# ­­Improving Estimates of Counts and Distributions of Salmon Redds from Aerial and Carcass Surveys

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Next Steps:

* Review data stored in-house (Matt also)
* Update all carcass inputs to FishModel (on final method)
* REPO https://github.com/nickobeer/SacramentoRedds. Will move to a named CBR repo Code, data and supplementary map. Smoothed vs. raw yearly plots NOT referenced nor generated.
* Attribute support to USFWS and/or PSMFC… ?
* Are there any others to acknowledge?
* RE: adjectives. “Adjusted” is the descriptive term for what happens to the carcass survey data to get to redd counts and locations, and “Estimated” is the term for the resulting distribution. The words: “Expanded” or “Corrected” are both potential terms to use. This is easy to change.

## Abstract

In the monitoring of threatened and endangered species, it is particularly important to apply a consistent and accurate assessment methodology. As part of the biological monitoring for the population status and conservation management of salmon, spawning ground surveys often include both redd counts and carcass counts. A method to estimate redd distributions directly from the carcass data was developed to complement the redd survey. The carcass survey method resulted in higher estimates of redd counts and smoother temporal distributions than from aerial survey methods and resolved the spatial distribution to 4 distinct reaches. We document the methods in this paper for access and transparency of the methods, and for use in subsequent studies using spawning ­ground data, and as an example adaptable to other similar species and systems.

## Keywords­­

Aerial survey; Carcass survey; Monitoring method; Redd; Sacramento River; Salmon spawning

## Highlights

* Aerial and carcass survey data are used to estimate salmon redd counts and distribution
* Greater abundance and smoother temporal resolution from carcass survey than aerial survey
* Location biases in carcass survey data are corrected with a drift proportion model
* Timing and location of redds can be used to direct water-management decisions

## Introduction

The accuracy and consistency of field survey methods for migratory, aquatic spawners is particularly important for estimating population status and efficiently prioritizing management actions (Johnson et al. 2007). This need becomes even more pressing under a changing climate because where and when spawning occurs has implications for exposure to environmental conditions associated with the egg and incubating fry life stages. The flow and temperature conditions experienced during these life stages can strongly influence survival. High temperatures can result in significant temperature-dependent mortality (McCullough 1999, USFWS 1999, Martin et al. 2017, Anderson et al. 2022), and flow fluctuations can dewater shallow redds if water levels drop below the location of the redds (Becker et al. 1983, USFWS 2006). In addition, spawn timing has consequences for fry emergence from the redds because the amount of time that the redds are occupied is a function of the thermally-dependent developmental rate of eggs (Alderdice and Velsen 1978, Blaxter 1988). Consequently, spawn timing is also a predictor of emergence timing (Beer and Steel 2017, Adelfio et al. 2024) which can affect subsequent juvenile survival influenced by habitat availability and predator response (Brännäs 1995, Hawkins et al. 2020). Thus the distribution of redds is important for river and fish managers charged with the responsibility of protecting migratory fish populations during their early life stages.

In the Sacramento River (California, USA), Winter-Run Chinook Salmon (WRCS; *Oncorhynchus tshawytscha*) were listed as endangered under the California Endangered Species Act in 1989 and under the Federal Endangered Species Act in 1994 (NMFS 1994). To monitor this population for recovery and conservation management, aerial surveys are conducted to count redds from a helicopter or airplane, and in-river surveys from boats are done for carcasses (Killam 2023). ­

The two survey methods are complementary because they assess different aspects of spawning and they can mitigate for limitations of the other method. Data from the aerial survey can serve as baseline that covers a greater spatial extent, and data from the carcass survey can provide higher resolution spatial and temporal information. For purposes of estimating spawning success, the aerial survey’s limitation is that redds may be difficult to detect in turbid or deep water, while the carcass survey’s limitation is the time and cost of labor-intensive field work.

The main objectives of this short note are to: 1) briefly document and compare the counts from the aerial redd survey to the counts from carcass survey, 2) document and refine a methodology applied to the carcass survey to account for downstream drift in determining redd locations, and 3) compare the spatial and temporal distributions of redd count estimates derived from the aerial survey and the carcass survey methods.

## Methods

## Aerial survey and data

Aerial surveys in the Sacramento River (California, USA; Supplemental Fig. 1) began in 1969 and continue annually to determine the timing of spawning and location of redds (Killam 2023). The aerial survey provides a consistent, rapid method of assessing the physical location of redds and identifying patterns in use of the spawning grounds. It is also used to expand estimates of the population distribution when redds are found downstream of the carcass survey area. The flights cover 222 km of the Sacramento River from the Keswick Dam down to Princeton Ferry. In 2004–2023, flights were conducted approximately weekly, and more specifically ranged 4–28 d, depending on personnel, resources, and flight conditions. New redds, not seen on a previous flight, were counted and aggregated by river reaches delineated by bridges or other landmarks. References to river kilometer (RKM)and river mile (RM) of landmarks are based on (SRF 2012).

