# Methodology for Inferring Seasonal Distributions of Endangered Winter-run Chinook Salmon Redds from Carcass and Aerial Surveys

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Next Steps:

* Review data stored in-house
* Update all carcass inputs to FishModel
* Avoiding counts since focus is on distributions. Should this be addressed? Adding the expansion methods is perhaps out of scope. I have removed the word “Counts” from the title.
* REPO https://github.com/nickobeer/SacramentoRedds. Will move to a named CBR repo Code, data and supplementary materials.
* Budget OK for $3200 to Ecological Indicators

## 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 Sacramento River winter-run Chinook salmon (*Oncorhynchus tshawytscha*), which are listed under the federal and state Endangered Species Acts, aerial surveys are conducted to quantify the number of redds (salmon nests) and the spatial extent of in-river spawning, and in-stream surveys are conducted to quantify the number of carcasses of adult spawners. Indices from these two surveys are used to estimate the annual distribution (location and timing) of spawning, but they differ in their estimates of redd counts and distribution since they vary in sampling frequency and detection probability. The aerial survey is used to quickly identify the relative locations of redds which are visible from the air, but the carcass survey provides less-biased estimates because it more consistently samples the spawning grounds. We document the methods in this paper for access and transparency of the methods, for use in subsequent studies using winter-run Chinook salmon redds data, and as an example adaptable to other similar species and systems.

Keywords

Aerial survey; Carcass; Monitoring method; Redd; Sacramento River; Winter-run Chinook

Highlights

Winter-run Chinook salmon redd distributions are inferred from survey methods

Consistent monitoring methods are used to identify trends and patterns in spawning

Timing and location of redds can be used to direct water-management decisions

## Introduction

Anadromous salmon return to freshwater to spawn as adults after maturing in the ocean. The timing of spawning, and the location of their redds (nests) has implications for their exposure to subsequent environmental conditions during the incubation period until the young fry emerge and swim freely in the river. The flow and temperature conditions they experience in the gravel can strongly influence their survival through this early life-history stage. 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 subsequent juvenile survival because the amount of time that the redds are occupied is a function of their thermally-dependent developmental rate (Alderdice and Velsen 1978, Blaxter 1988). Consequently, spawn timing interacting with the thermal regime will create inter-annual variability in emergence timing (Beer and Steel 2017, Adelfio et al. 2024) which may affect subsequent juvenile survival affected by habitat availability and predator response (Brännäs 1995, Hawkins et al. 2020).

In the Sacramento River, the Winter-run Chinook salmon (WRCS, named for the season when the adults return to the river) is a unique sub-population of salmon in North America because they spawn in the summer months (Healey 1991). Typically, the adults migrate into the Sacramento River in November and hold in deeper pools in the upper river until their spawning season from May through August. Although the historical range of WRCS in the Sacramento River basin included the Little Sacramento, Fall, Pit, and McCloud Rivers and other headwater areas, their habitat on the is now constrained below Keswick Dam which was completed in 1950 following the construction of the Shasta Dam in 1945. Although WRCS adult escapement was greater than 20,000 individuals from 1970 through 1978, the run began to decline precipitously and was listed as endangered under the California Endangered Species Act in 1989 (CDFW 2022). Four years later in 1993, only 186 individuals returned (CDFW 2023), and the next year, WRCS was listed as endangered under the Federal Endangered Species Act (NMFS 1994).

As part of the biological monitoring for the population status and conservation management of WRCS, the timing of spawning and the location of new redds are monitored annually (CDFW 2024) because the number of redds created is a key indicator of the strength of the next cohort, and their spatial and temporal distribution has implications for their exposure to varying flow and thermal conditions influenced by operations at Shasta and Keswick dams. This note illustrates how spawning ground surveys are used for a detailed assessment of the timing and location of redds.

