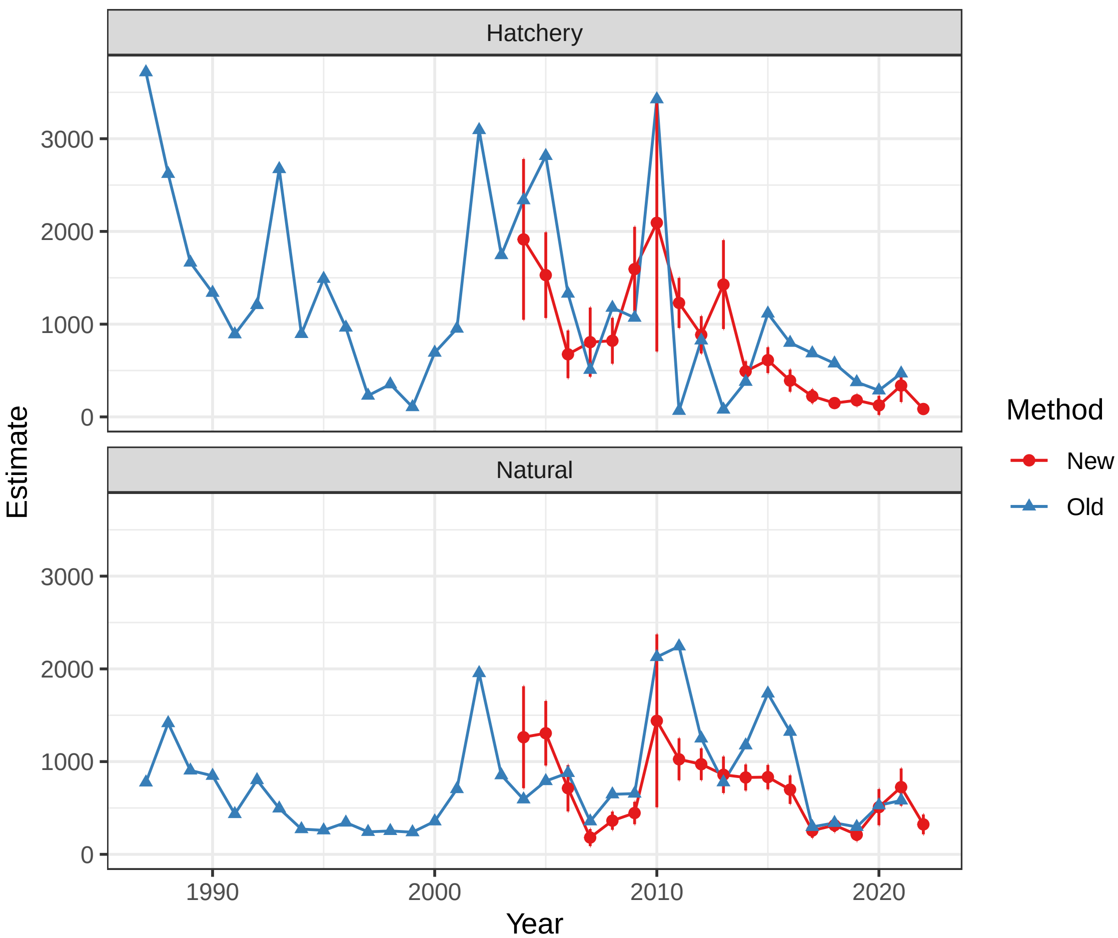

Figure 1: Time-series of hatchery and natural origin spawners in the Wenatchee, colored by what method was used. Error bars represent 95% confidence intervals where available.

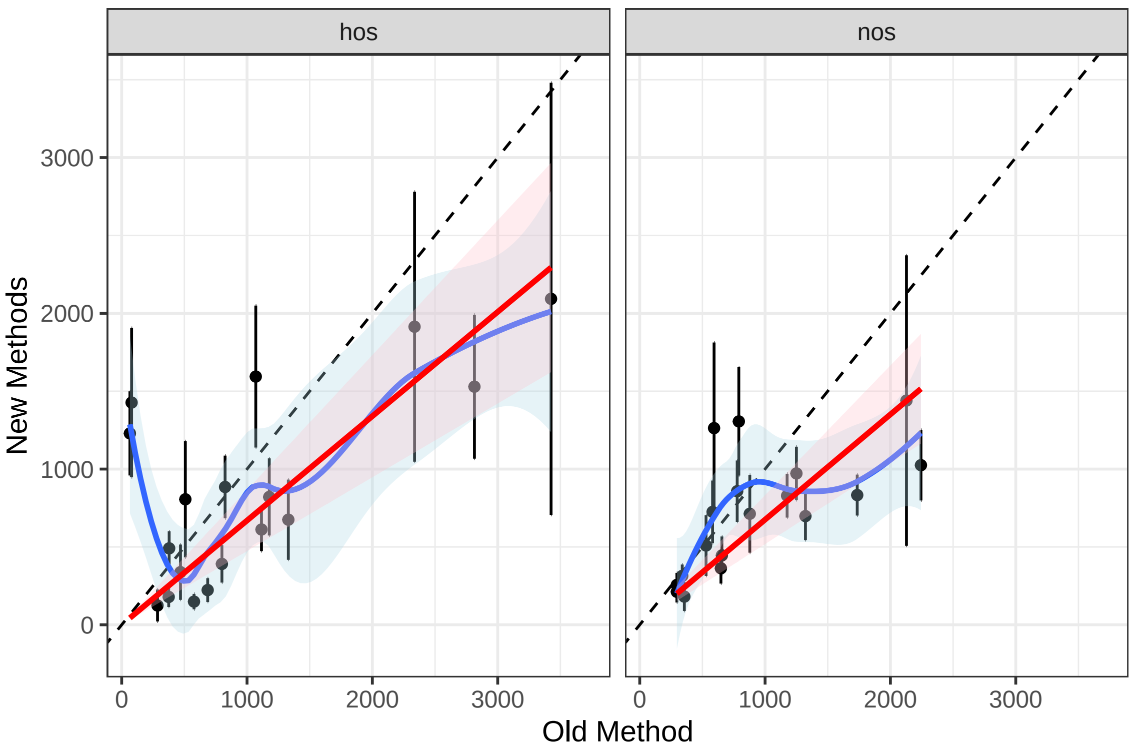

Figure 2: Scatterplots of hatchery and natural origin spawners in the Wenatachee, as estimated by the old method (x-axis) and new methods (y-axis). The blue line is a loess fit, and the red line shows a linear fit forced through the origin.

