# 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 (Matt also)
* Update all carcass inputs to FishModel (on final method)
* In this MS: 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.
* Terminology: CDFW uses “Expanded Counts” to refer to the adjustments made with the drift corrections. CDFW also uses “Expansion Factor” to refer to the final manipulation of all sources of data and the mark-recapture rate. Currently use wording “adjustment”
* 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.

## 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 abundance and distribution since the methods vary in sampling frequency, detection probability and the type of data collected. The aerial survey is used to quickly identify the relative locations of redds which are visible from the air, but the carcass survey provides a less-biased estimate because it more consistently samples the spawning grounds. The carcass survey resulted in a higher number of estimated redds, and a smoother temporal distribution. 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 survey; 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. The flow and temperature conditions they experience during this period 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 the thermally-dependent developmental rate of the eggs (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) spawn in the summer months, which is unique among populations of salmon in North America (Healey 1991). Typically, the WRCS 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 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 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

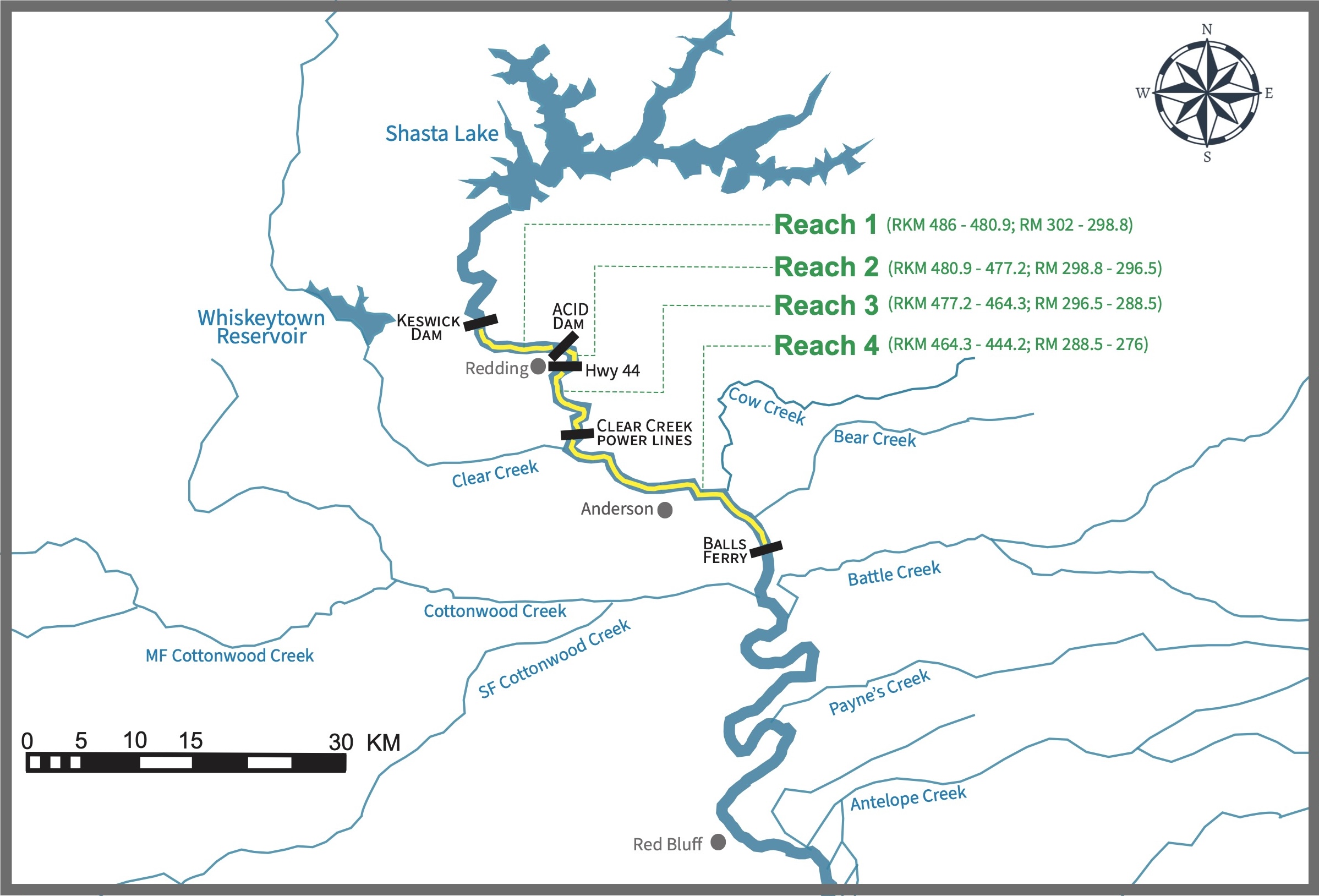
Surveys conducted from April through September enumerate the count and distribution (timing and location) of redds seen in aerial flights and the count and distribution of spawned, female carcasses found during in-river surveys. Here, we describe the two types of surveys and a model to infer distribution of spawning from the carcass survey data.

