https://doi.org/10.25923/a9n9-bn08

NOAA Technical Memorandum NMFS

AUGUST 2020

ESTIMATING HABITAT CAPACITY FOR SPRING-RUN CHINOOK SALMON AND STEELHEAD IN THE NORTH FORK FEATHER RIVER WATERSHED

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NOAA-TM-NMFS-SWFSC-633

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
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Recommended citation

Volk, Carol, David A. Boughton, and Lee R. Harrison. 2020. Estimating habitat capacity for spring-run Chinook salmon and steelhead in the North Fork Feather River Watershed. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-SWFSC-633.
56 p.
https://doi.org/10.25923/a9n9-bn08

Estimating habitat capacity for spring-run Chinook salmon and steelhead in the North Fork Feather River Watershed

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Abstract

We estimated thermal suitability and habitat capacity for spring-run Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*Oncorhynchus mykiss*) within the North Fork of Feather River upstream of Lake Oroville, with particular focus on areas upstream of Rock Creek Dam that may be appropriate for reintroduction. Thermal suitability of stream habitat for areas of interest in years 2014 through 2017 was estimated using simple linear regression models for temperature, using elevation, day-of-year, and remotely sensed land surface temperature as covariates. Eight-day mean water temperatures were estimated for all stream reaches, and evaluated for the relevant life-stages of each fish species using criteria for optimal and tolerable temperatures. Simple estimates of capacity (numbers of fish per generation) were also estimated based on geomorphic habitat type and predicted temperature. We found spawning and incubation life-stages for both species to be seasonally limited by temperature throughout the NF Feather, while juvenile rearing was less constrained by temperature. There appears to be capacity for reintroduction of steelhead and perhaps spring-run Chinook salmon in the reaches upstream of Rock Creek Dam. Substantial additional capacity appears to occur upstream of natural migration barriers on Indian Creek and Spanish Creek, and in tributaries upstream of Lake Almanor.

Extended Summary

To assist the recovery of ESA-listed Central Valley salmon and steelhead stocks, populations could be re-established in historically available areas that have been blocked by dams or insufficient flows (Lindley et al. 2007). Review of the capacity of these areas to support a viable population can guide reintroduction efforts by providing quantitative estimates of the number of salmon which could be produced if access to these areas was provided through reintroduction. In this report we estimate thermal suitability and habitat capacity for spring-run Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*Oncorhynchus mykiss*) within the Feather River, with particular focus on watersheds draining into the North Fork (NF) that may be appropriate for reintroduction efforts. Spatial domains of interest were areas upstream of Rock Creek Dam on the NF Feather (Seneca and Belden) and adjacent accessible domains (Yellow Creek, Upper Tributaries and East Branch NF). Thermal suitability and in-stream habitat were also assessed in areas inaccessible above Rock Creek (West Branch NF, Tributaries above Lake Almanor, Indian Creek, Spanish Creek and Above Dams) to provide historical context of available habitat throughout the NF Feather River.

We evaluated the thermal suitability for the NF Feather River areas of interest from the beginning of 2014 through 2017, using simple linear regression models for temperature. Remotely sensed Land Surface Temperature (LST), elevation, and day-of-year were used as covariates to estimate in-stream temperatures at 8-day intervals. Models were calibrated with continuous in-stream temperature data collated from local organizations. Estimated in-stream temperatures were summarized to lifestage-specific metrics for Chinook salmon and steelhead across spatial domains of interest. To evaluate physical habitat availability, gradient-based channel types (Buffington et al. 2004) were defined and empirical habitat unit data from the Belden and Seneca reaches of the North Fork Feather River (Thomas R. Payne Associates 2002) were used to calculate unit amount within each channel type. Habitat use and fish densities developed for the nearby Yuba River were then used to estimate Chinook salmon and steelhead capacity for domains accessible above Rock Creek Dam.

We found spawning and incubation life-stages for steelhead and spring-run Chinook salmon were seasonally limited by temperature throughout the NF Feather, and thermal limits for rearing and holding (Chinook-only) varied spatially across the watershed. Belden and Seneca were notably cooler than other domains accessible from a potential reintroduction site near Rock Creek Dam. The majority of preferred Chinook salmon and steelhead habitat was found in tributaries draining the East Branch NF Feather (Spanish and Indian Creeks), although Yellow Creek and East Branch NF Feather may provide valuable spawning habitat above Rock Creek Dam. Spanish and Indian Creeks both have migration barriers near their confluences that should be further investigated for passability.

Based on coarse estimates of population viability, there is geomorphic capacity for a viable population with a focused reintroduction of steelhead and to some degree, of Chinook salmon, in the Belden reach. Since capacity estimates were based on geomorphology, it is critical to consider the timing and impacts of thermal constraints within the Belden reach and greater NF Feather River. Both Chinook salmon and steelhead experience long durations of thermally difficult (tolerable or intolerable) temperatures during egg incubation in the mainstem Feather River, including Belden and Seneca reaches. Capacity in the Seneca reach is most likely limited by the availability of low-gradient habitat that would provide favorable gravel-beds for spawning.