The data are used to estimate spawning date by determining the counts·d-1 of new redds which is a component of WRCS management (Killam 2023). This direct relationship between the redd observation date and spawning date is an assumption. A more careful interpretation would include information on the status of redds. Knowing that a redd is under construction would help address a spawning date that is biased early, and knowing that a redd is associated with spawning that has already occurred would help address a spawning date that would be biased late. Only data in years 2004–2023 were used in this study because these data over-lapped with the carcass survey data.

## Carcass survey and data

Salmon carcass surveys in the Sacramento River (California, USA) started in 1996 and are conducted cooperatively by California Department of Fish and Wildlife, US Fish and Wildlife Service, and Pacific States Marine Fisheries Commission occur between April and September for WRCS. The data are used to assess population-level biological metrics for the WRCS (e.g. male-to-female ratio) and as an alternative index to redd counts for determining the distribution of spawning (Killam 2023). Survey crews move along the river by boat identifying and marking carcasses. A fresh, female, spawned (*FFS*) carcass is one that was not seen in a previous survey (i.e. unmarked) and it is associated with a new redd. The survey covers the upper 42 km (26 mi) of the Sacramento River from Balls Ferry to Keswick Dam (Table 1 and Fig. 1). The four reaches of the carcass survey cover the same extent as the upper four reaches of the aerial survey, but the division point between reach 3 and reach 4 in the carcass survey is 9 km upstream of the aerial survey division point. Each of the four reaches are sampled 2 or 3 times per week through the season. Data from 2004–2023 were used in this study because the reach designations used with drift fractions have been consistent over this 20 year period.

## Model

A model was developed to estimate the count, location, and timing of redds from the carcass survey data. Because carcasses drift downstream, the location of a *FFS* carcass is not the location of the redd, and the carcass data are adjusted to obtain the timing and location of each redd attributed to each carcass. The drift proportions of *FFS* are based on the recovery reach of marked carcasses relative to the reach where they were first detected and marked. The proportion is used to adjust the counts allocated to each reach. The multi-year, mean drift proportions (Table 2) are based on 10 years (2012–2021) of mark-recapture tagging of *FFS*. For example, of the carcasses tagged in Reach 1, 11.8% drifted downstream and were recovered in Reach 2, and 1.2% drifted downstream and were recovered in Reach 3. The final distribution and estimated redd count is determined in five steps with adjustments to the carcass-survey-based data using the drift proportions.

**Step 1. Initial counts per reach**: The *FFS* in each reach *R* are counted on­ each survey day and one redd is attributed to each *FFS*.

**Step 2. Drift-corrected counts per reach**: *FFS* per reach are adjusted by the observed downstream bias in carcass locations relative to redd locations (Table 2). The preliminary adjusted counts of spawners in each reach *R* () is computed sequentially from upstream to downstream using the drift proportions () and counts of *FFS* in each reach (*FFSR*).

 (Eq. 1)

 (Eq. 2)

 (Eq. 3)

 (Eq. 4)

If any  , they are adjusted to 0.

**Step 3. Carcass timing distribution**: are distributed in direct proportion to the fraction of *FFSR* in the temporal distribution. Thus, the fraction of  associated with a survey day (*D*) is the same as the fraction of *FFS* for that same date. They are allocated to each survey day and reach as:

 (Eq. 5)

**Step 4. Re-allocate fractional spawners**: Fractional values for any  are further adjusted in order to have a one-to-one correspondence of redds to carcasses. The final estimated counts of spawners () is computed by re-allocating fractional values. This is computed in sequence for each day *D* in chronological order as follows:

**Step 4.1.** Where any estimate of is greater than 0, designate = and then round to the nearest integer (rounded estimate symbolized by the asterisk).

**Step 4.2.** Calculate the remainder from – and add the remainder to .

**Step 4.3.** Repeat steps 4.1 and 4.2 for each survey day *D* in consecutive order for each reach *R*. If = 0 on any particular day *D*, then  remains 0.