## 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 each ~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 carcass survey is conducted between Balls Ferry (RKM 464) and Keswick Dam (RKM 486) with the four survey reaches identified. The ACID Dam refers to the Anderson Cottonwood Irrigation District’s water diversion dam. The aerial survey is conducted between Princeton Ferry (RKM364, downstream of Red Bluff), and Keswick Dam (RKM 486). See supplementary information for the larger map.



## 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. 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 (i.e. it is unmarked) 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 and Fig. 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 must be inferred 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 assess 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 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. The final distribution of redds is determined with adjustments to the carcass-survey-based data using the drift proportions in 5 steps.

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 |

**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.

 (1)

 (2)

 (3)

 (4)

After calculating , 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 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)

**Step 4, re-allocate fractional spawners** Fractional values for any  must be further adjusted in order to have a one-to-one correspondence of redds to carcasses. The final adjusted number of spawners () is computed by re-allocating fractional values. This is computed in sequence for each survey date (*D*) in chronological order as follows:

 == round(  > 0), and the remainder = - round () is added to . The remainder may be positive or negative. Days when  == 0 always remain 0. The process continues for each survey day *D* in each reach *R*.

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

 (6)

Small discrepancies each year between  and  are ignored. Discrepancies occur because adjusted reach counts that are 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 2004–2023 ranged from -1 to 23 redds, with a median of 4.5.

Two timing metrics are computed on the aerial survey distributions and the adjusted carcass-survey based distributions: the median spawning day and the spawning season duration which is computed as the range of days over the middle 95% of the redd distribution timing.

## Results

Each year, aerial and carcass survey data were used to infer the distribution of WRCS redds in the river, the median date of spawning, and the length of the spawning season. From 2004–2023, the number of redds inferred from the carcass survey was almost always greater that the redds counted in 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 method resulted in 167 and 136 redds respectively (Table 3). The number of inferred redds from the adjusted carcass survey averaged 824 ± SD 757 and ranged 58–2961, while the number redds from the aerial survey averaged 390 ± SD 432 and ranged 18–1968. The only year when there were fewer redds counted in 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 301% ± SD 212%, and were as great as 917%.

Over the years 2004 to 2023, 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 relative proportions found in the reaches varies slightly between years (Fig. 2) except in 2019 when the difference is greater than the other years since the aerial survey method attributed less than 2% of the redds to reach 1 and the carcass survey method attributed over 54%.

The population’s timing metrics for median spawning date and spawning season duration varied across the years and between the methods (Table 3). The median spawning date computed from the adjusted carcass data was typically later than computed from the aerial redd data, and ranged from -11 days in 2009 to 32 days in 2007 with a median difference of 2.5 days. The spawning season duration varied from 21 to 83 days with the aerial survey, and from 51 to 89 days with the adjusted carcass survey. The timing distributions with median spawning day and season length are illustrated in Fig. 3.