## Methods

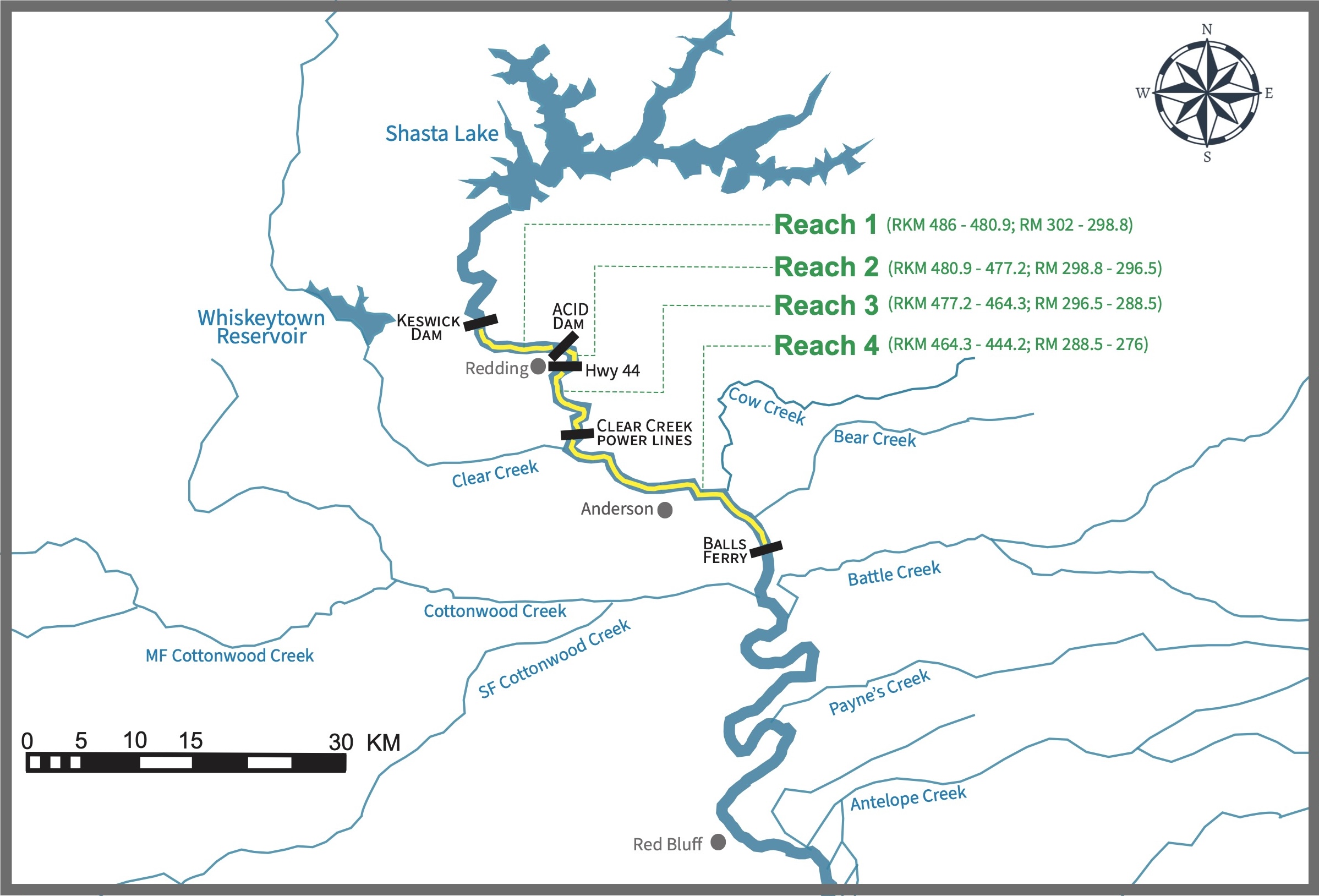
Surveys conducted from April through September enumerate the count and distribution (timing and location) of redds seen in aerial flights and the count and distribution of spawned, female carcasses found during in-river surveys. Here, we describe the two types of surveys and a model to infer the location and timing of spawning from the raw carcass survey data. Then smoothing methods are used to illustrate and compare the median spawning day and spawning season range across 20 years for the two methods.

## Aerial survey and data

Aerial surveys began in 1981 and are used to determine timing and location of newly found redds as seen from airplanes or helicopters. The flights cover > 100 km (61 mi) of the Sacramento River from the Princeton Ferry up to Keswick Dam (**Fig. 1**). Flights are conducted about every 7 d (range: 4–28 d since 2004) depending on personnel, resources, and flight conditions. New redds, not seen on a previous flight, are counted and aggregated by river reaches that are separated by bridges or other landmarks.

The data are used to infer spawning date by determining the counts·d-1 of new redds. This direct relationship between the redd observation date and spawning date is an assumption; careful interpretation would include redds under construction (leading to a spawning date biased early), and redds where spawning already occurred (leading to a spawning date biased late).

