Age composition, size, migration timing, and estimation of smolt-to-adult survival of natural-origin Sockeye Salmon (*Oncorhynchus nerka*) in the Wenatchee River (WA) watershed (1997-2019)

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ABSTRACT

Judson, B., Willard, C., and Stiff, H. 2023. Age composition, size, migration timing, and estimation of smolt-to-adult survival of natural-origin Sockeye Salmon (*Oncorhynchus nerka*) in the Wenatchee River (WA) watershed (1997-2019). Can. Manuscr. Rep. Fish. Aquat. Sci. 3269: xi + 43 p.

Lake Wenatchee is the dominant producer of Sockeye Salmon (*Oncorhynchus nerka*) within Washington State, and one of only two self-sustaining populations of Sockeye Salmon within the Columbia River watershed. The Lake Wenatchee Sockeye population is monitored by Chelan Public Utility District, and those data are used to estimate smolt-to-adult returns (SAR) for natural-origin Sockeye as an index of marine survival. Juvenile abundance was indexed using: i) the Wenatchee River rotary-screw traps, and ii) presmolt abundance estimates from Wenatchee Lake acoustic-trawl surveys. Annual adult returns were estimated via two methods: i) using adult returns to Tumwater Dam; and ii) apportioning adjusted annual Bonneville Dam counts to Wenatchee stock, based on the ratio of Rocky Reach to Rock Island dam counts. We estimate SAR by dividing each juvenile abundance index by the number of adult returns per smolt migration year (determined from age composition data). Mean SAR estimates increased as of 2012 from 2.8% to 8.3%. However, the location of smolt trapping was changed after 2011, potentially affecting trap efficiency, yielding significantly greater inter-annual variability in the smolt index post-2011, and reducing confidence in estimates based on the 18-year smolt-to-adult return time-series. SAR estimates for the data-limited (n = 9 years) presmolt-to-adult survival time-series averaged 2.5%.

RÉSUMÉ

Judson, B., Willard, C., and Stiff, H. 2023. Age composition, size, migration timing, and estimation of smolt-to-adult survival of natural-origin Sockeye Salmon (*Oncorhynchus nerka*) in the Wenatchee River (WA) watershed (1997-2019). Can. Manuscr. Rep. Fish. Aquat. Sci. 3269: xi + 43 p.

Le lac Wenatchee est le plan d'eau produisant le plus de saumons rouges (*Oncorhynchus nerka*) de l'État de Washington. Il abrite aussi l'une des deux seules populations autonomes de saumons rouges de tout le bassin hydrographique du fleuve Columbia. La population de saumons rouge du lac Wenatchee est suivie par le Chelan Public Utility District, et les données recueillies servent à estimer le pourcentage des smolts d'origine naturelle qui remontent en tant qu'adultes (*smolt-to-adult returns*), à titre d'indice de la survie en mer. L'abondance des juvéniles a été convertie en indice au moyen : i) des données issues des pièges rotatifs de la rivière Wenatchee; ii) des estimations de l'abondance des pré-smolts dans le lac Wenatchee issues de relevés acoustiques au chalut. Nous avons estimé le nombre d'adultes qui remontent annuellement en suivant deux méthodes : i) l'utilisation du nombre d'adultes qui ont remonté jusqu'au barrage Tumwater; ii) l'attribution d'une partie des individus dénombrés annuellement au barrage Bonneville au stock du lac Wenatchee, selon le rapport entre les saumons dénombrés au barrage Rocky Reach et ceux dénombrés au barrage Rock Island. Nous avons estimé le pourcentage des smolts qui remontent en tant qu'adultes en divisant chaque indice de l'abondance des juvéniles par le nombre d'adultes qui remontent par année de dévalaison des smolts (déterminé à partir des données sur la composition selon l'âge). Les estimations moyennes du pourcentage des smolts qui remontent en tant qu'adultes a augmenté en 2012, passant de 2,8 % à 8,3 %. Toutefois, l'emplacement des pièges à smolts a changé après 2011, ce qui pourrait avoir affecté l'efficacité des pièges, produit une très grande variabilité interannuelle de l'indice des smolts après 2011 et réduit la confiance associée aux estimations fondées sur la série chronologique du pourcentage des smolts qui remontent en tant qu'adultes (*n* = 18 ans). La moyenne des estimations du pourcentage des smolts qui remontent en tant qu'adultes découlant de la série chronologique sur la survie du stade de pré-smolt à celui d'adulte (compte peu de données; *n* = 9 ans) était de 2,5 %.

ACKNOWLEDGEMENTS

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INTRODUCTION

STUDY SYSTEM

The United States Fish and Wildlife Service, Washington Department of Fish and Wildlife, NOAA (National Oceanic and Atmospheric Administration) Fisheries, the Colville Confederated Tribes and the Yakama Nation finalized the Chelan Public Utility District's (PUD) Habitat Conservation Plan (HCP) in 2004 for operation of Rocky Reach and Rock Island Dams. The HCP's objective is to achieve No Net Impact to HCP species (i.e., spring Chinook Salmon, summer Chinook Salmon, Sockeye Salmon, Coho Salmon and steelhead) while operating the two dams. No Net Impact is achieved by measuring and maintaining juvenile and adult survival at the two dams, monetary contribution to aquatic habitat improvement projects, and salmonid population supplementation via hatchery production. Lake Wenatchee Sockeye Salmon (*Oncorhynchus nerka*) is one of only two lakes producing self-sustaining populations of Sockeye Salmon within the entire Columbia River watershed. In 2011, however, hatchery supplementation of Sockeye Salmon was terminated as a result of non-significant increases in escapement, natural-origin (N-O) recruits, and productivity.

Lake Wenatchee is an oligotrophic lake in Chelan County, Washington (USA) that drains through the 85 km Wenatchee River into the Columbia River near Wenatchee, Washington (Figures 1 and 2). The lake has an approximate area of 10.1 km^2, a volume of roughly 0.44 km^3, an average depth of 45 m, a maximum depth of 74 m (Figure 3) and is situated around 570 m elevation. The Little Wenatchee River and the White River drain into the western corner of the Lake and offer suitable spawning habitats for Sockeye Salmon (Figure 2).

In the fall, Sockeye Salmon spawn in the tributaries to Lake Wenatchee and, in the subsequent spring, juveniles emerge as fry from the gravel and move into the lake. The majority of juveniles rear in the lake as parr for approximately one calendar year, although a small but unknown proportion of parr stay in the lake for an additional year. Most parr transition into smolts and emigrate from Lake Wenatchee in the following spring and early summer. Wenatchee smolts must traverse eight hydroelectric dams and over 600 km of natural and modified riverine habitats (in the Wenatchee and Columbia Rivers) before reaching the Pacific Ocean (Figure 1). Sockeye Salmon spend between one and five years in the marine environment before migrating back to Lake Wenatchee, spawning and completing their semelparous life cycle. For each cohort of Sockeye Salmon, marine mortality is accrued over time and these mortality rates vary considerably between years as environmental conditions are continually changing.

Lake Wenatchee Sockeye Salmon are monitored at several stations along the Wenatchee River. Adults migrating upstream are enumerated and identified as hatchery-origin (H-O) or N-O at Tumwater Dam (TUM) based on presence/absence of adipose fin clips[1]. The construction of TUM was completed in 1909 and video-based salmonid counts at the dam's fishway were implemented in 1989 (Hatch and Schwartzberg 1990). Juvenile abundances were estimated from rotary smolt traps (RST) and acoustic trawl surveys (ATS). These corresponding adult and juvenile abundance metrics are used to develop two independent estimates of SAR.

[1] During hatchery operations (prior to 2011), broodstock were also collected at Tumwater Dam (Hillman et al., 2022).

STUDY PURPOSE

The purpose of this report is to compile annual estimates of juvenile, N-O[2] Wenatchee Sockeye salmon abundance and the resulting total adult N-O Wenatchee Sockeye returns, for derivation of two indices of annual 'marine survival', commonly referred to as the Smolt-to-Adult Recruits (SAR) ratio (Equation 5).

The two SAR indices are based on the same annual estimates of total Wenatchee Sockeye adult returns to the Columbia River in the numerator but differ in the juvenile abundance index supplied in the denominator of the equation.

The first index is based on populating the denominator with annual smolt abundance estimates obtained from RST data in Wenatchee River during the spring outmigration period. A secondary SAR index is based on populating the denominator with annual pre-smolt estimates obtained from acoustic trawl surveys in Wenatchee Lake during the fall-winter period prior to spring outmigration. The second SAR index is useful for comparison to other Sockeye stocks (e.g., Osoyoos Sockeye (Bailey et al. 2023)) for which smolt estimates are not available.

Assembly of annual SAR estimates by smolt outmigration year (*smolt year*) enables various covariation analyses for *marine survival* as a function of biological and environmental factors associated with the year of ocean entry. Biological factors might include salmon population traits, such as smolt size and migration timing. Environmental factors might include freshwater discharge and temperature, and marine conditions such as sea surface temperature, salinity, planktonic abundance and ichthyo-community indices.

[2] For the purposes of this study, hatchery-origin (H-O) Sockeye salmon are excluded from analyses wherever possible. Explicit statements are made whenever H-O Sockeye cannot be deducted from overall abundance estimates.

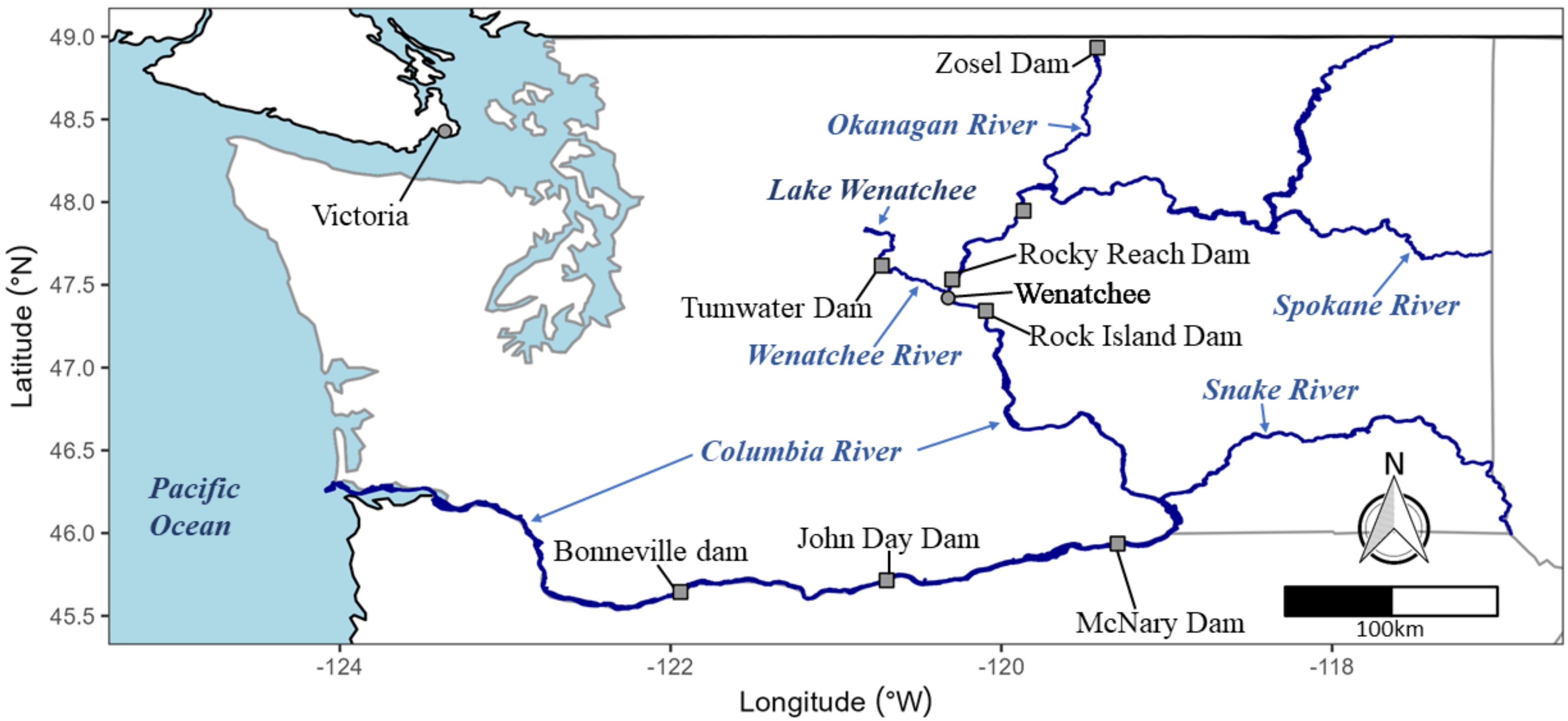

Figure 1. Map of Washington State, USA with features relevant to this study labelled. Water bodies are indicated by dark blue lines and corresponding blue, italicized text labels. Also labelled are cities (black and gray circles), hydroelectric dams (black and gray squares), state borders (pale gray lines), and the Canada-USA border (black line). Note that only hydroelectric dams directly mentioned in this study are shown. Shape files used to make this figure were obtained from the Washington Geospatial Open Data Portal (https://geo.wa.gov/) on January 12th, 2023. The R packages `ggsn v0.5.0` (Baquero 2019), `mapdata v2.3.1` (Deckmyn 2022), `maptools v1.1-6` (Bivand et al., 2022) and `ggspatial v1.1.7` (Dunnington et al., 2022) were used to construct this figure.

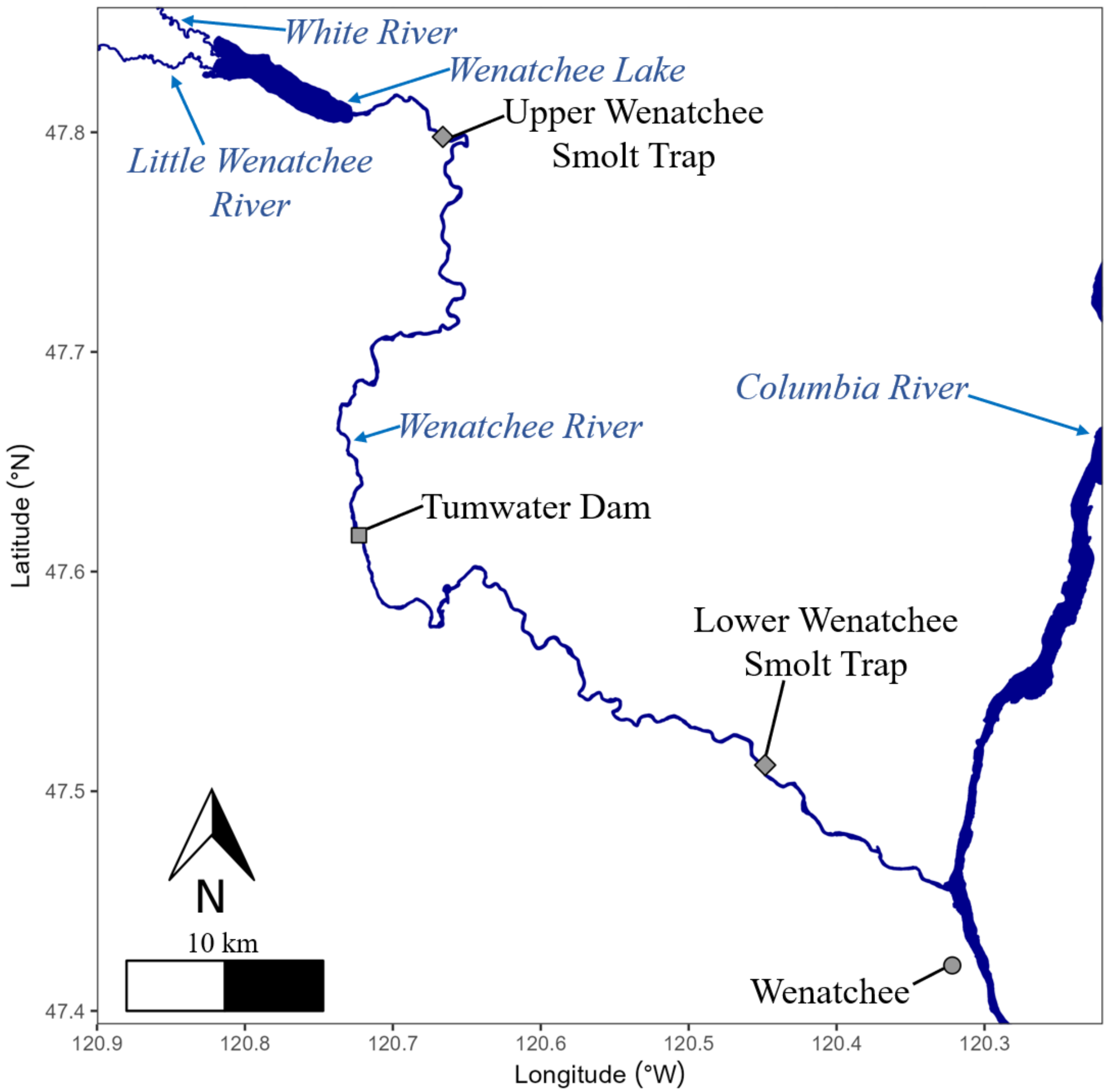

Figure 2. The Wenatchee River Watershed, Washington, USA. Water bodies are indicated by dark blue lines and corresponding blue, italicized text labels. Also labelled are cities (black and gray circles), hydroelectric dams (black and gray squares) and smolt traps (black and gray diamonds). Shape files used to make this figure were obtained from the Washington Geospatial Open Data Portal on January 12th of 2023. The same suite of R packages was used to create this figure as in Figure 1.