**Fig. 2.** Spatial distribution of winter-run Chinook salmon (WRCS) redds inferred from the aerial and carcass surveys.

**Table 3.** Aerial redd counts, Fresh Female Spawned (FFS) carcasses, inferred redds from the carcass-survey; and median spawning day and spawning season durations.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Survey year | Redds from aerial-survey | FFS carcasses | Inferred redds from adjusted carcass survey | Aerial-survey based median spawning day\* | Carcass-survey based median spawning day\* | Aerial-survey based season length (days) | Adjusted carcass-survey based season length (days) |
| 2004 | 621 | 1060 | 1068 | 191 | 185 | 62 | 63 |
| 2005 | 1968 | 2953 | 2961 | 175 | 180 | 64 | 58 |
| 2006 | 717 | 2194 | 2195 | 183 | 178 | 37 | 64 |
| 2007 | 288 | 544 | 554 | 152 | 184 | 53 | 73 |
| 2008 | 441 | 381 | 382 | 171 | 172 | 52 | 65 |
| 2009 | 86 | 550 | 554 | 184 | 173 | 31 | 50 |
| 2010 | 223 | 361 | 362 | 168 | 177 | 49 | 81 |
| 2011 | 18 | 165 | 173 | 188 | 187 | 21 | 65 |
| 2012 | 261 | 595 | 618 | 182 | 189 | 71 | 59 |
| 2013 | 569 | 1029 | 1033 | 192 | 189 | 54 | 58 |
| 2014 | 127 | 413 | 418 | 182 | 186 | 64 | 63 |
| 2015 | 196 | 391 | 394 | 182 | 185 | 71 | 72 |
| 2016 | 18 | 127 | 134 | 188 | 183 | 83 | 93 |
| 2017 | 26 | 59 | 58 | 197 | 197 | 42 | 110 |
| 2018 | 197 | 404 | 409 | 182 | 194 | 69 | 79 |
| 2019 | 515 | 1083 | 1084 | 175 | 183 | 51 | 65 |
| 2020 | 491 | 1575 | 1577 | 177 | 185 | 70 | 60 |
| 2021 | 578 | 1661 | 1667 | 175 | 186 | 66 | 60 |
| 2022 | 406 | 604 | 617 | 182 | 184 | 67 | 76 |
| 2023 | 64 | 227 | 230 | 194 | 183 | 62 | 57 |
| Minimum | 18 | 59 | 58 | 152 | 172 | 21 | 50 |
| Maximum | 1968 | 2953 | 2961 | 197 | 197 | 83 | 110 |
| Mean | 391 | 819 | 824 | 181 | 184 | 57.0 | 68.6 |

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



**Fig. 3.** Temporal distributions of redds inferred from aerial survey and adjusted carcass survey data. The median spawning date is shown with black line and the spawn timing range (inner 95% quantile) is shaded in light grey.

## 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 flow controls to mitigate redd 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 can be 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 corresponding 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 duration), 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 ~ 80% of fully-developed based on WRCS requiring 960 °C ATU (Zeug et al. 2012) for emergence, while other redds 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 duration, the range of development stages would be more varied as well.

Although the carcass survey method is an invaluable assessment and monitoring tool, the aerial survey provides 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 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 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.

## 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.

## References

Adelfio, L.A., S.M. Wondzell, N.J. Mantua, and G.H. Reeves. 2024. Expanded, compressed, or equal? Interactions between spawning window and stream thermal regime generate three responses in modeled juvenile emergence for Pacific salmon. Canadian Journal of Fisheries and Aquatic Sciences 81(5): 573-588.

Al-Chokhachy, R., P. Budy, and H. Schaller. 2005. Understanding the significance of redd counts: A comparison between two methods for estimating the abundance of and monitoring bull trout populations. North American Journal of Fisheries Management 25(4): 1505-1512.

Alderdice, D.F., and F.P.J. Velsen. 1978. Relation between temperature and incubation time for eggs of Chinook Salmon (*Oncorhynchus tshawytscha*). Journal of the Fisheries Research Board of Canada 35(1): 69-75.

Anderson, J.J., W.N. Beer, J.A. Israel, and S. Greene. 2022. Targeting river operations to the critical thermal window of fish incubation: Model and case study on Sacramento River winter-run Chinook salmon. River Research and Applications 38(5): 895-905.

Becker, C.D., D.A. Neitzel, and C.S. Abernethy. 1983. Effects of Dewatering on Chinook Salmon Redds: Tolerance of Four Development Phases to One-Time Dewatering. North American Journal of Fisheries Management 3(4): 373-382.

Beer, W.N., and E.A. Steel. 2017. Impacts and Implications of Temperature Variability on Chinook Salmon Egg Development and Emergence Phenology. Transactions of the American Fisheries Society 147(1): 3-15.

Blaxter, J.H.S. 1988. Pattern and Variety in Development. Page 499 *in* W. S. Hoar, Randall, D.J. , editor. Fish Physiology Volume XI The Physiology of Developing Fish, Part A: Eggs and Larvae. Harcourt Brace Jovanovich, New York.