**Fig. 1.** Map of study area in the Sacramento River, California. The aerial survey is conducted between Princeton Ferry (RKM364, downstream of Red Bluff), and Keswick Dam (RKM 486). The carcass survey is conducted between Balls Ferry (RKM 464) and Keswick Dam. The ACID Dam refers to the Anderson Cottonwood Irrigation District’s water diversion dam.



## Carcass survey and data

Carcass surveys were begun in 1996 and are used to determine redd distributions using the timing and location of newly-found, spawned, female carcasses. The survey is conducted cooperatively by California Department of Fish and Wildlife, U.S. Fish and Wildlife Service, and Pacific States Marine Fisheries Commission personnel between April and September each year. Since 2004, a consistent method has been utilized where survey crews move along the river by boat identifying and marking carcasses. A fresh, female, spawned carcass (FFS) is one that was not seen in the previous survey and it is associated with a new redd. This survey covers the upper 42 km (26 mi) of the Sacramento River from Balls Ferry to Keswick Dam and is divided across four reaches (Table 1). Each reach is sampled 2 or 3 times per week through the season.

Table 1. Carcass survey reach length and river locations in river kilometer (RKM) and river mile (RM) in the upper Sacramento River. Please note that the river length and locations estimates are approximate because they vary slightly over time in a dynamic river system.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Reach # | Reach name | Length (km) | Reach location | |
| (RKM) | (RM) |
| 1 | Keswick Dam to ACID1 Dam | 5.1 | 486 – 480.9 | 302 – 298.8 |
| 2 | ACID1 Dam to Hwy 44 | 3.7 | 480.9 – 477.2 | 298.8 – 296.5 |
| 3 | Hwy 44 to Clear Creek  power lines | 12.9 | 477.2– 464.3 | 296.5 – 288.5 |
| 4 | Clear Creek power lines to  Balls Ferry | 20.1 | 464.3 – 444.2 | 288.5 – 276 |

1 Anderson Cottonwood Irrigation District diversion dam

## Model

The number, location, and timing of redds are important metrics to determine the strength of the WRCS cohort and are inferred from the carcass survey data for improved accuracy in timing and location. Because carcasses drift downstream, the location of the carcass is not the location of the redd, and the carcass data are adjusted for the location and timing of each redd’s creation. 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 numbers 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 are recovered in Reach 2, and 1.2% drifted downstream and were recovered in Reach 3.

Table 2. Drift proportions of fresh, female, spawned carcasses (FFS) of winter-run Chinook salmon (WRCS) used for adjusting spawner numbers in reaches. The subscripts on the proportions (*f*) denote the source reach first, and the recovery reach second.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Captured and tagged | | | |
| Recaptured | Reach 1 | Reach 2 | Reach 3 | Reach 4 |
| Reach 1 | *f11* = 0.868 |  |  |  |
| Reach 2 | *f12*= 0.118 | *f22*= 0.778 |  |  |
| Reach 3 | *f13*= 0.012 | *f23*= 0.213 | *f33*= 0.965 |  |
| Reach 4 | *f14*= 0.002 | *f24*= 0.009 | *f34*= 0.035 | *f44*= 1.00 |

The spatial distribution of redds is determined with steps 1 and 2 and the temporal distribution is determined with steps 3 and 4 to obtain the adjusted carcass-survey-based distribution.

**Step 1, initial counts per reach**: The number of FFS per reach 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 for the known downstream bias in carcass locations relative to redd locations using Table 2.

The preliminary adjusted number of spawners in each reach ( ) are computed sequentially from upstream to downstream using the drift proportions () and FFSR counts. If , it is adjusted to be 0.

 (1)

 (2)

 (3)

 ()

**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 date (*D*) is the same as the fraction of FFS for that same date. They are allocated to each survey day and reach as:

 (5)

In practice, this step can generate fractional fish. To handle this and obtain the final adjusted number of spawners (), it is computed in sequence for each survey date (*D*). If  <= 0,  == 0 and if  > 0,  == ceiling () and the remainder of - ceiling () is added to . The process continues for each survey day *D* and reach *R*.

**Step 4, redd timing correction**: Finally, spawn timing is computed by assuming that 7 days passed between spawning and detection of the FFS so the number of redds on any day *D* in reach *R* is:

 (6)

Small discrepancies each year between  and  are ignored. Discrepancies occur because adjusted reah counts less than zwreo are ignored, and because the timing distribution adjustment ignores the potentially negative fractional values left over for the day after the survey period. The annual discrepancies in 2004–2023 ranged 2-14 redds, with a median of 3.5.