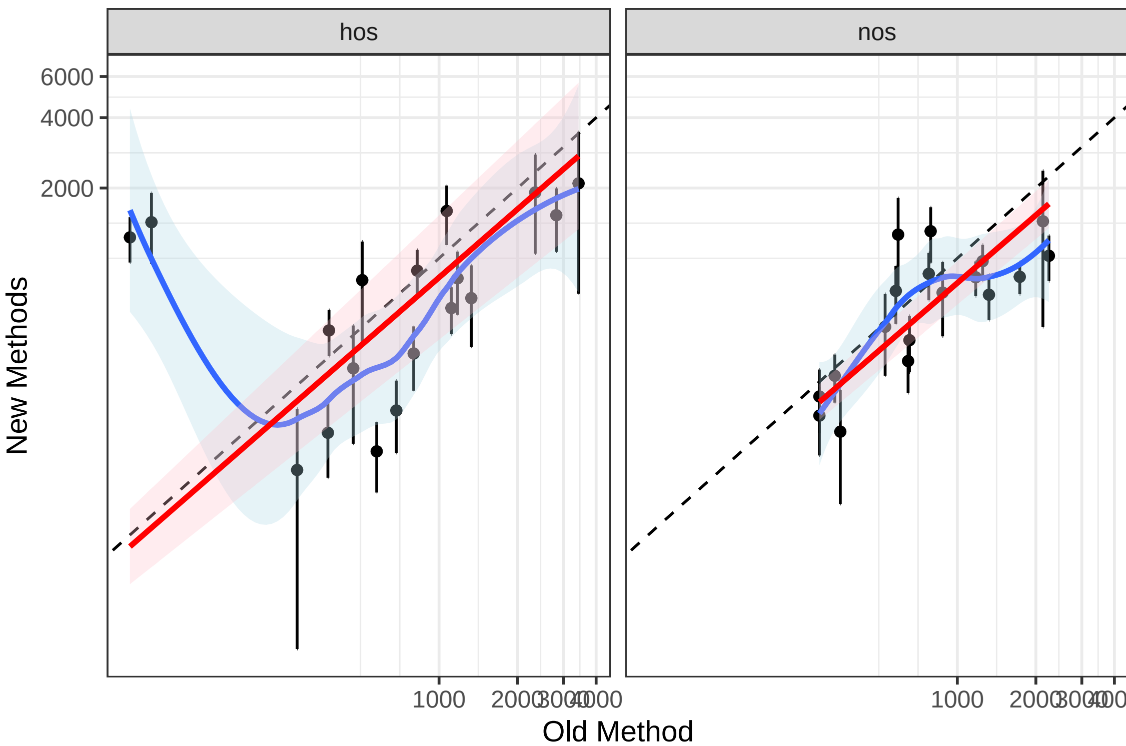

Figure 3: Log-log scatterplots of hatchery and natural origin spawners in the Wenatachee, as estimated by the old method (x-axis) and new methods (y-axis). The blue line is a loess fit, and the red line shows a linear fit forced through the origin.

2 Methods and Results

2.1 Linear Model

Our first approach was to treat each year as independent, and fit a linear model that includes interactions with origin for both the intercept and slope, with the new estimates as the independent variable and old estimates as the dependent variable. We also tested a log-log linear regression, which involved taking the natural logarithm of each time-series before fitting a linear regression.

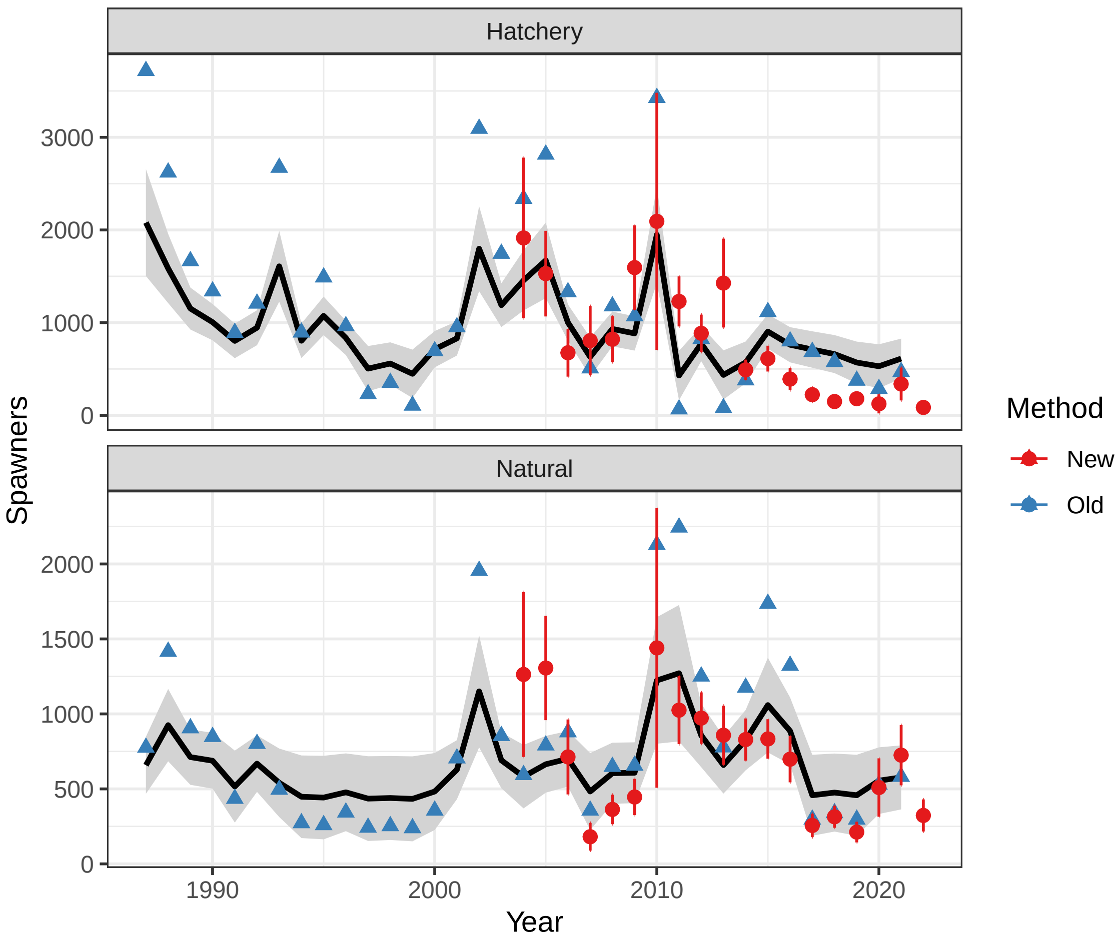

Figure 4: Black lines show linear regression estimates with the 95% confidence intervals depicted as grey ribbons. Blue triangles depict estimates from the old time-series, while red points and 95% confidence intervals are from the new time-series.