Future work could focus on collection of habitat type data in Yellow Creek and the East Branch to verify the gradient-based channel typing approach used here. The water temperature modeling could also be improved through the addition of full-year temperature monitoring and additional loggers in the East Branch NF Feather to verify its predicted thermal suitability and large capacity. It would also be valuable to consider other reintroduction scenarios more fully, such as introduction above Lake Almanor, in Indian

Creek, or in Spanish Creek, and also conduct a detailed assessment of passability during spring snowmelt at the migration barriers on Indian Creek and Spanish Creek. Although our thermal modeling was relatively successful in the unmanaged sections of the stream network, it was less successful in the highly-managed flow regime on the mainstem of the North Fork between Lakes Almanor and Oroville. Impacts from water supply diversions and returns were not explicitly considered in this study. Future work could consider all water return locations, as these locations may be differentially warmer or cooler than the mainstem Feather, depending on the source and the transport of the water, the season, and the amount of precipitation in the water year.

Introduction

To recover ESA-listed salmon and steelhead in the Central Valley, Lindley et al. (2007) proposed re-establishing populations in historic habitats from which they are now excluded. For such reintroductions, a key question is whether the freshwater habitat in the proposed area has the capacity to support a viable population. Capacity in this context refers to carrying capacity—the degree of saturation of habitat at which additional animals introduced to the habitat fail to further increase abundance due to density-dependent mortality or emigration. The life-history complexity of anadromous salmonids complicates the concept of capacity, as these fish progress through a sequence of life-stages and each stage is therefore connected to the other stage-specific habitats (Mobrand et al. 1997). Productive and abundant Chinook salmon and steelhead populations therefore require suitable freshwater habitat that can sustain adult, egg, and juvenile lifestages, which each require distinct amounts and types of habitat (e.g. Sharma and Hilborn 2001, McHugh and Budy 2011). In addition, capacity likely varies substantially from year to year due to fluctuations in streamflow, water temperature and disturbance events and thus an assessment of capacity for salmonid populations involves estimating capacity of multiple lifestages over multiple years.

The goal of this project was to evaluate the habitat capacity of the North Fork Feather River basin for reintroduction of two anadromous stocks of Pacific salmonids: Central Valley steelhead and Central Valley spring-run Chinook salmon. Currently in the Feather River, spring-run Chinook salmon and steelhead are confined to the main river below Lake Oroville, and excluded from their historic spawning areas in the mountains upstream of the reservoir. The numbers of each spawning in the Feather River are not well known, due to lack of monitoring for non-hatchery steelhead (Williams et al. 2016) and inability to distinguish spring-run Chinook salmon from the much-more abundant fall-run Chinook salmon spawning in the Feather River below Lake Oroville at about the same time; the population is also impacted by the adjacent hatchery population, with the majority of spawners being first-generation hatchery-produced fish (Williams et al. 2016, p. 94-95). Thus neither steelhead nor spring-run Chinook salmon in the Feather River below Lake Oroville appear to comprise a wild, viable population.

Here we focus on broad-scale assessments of habitat capacity for reintroduction of each species in the North Fork upstream of Lake Oroville. We generated spatially explicit models of water temperature in the NF Feather River watershed for 2014-2017, which represent drought (2014-2015), nearly average rainfall (2016) and an exceptionally wet year (2017) (See Figure S22 in the supplemental material). The water temperature models were used to characterize the thermal suitability of key spatial domains for each life-stage. We used remote sensing and field data to characterize channel types, which were then combined with fish use and density metrics from the nearby Yuba River to estimate capacity (Stillwater Sciences 2013). The capacity estimates help inform whether the available habitat has sufficient capacity to support viable populations of each species.

Approach

Stream Network and Spatial Domains

The stream network of interest was the named tributaries and full mainstem of the North Fork Feather River (NFFR), comprising HUCs 18020121 and 18020122 of the 1:24k National Hydrography Dataset (NHD) upstream from Lake Oroville (Figure 1c and d). This network was further trimmed to exclude all streams with gradients greater than 12% and all areas above reaches with gradients greater than 8% for more than 300 m. These exclusions targeted streams that are largely ephemeral and impassible to Chinook salmon (Stillwater Sciences 2013), but omit some that probably are accessible to steelhead. Hydrography was further split into 2 km reaches, with reach catchment areas (RCA) generated for each unique reach. RCAs delineate the adjacent upland area draining directly into an individual reach, and in this

Table 1. Spatial domains of interest in the NF Feather River Watershed.