**Step 5. Spawn timing correction**: Spawn timing is adjusted by assuming that 7 days pass between spawning and detection of the *FFS* so the redd count estimated for day *D* in reach *R* is:

 (Eq. 6)

Small discrepancies each year between and  occur because adjusted reach counts less than zero are ignored (Step 2), and the timing adjustment (Step 5) ignores any fractional values after the survey period. The annual discrepancies in counts from 2004–2023 ranged from -1 to 23 redds, with a median of 4.5.

The estimated counts and distribution (spatial and temporal) are compared to the aerial survey’s counts and distribution for assessment of WRCS spawning.

## Results

From 2004–2023, the estimated counts were almost always greater than the aerial counts (Fig. 2; Table 3). The most noticeable improvements in counts were in 2011 and 2016 with 18 redds in the aerial survey, while estimated counts yielded 167 and 136 redds, respectively (Table 3). The estimated counts averaged 824 ± SD 757 and ranged 58–2961, while the aerial counts averaged 391 ± SD 432 and ranged 18–1968. The only year when there were fewer estimated counts than aerial counts was in 2008 with 383 and 441 redds respectively. Overall increases from aerial counts to estimated counts averaged 301% ± SD 212%, and were as great as 917%.

Even though the location of a redd corresponding to a female carcass could not be known precisely, the carcass location was used to determine the upstream reach where the corresponding redd was located. In this study, the reaches varied in length from 3.7 to 20.1 km and the estimated redd distributions are compared to the aerial distributions. The relative proportions of redds in each reach varied slightly between years (Fig. 2) with both surveys attributing most spawning to the reaches 1 and 2 (8.8 km total), but with a notable exception in 2019, when the proportion attributed to Reach 1 from the aerial and carcass surveys were 1.8% and 54% respectively. Over the period of this study there were 13 redds outside of the carcass survey bounds (0.2% of total) and 11 of them in 2007.

The median spawning date and spawning season length varied across the years and between the methods (Table 3). The multi-year peak spawning day from both surveys was July 2 (day 184), but there were a range of differences within years. The most extreme differences occurred in 2007 and 2009. In 2007, the aerial survey resulted in median date of June 7 and the carcass method was 23 days later on July 3. However, in 2009 the aerial method resulted in median spawning on July 8 and the carcass method 17 days earlier on June 21. The spawning season duration varied from 20 to 83 days with the aerial distributions, and from 50 to 89 days with the estimated distributions (Fig. 3). The carcass method seasons were longer than the aerial survey seasons in 14 of the 20 years, more than twice as long in 2017 and nearly 3 times as long in 2011.

## Discussion

The carcass survey data, used to assess counts and distribution of WRCS redds on the spawning grounds, accounted for more redds than the aerial survey in almost all years, and with a drift-correction model refined estimates of redd distributions. The locations of redds was resolved to one of four reaches (average 10.5 km length) across the 41.8 km of the study area with a temporal resolution of ~3 days which provides a timely and accurate count of redds and their locations. The aerial survey corroborated the spatial distributions and helped identify spawning in reaches outside of the carcass survey area.

Timely and accurate counts of redds and their locations are used for in-season management. The location of redds and the duration of the spawning season affect exposure to time varying environmental conditions. In the upper Sacramento River, water operations include cold-water releases from Shasta Reservoir to help control water temperatures during the spawning and egg development period (USBR 2020) as well as flow controls which can impact redd dewatering (Killam 2023). In the Sacramento River, for these unique summer-spawning salmon, temperatures can reach critical levels that increase the risk of temperature dependent mortality (TDM) (Martin et al. 2017, Anderson et al. 2022). Therefore, forecasting and monitoring TDM is an important component of river operations (USBR 2023). Using an online tool for assessing egg to fry development (CBR 2023), TDM through the incubation period in 2022 was calculated at 7.0%, 12.4%, and 19.5% using the estimated, raw-carcass distributions and aerial data respectively. In most years when spawning is constrained to the carcass survey area, simulated TDM for the estimated distribution would be more representative of the actual impact on the population.

The duration of the spawning season and physical size of the spawning ground have direct impacts on the critical management period and its spatial extent. In order to protect as many redds as possible within the constraints of other demands on operations (USBR 2023), evidence from either survey suggesting the broader temporal or spatial range would be helpful, and this could come from either line of evidence. For example, in 2019, the aerial survey identified 9 redds in Reach 1, but the estimated count was 591; while in 2007 the aerial survey identified WRCS redds in three reaches downstream of the carcass survey area.