2.1.1 Linear Modeling Results

Neither a linear nor a log-log linear model fit the data very well (Figures 2 and 3). A linear fit to these scatter plots would imply a consistent bias (either additive or multiplicative). The lack of such an obvious fit implies the relationship between the two time-series is more complicated. Both appeared to underestimate abundance during years when the older method predicted high numbers steelhead spawners (Figures 4 and 5).

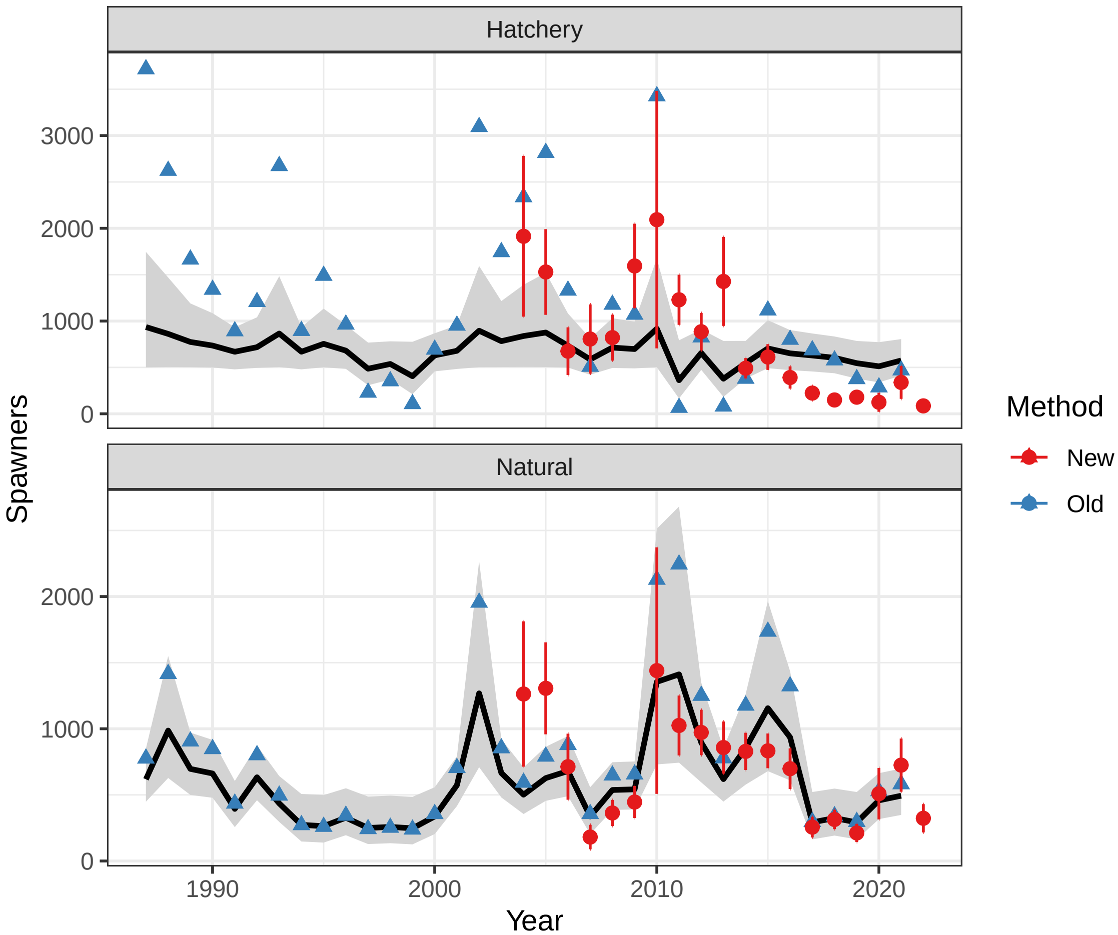

Figure 5: Black lines show log-log linear regression estimates with the 95% confidence intervals depicted as grey ribbons. Blue triangles depict estimates from the old time-series, while red points and 95% confidence intervals are from the new time-series.

2.2 MARSS

Our next approach was to fit a multivariate auto-regressive state-space (MARSS) model (Holmes et al. 2012, 2021) to the two time-series, ensuring that the only offset of the true states is for the old time-series and that the observation error of the new time-series is informed by mean standard error from the new time-series.

A MARSS model is of the form:

$$\mathbf{x}_t = \mathbf{B}\mathbf{x}_{t-1} + \mathbf{u} + \mathbf{C}_t\mathbf{c}_t + \mathbf{w}_t, \text{where } \mathbf{w}_t \sim MVN(0, \mathbf{Q})$$
$$\mathbf{y}_t = \mathbf{Z}\mathbf{x}_t + \mathbf{a} + \mathbf{D}_t\mathbf{d}_t + \mathbf{v}_t, \text{where } \mathbf{v}_t \sim MVN(0, \mathbf{R})$$

where $\mathbf{x}_t$ represents the true state at time t, which change as a correlated random walk through time. The $\mathbf{u}$ term represents average drift or trend through time. Meanwhile, $\mathbf{y}_t$ represent the observations of those true states, $\mathbf{x}_t$. Which state each element of $\mathbf{y}_t$ is an observation of is determined by the $\mathbf{Z}$ matrix, while $\mathbf{a}$ represents a fixed offset between different elements of $\mathbf{y}$. $\mathbf{C}_t$ and $\mathbf{D}_t$ are possible parameters that show how inputs $\mathbf{c}_t$ and $\mathbf{d}_t$ influence the states ($\mathbf{x}_t$) or observations ($\mathbf{y}_t$); in other words they are covariates. Finally $\mathbf{Q}$ is the process error variance, while $\mathbf{R}$ is the observation error covariance matrix. This framework works best in log-space, so we log-transformed $\mathbf{y}_t$. Further details of MARSS models can be found in the MARSS user guide.