Spatial Domain	Length (km)	% Accessible Subdomain	% All Domains
Accessible above Rock Creek Dam			
Belden	15.3	8.7	1.0
Seneca	19.1	10.9	1.2
East Branch NF Feather	29.3	16.7	1.9
Yellow Creek	65.1	37.1	4.1
Upper Tributaries	46.5	26.5	3.0
Subtotal	175.3	100.0	11.1
Inaccessible above Rock Creek Dam			
Lower NF Feather	67.8	4.8	4.3
Lower NF Feather Tributaries	53.4	3.8	3.4
West Branch NF Feather	137.1	9.8	8.7
Spanish Creek	172.6	12.3	11.0
Indian Creek	517.3	37.0	32.8
Tributaries above Almanor	310.2	22.2	19.7
Above Dams	141.2	10.1	9.0
Subtotal	1399.6	100.0	88.9
TOTAL	1574.9		100.0

study averaged about 9 km^2. RCAs are non-overlapping polygons and were used as the zonal summary areas for the water temperature modeling described in the next section.

The NFFR watershed was divided into 12 spatial domains (Table 1), based on relevance for Chinook salmon and steelhead reintroduction in terms of location, access, and stream size (Figure 1d and Table 1). The total length of channel within each domain varied from 15 to 517 km and included mainstem reaches of the North Fork as well as entire tributary systems. The mainstem NF Feather has three spatial domains between Lake Oroville and Lake Almanor: Lower NFFR, Belden, and Seneca. The Lower NFFR contains three dams as part of the 'Stairway of Power' ("A," "B" and "C" in Figure 1d), a hydroelectric generating system built in the early 1900's that is heavily flow-regulated. Summer air temperatures here can reach as high as 28°C. The upstream end of the mainstem between Rock Creek Dam and Canyon Dam (base of Lake Almanor) was split into Belden and Seneca domains, which are both heavily impacted by flow regulation and likely have unique temperature regimes. Seneca receives flows from Canyon Dam ("F" in Figure 1d) and is subjected to thermal fluctuations of Lake Almanor while Belden receives piped water from Butt Reservoir and is flow-regulated at Caribou Afterbay Dam ("D" in Figure 1d). Small tributaries to the NFFR above and below Rock Creek Dam were grouped into two spatial domains, the Upper NF Tributaries and Lower NF Tributaries, respectively. The Upper NF Tributaries also included several small tributaries draining into the East Branch NF Feather. Yellow Creek is a large tributary to the mainstem above Rock Creek Dam that was assigned its own spatial domain. It is accessible to fish, averages 20°C in the summer, and has low gradient reaches in the upper watershed that potentially offer valuable spawning habitat. The East Branch NF Feather, also accessible from above Rock Creek Dam, drains a large eastern portion of the watershed. Its spatial domain has cooler average summer air temperatures (18.8°C) and the highest average watershed elevations of all the domains (1,788 m).

Two western domains, West Branch NF Feather and Tributaries above Almanor, are not easily accessible to fish from the mainstem. The West Branch NF Feather drains directly into Lake Oroville and