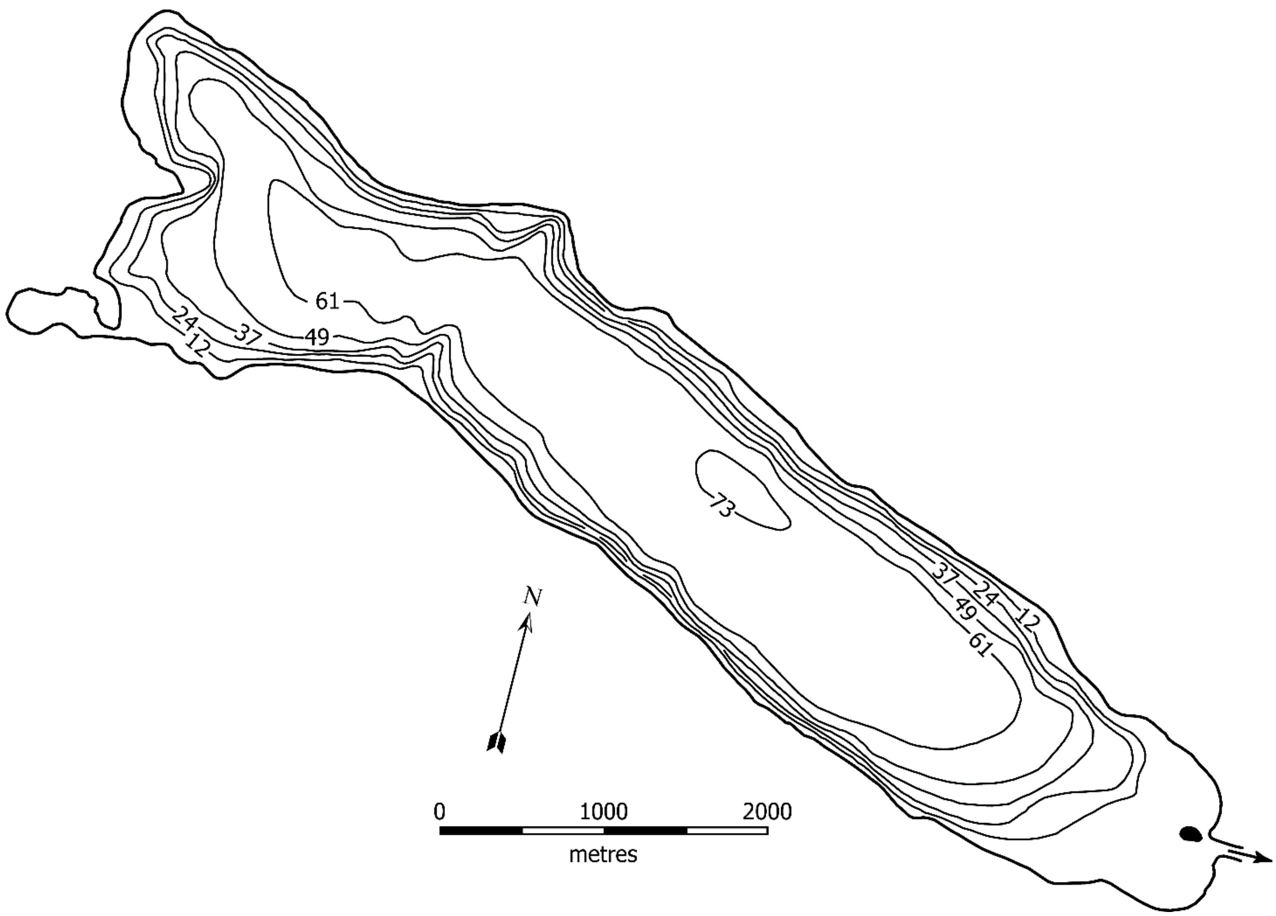

Figure 3. Bathymetric map of Lake Wenatchee Washington USA. Depths are in meters. Adapted from Dion et al., 1976.

METHODS

ADULT SOCKEYE SALMON RETURNS

Estimates of Wenatchee-bound N-O Sockeye Salmon returning to the mouth of the Columbia River were primarily derived from Tumwater Dam fish passage counts plus estimated downstream mortalities of Wenatchee Sockeye (Equation 3), based on the following data:

1. Total annual fish passage estimates at Tumwater Dam (TUM; 1989-2021), which include:
    a. Broodstock removals for hatchery operations (1989-2011)
    b. Recreational harvest estimates above Tumwater Dam (available years, 2001-2021)
2. Stock composition estimates derived from Sockeye passage count ratios between Rock Island (RIS) and Rocky Reach (RRH) dams (1977-2021), which are used to apportion the following aggregated annual time-series to stock:
    a. Mainstem Columbia harvest (Commercial Zones 1-5 (commercial) and Tribal Zone 6) (1980-2021; Joint Staff Report 2021)
    b. Natural mortality downstream of Tumwater Dam, including:
        i. Natural mortality between Bonneville Dam (BON) and Rock Island Dam
        ii. Natural mortality between the Columbia/Wenatchee confluence and Tumwater Dam

STOCK COMPOSITION

The proportion of the aggregate mainstem Sockeye harvest and natural mortality estimates attributable to Lake Wenatchee was estimated from the annual ratio of dam counts between Rock Island (RIS; downstream of the Wenatchee and Columbia River confluence) and Rocky Reach (RRH; upstream of the Wenatchee River confluence) dam counts (Equation 1) (Buchanan and Gosselin, 2023). In some years, however, the annual passage of Sockeye at Tumwater Dam (TUM) was greater than the estimated numbers based on the proportion of Wenatchee-bound fish from Equation 1 for unknown reasons, but likely due to a combination of errors associated with dam counts, harvest, and fall-back rates (Catherine Willard, *pers. comm*). Adult Sockeye fall-back estimates from PIT-tag (Passive Integrated Transponder tag) studies suggest that fall-back rates are typically highest at Bonneville Dam, whereas rates at upstream dams are generally lower (Naughton et al., 2006). However, fall-back rates vary between years and are likely influenced by environmental conditions (e.g., Boggs et al., 2004; Naughton et al., 2006; Fryer et al., 2007). To address this issue, the Wenatchee stock composition estimate was annually set to the maximum of either:

$$P(Wenatchee) = 1 - {}^{\Sigma RRH_t}/_{\Sigma RIS_t} \quad \text{(Eq. 1)} \qquad \text{or} \qquad P(Wenatchee) = {}^{\Sigma TUM_t}/_{\Sigma RIS_t} \quad \text{(Eq. 2)}$$

Where *t* is return year. Equation 2 reflects an alternative stock composition estimate derived from the ratio of Sockeye Salmon at TUM vs. RIS. Stock composition estimates from equations 1 and 2 are calculated and the larger estimate is retained to ensure that count differences between dams remain positive in the upstream direction.

The proportion of Sockeye bound for Lake Wenatchee was multiplied by the sum of mainstem Columbia River harvest and natural mortality estimates to calculate the number of Wenatchee recruits that failed to pass TUM. Mainstem harvest estimates were provided by the Joint

Columbia River Management Staff (Joint Staff Report 2021). Natural mortality along the mainstem was estimated as the difference between counts at Bonneville dams and Rock Island (after adjusting dam counts to reflect 24-hour monitoring periods, see Appendix 3) and accounting for Zone 6 harvest and the passage of Snake River Sockeye at Bonneville Dam (also from Joint Staff Report 2021). Notably, this method yields erroneously negative natural mortality estimates for 1995, 1999 and 2007 for which RIS counts are 4 - 13% greater than BON counts. As meta-data were unavailable to explain these differences, we increased the Bonneville Dam counts for these years by the expected natural mortality rate between BON and RIS (14.9 ± 9.5%), which was estimated as the mean percent difference between the 24-hour (adjusted) BON and RIS Sockeye counts for the years 1977-1994, 1996 - 1998, and 2008 - 2019, after adjusting for Zone 6 harvest and the passage of Snake River Sockeye.
Together, the above data are compiled annually and used to estimate the total number of Wenatchee-bound adult Sockeye to the mouth of the Columbia River by evaluating the following equation:

$$\begin{matrix} Wenatchee \\ returns \end{matrix} = TUM + P(Wenatchee) \cdot \begin{pmatrix} Zones\ 1\text{-}6 \\ harvest \end{pmatrix} + \begin{matrix} Mainstem \\ mortality \end{matrix} \qquad \text{(Eq. 3)}$$

Where *Mainstem mortality* refers to the natural mortality of adults migrating up the Columbia River mainstem between BON and RIS, and P(*Wenatchee*) is the proportion of the aggregate Sockeye stock attributable to Lake Wenatchee. This method reflects our best estimate of the abundance of Wenatchee-bound adult Sockeye Salmon returning to the Columbia River.

ADULT SOCKEYE ESCAPEMENT

For this report, we detail two escapement estimates: i) run escapement, and ii) spawning escapement. The former escapement estimates (1989 – 2021) were derived from deducting recreational harvest whenever applicable (2001 – 2021) and broodstock collections (1989-2011) from aggregate (H-O and N-O) Tumwater Dam counts (Appendices 1 and 2). The latter spawning escapement estimates are provided by Chelan PUD, which rely on a combination of area-under-the-curve (AUC) and capture-mark-recapture (CMR) models (Hillman et al., 2022). These escapement estimates are separated in both space and time, as the run escapement data are collected at Tumwater Dam while fish are migrating upstream and run escapement data are collected on the terminal spawning grounds later in the fall. Consequently, the spawning escapement values are generally lower than the run escapement estimates obtained at Tumwater Dam. However, these estimates are strongly correlated ($R^2 = 0.91$, $p < 0.001$; $n = 16$), and thus can be used to extend spawner escapement estimates backwards in time (Appendix 2). For all subsequent analyses, however, we use Tumwater Dam-count based run escapement estimates as this time series is longer and more consistent methodologically.

ADULT SOCKEYE MIGRATION AND BIOMETRICS

Adult Sockeye salmon migration timing was monitored from 1998 to 2021 by video at Tumwater Dam and all migrating fish were enumerated and classified as N-O or H-O based on the presence or absence of an adipose fin, respectively (Table 4 and Table A5). Migration timing data are detailed in Appendix 5 (Figure A4 and Table A5). Starting in 1994, annual biosampling was conducted to collect scales from adult N-O Sockeye. Scale data were used to estimate the age of sampled individuals, the approximate age composition of the returning cohort (Table 1), and whether returning individuals were of natural or hatchery origin. All samples were processed by the Washington Department of Fish and Wildlife. Furthermore, individual adults were measured to estimate average individual sizes and size-at-age estimates (Appendix 6).

JUVENILE SOCKEYE ABUNDANCE AND AGE COMPOSITION

Juvenile Sockeye abundances were estimated in two ways: i) emigrating smolt age and abundance were estimated from captures at rotary screw traps (RSTs) along the Wenatchee River (Figure 2), and ii) acoustic-trawl surveys (ATS) were employed in the winter to estimate the in-lake abundance of presmolts as a proxy for smolt abundance given that overwinter mortality rates in their final freshwater winter are typically low (Hyatt et al., 2017). We provide data and methods for both methodologies, as each method has varying biases and the length of each time series differs considerably (Table 3). For instance, the relocation of the Wenatchee River RST and the subsequent changes in age composition (Table 3) and the 7-fold difference in variance in the population size estimates (two sample variance F-test; F = 6.9, $p = 0.013$) indicate that the RST smolt data may not be a consistent indicator of juvenile abundance. Indeed, the estimated abundance of emigrating smolts is statistically unrelated to the abundance index derived from the ATS data (Appendix 7). Furthermore, ATS methods are standardized throughout much of the Okanagan basin and thus permit comparisons with other systems, such as Osoyoos Lake (e.g., Hyatt et al., 2018). We therefore outline each methodology and calculate SAR using both metrics of juvenile abundance.

WENATCHEE RIVER SMOLT TRAPS

Smolt abundance data (1997-2011) were adopted from Hillman et al., 2022. Smolt abundances were monitored at the Upper Wenatchee River RST prior to 2012 and 68 km downstream at the Lower Wenatchee River RST beginning in 2013 (Figure 2). Rotary smolt traps were not operated in 2012. Smolt RST are typically monitored daily between February and July (Hillman et al., 2022; Appendix C) (Appendix 8; Figure A6). Smolt trap monitoring follows the standardized basin-wide monitoring plan developed by the Upper Columbia Regional Technical Team for the Upper Columbia Salmon Recovery Board (UCSRB; Hillman 2004, adapted from Murdoch and Petersen 2000). The RST operates 24 hours per day, although traps are occasionally closed as a result of mechanical failure, human activities, large hatchery releases, and environmental conditions (e.g., extreme flow or temperature).

At a minimum of once a day, all fish collected in the RST were enumerated, weighed, measured (fork length), scales collected for age analysis, PIT-tagged and classified by origin (hatchery or wild) (Table 4). Mark-recapture trials were utilized to determine trap efficiencies at different flows by releasing groups of PIT-tagged smolts upstream during a range of stream discharges to determine trap efficiencies under the varied flow regime. Emigration estimates were calculated using daily trap efficiencies derived from a regression formula for trap efficiency as a function of river discharge rate. The Bailey estimator (recaptures + 1) was used to correct for some bias in the calculation of trap efficiency. If a significant relationship ($R^2 > 0.5$ and $p < 0.05$) could not be found, a pooled trap efficiency estimate was used to estimate the number of emigrating Sockeye Salmon smolts (Hillman et al., 2022).

During minor breaks in operation (less than seven days), the number of individual fish collected at the RST was estimated. This estimate was calculated using the mean number of fish captured two days prior and two days after the break in operation. For major breaks in operations (greater than seven days), an estimate based on historical run timing was developed. This estimate of daily capture was incorporated into the overall emigration estimate.

In 2012, Wenatchee Lake smolts were not trapped or counted as the trap had not yet been moved to the Lower Wenatchee trap site (Figure 2). To estimate these missing values, we used the following procedure: Based on age-composition data all smolts were assigned to their respective brood year (i.e., missing data are age-1 in BY2011 and age-2 in BY2010). Then, the average ratios between age-1 and age-2 Sockeye were estimated using the entire time series (n = 21) except for BY1996, which presented an uncharacteristically low ratio between age classes. Given that the missing age-specific data are offset by a full brood year, the multi-year average ratio between ages by brood year was used to impute the missing abundance values for each age. Note that only age-1 and age-2 smolt abundances were estimated as the relative abundances of age-3 smolts were small (< 0.1%). An example of this process can be expressed as:

$$Age\text{-}1\ smolts_{BY2011} = (Total\ Smolts_{BY2011}) \cdot (Average\ Age\text{-}1\ Proportion) \quad \text{(Eq. 4a)}$$

$$Age\text{-}2\ smolts_{BY2010} = (Total\ Smolts_{BY2010}) \cdot (Average\ Age\text{-}2\ Proportion) \quad \text{(Eq. 4b)}$$

ACOUSTIC TRAWL SURVEY

Multiple acoustic trawl surveys (ATS) are employed between June and the following March in Lake Wenatchee (2010-2020) to estimate the abundance of parr and presmolt Sockeye salmon (McQueen et al., *in prep*). The mean of the June – September ATS data may be used to estimate summer parr abundances, while the fall-winter (October – February) surveys are used as a proxy for the abundance of emigrating juveniles (Hyatt et al., 2018). Acoustic-trawl surveys were conducted on average three times per winter since 2011 (raw data available from McQueen and Pham, 2023). In brief, fish densities were estimated from echo-integration analyses and trawl samples, where size-frequency distributions and acoustic signals were used to estimate the density of nerkids of several age classes (methods detailed in MacLennan and Simmonds, 1992 and Hyatt et al., 2017). Given that overwinter mortality rates are generally low for juvenile Sockeye Salmon (Hyatt et al., 2017), these presmolt abundance estimates are a suitable proxy for the abundance of emigrating smolts in the following spring.