- We set $\mathbf{y}_{1,t}$ and $\mathbf{y}_{3,t}$ to be the estimates of hatchery and wild spawners using the most updated methods, while $\mathbf{y}_{2,t}$ and $\mathbf{y}_{4,t}$ are the vector of estimates of hatchery and wild spawners using the older method.
- We fixed the first and third element of $\mathbf{a}$ to be 0, to ensure there was no offset between the updated estimates and the MARSS model states (The second and fourth element of $\mathbf{a}$ was estimated, as the average multiplicative offset between the older time-series and the true states).
- We set $\mathbf{B}$ to be the identity matrix.
- We tested setting $\mathbf{u}$ to 0, the equivalent of a random walk model, and allowing it be estimated, the equivalent of a random walk with drift or trend model.
- The other element we wanted to feed *a priori* into the MARSS framework was the observation error variance, based on the estimated standard errors in the updated estimates. Because the model is set in log-space, we transformed the estimated standard errors by calculating the coefficient of variation, adding 1, logging that value and then calculating the square root. We then took the mean of the log-space standard errors before squaring it. These two values for hatchery and wild observation error were set as the first and third term along the diagonal of the $\mathbf{R}$ matrix, while the off-diagonals were set to 0 and the observation variance of the older methods was left for the MARSS model to estimate.
- Because hatchery and natural origin returns may be correlated to other dam counts, we compiled time-series of counts from several other Columbia River dams: Bonneville, Ice Harbor, McNary, Prosser and Rock Island dams. These were treated as separate states in the MARSS framework, each with a single observation. For all dams, counts were summed from June 1 the year prior to May 31 of that spawn year. These counts are plotted in Figure 6. The hypothesis here is that other dam counts may inform the (Q) matrix, allowing for better inference of the states we are interested in.
- We also compiled one more possible input, hatchery releases of smolts. We hypothesized that the hatchery release numbers from previous years might inform the predicted returns of adults. We used the weighted average of salt age 1 and salt age 2 releases, weighted 70% towards salt age 1 and 30% towards salt age 2 based on average age composition data. Salt age 1 fish returned 2 years after their release, while salt age 2 fish returned after 3 years. This time-series extended back to 1987 and was normalized to have a mean of zero and standard deviation of one. This was treated as a possible covariate for the estimated state of hatchery spawners. This time series is shown in Figure 7.
- We tested several configurations of this model:

1. Treated all states (Wenatchee hatchery and wild spawners, and other dam counts) as independent, by setting the off-diagonal terms of **Q** to 0. (`Q = "diagonal and unequal`)
2. Similar to (1), but allowed for the process errors of Wenatchee hatchery and wild spawners to co-vary by estimating a single off-diagonal element of **Q**.
3. Allowed the process errors to co-vary across all states, and estimated their covariance as the off-diagonal term of **Q**. (`Q = "unconstrained`)
4. Same as (1), but included a covariate of hatchery smolt releases to inform hatchery returns.
5. Same as (2), but included a covariate of hatchery smolt releases to inform hatchery returns.
6. Same as (3), but included a covariate of hatchery smolt releases to inform hatchery returns.
7. 7-12. Same as above, but included a possible trend (`U = "unequal"`).

Models 1, 2, 4 and 5 essentially ignore the dam counts when it comes to fitting and predicting for the Wenatchee states. Models 1 and 4 treat hatchery and wild spawners as independent time-series which is the equivalent of fitting separate models for wild and hatchery spawners.

- All models were compared with AICc.
- All models were fit using the `MARSS` package in R.

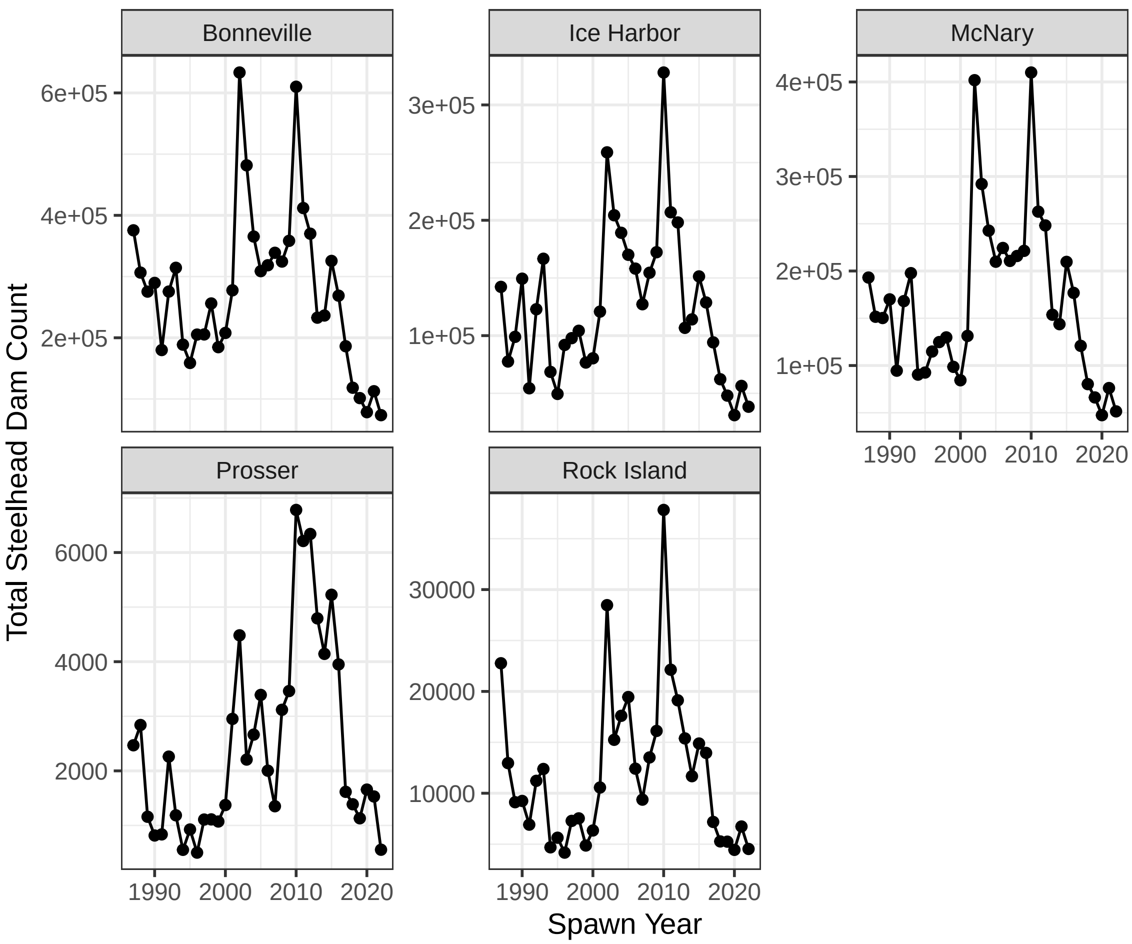

Figure 6: Time-series of counts from various Columbia River dams, from June 1 the year prior to May 31 of that spawn year.