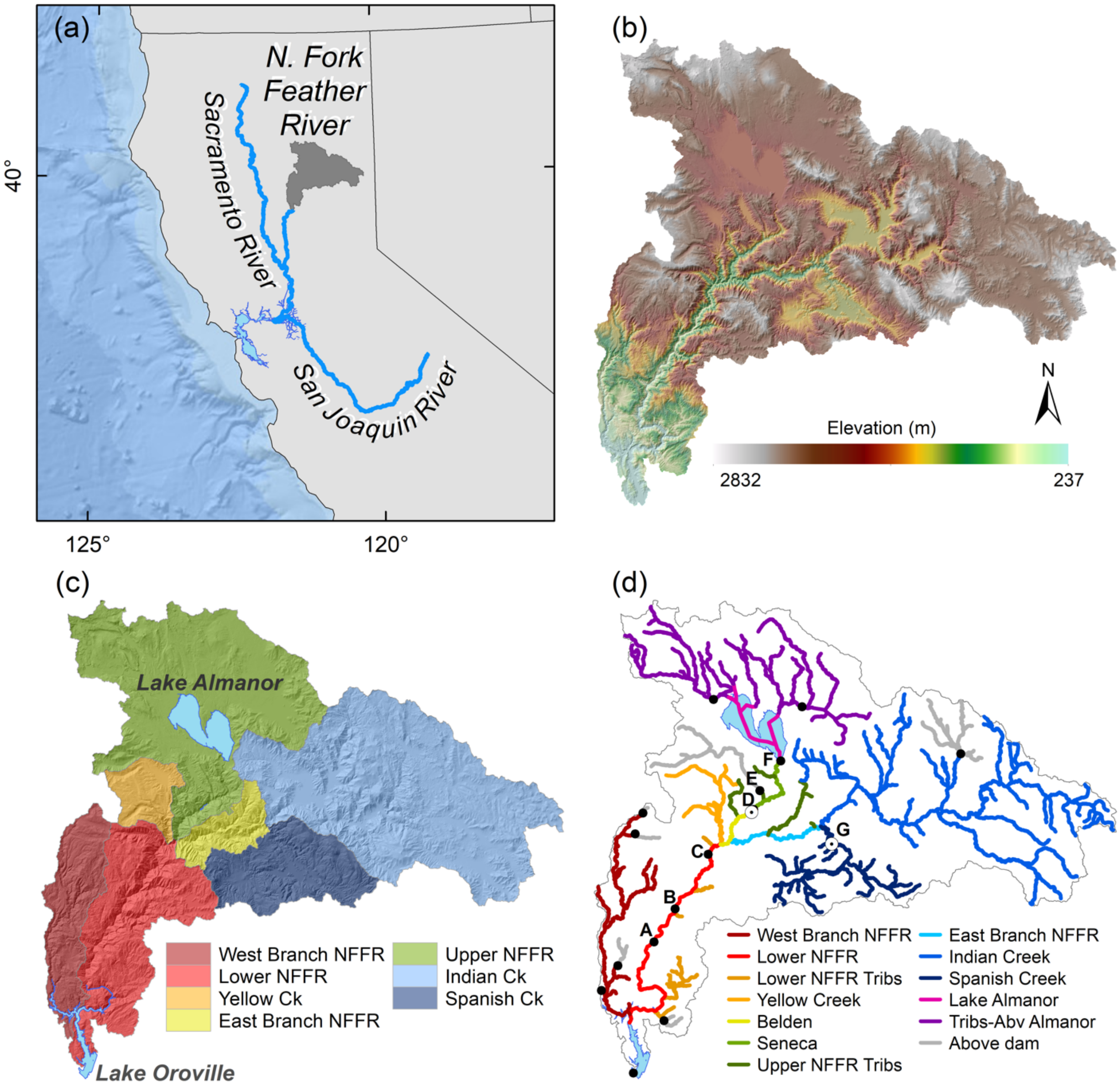

Figure 1. ***(a)*** *Location of the North Fork Feather River watershed in northern California, USA.* ***(b)*** *Elevations in the watershed.* ***(c)*** *HUC 10 boundaries.* ***(d)*** *Network extent (lines) and spatial domains (colors) considered in this report. Dams are shown as solid black circles, two USGS stream gages are shown as open white circles. A = Poe Dam, B = Cresta Dam, C = Rock Creek Dam, D = Caribou Afterbay Dam and USGS gage below Belden (USGS station 11401112), E = Butt Canyon Dam, F = Canyon Dam and G = USGS gage on Spanish Creek (USGS station 11402000). Potential fish reintroductions could occur upstream of Rock Creek Dam (C), which would provide access to the Seneca and Belden reaches on the mainstem NFFR and as well as Yellow Creek and the East Branch NFFR.*

Tributaries Above Almanor include high elevation (~1,650 m) tributaries that empty into Lake Almanor. Prior to the construction of Canyon Dam and Lake Almanor, the upper NF Feather River system was accessible to salmon. Reaches currently underneath Lake Almanor, Mountain Meadows Reservoir (east of Lake Almanor), and possibly Butt Valley Reservoir (upstream of "E" in Figure 1d), were low-gradient streams that likely had extensive gravel-bedded channels. The West Branch NF also has a high average watershed elevation (1,653 m), with summer air temperatures averaging 18.5°C. The largest tributary domains were in the eastern watershed: Indian and Spanish Creeks, whose confluence forms the East Branch. These both have natural barriers to anadromy near their confluence (a waterfall and rapids, respectively), but may have been historically accessible areas (Yoshiyama et al. 2001). These domains were expected to be useful comparative reaches for understanding natural thermal patterns and limitations within the NF Feather River watershed. Last, a domain that combined tributary habitat above dams (Above dam in Figure 1d) had the coolest summer air temperatures (~17.9°C) but are the least accessible from the NF Feather River mainstem. It represents the upper extents of potential Chinook salmon and steelhead habitat.

Modeling Stream Temperature

We used remotely-sensed data on land surface temperature (LST) as a key predictor to develop statistical models of stream temperature. LST effectively integrates many environmental and climatic factors into a single term with predictive capacity, and can be directly measured via satellite over broad geographic regions (e.g. Figure S1 in the Supplemental Material). This makes it a simple and powerful predictor of stream temperature (Figure S2), but of less use for understanding the mechanistic relationship between stream temperature and individual factors, such as air temperature or solar radiation. Both LST and stream temperature are sensitive to similar environmental factors; LST is related to air temperature, wind patterns and convective heat loss, vegetative cover, soil saturation (and therefore precipitation), aspect, exposure, and elevation (Caissie 2006).

Since 2000, LST data from the NASA satellite platform Moderate Resolution Imaging Spectroradiometer (MODIS) has been freely available in daily and 8-day temporal resolutions with a 1 km spatial resolution, providing consistent and widely available LST measurements. Previously, a collaboration between South Fork Research and NOAA Fisheries successfully used LST, day of year, discharge, and elevation as predictor variables in a series of linear statistical models. The models estimated 8-day mean, maximum and minimum stream temperature for stream reaches in watersheds of the interior Columbia River Basin from 2000-2017, and included over 100 unique models across space and time (McNyset et al. 2015; https://github.com/SouthForkResearch/StreamTemperature/wiki).