MARINE SURVIVAL: SMOLT-TO-ADULT RETURNS

Derivation of “marine survival” generally involves calculating the proportion of annual smolt production (i.e., the total abundance of juveniles entering the ocean) that recruit to the adult life stage in the marine environment – prior to harvest mortality – to become potential spawners.

As marine fisheries for adult Columbia Sockeye salmon are considered negligible in recent decades (R. Bussanich, ONA Fisheries, *unpub. data*)[3] and zero Lake Wenatchee Sockeye Salmon adults were estimated to have been harvested between 1989 to 2016 (Hillman et al., 2022), total annual adult returns to the mouth of the Columbia River would serve as the numerator in the calculation, if these data existed. However, in the absence of (a) marine harvest data; (b) population count data at the mouth of the Columbia River[4], and (c) downstream smolt

[3] Marine harvest of Columbia Sockeye salmon is considered negligible and has not factored into past marine mortality analyses (Fryer 1995; Fryer et al. 2010; Williams et al. 2014).
[4] The closest salmon counts occur at the Bonneville Dam, approximately 235 km upstream of the mouth of the Columbia.

mortality (in the Columbia mainstem)[5], the “marine survival” indices derived in this study more accurately constitute an index of Smolt-to-Adult Returns (SAR).

Given the above data limitations, two SAR indices are proposed in this study in the form:

$$SAR_t = \sum_{a=1}^{n} Recruits_t \;/\; \sum Juveniles_t \qquad \text{(Eq. 5)}$$

where:

- *t* = outmigration year, and
- *a* = ocean age (1 to *n*) of adult recruits that migrated seaward in year *t.*

The two SAR indices are based on the same annual estimates of total Wenatchee Sockeye adult returns to the Columbia River in the numerator (see section *Adult Sockeye Returns*)[6] but differ in the juvenile abundance index supplied in the denominator of the equation:

1. The first juvenile abundance index is based on annual smolt abundance estimates (all ages combined) obtained from rotary screw trap (RST) data in Wenatchee River during the spring outmigration period. As mentioned above, this time-series extends from 1997 to present (25 years), but may be limited for SAR index purposes for several reasons:
    a. The juvenile abundance data are characterized by a change in physical location as of 2012, with undeterminable differences in sampling efficiency due to a lack of inter-site calibration[7];
    b. Estimated smolt population sizes become increasingly imprecise over time, with recent estimates having very large confidence intervals that differ from mean abundance estimates by an average of 750% (Table 3).

2. A secondary SAR index is based on populating the denominator with an index of annual pre-smolt abundances obtained from ATS in Lake Wenatchee during the fall-winter period prior to spring outmigration. The second SAR index is useful for comparison to other Sockeye stocks (e.g., Osoyoos Sockeye (Bailey et al. 2023)) for which ATS data are available but smolt trap data are not. Note that the Wenatchee Sockeye pre-smolt-to-adult time-series is currently limited to 2011-present (10 years), of which one year (2010-2011) was characterized by a single fall survey in September.

The principal assumption associated with using pre-smolt data for SAR estimation is that mortality between the in-lake fall-winter pre-smolt life-stage and the outmigrating spring smolt stage is low. However, this assumption is difficult to evaluate in any given year without extensive pre-smolt (in-

[5] Future studies may wish to assess smolt survival along the mainstem of the Columbia to get a better understanding of survival to and from the mouth of the Columbia River. Data from PTAGIS, for example, may provide useful mainstem survival estimates based on PIT-tag recapture data.
[6] Because the Tumwater Dam counts comprise the longest and methodologically most consistent time series of adult Wenatchee Sockeye counts and are more akin to a census-type population size estimate as almost all adults traversing the dam are counted (see section Escapement Estimate Method I, above), we use these values in conjunction with expected Wenatchee stock removals due to harvest and natural mortality downstream of Tumwater in the Columbia River in our estimation of Wenatchee Sockeye SAR.
[7] The two segments of the smolt RST data may be considered similar but unique and likely incompatible components of juvenile abundance, yielding two discontinuous indicators of SAR in conjunction with adult returns. Caution should be used in interpretation of the data as a continuous time-series from 1997-2021.

lake) and smolt (in-river) survey data. Furthermore, the pre-smolt-based survival index demonstrated consistently lower survival than the same index calculated from smolt abundances (mean difference (2012-2018): 5.9%, Table 2), it is difficult to know how to attribute these large differences in survival without perfect knowledge of the numbers of fish at each life stage. For example, these data suggest large mortality rates between the pre-smolt and smolt life stages, but likely also reflect significant differences or bias in one (or both) of the juvenile abundance index methods.

Temporal variation in the above SAR estimates is characterized with a series of regime shift analyses (Rodionov 2004) that identify persistent changes in the mean or variance of SAR (or its component smolt and adult abundance indices) throughout each available time series (Appendix 9).

RESULTS

Age 1.2 and Age 1.3 are the dominant age classes of adult Sockeye returning to Lake Wenatchee. Age 3.1 individuals are only observed in some years and generally comprise the least common age class.

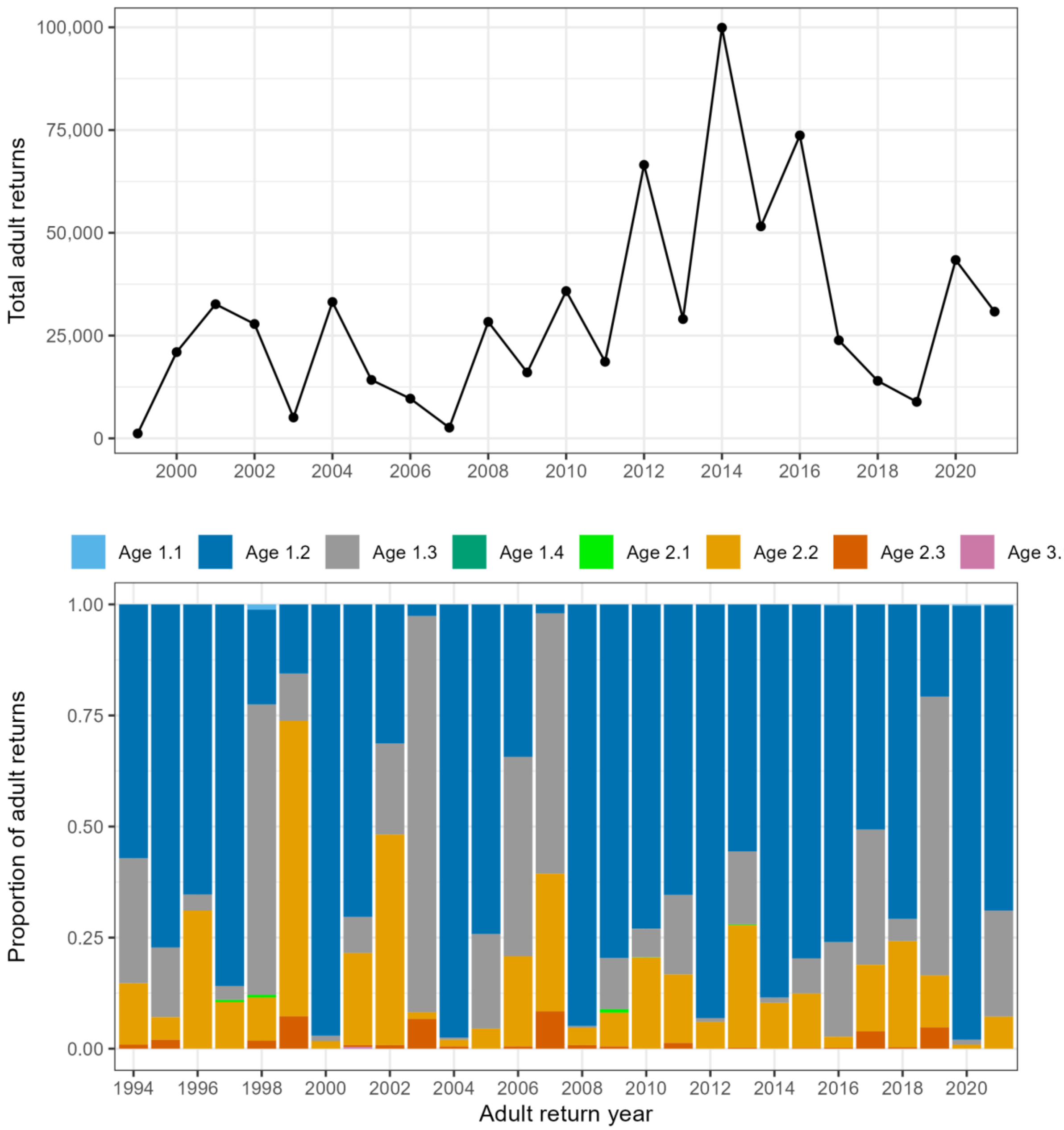

Figure 4. Age composition of adult Sockeye Salmon after returning to Lake Wenatchee. Visualized are abundances per age class (top) and the relative proportions of each age class (bottom). Individuals were sampled from fish ladders, dead pitch and broodstock collection. Age estimates were obtained from otolith analyses.

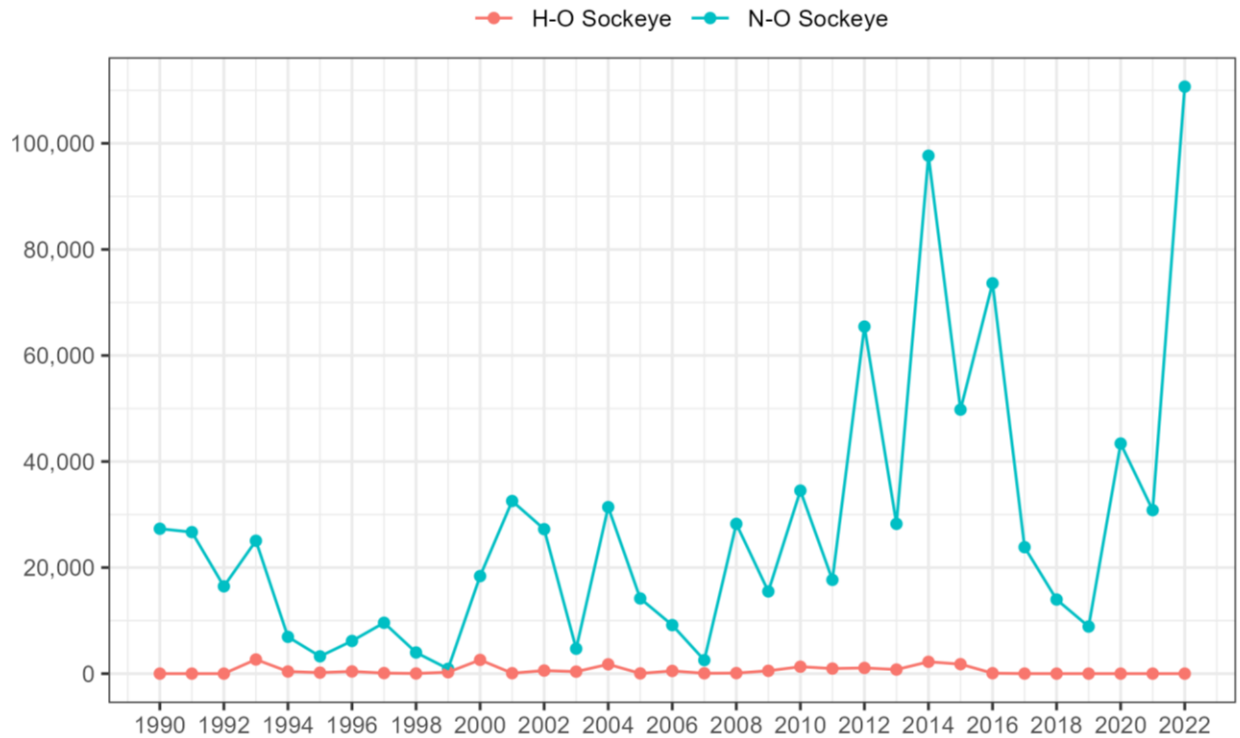

Figure 5. Natural-origin (blue) and hatchery-origin (salmon) Sockeye abundance estimates at Tumwater Dam for return years 1989 to 2021. N-O and H-O Sockeye were counted from video and adipose fin clips were used to identify H-O adults. In most years, hatchery-origin adults comprised a small fraction (mean 3%, range 0-10%, RY1993-2015) of the total returning Sockeye salmon.

Table 1. Annual age composition of adult, N-O Sockeye Salmon on the spawning grounds. Ages are presented as European ages with equivalent Gilbert-Rich ages in parentheses. Age composition percentages were inferred from scale samples taken from a subset of broodstock individuals, dead pitch carcasses, and adults trapped at ladders. Abundances are annual run escapement estimates derived from Tumwater dam counts after accounting for upstream harvest and broodstock removals (Appendix 1). Both the numbers of individuals (*n*) and the annual, age-specific percentage of the population (%) are presented.

Adult return year	Age																Total
	1.1 (3_2)		1.2 (4_2)		2.1 (4_3)		1.3 (5_2)		2.2 (5_3)		1.4 (6_2)		2.3 (6_3)		3.1 (5_4)		
	n	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	*n*	%	
1994			4,083	57.8			1,917	27.1	994	14.1	0	0	71	1.0	0	0	7,065
1995			2,517	77.7			493	15.2	176	5.4	0	0	53	1.6	0	0	3,239
1996			4,132	65.1			177	2.8	2,037	32.1	0	0			0	0	6,346
1997			8,161	86.2	54	0.6	218	2.3	1,034	10.9	0	0			0	0	9,467
1998	53	1.4	829	21.7			2,514	65.7	348	9.1	0	0	80	2.1	0	0	3,824
1999			168	16.4			126	12.3	639	62.3	0	0	91	8.9	0	0	1,024
2000			20,169	97.0			246	1.2	369	1.8	0	0			0	0	20,784
2001			21,634	74.3			1,159	4.0	6,181	21.2	0	0	129	0.4	0	0	29,103
2002			9,518	34.5			3,337	12.1	14,462	52.5	0	0	247	0.9	0	0	27,564
2003			193	4.0			4,316	88.9	116	2.4	0	0	231	4.8	0	0	4,856
2004			26,953	97.8			151	0.5	452	1.6	0	0			0	0	27,556
2005			10,401	74.2			2,923	20.9	688	4.9	0	0			0	0	14,012
2006			3,129	33.2			4,470	47.4	1,788	18.9	0	0	50	0.5	0	0	9,437
2007			56	2.4			1,351	56.8	788	33.1	0	0	183	7.7	0	0	2,378
2008			21,869	94.2			103	0.4	1,032	4.4	0	0	206	0.9	0	0	23,210
2009			10,951	81.2	87	0.6	1,301	9.6	1,084	8.0	0	0	65	0.5	0	0	13,488
2010			23,080	73.3	34	0.1	1,881	6.0	6,497	20.6	0	0			0	0	31,492
2011			12,710	69.0			2,330	12.6	3,178	17.2	0	0	212	1.1	0	0	18,430
2012			50,642	93.1			404	0.7	3,367	6.2	0	0			0	0	54,413
2013			12,570	55.3	59	0.3	3,642	16.0	6,403	28.2	0	0	59	0.3	0	0	22,733
2014			74,125	88.6			1,083	1.3	8,412	10.1	0	0			0	0	83,620
2015			34,627	79.3			3,655	8.4	5,322	12.2	0	0	64	0.1	0	0	43,668
2016	121	0.2	45,119	76.4			12,129	20.5	1,577	2.7	0	0	121	0.2	0	0	59,067
2017			11,962	50.1			7,361	30.9	3,610	15.1	0	0	920	3.9	0	0	23,853
2018			9,884	70.7			689	4.9	3,362	24.1	0	0	41	0.3	0	0	13,976
2019			1,855	20.9			5,500	62.0	1,087	12.2	0	0	435	4.9	0	0	8,877
2020	88	0.2	35,046	97.8			439	1.2	263	0.7	0	0			0	0	35,836
2021	24	0.1	17,525	67.9			6,347	24.6	1,923	7.4	0	0			0	0	25,819

Age composition of N-O sockeye smolts emigrating from Lake Wenatchee. Age composition data were obtained from samples at the Upper and Lower Wenatchee River smolt trap (pre- and post-2012, respectively; Figure 2). These data indicate that smolts emigrating from Lake Wenatchee are predominantly age-1 individuals, although in some years (e.g., 2005) age-2 individuals can make up a large proportion of smolt population. Methodological changes may explain why fewer age-2 individuals are observed after 2012.