The distribution of redds inferred from the two surveys can be re-allocated across days when observations were missing to aid in interpretation and comparison of distributions. For the aerial survey, the counts·d-1 are smoothed by a backwards-moving average with an adaptive time window. Counts are re-allocated from the observed day in a backward calculation to the day after the previous survey day or 7 days, whichever is less. The average counts·d-1 over the time window is rounded to the nearest integer to associate with each day, with higher number(s) of redds being on and previous to the observation day (e.g., 9 new redds seen on a survey day one week after the previous survey day are allocated as 2 redds on that day, 2 on the previous day, and 1 on each of the 5 days prior).

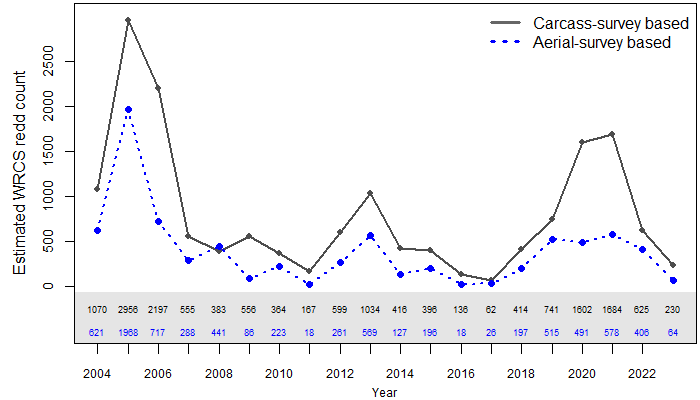
The carcass survey counts·d-1 are not re-allocated backwards, but smoothed twice with a 3-day centered, moving average. The reallocated redds are then interpreted to obtain the median spawning day and the length of the spawning season. The median spawning day is the mean day on which the cumulative number to-date equals 50% of the final count. The length of the spawning season is based on the timing of the middle 95% of the redd distribution using the the number of days between the 2.5% and 97.5% quantiles of timing.

## Results

Aerial and carcass survey data are used to infer the number of redds in the river, the median date of spawning, the length of the spawning season, and the location of the redds. From 2004–2023, the redd counts inferred from the carcass survey were almost always greater that the redd counts from the aerial survey (Fig. 2). The most noticeable improvements in redd counts were in 2011 and 2016 when aerial surveying found 18 redds both years, while the carcass survey resulted in 167 and 136 redds, respectively. The annual number of inferred redds from the carcass survey averaged 824 ± SD 757 and ranged 62–2952, while the number redds from the aerial survey averaged 390 ± SD 432 and ranged 18–1968. The only year when there were fewer redds estimated from the carcass survey than the aerial survey was in 2008 with 383 and 441 redds, respectively. Overall, improvements in redd counts, from the carcass survey compared to the aerial survey, averaged 305% ± SD 218%, and were as great as 927%.

Over the 20 years of this study, the aerial surveys identified only 13 redds outside of the carcass survey bounds (0.2% of total) and 11 of them were in 2007. Thus the carcass survey is generally accounting for the distribution of the WRCS redds.

The population’s timing metrics for median spawning date and length of spawning season varied across the years and between the methods (Table 3). The median spawning date computed from the expanded carcass data was typically later than computed from the aerial redd data, and ranged from -11 days in 2023 to 32 days in 2007 with a median difference of 2.5 days. The length of the spawning season varied from 21 to 83 days with the adjusted aerial survey, and from 50 to 110 days with the adjusted carcass survey.



**Fig. 2.** Annual count of Sacramento River winter-run Chinook salmon (WRCS) redds, estimated from aerial and carcass survey methods.

**Table 3.** Spawning season length and median spawning day from the aerial and carcass surveys.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Survey year | Aerial-based season length (days) | Adjusted Carcass-based season length (days) | Aerial-based median spawning day\* | Carcass-based median spawning day\* |
| 2004 | 62 | 63 | 191 | 185 |
| 2005 | 64 | 58 | 175 | 180 |
| 2006 | 37 | 64 | 183 | 178 |
| 2007 | 53 | 73 | 152 | 184 |
| 2008 | 52 | 65 | 171 | 172 |
| 2009 | 31 | 50 | 184 | 173 |
| 2010 | 49 | 81 | 168 | 177 |
| 2011 | 21 | 65 | 188 | 187 |
| 2012 | 71 | 59 | 182 | 189 |
| 2013 | 54 | 58 | 192 | 189 |
| 2014 | 64 | 63 | 182 | 186 |
| 2015 | 71 | 72 | 182 | 185 |
| 2016 | 83 | 93 | 188 | 183 |
| 2017 | 42 | 110 | 197 | 197 |
| 2018 | 69 | 79 | 182 | 194 |
| 2019 | 51 | 65 | 175 | 183 |
| 2020 | 70 | 60 | 177 | 185 |
| 2021 | 66 | 60 | 175 | 186 |
| 2022 | 67 | 76 | 182 | 184 |
| 2023 | 62 | 57 | 194 | 183 |