Temperature Model Development

The mainstem NFFR is flow-regulated, including impacts by water returns from hydroelectric infrastructure that may be either warmer or cooler than the river depending on season. The natural relationship between flow-related variables and stream temperature in the mainstem is likely weakened and very different from unregulated tributaries and therefore best captured in a distinct model. For modeling we therefore split the watershed into a tributary and a mainstem modeling sector for temperature estimation (Figure 2). A simple linear regression model was developed to predict 8-day mean temperature from land surface temperature, day of year, elevation and discharge for each sector.

The discharge covariate was used to account for annual variation and patterns in flows; a single station that captured the representative flows was used in each of the tributary and mainstem sectors. The mainstem sector used mean daily discharge for the North Fork Feather River below Belden (USGS station 11401112, “D” in Figure 1d). The tributary sector used mean daily discharge in Spanish Creek (USGS station 11402000, “G” in Figure 1d), representing the best available gage data for 2014-2017. For the elevation covariate, zonal statistics were used to extract the minimum RCA elevation for each reach, using a 10 m digital elevation model (DEM). For the LST covariate, 8-day data between January 1, 2014 and December 31, 2017 were downloaded from the EarthData Portal (https://earthdata.nasa.gov). The data product is MOD11A2: MODIS/Terra Land Surface Temperature/Emissivity 8-Day L3 Global 1km SIN Grid V005. Additional information on the dataset and preprocessing can be found in the supplementary material.

In the regressions, for each year in each sector we considered a variety of models. For effects of LST, we examined both first- and second-order polynomials to consider the possibility of a non-linear relationship between LST and water temperature. For seasonality, we considered a full-year model and paired spring-and-fall models. For the latter, each year's data was split into before and after the maximum temperature observed in the summer, separating the calendar year time-series into 'rising' temperatures (spring) and 'falling' temperatures (fall). Spring-and-fall models were only considered for years in which 5 or more loggers were deployed for both spring and fall periods (McNyset et al. 2015). We did not attempt this in the mainstem sector due to the limited number of stream temperature loggers with full-year coverage. Since logger data in the mainstem sector were only common in summer months, temperature summaries for Seneca, Belden, and the Lower NFFR sometimes did not cover the full calendar year.

The R computer code for model development was adapted from similar work previously conducted in the interior Columbia River basin (McNyset et al. 2015; Albrecht et al. 2015). PRESS statistics (predicted residual error sum of squares) and model diagnostics (e.g. skewness, kurtosis, and heteroscedascity) were reviewed and once a final model was selected, model coefficients were used to estimate water temperature for all reaches within the Feather River watershed at each 8-day time step. Models were validated by comparing observed stream temperatures to predicted values, and site-specific error was calculated as the average difference between observed and predicted stream temperatures for each location where in-stream temperature was available.

Additional hydrologic factors may directly impact stream temperature but are not inherently captured by LST, such as groundwater and water storage (lakes, reservoirs, or subsurface aquifers) (e.g. review by Caissie 2006). Effects of groundwater and aquifers were not explored due to data availability and the complex interaction between ground- and surface-water exchange. The influence of Lake Almanor storage on mainstem temperatures was briefly explored by incorporating a 'distance from Lake Almanor' covariate. This covariate was strongly correlated to elevation and therefore not incorporated into final models. Discharge was considered as a predictor variable in the mainstem NFFR using a single gauge, as described above, but we note that regulation of the mainstem NFFR through multiple diversion dams and tunnels may have complex anthropogenic effects on the relationship between flow and temperature. Fully modeling this complexity was beyond the scope of this investigation.

All model code is available from the South Fork Research Stream Temperature repository on GitHub (https://github.com/SouthForkResearch/StreamTemperature/tree/master/Notebooks).

Temperature Logger Data

For the dependent variable in the regressions, continuous water temperature monitoring data were compiled from the US Forest Service, Pacific Gas and Electric (PG&E), California Department of Water Resources, and the Plumas Corporation. Compiled data were initially summarized to daily mean temperatures for the available period of record, and reviewed graphically for quality assurance and consistency. We removed data where changes of more than 15° C per day marked periods when the logger was likely not submerged in water. Then, daily means were summarized to 8-day means that matched the temporal resolution and timing of the LST data. The 8-day mean captures a smoothed trend of daily temperatures, which we assumed to be of sufficient resolution for identifying sustained periods of high and low temperatures likely to affect suitability for steelhead or Chinook salmon. Note that 8-day means will tend to smooth over brief spikes and drops in temperature that may stress or even kill steelhead and Chinook salmon in real life.

Logger densities varied by year and modeling sector, with 19 to 38 loggers available for the tributary sector and 7 to 9 loggers for the mainstem sector in the years modeled (Figure 2, Table S1). Logger densities were highest in the Upper Tributaries and Indian Creek domains, with limited to no coverage in East Branch NF Feather River, Yellow Creek, Tributaries above Lake Almanor, Lower North Fork Feather, West Branch NF Feather, and Spanish Creek (Figure 2). Low densities of loggers can limit validation of temperature models, and loggers spaced unevenly across the primary drivers of stream temperature (e.g. elevation and discharge) can negatively impact model development.