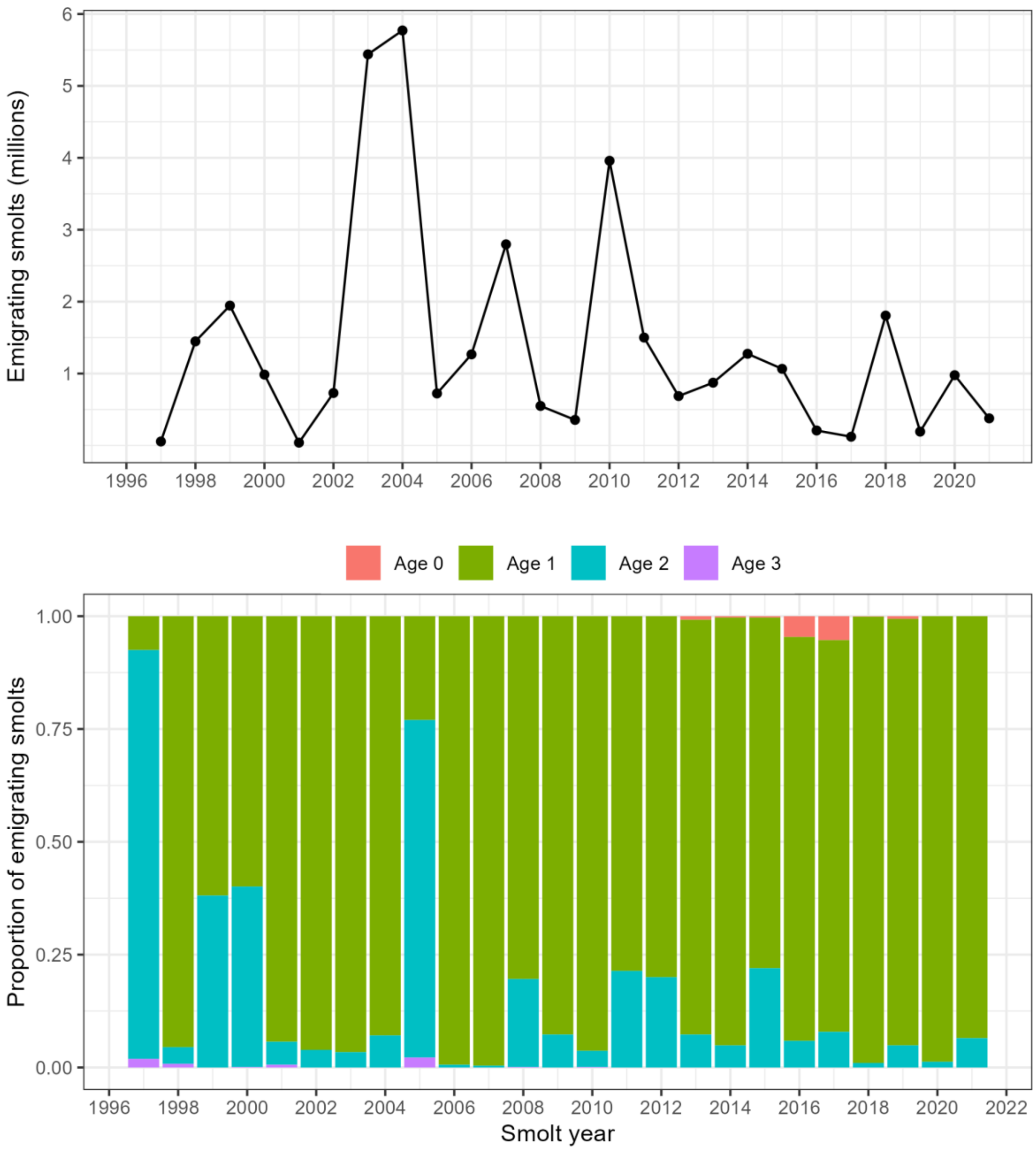

Figure 6. Age composition of N-O smolts emigrating out of Lake Wenatchee between 1997 and 2021. Smolt abundances (top) were estimated from rotary screw traps along the Wenatchee River. The bottom plot shows illustrates the relative proportions of each smolt age class over time. Across all years, age-1 smolts are generally more abundant than their age-2 counterparts.

Smolt trap data were not collected in 2012. Furthermore, the last cohort of H-O fish produced from the Lake Wenatchee Hatchery were released into the lake in 2012. Consequently, these H-O fry would have predominantly emigrated as age-1 smolts in the spring of 2013. However, the Lower Wenatchee River smolt trap caught very few H-O smolts in 2013, and thus the abundance of H-O smolts could not be estimated.

Figure 7. Annual N-O and hatchery-origin (H-O; blue) smolt abundance estimates derived from rotary screw trap data (1997 to 2021). No regime shifts were detected. Production and release of hatchery-origin smolts was terminated in 2012. Only in 2001 did hatchery smolt production exceed natural smolt production. Smolt trapping prior to 2011 was conducted at the Upper Wenatchee River smolt trap (green) and trapping after 2012 was conducted at the Lower Wenatchee River smolt trap (red) (Figure 2). Smolt trapping was not conducted on the Wenatchee River in 2012 (gray vertical line). Hatchery smolt abundances are shown separately (bottom panel).

Table 2. Marine survival estimates for Lake Wenatchee N-O Sockeye Salmon. All values are aligned by smolt migration year. Smolt abundance estimates were obtained from i) rotary screw traps situated at the Lower Wenatchee Smolt Trap (post-2011) and the Upper Wenatchee Smolt Trap (pre-2011), and ii) acoustic trawl survey data, which provides an index of the abundance of pre-smolts holding in the lake prior to smoltification. In smolt migration years 2011 and 2012, an unknown number of H-O juveniles are included in the pre-smolt abundance estimates, whereas all other data presented here are exclusively from N-O individuals. Smolt to Adult Returns (SAR) is expressed as the percentage of a smolt cohort that returned to the mouth of the Columbia River as adults.

Smolt migration year	Total Adult Returns	Smolt trap estimates		Pre-smolt ATS data		
		Smolt abundance	SAR (%)	Pre-smolt abundance	Pre-smolt surveys	SAR (%)
1997	1,324	55,359	2.39%			
1998	25,853	1,447,259	1.79%			
1999	40,273	1,944,966	2.07%			
2000	30,629	985,490	3.11%			
2001	603	39,353	1.53%			
2002	40,072	729,716	5.49%			
2003	16,432	4,166,299	0.39%			
2004	7,221	5,771,187	0.13%			
2005	1,247	723,413	0.17%			
2006	34,318	1,266,971	2.71%			
2007	19,501	2,797,313	0.70%			
2008	44,461	549,682	8.09%			
2009	19,324	355,549	5.43%			
2010	88,761	3,958,888	2.24%			
2011	29,721	1,500,730	1.98%	1,462,558	1	2.03%
2012	115,545	686,900	16.82%	2,110,968	2	5.47%
2013	108,854	873,096	12.47%	2,833,833	1	3.84%
2014	77,158	1,275,027	6.05%	2,627,589	1	2.94%
2015	20,579	1,065,614	1.93%	1,641,864	2	1.25%
2016	21,961	208,250	10.55%	2,319,234	2	0.95%
2017	3,723	121,825	3.06%	1,153,551	1	0.32%
2018	64,800	1,806,164	3.59%	2,196,903	3	2.95%
2019	36,780	192,512	19.11%	1,251,618	2	2.94%

Note that from 2019 to 2021, smolt trap abundance estimates have very low levels of precision (Table 3 below, from Hillman et al., 2022).

Table 3. Abundance and age-composition of N-O and H-O Sockeye smolts emigrating from Lake Wenatchee. Blank cells indicate that data were unavailable. Estimated values are presented in italics (see Methods for more details). Age composition data were unavailable for Hatchery-origin smolts. The Lake Wenatchee hatchery program was terminated in 2011. Note that the smolt monitoring site changed in 2013, from the Upper Wenatchee River Smolt Trap location to the lower Wenatchee River Smolt Trap (Figure 2). The 95% confidence intervals in 2019-2021 exceeded the annual total N-O smolt abundance estimates by an average of 750%. The proportions of N-O and H-O smolts are presented in greater detail in Table 10.

Smolt migration year	Natural-origin smolts						Total Hatchery-origin smolts
	Age-0	Age-1	Age-2	Age-3	Total	95% CI	
1997		4,152	50,155	1,052	55,359	NA	22,828
1998		1,382,132	53,549	11,578	1,447,259	NA	55,985
1999		1,203,934	741,032	0	1,944,966	NA	112,524
2000		590,309	394,196	985	985,490	NA	24,684
2001		37,110	2,007	236	39,353	NA	94,046
2002		701,257	28,459	0	729,716	NA	121,511
2003		4,024,884	141,415	0	4,166,299	NA	140,322
2004		5,361,433	409,754	0	5,771,187	NA	216,023
2005		166,385	541,113	15,915	723,413	NA	122,399
2006		1,259,369	7,602	0	1,266,971	NA	159,500
2007		2,786,124	11,189	0	2,797,313	NA	140,542
2008		441,944	107,188	550	549,682	NA	121,843
2009		329,594	25,955	0	355,549	NA	119,908
2010		3,812,409	142,520	3,959	3,958,888	NA	126,326
2011		1,179,574	321,156	0	1,500,730	NA	159,089
2012[8]	NA	*549,406*	*137,493*	NA	*686,899*	NA	No program
2013	6,985	802,375	63,736	0	873,096	95,132	No program
2014	3,825	1,208,726	62,476	0	1,275,027	211,615	No program
2015	3,197	827,982	234,435	0	1,065,614	238,901	No program
2016	9,580	186,384	12,287	0	208,250	29,447	No program
2017	6,457	105,744	9,624	0	121,825	22,904	No program
2018	1,806	1,786,296	18,062	0	1,806,164	13,586,160	No program
2019	1,156	181,914	9,443	0	192,512	1,449,588	No program
2020	0	964,840	12,415	0	977,255	7,353,240	No program
2021	0	352,627	24,514	0	377,141	2,924,774	No program

[8] No RST smolt trapping in 2012. Missing data (italicized values) were estimated by aligning fish abundances to brood year and applying the multi-year mean proportions of each age class.

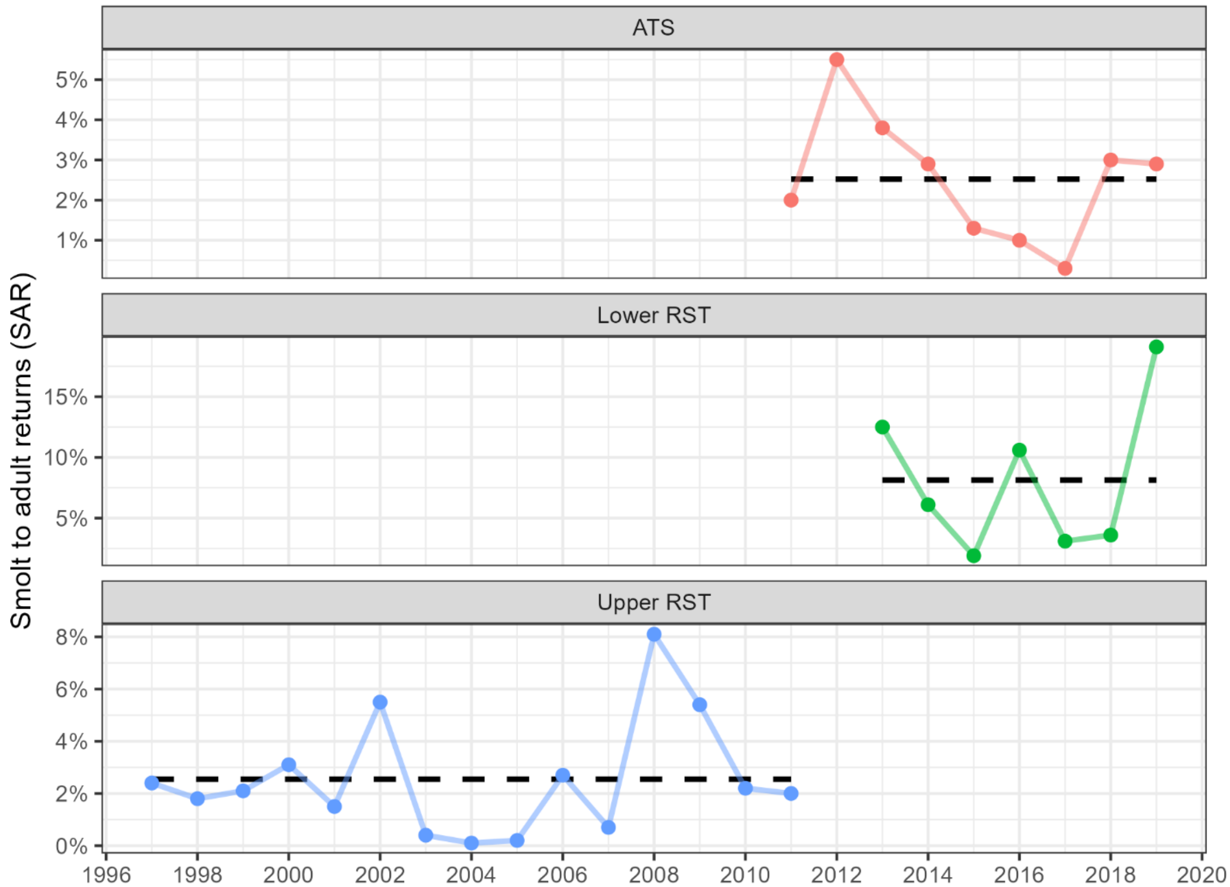

Figure 8. Annual Smolt to Adult Returns (SAR) for Lake Wenatchee Sockeye, SY1997-2019. SAR estimates were derived from the estimated abundance of N-O smolts emigrating from Lake Wenatchee (blue; bottom two panels) at separate smolt rotary-screw trap sites (upper and lower), or estimates of in-lake winter pre-smolt abundances obtained from acoustic trawl surveys (red; top panel), divided by the number of Wenatchee N-O adults returning to the mouth of the Columbia River for each smolt year. Note that the abundance of smolts for 2012 (from the smolt trap data) are imputed from age class proportions from corresponding brood years. The mean of each time series is illustrated by a gray, dashed horizontal line. SAR estimates using smolt trap data exhibit an apparent increase from an average of ~3 ± 2% prior to 2011, to an average of ~8 ± 6% between 2012 and 2019. Due to the significant difference in variances between the two time-periods ($F = Variance_{LATE} / Variance_{EARLY} = 6.9$, $p = 0.001$), and the methodological/locational changes in smolt trapping, there is low confidence in the concatenated SAR time-series as a consistent indicator of Wenatchee Sockeye smolt-to-adult return rates. However, interannual comparisons of SAR *within* the separate components of the time-series (1997-2011, 2013-2019) as a metric of annual variability should be valid.

CONCLUSIONS & RECOMMENDATIONS

Our data indicate that annual SAR estimates for Lake Wenatchee Sockeye Salmon are similar to those observed in Osoyoos Lake (Bailey et al., 2023) as they do not exhibit apparent regime changes over the last two decades, typically range between less than 1% and 19%, and are contingent upon abundance estimation methods (adults in Osoyoos, juveniles in Wenatchee). As H-O individuals historically comprised a small fraction of the Lake Wenatchee Sockeye stock, fluctuations in SAR are unlikely to be attributable to effects of hatchery supplementation. SAR estimates are highly contingent upon the method used for estimating smolt abundance, characterized by two distinct Wenatchee River RST smolt sampling locations and time periods (1997-2011 and 2013-2019) with no temporal overlap for the necessary cross-calibration of abundance data, which likely precludes our ability to make strong conclusions about a continuous, inter-annually comparable time-series indexing the abundance of emigrating smolts. Temporally disjunct time-series corresponding to the two RST site periods are available, however, but the resulting component SAR time series are therefore disjunct and relatively short. While no significant shifts in mean survival are observed within the component SAR time series, long-term patterns are likely undetectable as a result of methodological discontinuities.