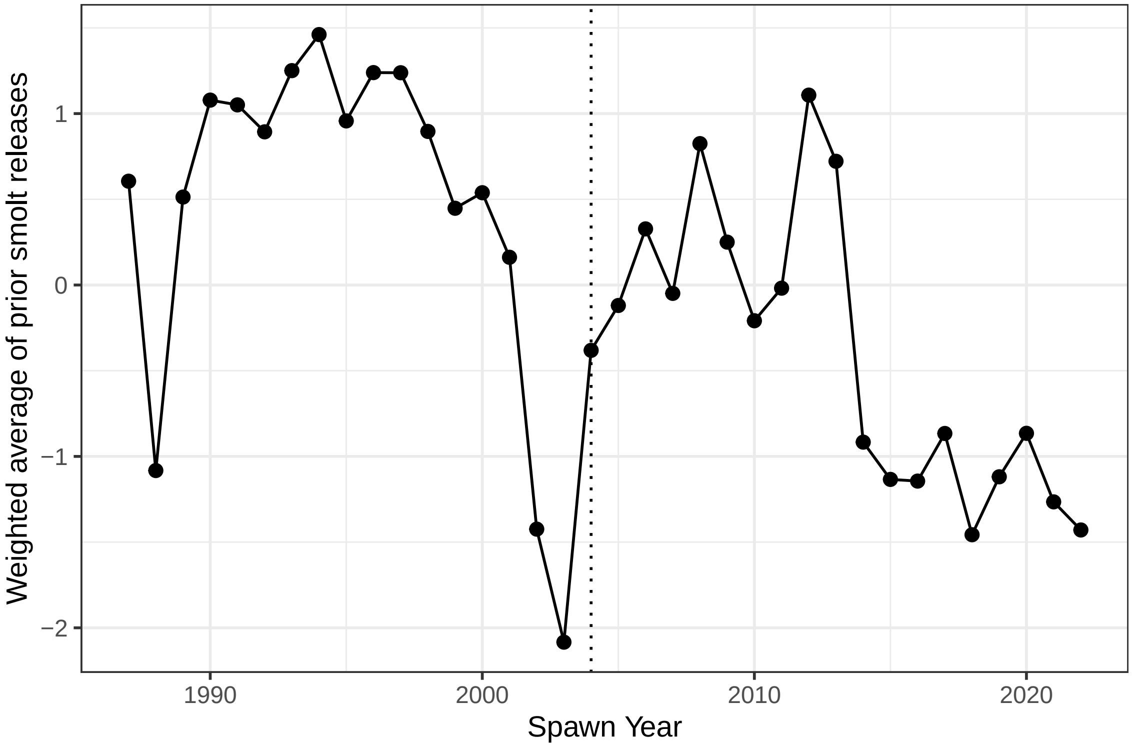

Figure 7: Time-series of normalized weighted average of smolt releases prior to the spawn year (x-axis). Dotted line shows when the new time-series begins.

2.2.1 MARSS Results

The results (Table 1) show model number 3 to be best supported by the data. This model allows for correlated process errors between hatchery and natural spawners and various dam counts. The second best model by AICc was model 6, which was identical to model 3 but also included a covariate of previous smolt releases to help predict hatchery spawners. The next two models (by AICc) were identical to the previous two but included a possible trend in each time-series. Although the trends for all states were estimated to be slightly negative in both models, the 95% confidence intervals overlapped zero in every case. These models also had very low weight (Table 1).

Table 2 shows the estimates of the process error covariance matrix, $\mathbf{Q}$, from the best supported model. Table 3 shows other parameter estimates from the selected model.

Figure 8 compares the predictions of hatchery spawners from a model that does not use smolt releases as a covariate and one that does, although both have unconstrained $\mathbf{Q}$ matrices. (models 3 and 6). Predictions are slightly greater for the model with a smolt release covariate, but only in the earlier years.

3 Conclusions

The MARSS framework appear to fit the data better than the linear regression for several reasons, so we chose to use that. First, there does not appear to be a consistent additive or multiplicative bias between the two time-series. Second, a MARSS model is explicitly a time-series model, which is appropriate for this comparison. Finally, the MARSS framework allowed us to test a variety of model structures, including bringing in other time-series and covariates. AICc supported a model that included several time-series of various dam counts, with correlated process errors (true year-to-year variability), including a positive

Table 1: AICc values for all models.

Model Num.	Description	n Params	LogLik	AICc	delta AICc	Model Weight
3	Q unconstrained, no covariates	44	-27.0	158.3	0.0	0.724
6	Q unconstrained, smolt covariate	45	-27.0	161.1	2.7	0.185
9	Q unconstrained, no covariates, U unequal	51	-19.2	162.9	4.6	0.073
12	Q unconstrained, smolt covariate, U unequal	52	-19.2	165.8	7.5	0.017
2	Q mostly independent, no covariates	24	-190.6	433.8	275.4	0.000
5	Q mostly independent, smolt covariate	25	-190.6	436.1	277.8	0.000
8	Q mostly independent, no covariates, U unequal	31	-185.3	440.3	281.9	0.000
11	Q mostly independent, smolt covariate, U unequal	32	-184.4	441.0	282.7	0.000
1	Q diag and unequal, no covariates	23	-195.9	442.0	283.6	0.000
4	Q diag and unequal, smolt covariate	24	-195.9	444.4	286.0	0.000
7	Q diag and unequal, no covariates, U unequal	30	-193.3	453.8	295.5	0.000
10	Q diag and unequal, smolt covariate, U unequal	31	-193.3	456.3	297.9	0.000

Table 2: Estimates of Q matrix from model 3, showing variance and co-variance estimates.

	Wen. Hatch	Wen. Wild	BON	IHR	MCN	PRO	RIS
Wen. Hatch	0.238	0.188	0.143	0.163	0.166	0.158	0.185
Wen. Wild	0.188	0.214	0.097	0.106	0.112	0.205	0.173
BON	0.143	0.097	0.098	0.115	0.114	0.085	0.110
IHR	0.163	0.106	0.115	0.138	0.136	0.086	0.125
MCN	0.166	0.112	0.114	0.136	0.136	0.090	0.128
PRO	0.158	0.205	0.085	0.086	0.090	0.226	0.161
RIS	0.185	0.173	0.110	0.125	0.128	0.161	0.159

Table 3: Estimates of selected parameters from the best model. Terms containing "new" were inputs to the model, derived from the new time-series estimates.