The duration of the spawning season also influences the range and variability of emergence timing (Beer and Steel 2017, Adelfio et al. 2024). This can lead to a potentially complex management task of managing for fish at different stages of development. For example, based on WRCS requiring 960 °C·d accumulated temperature units (ATU) (Zeug et al. 2012) for emergence, in 2021 the earliest-spawned redds on April 28, emerged July 12, but spawning continued for another 27 days until August 8 and those redds emerged on October 17. In years with this kind of non-overlapping occupancy of redds, the management season is especially protracted.

Although the carcass method results in higher spatial and temporal resolution of the spawning distribution, it has some limitations. Over very large spawning grounds it may be prohibitively expensive and time consuming to collect high resolution data, and still may not account for every redd created. Some carcasses are not recovered which biases the counts low; and annual estimates of drift proportions (Killam 2023) vary with capture and detection efficiency which may be different than the multi-year proportions used in this study.

Carcass and redd surveys are common methods for salmon spawning assessment. Other Sacramento River salmon (spring, fall and late-fall Chinook) are monitored with similar methods (Killam 2023), and in a Sacramento River tributary, the American River, carcass survey data are used to estimate escapement (Grimes and Galinat 2022), and aerial surveys have been used to document spawning after habitat restoration (Perkins and Hannon 2020). Comparable methods are used for salmon populations throughout their North American range (Copeland et al. 2019) (Homel and Scheibel 2016) (Johnson et al. 2007) (PSF 2024).

Redd and carcass survey methods are complementary for assessing escapement, population trends, and the spatial and temporal distribution of redds (Johnson et al. 2007). The method here of estimating redd distributions from carcass distributions extends the utility of these data to the management of local river conditions which are critical in recovering and sustaining aquatic species (Buddendorf et al. 2017, Sundt-Hansen et al. 2018, Anderson et al. 2022). Estimated distributions can be used for modeling of development time and analysis of exposure to environmental conditions including temperatures, dewatering flows, and scouring floods. This short note demonstrates how combining aerial and carcass data through a simple drift correction model can help provide both near real-time and more accurate estimates of redd distributions.

## Acknowledgements

This work was made possible by the commitment and dedication of many field biologists and survey crews that have collected these data for many years. This study was supported by the U.S. ­­Bureau of Reclamation and by the California Department of Fish and Wildlife.

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## Tables

**Table 1. Aerial and carcass survey reach lengths (km) and landmarks in river kilometer (RKM) and river mile (RM) in the upper Sacramento River (SRF 2012) . The reaches are numbered downstream from their uppermost location.**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Reach # | Location name | RKM | RM | Aerial reach length (km) | Carcass reach length (km) |
| 1 | Keswick Dam | 486 | 302 | 5.6 | 5.6 |
| 2 | ACID1 Dam | 480.4 | 298.6 | 3.2 | 3.2 |
| 3 | Hwy 44 Bridge | 477.2 | 296.6 | 19.9 | 9.8 |
| 4 Aerial | Airport Road Bridge | 457.3 | 284.2 | 12.9 |  |
| 4 Carcass | Clear Creek Powerlines | 467.4 | 290.5 |  | 23 |
| Shared Reach 4 end | Balls Ferry | 444 | 276.2 | **41.6 total** | **41.6 total** |
| Aerial Survey end | Princeton Ferry | 264.4 | 164.3 | **221.6 total** |  |

1 Anderson Cottonwood Irrigation District Diversion Dam

**Table 2. Drift proportions () of fresh, female, spawned carcasses of Winter-Run Chinook Salmon used for correcting the bias in spawner counts due to downstream drift across river reaches. The subscript *R1* denotes the reach where carcasses were first captured and tagged, and the subscript *R2* denotes the reach where it was recaptured.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Reach where recaptured** | **Reach where captured and tagged** | | | |
| **Reach 1** | **Reach 2** | **Reach 3** | **Reach 4** |
| **Reach 1** | *f1,1* = 0.868 | - | - | - |
| **Reach 2** | *f1,2*= 0.118 | *f2,2*= 0.778 | - | - |
| **Reach 3** | *f1,3*= 0.012 | *f2,3*= 0.213 | *f3,3*= 0.965 | - |
| **Reach 4** | *f1,4*= 0.002 | *f2,4*= 0.009 | *f3,4*= 0.035 | *f4,4*= 1.00 |