To improve our ability to detect temporal patterns in Lake Wenatchee SAR, we suggest that annual juvenile population monitoring via ATS be continued indefinitely with multiple fall and winter surveys per year. An increase in the frequency of summer ATS would also enable derivation of annual spawner-to-parr survival estimates. A review of the efficacy of Wenatchee River rotary-screw trap operations for the purposes of annual smolt abundance estimation is also advised.

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APPENDICES

Appendix 1: Lake Wenatchee Sockeye escapement based on Tumwater Dam counts

Here, we follow the methods of Chelan PUD prior to 2006 (*sensu* Hillman et al., 2022), where run escapement is calculated as the number of adults returning to Tumwater Dam minus the number of fish collected for broodstock and fish recreationally harvested above Tumwater Dam (Table A1). Annual Sockeye totals at Tumwater Dam were retrieved from the Columbia Basin Data in Real Time (DART) web portal (Buchanan and Gosselin 2023), and broodstock collections are presented in Hillman et al., 2022 (Table 4.24). Recreational Sockeye harvest upstream of Tumwater Dam are reported by the Joint Columbia River Management Staff (2021). This method does not account for natural mortalities above Tumwater Dam.

Table A1. Run escapement estimation and components for N-O, H-O, and aggregate (H-O and N-O) Lake Wenatchee Sockeye Salmon.

Return year	Tumwater Dam Count			Harvest			Broodstock			Run escapement		
	Total	N-O	H-O	Total	N-O	H-O	Total	N-O	H-O	Total	N-O	H-O
1989	21,802	21,802	0	0	0	0	255	255	0	21,547	21,547	0
1990	27,325	27,325	0	6,523	6,523	0	316	316	0	20,486	20,486	0
1991	26,689	26,689	0	6,311	6,311	0	233	233	0	20,145	20,145	0
1992	16,461	16,461	0	3,565	3,565	0	343	343	0	12,553	12,553	0
1993	27,726	25,056	2,670	6,400	5,761	639	307	307	0	21,019	18,988	2,031
1994	7,330	6,931	399	0	0	0	265	260	5	7,065	6,671	394
1995	3,448	3,261	187	0	0	0	209	206	3	3,239	3,055	184
1996	6,573	6,160	413	0	0	0	227	227	0	6,346	5,933	413
1997	9,693	9,592	101	0	0	0	226	207	19	9,467	9,385	82
1998	4,014	3,984	30	0	0	0	190	184	6	3,824	3,800	24
1999	1,172	908	264	0	0	0	147	87	60	1,025	821	204
2000	20,979	18,390	2,589	0	0	0	195	190	5	20,784	18,200	2,584
2001	32,633	32,554	79	3,265	3,265	20	245	237	8	29,103	29,052	51
2002	27,821	27,241	580	0	0	0	257	257	0	27,564	26,984	580
2003	5,074	4,699	375	0	0	0	219	219	0	4,855	4,480	375
2004	33,167	31,409	1,758	5,410	4,981	429	202	202	0	27,555	26,226	1,329
2005	14,218	14,176	42	0	0	0	207	207	0	14,011	13,969	42
2006	9,657	9,150	507	0	0	0	220	220	0	9,437	8,930	507
2007	2,607	2,542	65	0	0	0	228	228	0	2,379	2,314	65
2008	28,340	28,240	100	5,057	4,849	21	260	258	2	23,210	23,133	77
2009	16,034	15,502	532	2,229	2,229	56	261	258	3	13,488	13,015	473
2010	35,821	34,519	1,302	4,129	3,716	413	201	201	0	31,491	30,602	889
2011	18,634	17,680	954	0	0	0	204	204	0	18,430	17,476	954

Return year	Tumwater Dam Count			Harvest			Broodstock			Run escapement		
	Total	N-O	H-O	Total	N-O	H-O	Total	N-O	H-O	Total	N-O	H-O
2012	66,520	65,448	1,072	12,107	11,795	312	0	0	0	54,413	53,653	760
2013	29,015	28,245	770	6,262	6,084	199	0	0	0	22,732	22,161	571
2014	99,901	97,672	2,229	16,255	16,070	211	0	0	0	83,620	81,602	2,018
2015	51,566	49,779	1,787	7,898	7,624	274	0	0	0	43,668	42,154	1,514
2016	73,697	73,619	78	14,630	14,615	15	0	0	0	59,067	59,004	63
2017	23,854	23,845	9	0	0	0	0	0	0	23,854	23,845	9
2018	13,976	13,976	0	0	0	0	0	0	0	13,976	13,976	0
2019	8,877	8,877	0	0	0	0	0	0	0	8,877	8,877	0
2020	43,391	43,391	0	7,555	7,555	0	0	0	0	35,836	35,836	0
2021	30,826	30,826	0	5,002	5,007	0	0	0	0	25,819	25,819	0

Appendix 2: Lake Wenatchee Sockeye spawning escapement based on statistical models

Beginning in 2006, annual spawner escapement into the spawning tributaries of Lake Wenatchee was estimated using AUC models (2006 to 2008), CMR models (≥ 2014) and a combination of AUC and CMR (2009 to 2013). The AUC method is comprised of repeatedly surveying the spawning grounds and enumerating live adults to develop an abundance distribution, which is used to estimate the total abundance of spawning individuals given a known residency time (Hyatt et al., 2010, Perrin and Irvine, 1990). The CMR models are based on the proportion of PIT-tagged individuals detected downstream, which are then redetected on the spawning grounds. The frequencies of tagged and detected individuals are used to estimate the abundance of the spawning population.

Escapement estimates for Lake Wenatchee Sockeye Salmon vary considerably between years regardless of the methodology used to estimate escapement. Run escapement estimates obtained from Tumwater Dam counts, broodstock collections and harvest estimates are, however, consistently higher by about 27% than the spawning escapement estimates (AUC and/or CMR) (paired t-test, $t = 3.40$, $df = 15$, $p < 0.004$). This observation likely reflects that the AUC and/or MR models likely capture some of the instream mortality of adults between Tumwater Dam and the spawning grounds and that the spawning escapement data are based higher upstream and later in the year than the counts obtained at TUM. Modelled escapement estimates were extended from 2006 back to 1989 based on the strong, linear relationship with estimates derived from Tumwater Dam counts ($R^2 = 0.91$, $p < 0.0001$, $N = 16$ years; Figures A1 and A2). The time series of escapement estimates from both Appendix 1 and 2 are visualized in Figure A2.

Table A2. Sockeye escapement estimates for return years 1989 to 2021. Conventional *run escapement* estimates are provided as the abundance of adults passing Tumwater Dam after deducting the number of fish collected for broodstock and those harvested upstream of Tumwater Dam. For years after 2006 we present modelled “spawning escapement” estimates from Hillman et al., 2022 that use a combination of area-under-the-curve (AUC) and capture-mark-recapture (CMR; using PIT-tagged individuals) to estimate escapement on the spawning grounds. The strong linear relationship between modelled and dam count-based escapement estimates enables the extension of modelled spawning ground escapement estimates back 17 years. Spawning escapement values estimated from linear regression are presented with 95% confidence intervals.

Return year	Run escapement	Spawning escapement	Modelling method
	Tumwater – (Broodstock + Recreational Harvest)	Modelled	
1989	21,547	16,647 (14,096 – 18,778)	Linear regression
1990	20,486	15,801 (13,419 – 18,183)	Linear regression
1991	20,145	15,597 (13,200 – 17,993)	Linear regression
1992	12,553	11,048 (8,233 – 13,862)	Linear regression
1993	21,019	16,121 (13,760 – 18,481)	Linear regression
1994	7,065	7,759 (4,552 – 10,967)	Linear regression
1995	3,239	5,466 (1,955 – 8,978)	Linear regression
1996	6,346	7,328 (4,065 – 10,591)	Linear regression
1997	9,467	9,198 (6,170 – 12,227)	Linear regression
1998	3,824	5,817 (2,353 – 9,281)	Linear regression
1999	1,025	4,140 (444 – 7,835)	Linear regression

Return year	Run escapement	Spawning escapement	Modelling method
	Tumwater – (Broodstock + Recreational Harvest)	Modelled	
2000	20,784	15,980 (13,610 – 18,350)	Linear regression
2001	29,103	20,965 (18,773 – 23,156)	Linear regression
2002	27,564	20,042 (17,843 – 22,42)	Linear regression
2003	4,855	6,435 (3,054 – 9,815)	Linear regression
2004	27,555	20,037 (17,837 – 22,237)	Linear regression
2005	14,011	11,921 (9,200 – 14,643)	Linear regression
2006	9,437	6,208	AUC
2007	2,379	1,870	AUC
2008	23,210	20,248	AUC
2009	13,488	14,452	AUC & CMR
2010	31,491	21,604	AUC & CMR
2011	18,430	17,013	AUC & CMR
2012	54,413	28,473	AUC & CMR
2013	22,732	16,720	AUC & CMR
2014	83,620	53,340	CMR
2015	43,668	22,804	CMR
2016	59,067	45,549	CMR
2017	23,854	20,521	CMR
2018	13,976	11,384	CMR
2019	8,877	7,466	CMR
2020	35,836	30,686	CMR
2021	25,819	19,882	CMR

Across all years with relevant data, the mean absolute percent error between estimates from Tumwater Dam and the modelled values was 29.0% (range 2.9% in 1997 to 75.2% in 1999), and is likely the result of error in estimating the ratio between dam counts in certain years and/or inaccuracies in estimating spawning escapement values.

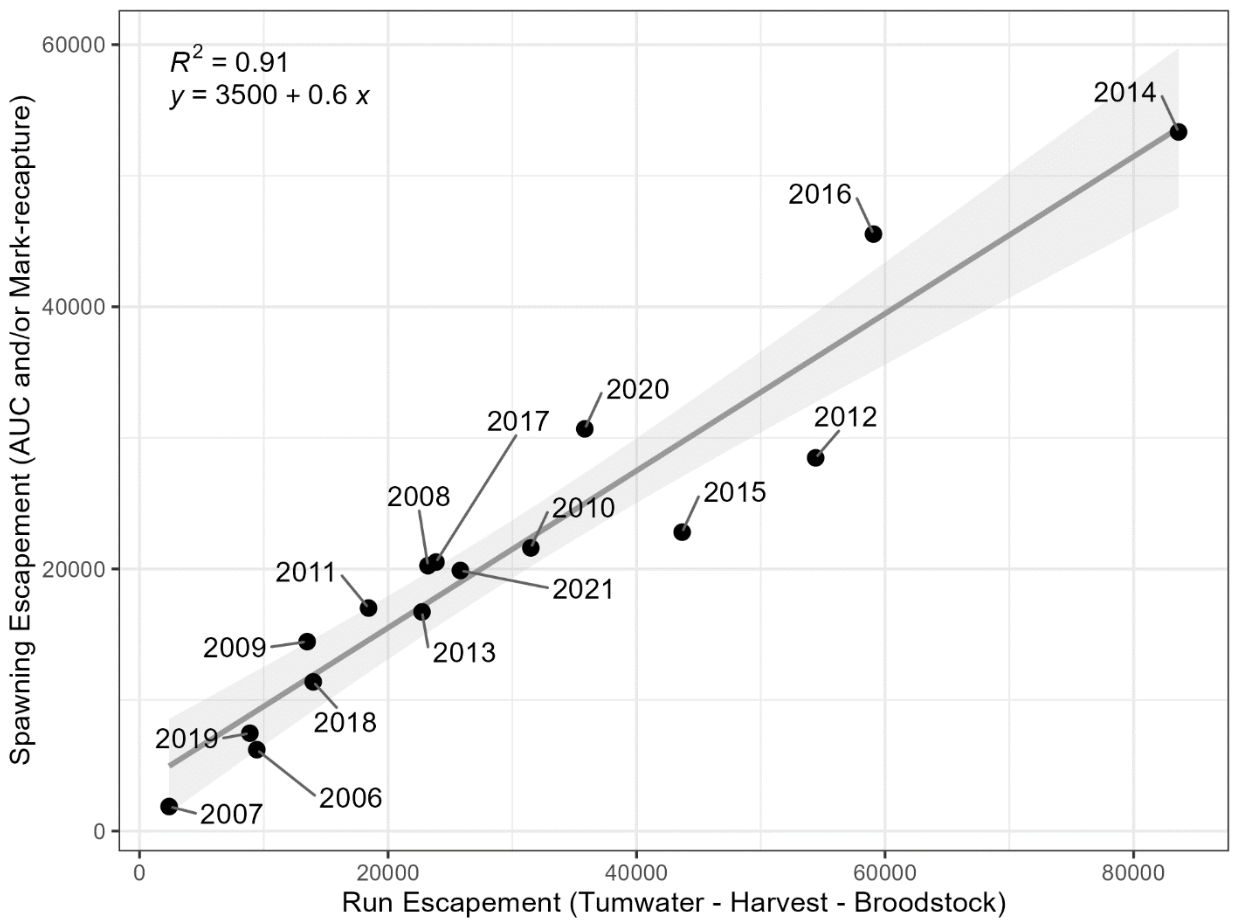


Figure A1. Relationship between Lake Wenatchee Sockeye Salmon escapement estimates derived from AUC and/or mark-recapture (y-axis) and Tumwater Dam counts after accounting for recreational harvest and broodstock collections (x-axis). Adult return years are labelled. The solid, gray line represents the regression formula (summarized in the top left) and the light gray ribbon surrounding the regression line represents the 95% confidence interval.

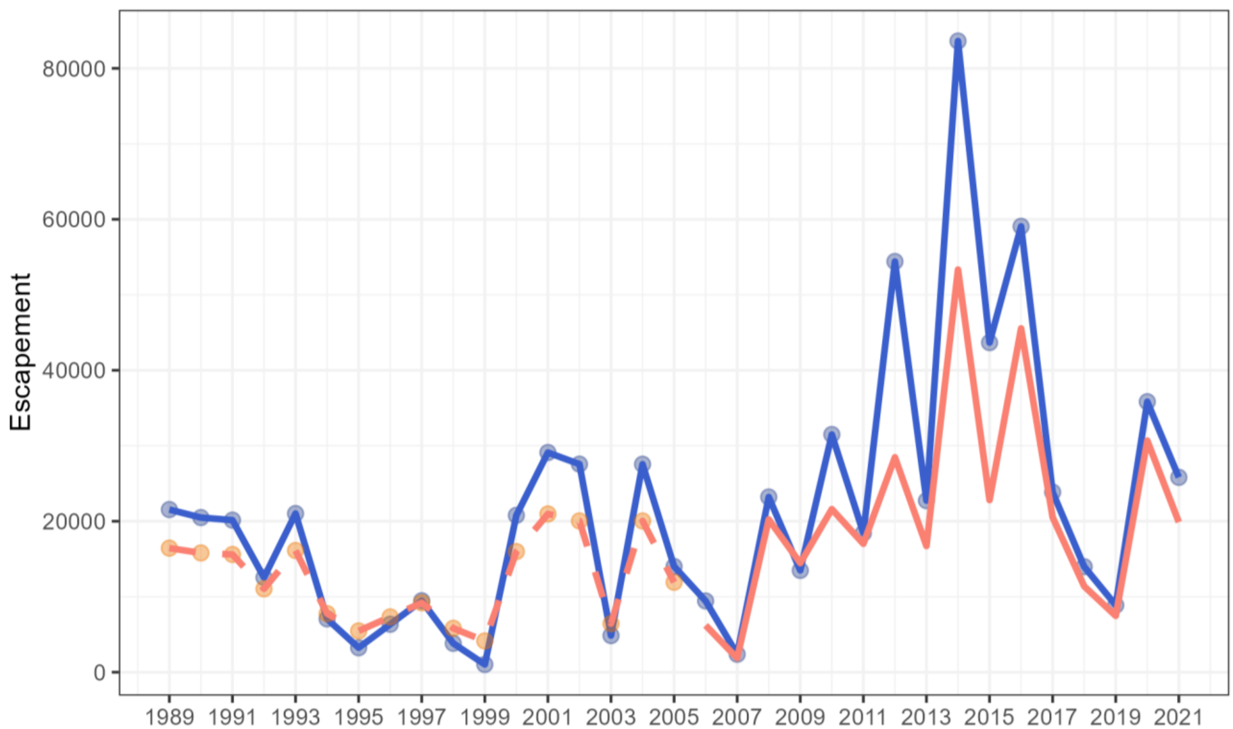


Figure A2. Escapement estimates for spawning Lake Wenatchee Sockeye Salmon (aligned by adult return year). The solid blue line represents escapement estimates calculated as the abundance of adults at Tumwater Dam, minus the numbers of fish collected for broodstock and those captured in the recreational harvest upstream of Tumwater Dam. The solid, salmon-coloured line represents escapement estimates obtained from AUC, mark-recapture (or both) models. The dashed, salmon-coloured line represents AUC and mark-recapture "equivalents" obtained from a linear regression formula between the Tumwater estimates and the AUC and mark-recapture estimates for 16 years where data are available for both methods (Figure A1).