Term	Estimate	Std Error	Conf Low	Conf Up
A.a__old__hos	0.077	0.196	-0.308	0.461
A.a__old__nos	0.235	0.108	0.023	0.447
R.r__old__hos	0.670	0.165	0.345	0.994
R.r__old__nos	0.087	0.026	0.037	0.137
R.r__new__hos	0.173	0.075	0.099	0.378
R.r__new__nos	0.139	0.066	0.079	0.304

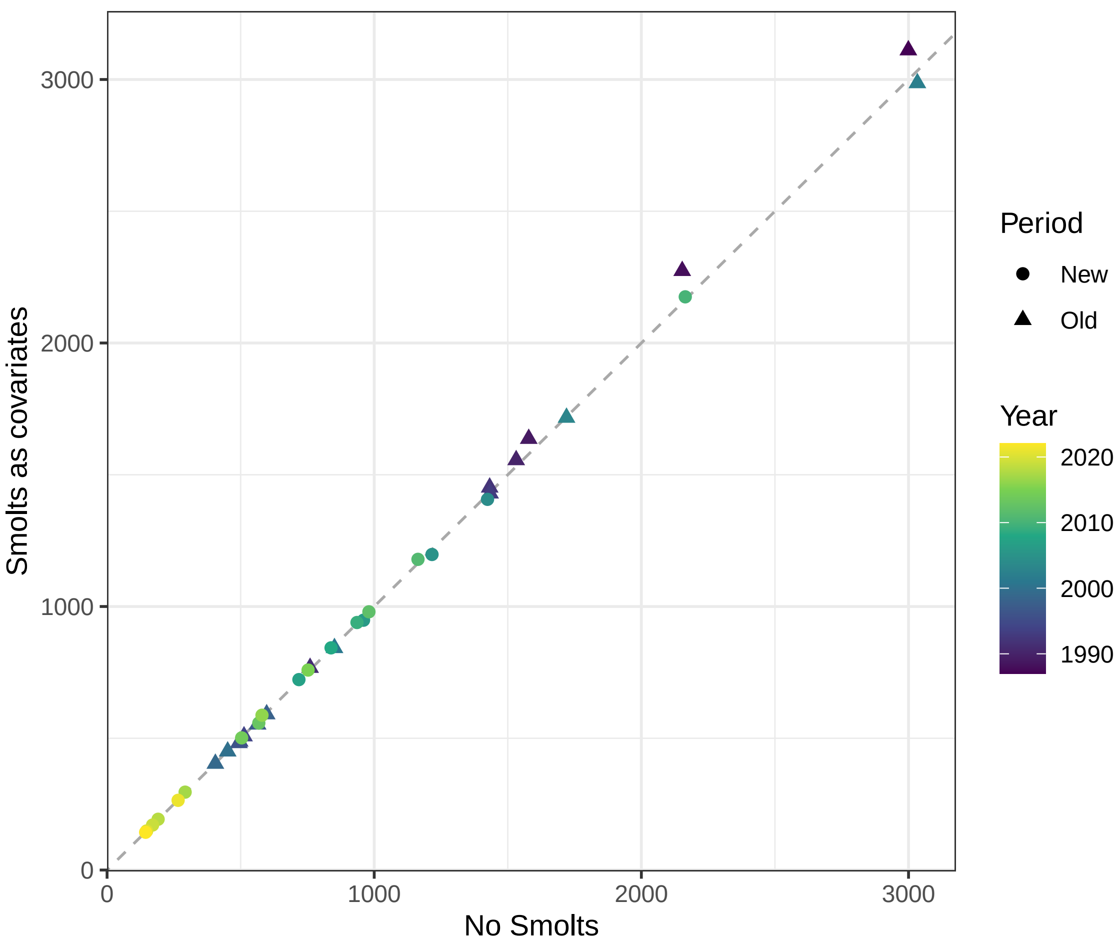

Figure 8: Comparison of predicted states of hatchery spawners for a model with no smolt release covariate (x-axis) and one that includes that covariate (y-axis). The period refers to whether the new time-series estimates exist.

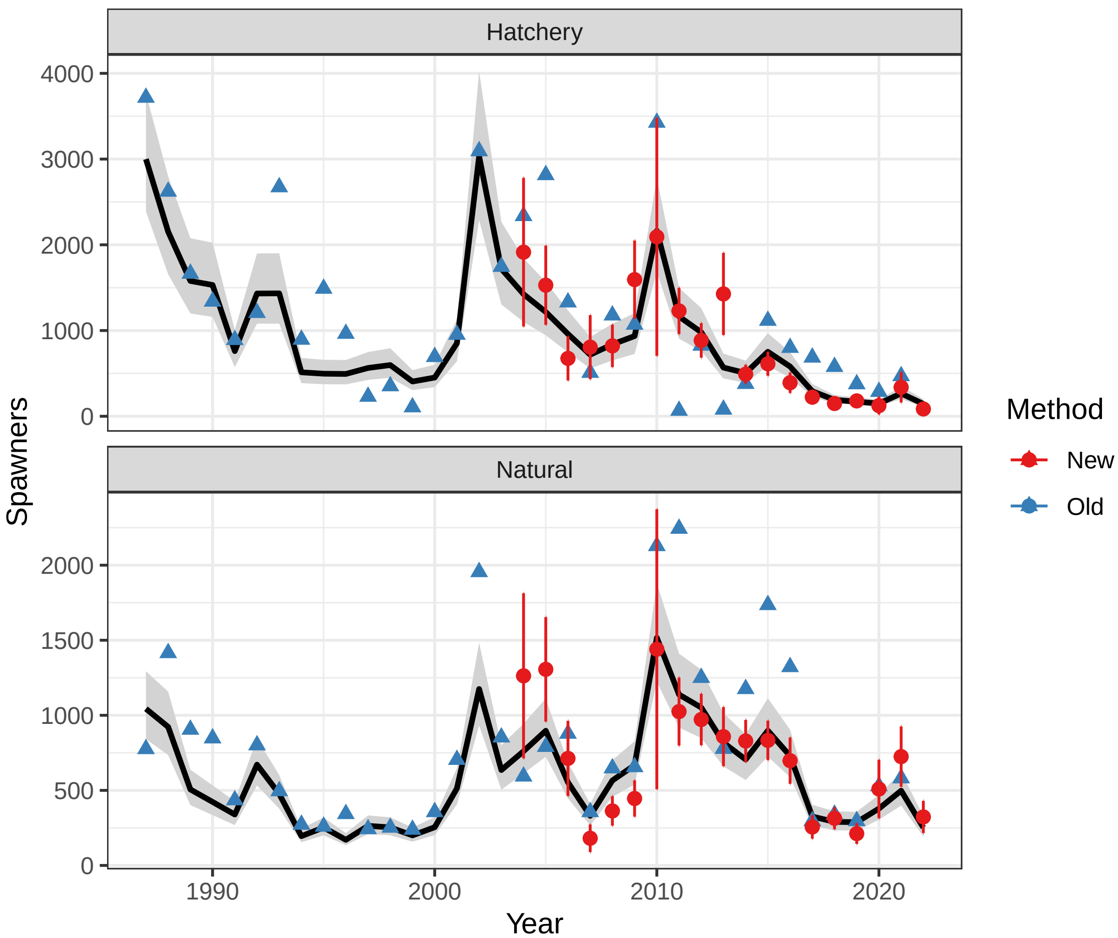

Figure 9: Estimates of spawners through the years, faceted by origin. Predicted spawners is the black line with 95% confidence interval in gray. Blue triangles depict estimates from the old time-series, while red points and 95% confidence intervals are from the new time-series.