\*For reference: Day 152 = June 1 and Day 182 = July 1

Relative to the aerial survey, the carcass survey resulted in a higher number of estimated redds, and a smoother temporal distribution. Detailed graphics depicting each year’s adjusted distributions and smoothed distributions are available in the supplementary material.



**Fig. 3.** Seasonal spawning distributions inferred from aerial survey data and adjusted carcass survey data. Aerial data are smoothed in time by the gap (maximum 7 days) between successive flights for 2014-2023 (panel a), and 2004-2013 (panel b). The adjusted carcass survey data are smoothed twice by a 3-day moving average. Each area under the curve is proportional to the total number of redds in that y­­ear. Details of each year including the raw aerial data and the adjusted carcass data are in the supplementary materials (https://github.com/nickobeer/SacramentoRedds/blob/main/yeardetails.pdf)

## Discussion

Two methods of assessing the annual distribution of WRCS redds were evaluated for their utility in management of this ESA-listed fish species. Timely and accurate counts of redds and their locations are needed for management of water operation plans that include cold-water releases from Shasta Reservoir to help control water temperatures during the spawning and egg development period and control of flow to avoid dewatering. Aerial surveys provide near-real-time data but are sometimes affected by poor visibility (due to smoke, clouds, and fog), turbid river water, and scheduling of pilots and aircrafts. Carcass surveys, in conjunction with the aerial surveys, help provide more accurate data on redd counts and timing of spawning. Although the location of a redd that corresponds to a female carcass can not be know precisely, the location in the river is used to infer the upstream area where the corresponding redd is located.

The spawning season can be quite protracted (up to 110 days) and this results in a wide range of emergence times. This can lead to a potentially complex management task because at any particular time, portions of the population will be at different stages of development. Over a 64 day period (the median spawning season length), if the earliest redds were exposed to an average 12°C, they would have matured by 768 °C ATU (accumulated temperature units) , which would be considered to be 80% of fully developed based on WRCS requiring 960 °C ATU (Zeug et al. 2012) for emergence, while others are just begin created . In warmer temperatures, this development would proceed even more quickly and thus separate the life-history stages of the population further. Similarly, in years with a more protracted spawning season, the range of development stages would be even more varied.

Although the carcass survey method is an invaluable assessment and monitoring tool, the aerial survey’s utility is to provide a consistent, rapid method of assessing the physical location of redds and identifying patterns in use of the spawning grounds. In addition, the aerial survey gives an immediate assessment that would be otherwise delayed when using the carcass survey because it takes some days for the redd-building females to expire and be detected by the survey crews. The aerial survey is also used to expand estimates of the population distribution if any redds are found downstream of the carcass survey area. Finally, it is requested by some stakeholders as a legacy index to describe the timing and distribution of spawning in the river across a longer time series, and can be compared to the spawning distributions of other Sacramento River salmon runs.

As the region continues to encounter increasingly variable conditions, including severe and frequent droughts, heatwaves, and floods; the management of river conditions (e.g., release of cool water from Shasta Dam) will remain critical in recovering and sustaining aquatic species (Buddendorf et al. 2017, Sundt-Hansen et al. 2018, Anderson et al. 2022). More accurate count estimates from expanded redd count methodologies will also be important, and can depend on a number of factors such as the species, their life history traits, the rearing environment, and implementation cost (Al-Chokhachy et al. 2005, Courbois et al. 2008). This short note demonstrates how combining aerial and carcass surveys through a simple drift correction model can help provide near-real-time and more accurate estimates of redd distributions of WRCS.

The inferred redd distributions resulting from both methods described here are available from https://cbr.washington.edu/sacramento/fishmodel, a web-based tool for modeling the development and survival consequences of Chinook eggs on the spawning grounds.

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