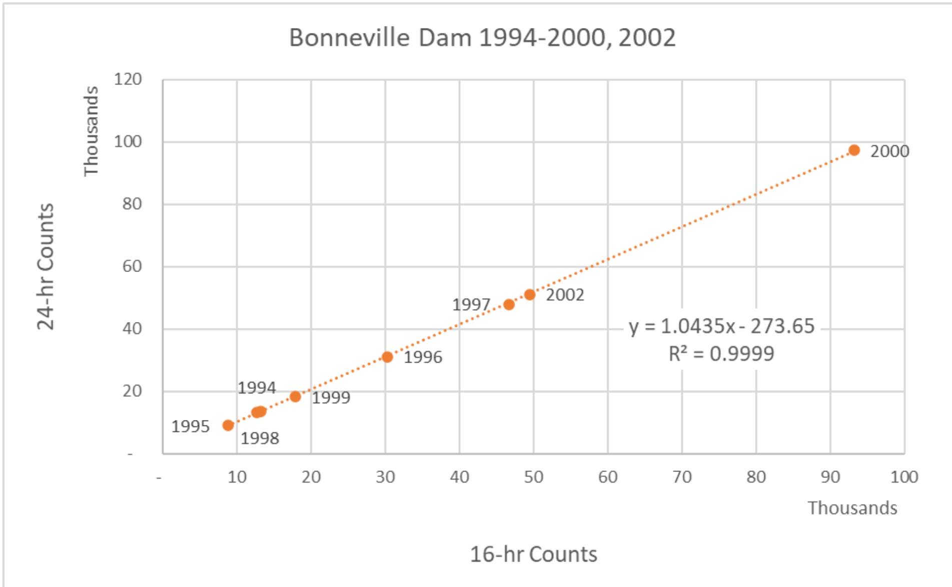
Appendix 3: Adjusting Bonneville dam counts

Annual Bonneville Dam salmon counts available online (Columbia River DART, 2023) are restricted to 16-hour counts per day (from 0400 to 2000 PST), thereby underestimating salmon passage. However, 24-hour counts are also available between 1994 and 2002, and 2013 to 2022 (hourly counts available from the Fish Passage Center). The relationship between 24-hour and 16-hour counts have a strong, linear relationship ($r \geq 0.997$) (Table A3 & Figure A3), although the slopes are significantly different between the two time periods ($p < 0.05$). Therefore, to adjust 16-hour counts to 24-hour estimates for years with 24-hour calibration data, parameters from the regression for 1994-2002 were applied to posted 16-hour dam counts for years 1977 to 1993, 2001, and 2003 to 2007. Similarly, coefficients from the regression for 2013 to 2022 were applied to the posted 16-hour dam counts for years 2008 to 2002.

Table A3. Statistical relationships between 16 and 24-hour Sockeye Salmon counts at Bonneville dam for years 1977 to 1993, and 2008 to 2012. Relationships are visualized in Table A3.

Year	Night Counts	16-hr Counts	24-hr Counts	Pct Diff	Adjustment
1977-93		Various	None		BON24 = BON16 * 1.0435 – 273.65
1994	475	12,666	13,141	3.6%	BON24 = BON16 * 1.0435 – 273.65
1995	358	8,717	9,075	3.9%	BON24 = BON16 * 1.0435 – 273.65
1996	941	30,208	31,149	3.0%	BON24 = BON16 * 1.0435 – 273.65
1997	1,334	46,617	47,951	2.8%	BON24 = BON16 * 1.0435 – 273.65
1998	390	13,127	13,517	2.9%	BON24 = BON16 * 1.0435 – 273.65
1999	425	17,817	18,242	2.3%	BON24 = BON16 * 1.0435 – 273.65
2000	4,134	93,192	97,326	4.2%	BON24 = BON16 * 1.0435 – 273.65
2001		114,934	None		BON24 = BON16 * 1.0435 – 273.65
2002	1,590	49,519	51,109	3.1%	BON24 = BON16 * 1.0435 – 273.65
2003-07		Various	None		BON24 = BON16 * 1.0435 – 273.65
ALL	**9,647**	**271,863**	**281,510**	**3.4%**	

Year	Night Counts	16-hr Counts	24-hr Counts	Pct Diff	Adjustment
2008-12		**Various**	**None**		BON24 = BON16 * 1.0631 – 2550.8
2013		185,438	197,737	6.2%	BON24 = BON16 * 1.0631 – 2550.8
2014		614,113	655,983	6.4%	BON24 = BON16 * 1.0631 – 2550.8
2015		510,662	545,156	6.3%	BON24 = BON16 * 1.0631 – 2550.8
2016		342,459	357,826	4.3%	BON24 = BON16 * 1.0631 – 2550.8
2017		87,606	89,955	2.6%	BON24 = BON16 * 1.0631 – 2550.8
2018		193,755	198,150	2.2%	BON24 = BON16 * 1.0631 – 2550.8
2019		63,046	66,279	4.9%	BON24 = BON16 * 1.0631 – 2550.8
2020		341,739	357,555	4.4%	BON24 = BON16 * 1.0631 – 2550.8
2021		151,765	161,564	6.1%	BON24 = BON16 * 1.0631 – 2550.8
2022		663,253	696,983	4.8%	BON24 = BON16 * 1.0631 – 2550.8
ALL		**3,153,836**	**3,327,188**	**5.2%**	



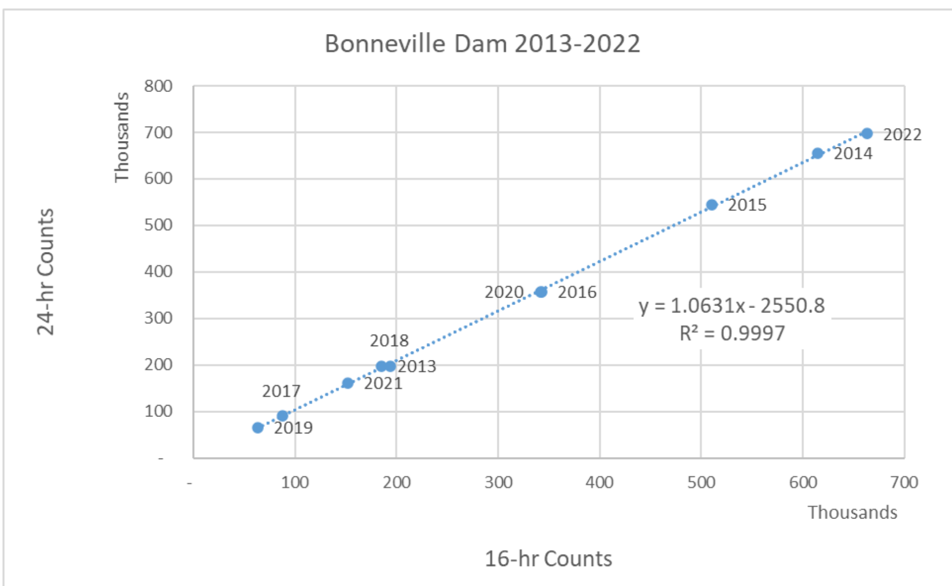


Figure A3. Bonneville 24-hr dam counts as a function of 16-hr dam counts, 1994-2002 and 2013-2022.

Appendix 4: Estimating adult returns from Bonneville dam counts and upstream dam count ratios

An alternative method of calculating total N-O Sockeye returns to the Wenatchee system is based on Bonneville Dam counts (after adjusting the 16-hour daily dam counts to 24-hour equivalents, see Appendix 3) (Columbia River DART, 2023) plus harvest downstream of Bonneville (Zones 1 to 5), to get an aggregate multi-stock total annual estimate of Sockeye returning to the Columbia system (following Bailey et al., 2023). From this number, annual estimates of Snake River Sockeye can be deducted to leave total Wenatchee- and Okanagan-bound Sockeye (Joint Columbia River Management Staff 2021). The proportion of Okanagan-bound Sockeye can be derived from the ratio of Rocky Reach (RRH) to Rock Island (RIS) 24-hour dam count ratios and, conversely, the proportion of Wenatchee-bound Sockeye is derived from (1 – RRH/RIS) to calculate annual aggregated (N-O + H-O) Wenatchee adult returns (Bailey et al., 2023). The result can be multiplied by the N-O proportion of Wenatchee Sockeye to account for H-O contributions to estimate total annual N-O Wenatchee abundance.

Table A4. Estimated abundances of adult, Wenatchee-bound (WEN) Sockeye Salmon returning to the mouth of the Columbia River. Note that all dam counts have been converted to 24-hour equivalents (see Table A3 and Figure A3).

Return Year	WEN Sockeye at Columbia Mouth (NO)	Total Sockeye at Columbia River mouth	Total Sockeye at Bonneville Dam	Total Snake River Sockeye	Natural mortality BON to RIS	Total Sockeye at Rock Island	Total Sockeye at Rocky Reach	% WEN	WEN at Rock Island	WEN %H-O	WEN Sockeye at Tumwater	Natural mortality RIS to TUM
1989	25,124	43,322	43,286	4	8.74%	37,360	18,116	58%	21,669	0%	21,802	0
1990	39,627	51,464	51,291	1	8.64%	44,143	10,412	77%	33,990	0%	27,325	6,406
1991	42,008	79,270	79,267	10	17.49%	62,119	31,119	53%	32,923	0%	26,689	4,311
1992	27,308	88,126	88,118	35	19.90%	68,359	47,489	31%	21,191	0%	16,461	4,409
1993	39,666	83,175	83,111	18	14.97%	65,630	31,717	53%	34,784	10%	25,056	8,857
1994	10,177	12,912	12,911	5	8.26%	11,367	1,886	83%	9,435	5%	6,931	2,550
1995	2,605	8,852	8,851	5	3.98%	8,049	5,538	31%	2,495	5%	3,261	0
1996	7,461	31,193	31,168	3	0.81%	29,500	21,741	26%	7,670	8%	6,160	1,599
1997	12,512	48,627	48,615	16	10.39%	41,504	30,661	26%	10,791	1%	9,592	1,251
1998	6,001	13,475	13,473	4	27.54%	9,334	5,988	45%	4,200	1%	3,984	0
1999	1,721	18,319	18,318	15	10.77%	15,627	14,111	10%	1,563	6%	908	608
2000	23,673	97,226	96,860	365	17.63%	76,512	59,944	26%	19,893	6%	18,390	0
2001	35,184	120,949	119,258	41	5.93%	104,840	74,486	30%	31,452	3%	32,554	0
2002	36,553	51,345	51,321	64	8.52%	44,320	12,373	72%	31,910	1%	27,241	4,706

Return Year	WEN Sockeye at Columbia Mouth (NO)	Total Sockeye at Columbia River mouth	Total Sockeye at Bonneville Dam	Total Snake River Sockeye	Natural mortality BON to RIS	Total Sockeye at Rock Island	Total Sockeye at Rocky Reach	% WEN	WEN at Rock Island	WEN %H-O	WEN Sockeye at Tumwater	Natural mortality RIS to TUM
2003	5,620	40,589	40,589	40	11.53%	34,779	30,355	14%	4,869	1%	4,699	0
2004	35,405	128,631	127,949	118	13.17%	106,666	81,338	29%	30,933	5%	31,409	0
2005	16,632	75,620	75,616	19	2.12%	71,226	55,570	22%	15,670	0%	14,176	1,480
2006	10,382	38,276	38,275	51	3.91%	35,132	25,377	28%	9,837	3%	9,150	605
2007	2,697	25,077	25,077	58	1.43%	23,246	22,273	11%	2,557	2%	2,542	0
2008	33,594	224,847	223,873	890	9.04%	193,739	165,334	15%	29,061	0%	28,240	165
2009	30,714	187,675	186,487	1,414	6.71%	162,830	134,937	17%	27,681	3%	15,502	12,391
2010	50,640	407,634	407,166	1,861	10.04%	338,310	295,638	13%	43,980	4%	34,519	8,153
2011	20,347	196,266	194,393	1,561	17.42%	146,111	132,096	11%	16,072	5%	17,680	0
2012	86,090	549,554	544,063	512	16.10%	410,620	363,314	16%	65,699	2%	65,448	0
2013	33,836	194,802	194,084	1,011	13.30%	159,219	131,660	18%	28,659	3%	28,245	0
2014	107,906	650,217	648,479	2,523	5.26%	581,121	492,892	17%	98,791	2%	97,672	0
2015	99,263	540,345	538,798	1,749	44.97%	264,678	216,389	19%	50,289	3%	49,779	0
2016	86,580	361,694	360,497	946	9.02%	310,341	235,925	24%	74,482	0%	73,619	797
2017	32,540	90,833	90,404	444	13.56%	73,218	46,701	36%	26,358	0%	23,845	2,672
2018	16,217	203,006	202,894	297	11.27%	172,009	162,684	8%	13,761	0%	13,976	0
2019	9,598	64,319	64,278	335	6.63%	58,562	50,464	15%	8,784	0%	8,877	0
2020	54,345	363,050	359,693	750	17.58%	280,440	249,521	15%	42,066	0%	43,391	0
2021	44,217	158,870	158,320	953	24.30%	109,367	82,643	28%	30,623	0%	30,826	0

Appendix 5: Adult migration past Tumwater Dam

Adult Sockeye salmon migrating past Tumwater Dam are counted from videos. Individuals are identified as N-O or H-O based on the presence or absence of an adipose fin (Table A5). Below, we visualize and tabulate (Figure A4 and Table A5, respectively) interannual variation in migration timing past Tumwater Dam.

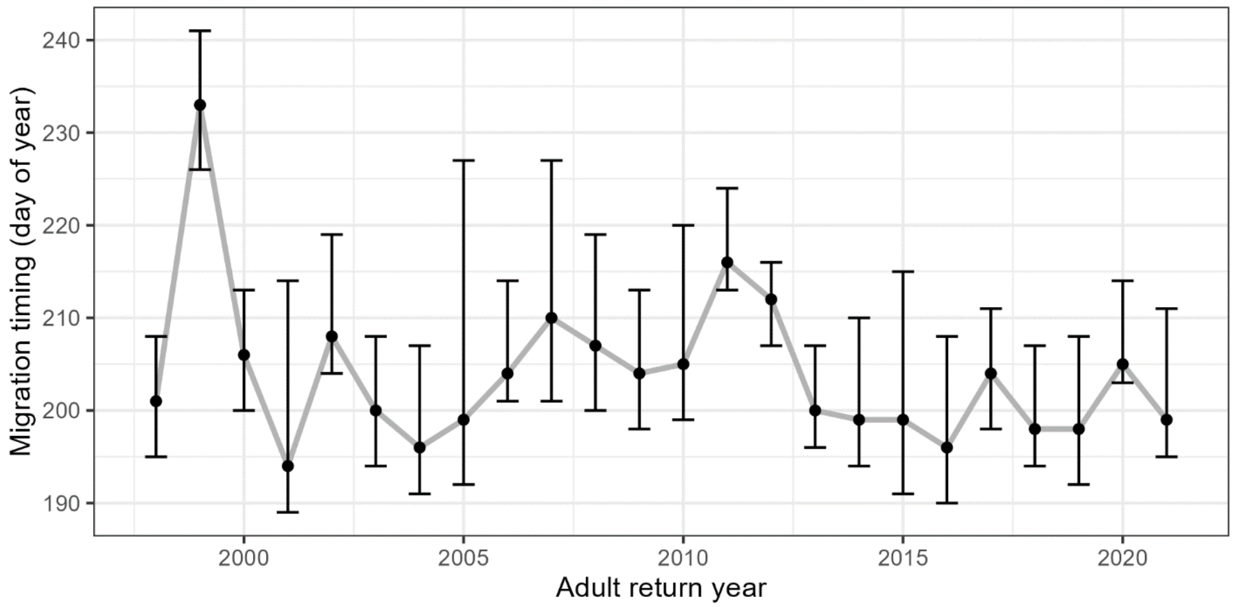


Figure A4. Migration timing for adult N-O Sockeye Salmon returning to Lake Wenatchee between 1998 and 2021. The bottom and the top of the error bars represent the 1st quartile (10% of fish passed) and the third quartile (90% of fish passed), respectively. The middle point represents the peak of migration (50% passage). Note that the late migration estimate from 1999 may be affected by the relatively small sample size for that year (Table 3).