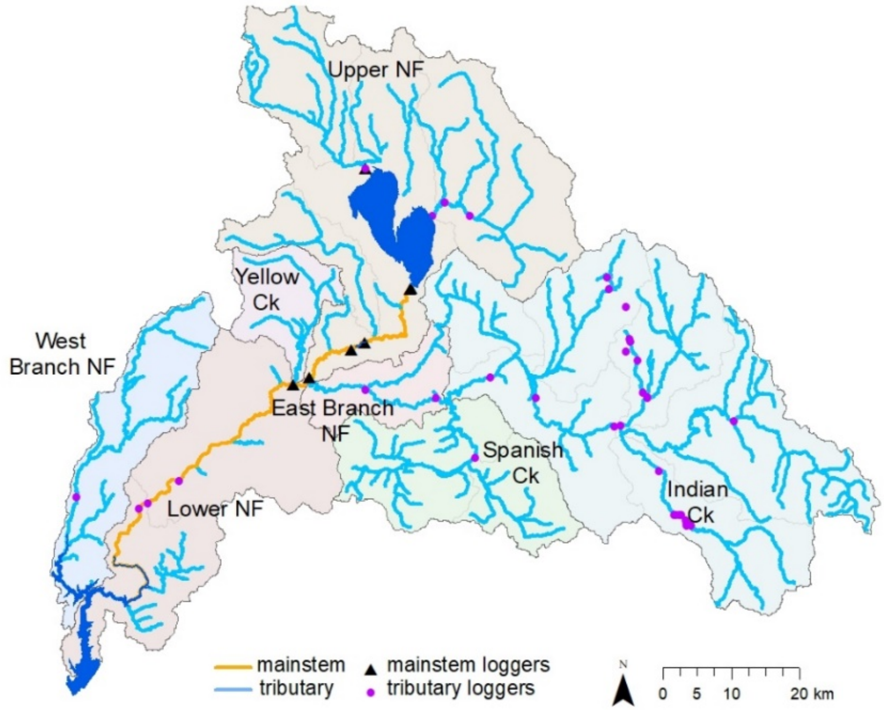

Figure 2. Model sectors (mainstem, tributary) and temperature logger locations for 2016. See Figures S3-S6 for logger locations in all years. Note that tributary loggers near the Lower NF mainstem are indeed on small side tributaries (not depicted) near their confluences.

Seasons and Thermal Criteria for Salmonid Life-stages

Chinook salmon and steelhead have complex anadromous life histories. Transitions between life-stages are generally timed according to genetic and maturation controls, and fine-tuned by environmental signals related to discharge, temperature, and photoperiod (Dingle and Drake 2007; Quinn, 2018). Temperature sensitivity varies by species, life-stage, and sometimes time of year (e.g. run-timing). Therefore, we used information on Central Valley salmonids (McEwen 2001; Moyle 2002) to divide the calendar year into a series of temporal seasons mapping to key life-stages of each species (Table 2). Holding and incubation stages were characterized as having a middle season typically experienced by most or all of the cohort, and early and late seasons when a smaller fraction of a cohort would be exposed but good conditions would promote higher overall survival of the cohort. Suitable early and late seasons are thus expected to contribute to greater abundance overall, and reliable early or late seasons (suitable even in drought years) contribute to population resilience.

Rearing season can be more extended and linked to specific life-histories. For Chinook salmon, rearing season was divided into a subyearling season, within which juveniles can complete the subyearling life-history (emigrating the first spring after spawning); and a yearling season, an extension of the subyearling season through the summer and fall that is necessary for juveniles to express the yearling life-history (emigrating the fall or winter a year after spawning). For steelhead, rearing season was divided into a wet season, when cool weather and intermittent rainfall drives thermal suitability; and a dry season, when lack of precipitation, hotter conditions, and melting of the snowpack drives thermal suitability.

Eight-day temperature estimates were summarized for each of these seasons in each year to quantify thermal habitat. Some seasons (Chinook salmon subyearling, steelhead incubation, and steelhead rearing) crossed calendar years, in which case thermal summaries are labelled with the starting year. Note that thermal summaries for lifestages beginning in 2013 and ending in 2018 only include the 2014 and 2017 portions of the seasons respectively, since 2013 and 2018 were outside the modeling scope.

Table 2. Temporal seasons used for summarizing temperature metrics by life-stage.