Brännäs, E. 1995. First access to territorial space and exposure to strong predation pressure: A conflict in early emerging Atlantic salmon (*Salmo salar* L.) fry. Evolutionary Ecology 9(4): 411-420.

Buddendorf, W.B., I.A. Malcolm, J. Geris, L. Fabris, K.J. Millidine, M.E. Wilkinson, and C. Soulsby. 2017. Spatio-temporal effects of river regulation on habitat quality for Atlantic salmon fry. Ecological Indicators 83: 292-302.

California Department of Fish and Wildlife (CDFW) 2022. California Natural Diversity Database (CNDDB). October 2022. State and Federally Listed Endangered and Threatened Animals of California. California Department of Fish and Wildlife. Sacramento, CA. Pages <https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=109405&inline>

California Department of Fish and Wildlife (CDFW) 2023. California Central Valley Chinook Escapement Database Report. 29 Pages <https://nrm.dfg.ca.gov/FileHandler.ashx?DocumentID=84381&inline>

California Department of Fish and Wildlife (CDFW) 2024. CDFW Upper Sacramento River Basin Salmonid Monitoring. <https://www.calfish.org/ProgramsData/ConservationandManagement/CentralValleyMonitoring/CDFWUpperSacRiverBasinSalmonidMonitoring.aspx>

Courbois, J.-Y., S.L. Katz, D.J. Isaak, E.A. Steel, R.F. Thurow, A.M.W. Rub, T. Olsen, and C.E. Jordan. 2008. Evaluating probability sampling strategies for estimating redd counts: an example with Chinook salmon (Oncorhynchus tshawytscha). Canadian Journal of Fisheries and Aquatic Sciences 65(9): 1814-1830.

Hawkins, B.L., A.H. Fullerton, B.L. Sanderson, and E.A. Steel. 2020. Individual-based simulations suggest mixed impacts of warmer temperatures and a nonnative predator on Chinook salmon. Ecosphere 11(8): e03218.

Healey, M.C. 1991. Life History of Chinook Salmon *in* C. Groot, Margolis, L. , editor. Pacific Salmon Life History UBC Press, Vancouver, BC.

Martin, B.T., A. Pike, S.N. John, N. Hamda, J. Roberts, S.T. Lindley, and E.M. Danner. 2017. Phenomenological vs. biophysical models of thermal stress in aquatic eggs. Ecology Letters 20(1): 50-59.

McCullough, D.A. 1999. A Review and Synthesis of Effects of Alterations to the Water Temperature Regime on Freshwater Life Stages of Salmonids, with Special Reference to Chinook Salmon. Columbia River Inter-Tribal Fish Commission: Portland, OR.

National Marine Fisheries Service (NMFS) 1994. Endangered and Threatened Species; Status of Sacramento River Winter-run Chinook Salmon. Pages <https://www.federalregister.gov/d/93-31089>

Sundt-Hansen, L.E., R.D. Hedger, O. Ugedal, O.H. Diserud, A.G. Finstad, J.F. Sauterleute, L. Tøfte, K. Alfredsen, and T. Forseth. 2018. Modelling climate change effects on Atlantic salmon: Implications for mitigation in regulated rivers. Science of The Total Environment 631-632: 1005-1017.

United States Fish and Wildlife Service (USFWS) 1999. Effect of temperature on early-life survival of Sacramento River fall- and winter-run Chinook salmon. 52 Pages <https://docs.streamnetlibrary.org/USFWS/EffectTempEarlySurvSacramentoChinook.pdf>

United States Fish and Wildlife Service (USFWS) 2006. Relationships between flow fluctuations and redd dewatering and juvenile stranding for Chinook salmon and steelhead in the Sacramento River between Keswick Dam and Battle Creek. 87 Pages <https://www.noaa.gov/sites/default/files/legacy/document/2020/Oct/07354626849.pdf>

Zeug, S.C., P.S. Bergman, B.J. Cavallo, and K.S. Jones. 2012. Application of a Life Cycle Simulation Model to Evaluate Impacts of Water Management and Conservation Actions on an Endangered Population of Chinook Salmon. Environmental Modeling & Assessment 17(5): 455-467.