Table A5. Annual return timing of adult, N-O Sockeye Salmon to Lake Wenatchee.

Adult return year	1st quartile (10%)	Peak or Median (TT50%)	3rd Quartile (90%)	Sample size (*n*)
1998	14-Jul-98	20-Jul-98	27-Jul-98	4,173
1999	14-Aug-99	21-Aug-99	29-Aug-99	908
2000	18-Jul-00	24-Jul-00	31-Jul-00	18,390
2001	8-Jul-01	13-Jul-01	2-Aug-01	32,554
2002	23-Jul-02	27-Jul-02	7-Aug-02	27,241
2003	13-Jul-03	19-Jul-03	27-Jul-03	4,699
2004	9-Jul-04	14-Jul-04	25-Jul-04	31,408
2005	11-Jul-05	18-Jul-05	15-Aug-05	14,176
2006	20-Jul-06	23-Jul-06	2-Aug-06	9,151
2007	20-Jul-07	29-Jul-07	15-Aug-07	2,542
2008	18-Jul-08	25-Jul-08	6-Aug-08	29,229
2009	17-Jul-09	23-Jul-09	1-Aug-09	15,552
2010	18-Jul-10	24-Jul-10	8-Aug-10	34,519
2011	1-Aug-11	4-Aug-11	12-Aug-11	17,680
2012	25-Jul-12	30-Jul-12	3-Aug-12	21,246
2013	15-Jul-13	19-Jul-13	26-Jul-13	28,245
2014	13-Jul-14	18-Jul-14	29-Jul-14	97,670
2015	10-Jul-15	18-Jul-15	3-Aug-15	49,628
2016	8-Jul-16	14-Jul-16	26-Jul-16	73,619
2017	17-Jul-17	23-Jul-17	30-Jul-17	23,845
2018	13-Jul-18	17-Jul-18	26-Jul-18	13,960
2019	11-Jul-19	17-Jul-19	27-Jul-19	8,875
2020	21-Jul-20	23-Jul-20	1-Aug-20	13,089
2021	14-Jul-21	18-Jul-21	30-Jul-21	30,826

While migration timing estimates change between years, the error bars largely overlap between years. Estimates for 1999 and 2011 are the only years that statistically differ from other years, suggesting only moderate interannual variation in migration timing for most years.

Appendix 6: Adult Sockeye length at age

A total of 11,178 NO adult Sockeye were biosampled between 1994 and 2021. Across all years, 60.7% of fish were sampled as adults in the river, 28.5% were collected as broodstock, and the remaining 1.8% were carcasses retrieved from deadpitch surveys. To minimize the influence of outliers, fish belonging to the upper and lower 5% of the length distribution data were not included in the summary data tables below (i.e., we used the middle 90% of the size data). Using individual age values, size-at-age data were presented for each brood and return year (Tables A7 and A8, respectively). For this analysis, all biometric data were rotated by return year and the mean length (POH) was calculated for each age class. For each return year, the weighted mean and variance was estimated across all age classes. For this analysis, we estimated relative weights as $4*SD^{-2}$ (i.e., 95% Confidence $Interval^{-2}$). A maximum weight cut-off was not implemented given that weight values ranged from 0.82 (in 2014) to 136.5 (in 2009). The weighted average size of a returned adult Sockeye Salmon was also visualized as a time series plot for years 1994 to 2021 (Figure A5). Weighted annual estimates were computed using age-specific sample sizes (*n*) as weights (i.e., values with larger sample sizes contributed more to the mean estimate) (Table A7).

Table A6. Biometric data for adult N-O Sockeye Salmon after returning to Lake Wenatchee. Data presented are sample sizes (*n*), post-orbital hypural length (Length (cm)) by European age class (equivalent Gilbert-Rich age in parentheses). Data are presented for brood years between 1988 and 2018.

Brood Year	1.1 (3_2)		1.2 (4_2)		2.1 (4_3)		1.3 (5_2)		2.2 (5_3)		2.3 (6_3)		Total *n*	Weighted mean POH (weighted sd)
	n	**Length**	***n***	**Length**	***n***	**Length**	***n***	**Length**	***n***	**Length**	***n***	**Length**		
1988											2	44.5	2	44.5 (NA)
1989							54	45.5	28	42.6	3	45.7	85	44.5 (1.4)
1990			115	44.6			28	44.5	10	41.9			153	44.4 (0.7)
1991			143	41.5			6	47.0	69	42.8			218	42.0 (1.0)
1992			140	42.3			4	46.5	19	41.7	3	42.7	166	42.4 (0.7)
1993			150	41.0	1	40.0	94	44.6	13	42.4	13	45.5	271	42.5 (1.8)
1994			31	43.0			18	44.7	91	41.4			140	42.2 (1.2)
1995	2	42.0	24	41.5			2		3	43.3	1	47.0	32	42.1 (1.4)
1996			164	42.3			9		48	43.5	2	44.5	223	42.8 (0.9)
1997			168	43.2			27		117	43.6	6	45.7	318	43.7 (1.0)
1998			77	42.9			112		3	43.7			192	45.3 (2.0)
2009			5	44.2			1		3	44.0			9	44.2 (0.3)
2000			179	41.6			34		8	41.8	1	46.0	222	42.3 (1.6)
2001			121	41.4			90		36	40.9	13	45.0	260	42.7 (1.8)
2002			63	41.4			96		56	42.1	2	45.0	217	43.9 (2.5)

Brood Year	1.1 (3_2)		1.2 (4_2)		2.1 (4_3)		1.3 (5_2)		2.2 (5_3)		2.3 (6_3)		Total *n*	Weighted mean POH (weighted sd)
	n	**Length**	***n***	**Length**	***n***	**Length**	***n***	**Length**	***n***	**Length**	***n***	**Length**		
2003			4	45.2			1		10	41.5	3	43.3	18	42.6 (1.7)
2004			212	41.4			60		50	43.4			322	42.3 (1.3)
2005			505	43.1	4	45.0	55		190	43.2	3	47.0	757	43.2 (0.4)
2006			675	43.4	1	48.0	33		45	43.8			754	43.5 (0.6)
2007			180	42.9			6		50	42.4	1	42.0	237	42.8 (0.2)
2008			752	43.0			62		109	42.7			923	43.0 (0.1)
2009			214	42.8	1	45.0	13		101	43.3	1	39.0	330	43.0 (0.4)
2010			890	43.1			57		83	42.3	1	46.0	1,031	43.0 (0.2)
2011			540	42.6			100		13	44.5	13	43.8	666	42.8 (0.4)
2012			372	43.3			104		51	43.8	1	46.0	528	43.3 (0.3)
2013	1	43.0	169	42.8			17		83	43.4	34	44.9	304	43.2 (0.6)
2014			244	43.4			430		85	42.5			759	44.4 (1.1)
2015			145	42.8			10		6	42.2			161	42.8 (0.2)
2016			799	40.6			264		80	42.0			1,143	41.6 (1.7)
2017	1	40.0	729	41.7									731	41.7 (0.1)
2018	1	39.0											1	39.0 (NA)

Table A7. Length-at-age data for adult N-O Sockeye Salmon returning to Lake Wenatchee. Data presented are sample sizes (*n*), post-orbital hypural length (Length (cm)) by European age class (equivalent Gilbert-Rich age in parentheses). The last column presents the weighted mean and standard deviation of fish lengths per return year. Data are presented for return years between 1994 and 2021.

Return year	1.1 (3_2)		1.2 (4_2)		2.1 (4_3)		1.3 (5_2)		2.2 (5_3)		2.3 (6_3)		Total *n*	Weighted mean POH (weighted sd)
	n	Length	*n*	Length	*n*	Length	*n*	Length	*n*	Length	*n*	Length		
1994			115	44.6			54	45.5	28	42.6	2	44.5	199	44.6 (0.9)
1995			143	41.5			28	44.5	10	41.9	3	45.7	184	42.0 (1.2)
1996			140	42.3			6	47.0	69	42.8			215	42.6 (0.8)
1997			150	41.0	1	40.0	4	46.5	19	41.7			174	41.2 (0.8)
1998	2	42.0	31	43.0			94	44.6	13	42.4	3	42.7	143	44.0 (0.9)
1999			24	41.5			18	44.7	91	41.4	13	45.5	146	42.2 (1.5)
2000			164	42.3			2	45.5	3	43.3			169	42.4 (0.4)
2001			168	43.2			9	46.6	48	43.5	1	47.0	226	43.4 (0.7)
2002			77	42.9			27	46.6	117	43.6	2	44.5	223	43.7 (1.1)
2003			5	44.2			112	47.0	3	43.7	6	45.7	126	46.7 (0.8)
2004			179	41.6			1	45.0	3	44.0			183	41.7 (0.4)
2005			121	41.4			34	46.0	8	41.8			163	42.4 (1.8)
2006			63	41.4			90	44.9	36	40.9	1	46.0	190	43.0 (1.9)
2007			4	45.3			96	46.7	56	42.1	13	45.0	169	45.0 (2.1)
2008			212	41.4			1	40.0	10	41.5	2	45.0	225	41.5 (0.3)
2009			505	43.1	4	45.0	60	44.6	50	43.4	3	43.3	622	43.3 (0.5)
2010			675	43.4	1	48.0	55	44.2	190	43.2			921	43.4 (0.3)
2011			180	42.9			33	46.2	45	43.8	3	47.0	261	43.5 (1.2)
2012			752	43.0			6	42.3	50	42.4			808	43.0 (0.1)
2013			214	42.8	1	45.0	62	43.2	109	42.7	1	42.0	387	42.9 (0.2)
2014			890	43.1			13	43.6	101	43.3			1004	43.1 (0.1)
2015			540	42.6			57	43.0	83	42.3	1	39.0	681	42.6 (0.2)
2016	1	43.0	372	43.3			100	43.2	13	44.5	1	46.0	487	43.3 (0.2)
2017			169	42.8			104	42.8	51	43.8	13	43.8	337	43.0 (0.4)
2018			244	43.4			17	42.9	83	43.4	1	46.0	345	43.4 (0.2)
2019			145	42.8			430	45.4	85	42.5	34	44.9	694	44.5 (1.3)

Return year	1.1 (3_2)		1.2 (4_2)		2.1 (4_3)		1.3 (5_2)		2.2 (5_3)		2.3 (6_3)		Total *n*	Weighted mean POH (weighted sd)
	n	**Length**	***n***	**Length**	***n***	**Length**	***n***	**Length**	***n***	**Length**	***n***	**Length**		
2020	2	40.0	799	40.6			10	42.2	6	42.2			817	40.6 (0.2)
2021	1	39.0	729	41.7			264	44.6	80	42.0			1074	42.4 (1.2)

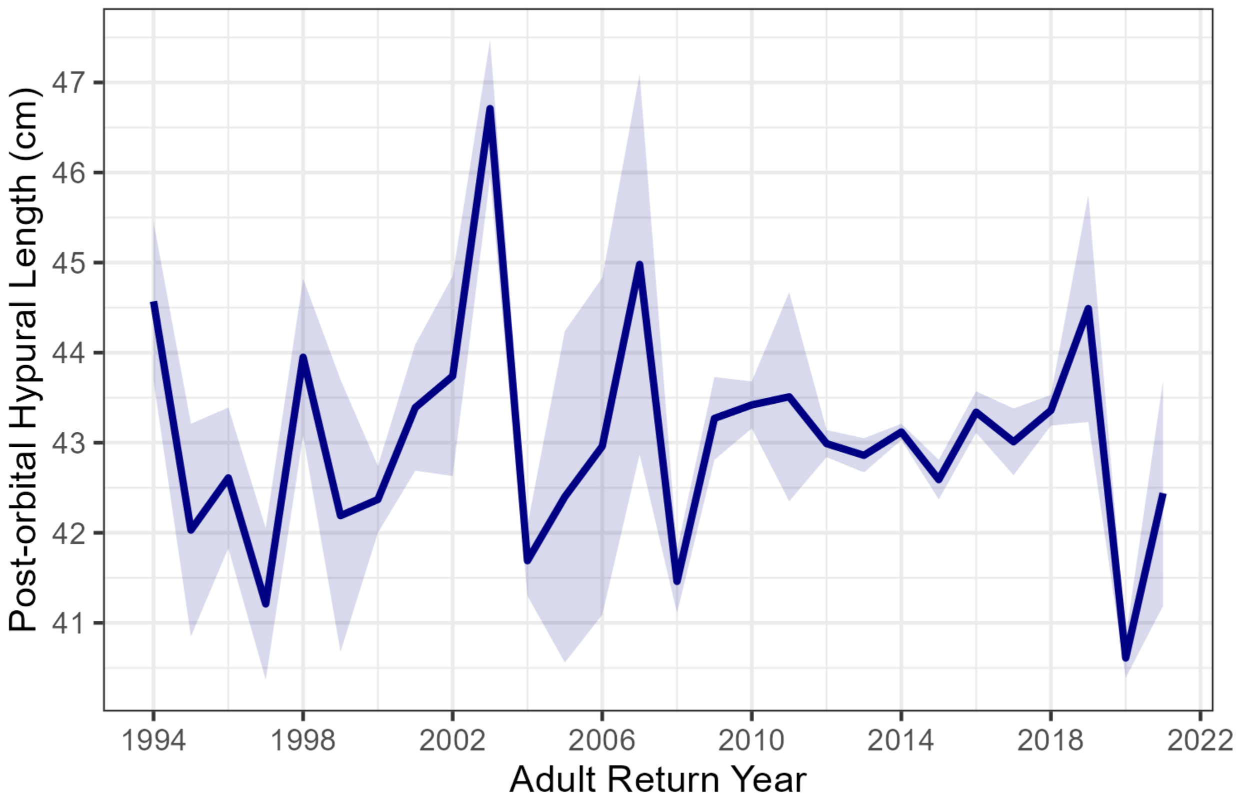


Figure A5. Mean Post-orbital Hypural Length of Adult N-O Sockeye Salmon returning to Lake Wenatchee between 1994 and 2021. The dark line represents the average length across all age groups weighted by the sample size of each age class. The lighter blue ribbon represents one standard deviation above and below each mean value.

Appendix 7. Acoustic Trawl Survey (ATS) vs Rotary-Screw Trap (RST) juvenile abundance estimates

We predicted that the estimated abundance of pre-smolts from ATS would be proportional to the RST-based abundance estimates of smolts emigrating from Lake Wenatchee in the following spring, given that juvenile mortality predominantly occurs in the spring and summer (e.g.,Hyatt et al., 2021). However, no relationship is observed between these abundance indices for 2011 (Upper Wenatchee smolt trap), 2013-2020 (Lower Wenatchee smolt trap) (Figure A6) (Spearman's $\rho = 0.26$).