<table>
<tr><th>CHINOOK</th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th><th>Dec</th></tr>
<tr><td>Holding</td><td></td><td colspan="3">Early</td><td colspan="5">Middle</td><td>Late</td><td></td><td></td></tr>
<tr><td>Incubation</td><td colspan="2">Late</td><td></td><td></td><td></td><td></td><td></td><td>Early</td><td colspan="4">Middle</td></tr>
<tr><td>Rearing</td><td colspan="4">Subyearling</td><td colspan="7">Yearling</td><td>Sub.</td></tr>
<tr><td></td><td colspan="12"></td></tr>
<tr><td>STEELHEAD</td><td colspan="12"></td></tr>
<tr><td>Incubation</td><td colspan="6">Middle</td><td colspan="2">Late</td><td></td><td colspan="2">Early</td><td>Mid.</td></tr>
<tr><td>Rearing</td><td colspan="5">Wet</td><td colspan="4">Dry</td><td colspan="3">Wet</td></tr>
</table>

To assess thermal suitability for each life-stage and species, we used temperature criteria defining optimal, tolerable and intolerable ranges (Table 3) drawn from Bratovich et al. 2012, who synthesized information from a wide variety of sources to develop criteria for assessing reintroduction conditions in the Yuba River basin just to the south of the Feather River. We incorporated two modifications of these criteria by Boughton et al. (2018) for holding Chinook salmon and rearing steelhead, based on new information (see Boughton et al. 2018 for details). We lump spawning, incubation and rearing prior to emergence from the gravel into a single "incubation" stage, and assume a single criterion applies to all.

Note that Boughton et al. (2018) applied the criteria using average daily temperatures but here we use 8-day average temperatures. Eight-day temperatures were convenient to estimate due to the structure of the LST data, and are biologically meaningful because they are not overly influenced by a single anomalous day that may stress salmonids but not necessarily eliminate them (EPA 2003). EPA (2003) recommended using the 7-day average daily *maximum* temperature (7DADM) rather than the 8-day average that we use here, but the thresholds they calculated for this metric were mostly derived by adding 1-2° C to studies done using average temperatures (EPA 2003, p. 20). Here we just apply the average temperatures to the thresholds from Bratovich directly.

Table 3. Thermal tolerance criteria for Chinook salmon and steelhead (Bratovich et al. 2012; see also Boughton et al. 2018).

Species	**Life-Stage**	**Thermal Criteria (° C)**		
		Optimal	**Tolerable**	**Intolerable**
Chinook salmon	Holding	≤ 16.1	16.1 – 20.0	> 20.0
	Incubation	≤ 13.3	13.3 – 14.4	> 14.4
	Rearing	≤ 16.1	16.1 – 18.3	> 18.3
Steelhead	Incubation	≤ 12.2	12.2 – 13.9	> 13.9
	Rearing	≤ 20.0	20.0 – 23.0	> 23.0

Quantifying Physical Habitat

Physical habitat was assessed using a watershed-wide classification of channel types, based on longitudinal gradients in the elevation of the channel bed, a predictor of geomorphic structure (Buffington et al. 2004). Channel gradient was calculated from a 10 m DEM using ~2 km reach endpoints. Stream segments were then classified into four channel types (pool-riffle, plane-bed, step-pool, and cascade) based on gradient (Montgomery and Buffington 1997; Buffington et al. 2004). Results from the Montgomery and Buffington (1997) classification for each spatial domain are provided in Table S10 of the Supplementary Material.

We also leveraged a fine-scale habitat dataset from a continuous field survey along the mainstem NF Feather in the Seneca and Belden domains (Thomas R. Payne Associates 2002). Survey data included habitat unit types (pool, run, low-gradient riffle and high-gradient riffle, and pocket water), habitat unit length and width, presence of large woody debris (LWD), and maximum pool depth. While the empirical habitat data for Belden and Seneca were collected nearly 20 years ago (Thomas R. Payne Associates 2002), previous sediment mobility calculations indicate that flow regulation has reduced peak flow events and limited bed scour in these reaches (North State Resources 2014). Thus while modest amounts of erosion and deposition may have occurred in the time since data collection, we expected the relative proportion of physical habitat units to be similar to 2000.

Capacity Estimation

While thermal modeling was conducted for the entire watershed, we focused habitat capacity estimates for steelhead and spring-run Chinook salmon on spatial domains accessible for potential Chinook salmon and steelhead reintroduction above Rock Creek Dam ("C" in Figure 1d). Spatial domains accessible to fish at this location include Belden, Seneca, East Branch NFFR, and Yellow Creek. Rock Creek Dam was selected as a promising reintroduction site as it would allow access to upstream habitats without requiring fish passage in the Stairway of Power (Poe, Cresta, and Rock Creek Dams, "A" to "C" in Figure 1d).

Habitat capacity for a given spatial domain was estimated as:

$$Capacity = \sum_g \sum_i A_{g,i} * P_{g,i} * F_{g,i} \tag{1}$$

where g indexes four channel-gradient classes (0-1%, 1-2%, 2-4% and 4-8%) and i indexes the unit types (pool, riffle, run). The terms are $A_{g,i}$ = total wetted area (m^2) of unit type i within gradient class g, across all units within a given spatial domain, $P_{g,i}$ = proportion of suitable habitat for a given unit type within a given gradient class, and $F_{g,i}$= fish density at capacity, per unit of suitable area (fish/m^2).