**Table 3.** Counts of redds from the aerial survey, coun­ts of fresh female spawned (FFS) carcasses from the carcass survey, estimated redds from the carcass survey; and median spawning day of year (DOY), date, and spawning season lengths.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Survey year** | **Counts** | | | **Median spawn timing** | | | | **Spawning season length** | |
| Aerial survey (observed redds) | Carcass  survey  (FFS carcasses) | Estimated  redds | Aerial survey | | Carcass survey | | Aerial  survey  (days) | Carcass survey  (days) |
| DOY | Date | DOY | Date |
| 2004\* | 621 | 1060 | 1068 | 195 | Jul 13 | 186 | Jul 4 | 61 | 62 |
| 2005 | 1968 | 2953 | 2961 | 179 | Jun 28 | 181 | Jun 30 | 62 | 56 |
| 2006 | 717 | 2194 | 2195 | 185 | Jul 4 | 178 | Jun 27 | 34 | 62 |
| 2007 | 288 | 544 | 554 | 158 | Jun 7 | 184 | Jul 3 | 48 | 74 |
| 2008\* | 441 | 381 | 382 | 174 | Jun 22 | 173 | Jun 21 | 50 | 59 |
| 2009 | 86 | 550 | 554 | 189 | Jul 8 | 172 | Jun 21 | 25 | 50 |
| 2010 | 223 | 361 | 362 | 172 | Jun 21 | 177 | Jun 26 | 48 | 71 |
| 2011 | 18 | 165 | 173 | 194 | Jul 13 | 188 | Jul 7 | 20 | 59 |
| 2012\* | 261 | 595 | 618 | 184 | Jul 2 | 190 | Jul 8 | 69 | 56 |
| 2013 | 569 | 1029 | 1033 | 199 | Jul 18 | 189 | Jul 8 | 49 | 56 |
| 2014 | 127 | 413 | 418 | 182 | Jul 1 | 185 | Jul 4 | 61 | 62 |
| 2015 | 196 | 391 | 394 | 182 | Jul 1 | 184 | Jul 3 | 74 | 71 |
| 2016\* | 18 | 127 | 134 | 188 | Jul 6 | 183 | Jul 1 | 83 | 89 |
| 2017 | 26 | 59 | 58 | 199 | Jul 18 | 196 | Jul 15 | 37 | 83 |
| 2018 | 197 | 404 | 409 | 185 | Jul 4 | 195 | Jul 14 | 69 | 77 |
| 2019 | 515 | 1083 | 1084 | 177 | Jun 26 | 182 | Jul 1 | 45 | 62 |
| 2020\* | 491 | 1575 | 1577 | 182 | Jun 30 | 185 | Jul 3 | 69 | 57 |
| 2021 | 578 | 1661 | 1667 | 178 | Jun 27 | 186 | Jul 5 | 68 | 59 |
| 2022 | 406 | 604 | 617 | 185 | Jul 4 | 185 | Jul 4 | 68 | 74 |
| 2023 | 64 | 227 | 230 | 198 | Jul 17 | 184 | Jul 3 | 62 | 53 |
| Minimum | 18 | 59 | 58 | 158 | Jun 7 | 172 | Jun 21 | 20 | 50 |
| Maximum | 1968 | 2953 | 2961 | 199 | Jul 18 | 196 | Jul 15 | 83 | 89 |
| Mean | 391 | 819 | 824 | 184.3 | Jul 2 | 184.1 | Jul 2 | 55.1 | 64.6 |
| SD | 432.5 | 757.3 | 757.3 | 10.14 | - | 6.14 | - | 16.8 | 10.5 |

\* Leap year

## Figure Captions

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## Figures

A map of a river with directions

Description automatically generated

**Fig. 1.** Map of aerial and carcass surveys in the Sacramento River, California, USA. The aerial survey is conducted between Keswick Dam (RKM 486) and Princeton Ferry (RKM264 downstream of Red Bluff). The carcass survey is conducted between Keswick Dam and Balls Ferry (RKM 464), separated into four reaches. ACID Dam = Anderson Cottonwood Irrigation District Diversion Dam. See Suppl. Info. for a map extending downstream to Princeton Ferry.



**Fig. 2.** Spatial distribution of Winter-Run Chinook Salmon redds from the aerial survey and estimated distribution. The two surveys result in comparable proportions across years with a notable exception in 2019 when the aerial survey found only 9 redds in Reach 1, while the estimated count in that reach was 591. In 2007, 11 redds where found in the aerial survey downstream of Reach 4 (not shown). The division between reaches 3 and 4 in the aerial survey is 9 km downsream of the carcass survey division point.

A screenshot of a graph

Description automatically generated

**Fig. 3.** Temporal distributions of aerial redds and estimated distribution from the adjusted carcass survey data. The black lines represent the median spawning dates through the years. The shading represents the inner 95% (i.e., 2.5th and 97.5th percentiles) through the years. Please note that the y-axes have two ranges: 0–40 and 0–250 for better visibility of low counts in some years.