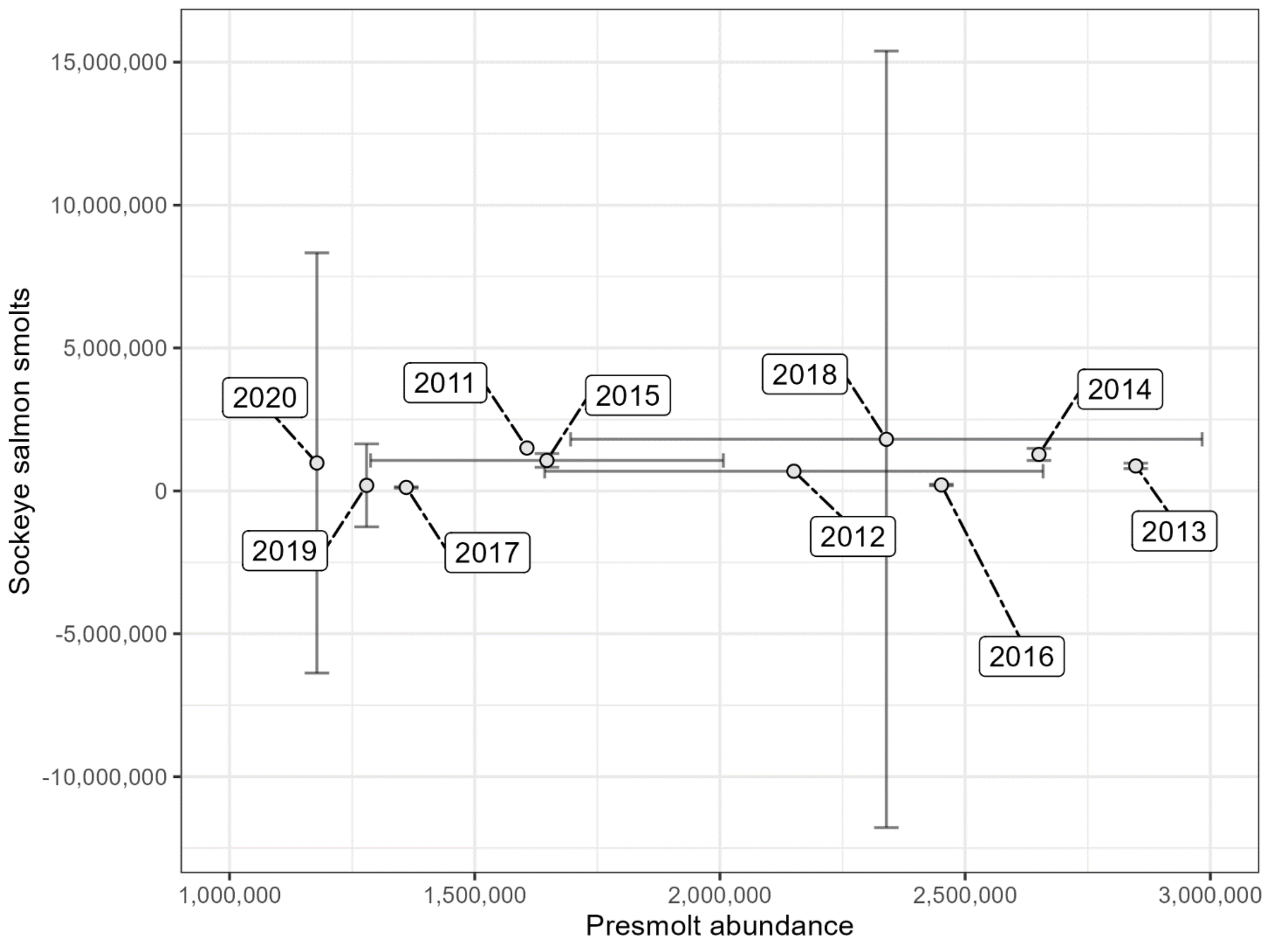


Figure A6. Lake Wenatchee Sockeye annual smolt abundance as a function of pre-smolt abundance estimates (± 95% Confidence Interval) obtained from smolt traps on the Wenatchee River and nocturnal acoustic trawl surveys (ATS) in the lake, respectively. Abundances are aligned by smolt emigration year.

Appendix 8: Smolt migration timing in the Wenatchee River

Smolt capture rates along the Wenatchee River were characterized as a proxy for smolt migration timing. The capture frequency among the upper and lower RSTs were visualized on an annual basis. These data were provided by Chelan PUD, and fry and parr were excluded from the dataset prior to analysis. Note that capture timing likely varies pre- and post-2012 as the lower RST is an additional 68 km downstream relative to the upper RST. Mean capture dates are on average 8.3 days later at the lower RST than the upper RST (t-test; df = 21.51, t = -4.194, $p < 0.0001$). Across all years, more than 98% of individuals are captured after April 1st. Sample sies (n) are displayed above the plot and ranged between 213 (in 1997) and 11,237 (in 2010) individuals per year (mean = 2,800, sd = 2,746)

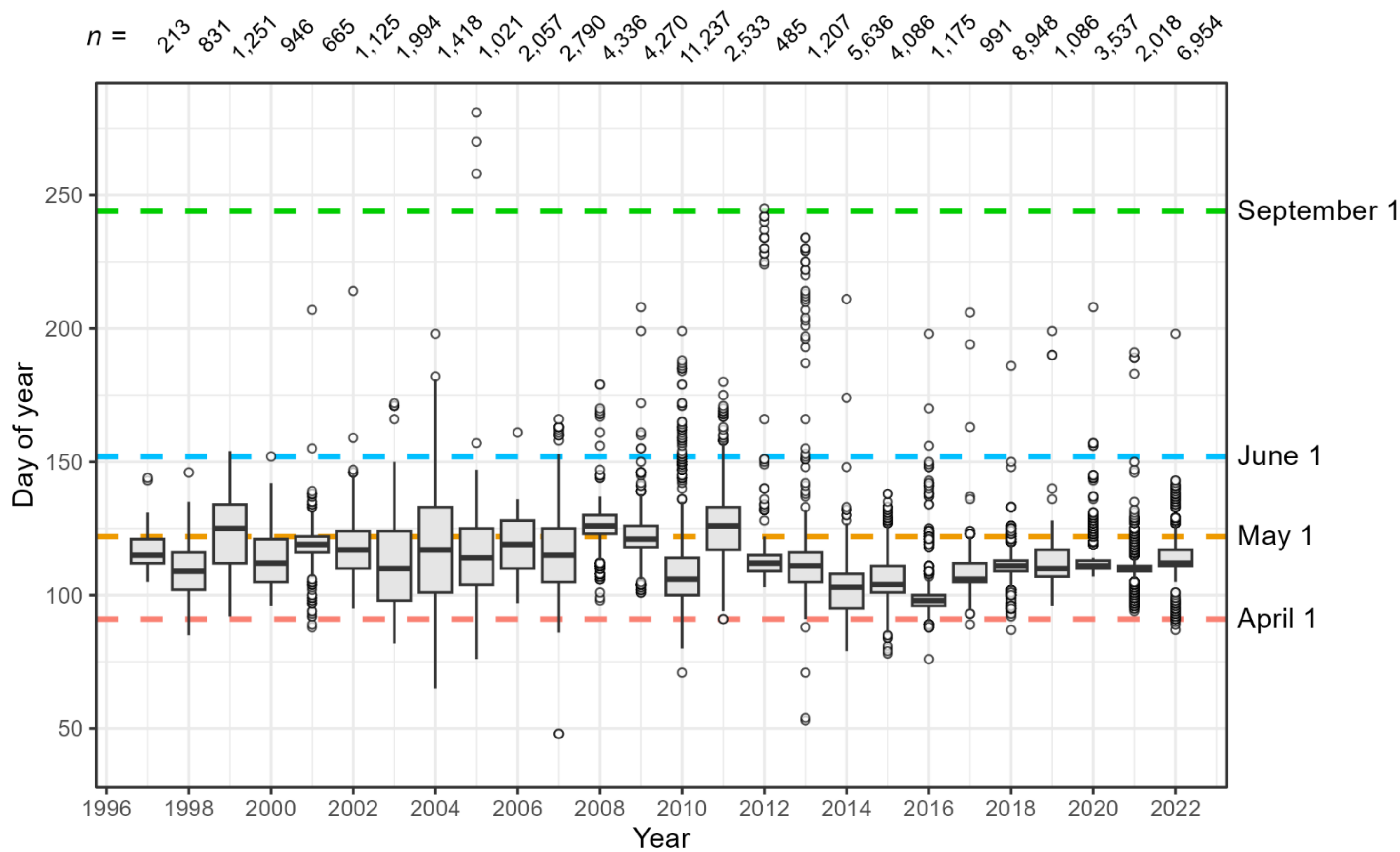
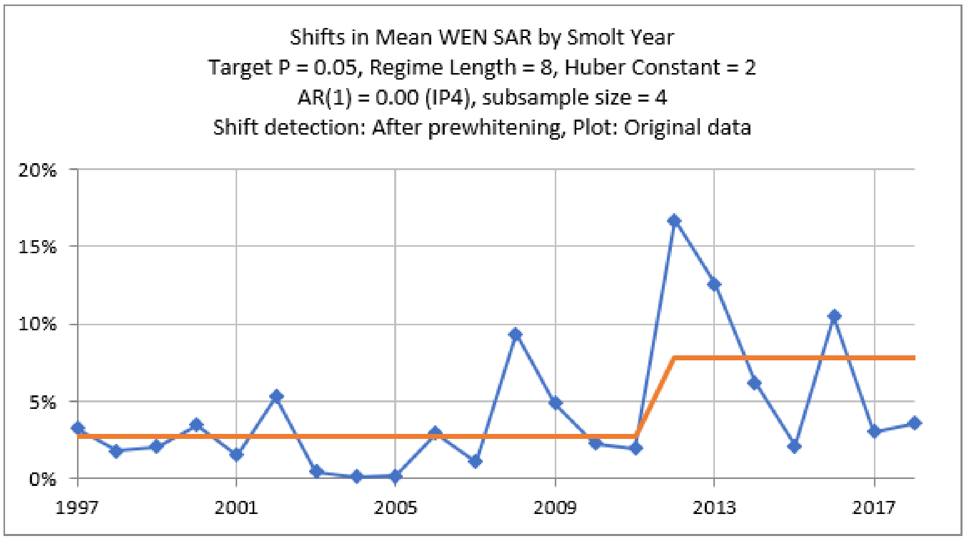


Figure A7. Capture frequencies of Sockeye Salmon smolts emigrating from Lake Wenatchee. Smolts were captured using rotary screw traps at the upper (pre-2012) and lower (post-2012) sites along the Wenatchee River. Annual sample sizes (n) are displayed above the plot.

Appendix 9: Smolt to adult return regime shifts

Temporal variation in SAR estimates were characterized with a series of regime shift analyses (RSAs) (Rodionov 2004). In brief, regime shift analyses conduct sequential t-tests to identify temporal shift points in the mean or variance of a time-series, which are then assessed for their significance and magnitude at which persistent changes are present in the data (Rodionov 2004). Below, concatenated SAR estimates from the Upper Wenatchee Smolt Trap (1997 to 2011) and the Lower Wenatchee Smolt Trap (2013 to 2018) are inputted to the RSA algorithm to identify and characterize shifts in the mean of i) untransformed SAR estimates, ii) standardized SAR estimates (in order to equilibrate across distinct sampling locations), and iii) the variance of the standardized SAR estimates. These analyses indicate an apparent positive shift in the mean as of 2012 (from ~3% to 8%) when applied to untransformed SAR estimates (top), but no shift in the mean of standardized SAR estimates (bottom). Furthermore, the RSA identified a significant increase in the standardized SAR variance estimates after 2012 (bottom; vertical dashed line).



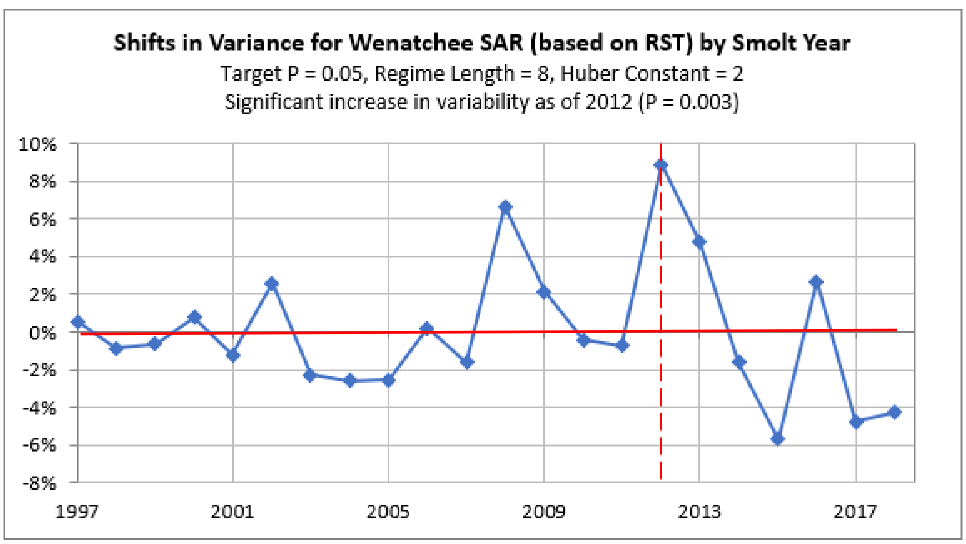


Figure A8. Wenatchee smolt-to-adult return (SAR) indices by smolt out-migration year, based on concatenated rotary-screw trap (RST) time-series (RST#1 1997-2011; RST#2 2013-2018). Top: based on untransformed smolt abundance estimates, with change-point analysis indicating significant positive change in the mean in SY2012 (solid red line); middle: based on standardized data for each time-series, indicating no shift in mean abundance (solid red line); bottom: standardized time-series, with change-point analysis indicating significant increase in variance of SAR as of SY2012 (red dashed line).

Since the SAR estimates are comprised of two indices – adult abundance divided by smolt abundance – the significant increase in the variance in Wenatchee SAR estimates as of SY2012 (Figure A8; bottom) could be a function of temporal changes in variability in either the smolt or the adult components, or both. However, no apparent shifts in the *mean* or *variance* of Wenatchee adult returns was apparent when organized by smolt year (Figure A9; top). The smolt time-series, standardized by RST and concatenated also showed no significant changes in mean abundance, but indicated a significant decrease in inter-annual variance as of SY2011 (Figure A9; bottom). Lower mean smolt abundance estimates after 2011, potentially as a result of relocating the rotary-screw trap, could lead to higher apparent smolt-to-adult return rates and/or increased variability shown in Figure A8.

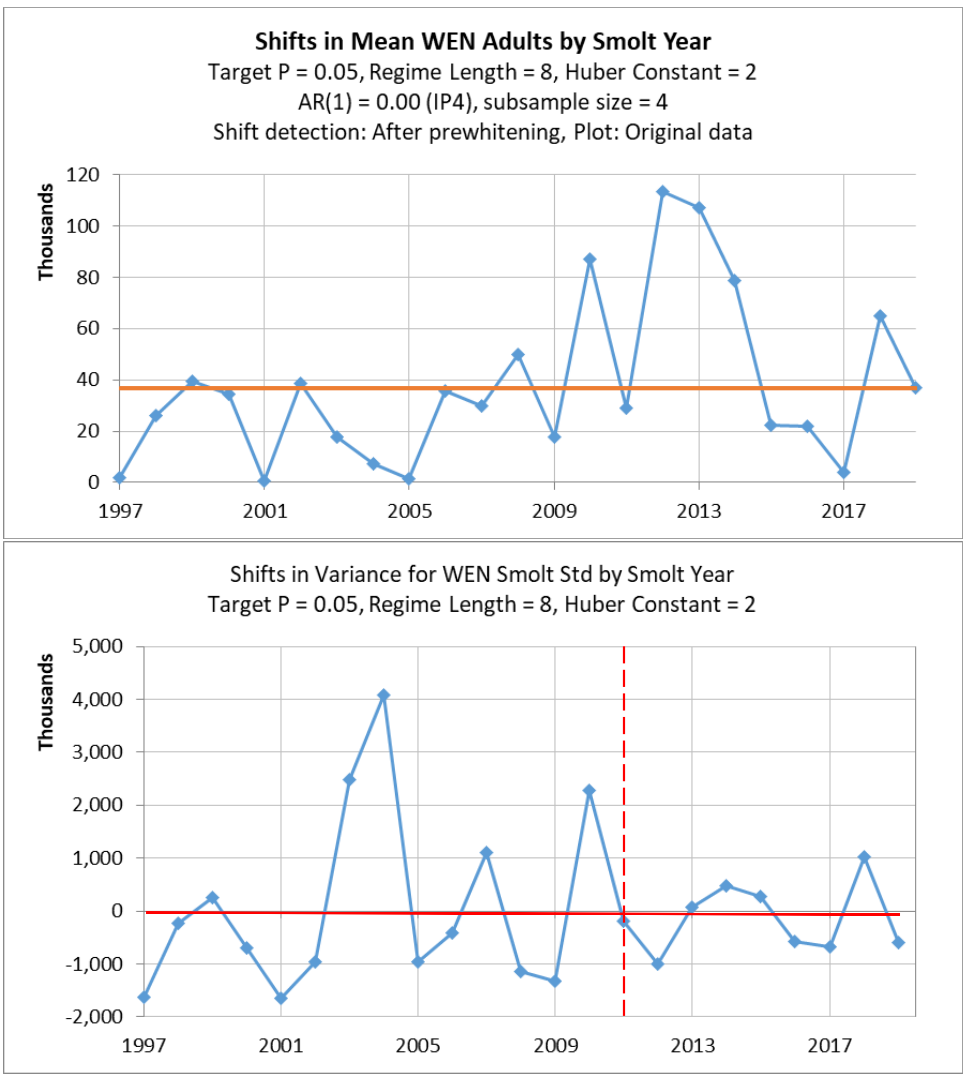


Figure A9. Top: RSA for Wenatchee adult returns, by outmigrating smolt year (no regime shift detected in interannual mean or variance statistics). Bottom: RSA for RST-standardized smolt abundance data (no regime shift detected in mean abundance, but significant shift in variance as of 2011). F-test for difference in variances indicates a ~7-fold decrease in smolt abundance variance after 2011/2012 (F = 6.9, p = 0.013).