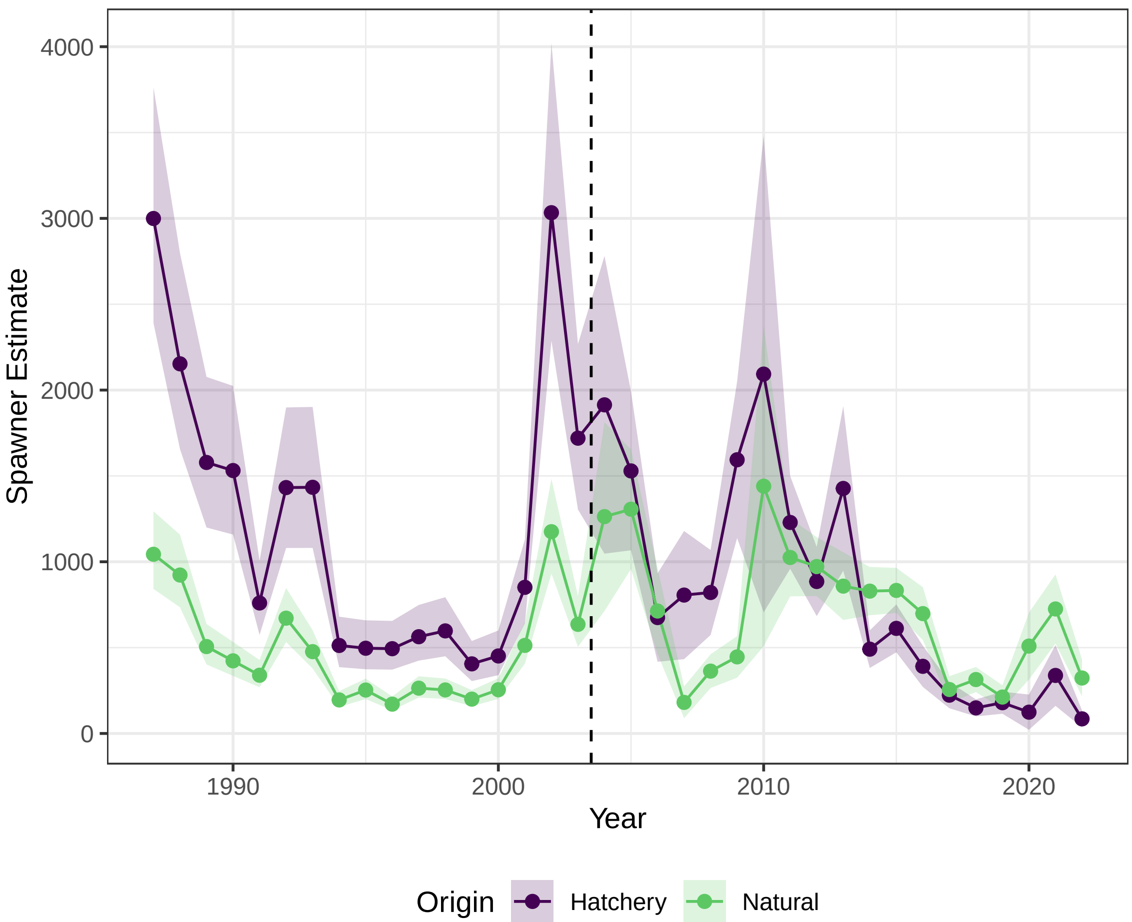

Figure 10: Updated estimates of spawners through the years, colored by origin, showing point estimates and 95% confidence intervals. Dashed vertical line differentiates older and newer time-series.

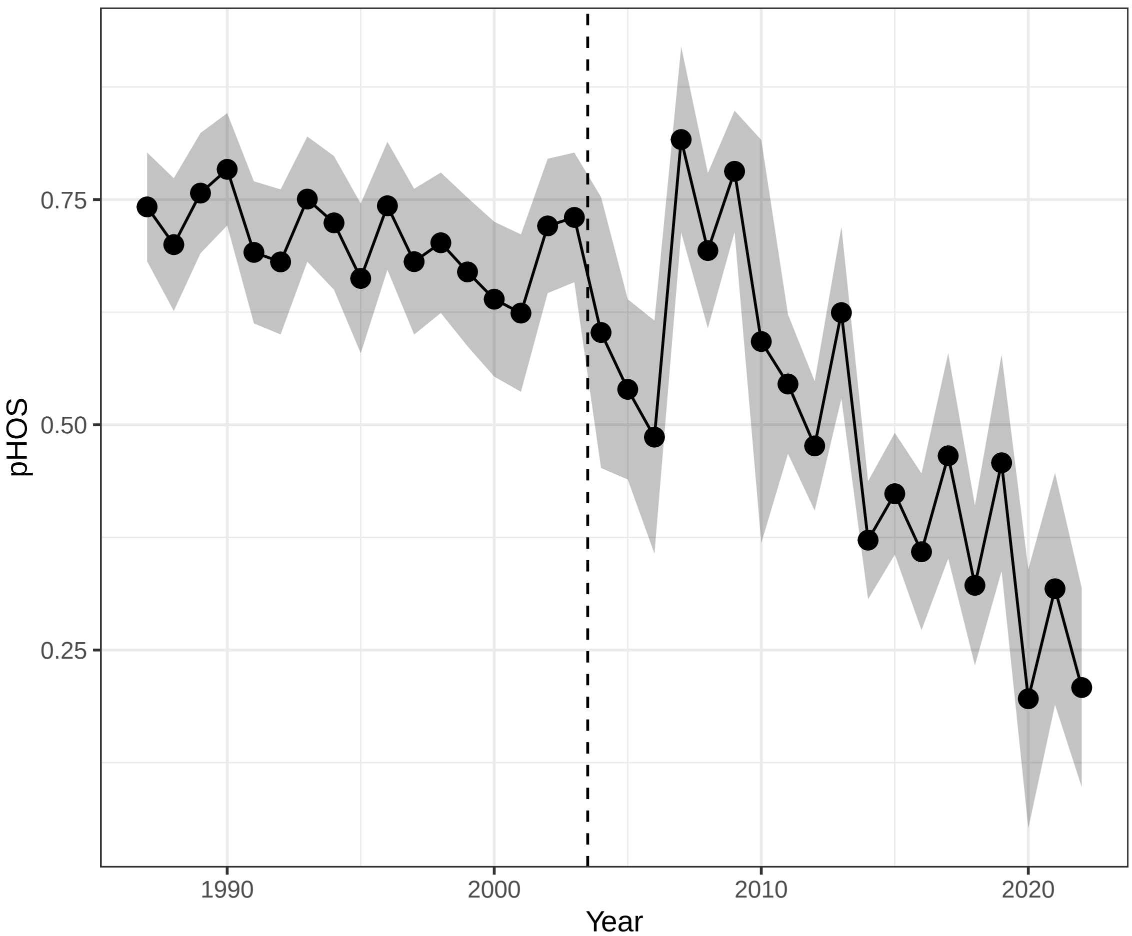

Figure 11: Estimates of pHOS based on the updated time-series, showing 95% confidence intervals. Dashed vertical line differentiates older and newer time-series.

correlation between hatchery and natural origin spawners. This positive correlation could reflect the impacts of shared ocean conditions. There was slightly less support for the same model that also included a covariate of weighted average of previous smolt releases to for the hatchery returns (but not natural origin returns). Because the coefficient of that covariate was negative, with confidence intervals that overlapped 0, and because including smolt releases had very little effect on spawner estimates (Figure 8), we decided against using that model and chose the one with the lowest AICc score.

Table 4 in Appendix A.1 shows the updated time-series, including a brief description of the method used to generate the estimate each year.

4 References

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A Appendix A

A.1 Updated Time Series

Table 4: Updated time-series of steelhead spawners in the Wenatchee, by origin.

Year	Origin	Method	Estimate	SE	LCI	UCI
1987	Hatchery	MARSS	2,999	350.8	2,390	3,764
1987	Natural	MARSS	1,044	115.5	842	1,294
1988	Hatchery	MARSS	2,153	291.8	1,657	2,798
1988	Natural	MARSS	923	108.1	735	1,158
1989	Hatchery	MARSS	1,578	224.2	1,200	2,077
1989	Natural	MARSS	506	60.2	402	637
1990	Hatchery	MARSS	1,531	221.4	1,158	2,024
1990	Natural	MARSS	423	50.6	335	533
1991	Hatchery	MARSS	760	110.7	574	1,007
1991	Natural	MARSS	339	40.6	269	428
1992	Hatchery	MARSS	1,432	209.3	1,080	1,899
1992	Natural	MARSS	671	80.5	532	847
1993	Hatchery	MARSS	1,434	210.0	1,081	1,902
1993	Natural	MARSS	477	57.2	378	601
1994	Hatchery	MARSS	513	75.2	386	680
1994	Natural	MARSS	195	23.4	155	246
1995	Hatchery	MARSS	496	72.9	374	659
1995	Natural	MARSS	253	30.4	200	319
1996	Hatchery	MARSS	494	72.6	372	656
1996	Natural	MARSS	171	20.5	135	215
1997	Hatchery	MARSS	563	82.9	424	748
1997	Natural	MARSS	264	31.7	209	333
1998	Hatchery	MARSS	597	88.0	450	794
1998	Natural	MARSS	254	30.5	201	320
1999	Hatchery	MARSS	405	59.7	305	539
1999	Natural	MARSS	200	24.0	158	252
2000	Hatchery	MARSS	451	66.5	340	600
2000	Natural	MARSS	255	30.6	202	321
2001	Hatchery	MARSS	851	125.2	641	1,130
2001	Natural	MARSS	513	61.7	406	648
2002	Hatchery	MARSS	3,033	443.1	2,288	4,021
2002	Natural	MARSS	1,175	141.0	931	1,483
2003	Hatchery	MARSS	1,720	246.4	1,304	2,268
2003	Natural	MARSS	635	75.6	504	800
2004	Hatchery	1 Obs. Model & Expansion	1,914	442.3	1,047	2,781
2004	Natural	1 Obs. Model & Expansion	1,263	280.5	713	1,813
2005	Hatchery	1 Obs. Model & Expansion	1,529	235.8	1,067	1,991
2005	Natural	1 Obs. Model & Expansion	1,306	177.5	958	1,654
2006	Hatchery	1 Obs. Model & Expansion	675	131.3	418	932
2006	Natural	1 Obs. Model & Expansion	713	127.5	463	963
2007	Hatchery	1 Obs. Model & Expansion	806	190.5	433	1,179
2007	Natural	1 Obs. Model & Expansion	181	47.1	89	273
2008	Hatchery	1 Obs. Model & Expansion	821	126.4	573	1,069

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Table 4: Updated time-series of steelhead spawners in the Wenatchee, by origin. *(continued)*

Year	Origin	Method	Estimate	SE	LCI	UCI
2008	Natural	1 Obs. Model & Expansion	363	50.2	265	461
2009	Hatchery	1 Obs. Model & Expansion	1,594	232.6	1,138	2,050
2009	Natural	1 Obs. Model & Expansion	446	61.8	325	567
2010	Hatchery	1 Obs. Model & Expansion	2,093	708.0	705	3,481
2010	Natural	1 Obs. Model & Expansion	1,440	475.7	508	2,372
2011	Hatchery	1 Obs. Model & DABOM	1,229	137.8	959	1,499
2011	Natural	1 Obs. Model & DABOM	1,025	115.6	798	1,252
2012	Hatchery	1 Obs. Model & DABOM	885	102.7	684	1,086
2012	Natural	1 Obs. Model & DABOM	972	87.5	800	1,144
2013	Hatchery	1 Obs. Model & DABOM	1,427	244.5	948	1,906
2013	Natural	1 Obs. Model & DABOM	858	100.6	661	1,055
2014	Hatchery	2 Obs. Model & DABOM	491	55.9	381	601
2014	Natural	2 Obs. Model & DABOM	829	71.8	688	970
2015	Hatchery	2 Obs. Model & DABOM	612	71.0	473	751
2015	Natural	2 Obs. Model & DABOM	833	67.1	702	964
2016	Hatchery	2 Obs. Model & DABOM	391	61.2	271	511
2016	Natural	2 Obs. Model & DABOM	698	78.7	544	852
2017	Hatchery	2 Obs. Model & DABOM	223	39.0	147	299
2017	Natural	2 Obs. Model & DABOM	256	39.7	178	334
2018	Hatchery	2 Obs. Model & DABOM	149	25.4	99	199
2018	Natural	2 Obs. Model & DABOM	314	37.3	241	387
2019	Hatchery	2 Obs. Model & DABOM	179	32.7	115	243
2019	Natural	2 Obs. Model & DABOM	212	35.1	143	281
2020	Hatchery	RT Survival	124	52.4	21	227
2020	Natural	RT Survival	509	99.4	314	704
2021	Hatchery	2 Obs. Model & DABOM	338	90.5	161	515
2021	Natural	2 Obs. Model & DABOM	725	102.7	524	926
2022	Hatchery	2 Obs. Model & DABOM	85	25.3	35	135
2022	Natural	2 Obs. Model & DABOM	323	54.6	216	430