Wetted areas ($A_{g,i}$) within Belden and Seneca were calculated directly from length and wetted-width measurements of stream units (pools, runs, low-gradient riffles, etc.), collected during summer field surveys when water discharges were low (ranged from 60 to 115 ft^3/s; Thomas R. Payne Associates 2002). Note that because we are using low-flow channel widths to estimate $A_{g,i}$, our capacity estimates should be viewed as minimum values and capacity could be greater at higher flows.

For Yellow Creek, East Branch NFFR and Upper Tributaries, we had no field data on habitat units (e.g. pool, riffle, run) to directly estimate $A_{g,i}$ as in Seneca and Belden. Total wetted areas in these domains were calculated by estimating channel widths for each stream segment from aerial photography and multiplying by the GIS segment length. To apportion this to pools, runs and riffles, we used the Seneca and Belden field data to create a lookup table (Table 4), giving proportion of unit type as a function of channel type.

Table 4. Look-up table for assigning proportions of unit-types to different channel-types.

Channel Type	Unit Type	Unit Proportion[1]
Pool-Riffle	Pool	0.30
	Run	0.48
	Riffle	0.21
	Cascade	0.01
Plane-Bed	Pool	0.45
	Run	0.32
	Riffle	0.14
	Cascade	0.09
Step-Pool	Pool	0.50
	Run	0.25
	Riffle	0.10
	Cascade	0.15

[1] Proportion of wetted area at low flow, derived from continuous measurements in the Belden and Seneca reaches.

Estimates for the proportions of suitable habitat ($P_{g,i}$) per habitat unit and the fish density at capacity ($F_{g,i}$) were unavailable for the Feather River. We used values from Stillwater Sciences (2013) that were developed to assess reintroduction in the nearby Yuba River (Table 5). Note that in order to match the unit types of Thomas R. Payne Associates (2002) to the unit types used by Stillwater Sciences (2013), pocket water was re-classified as a run and both high- and low-gradient riffles were merged into a single riffle category. This allowed us to use the continuous survey of Thomas R. Payne Associates (2002) to estimate suitable habitat area and fish capacity in the Belden and Seneca domains. To choose specific values of $P_{g,i}$ and $F_{g,i}$ from Stillwater Sciences (2013), the areal proportions of habitat units within gradient classes in the Seneca and Belden reaches (Table 4) were compared to those of the South Yuba, Middle Yuba, and North Yuba and the domain with the most similar proportions was chosen.

Finally, we integrated these estimates of geomorphic capacity with the thermal modeling by calculating the proportion of capacity that occurred in tolerable or optimal thermal conditions during the mid-season of each life-stage (Table 2). Overall, capacity estimates considered gradient class, species, lifestage, habitat unit type, and water temperature.

Table 5. Habitat type use fraction (UF) and fish densities (Stillwater Sciences 2013)..

Species	Life-stage	Gradient Class (%)	Unit Type[1] Pool $P_{g,i}$	Pool $F_{g,i}$	Riffle $P_{g,i}$	Riffle $F_{g,i}$	Run $P_{g,i}$	Run $F_{g,i}$	Source[2]
Chinook Salmon	Holding	0 – 1	0.051	1	0	0	0	0	F3
		1 – 2	0.036	1	0	0	0	0	
		2 – 4	0.085	1	0	0	0	0	
		4 – 8	0.084	1	0	0	0	0	
	Incubation	0 – 1	0.0282	0.185	0.0084	0.185	0.0057	0.185	F4
		1 – 2	0.0248	0.185	0.0047	0.185	0.0059	0.185	
		2 – 4	0.0093	0.185	0.0014	0.185	0.0036	0.185	
		4 – 8	0.0055	0.185	0	0	0	0.185	
	Rearing	0 – 1	1	2.89	1	0.395	1	1.711	F6
		1 – 2	1	0.772	1	0.108	1	0.467	
		2 – 4	0.75	0.772	0.75	0.108	0.75	0.467	
		4 – 8	0.25	0.772	0.25	0.108	0.25	0.467	
Steelhead	Incubation	0 – 1	0.0213	0.5	0.0064	0.5	0.0043	0.5	H1
		1 – 2	0.0146	0.5	0.0028	0.5	0.0034	0.5	
		2 – 4	0.0061	0.66	0.0009	0.66	0.0024	0.66	
		4 – 8	0.0036	0.66	0	0	0	0	
	Rearing	0 – 1	1	0.085	1	0.157	1	0.149	H3
		1 – 2	1	0.085	1	0.157	1	0.19	
		2 – 4	1	0.104	1	0.044	1	0.037	
		4 – 8	1	0.104	1	0.044	1	0.037	

[1] $P_{g,i}$ corresponds to the habitat use fraction (UF) of Stillwater Sciences (2013), for unit type *i* in gradient class *g*. $F_{g,i}$ is fish density for each life-stage in fish per m^2 (adult females or redds per m^2 for incubation habitat).
[2] Identifies the appendix from Stillwater Sciences (2013) used as the source for $P_{g,i}$ and $F_{g,i}$.

Results

Temperature Models

Comparisons of models indicated that covariate correlation varied among years and sectors. Even so, the fundamental positive relationship between stream temperature and LST was present in all four years for both model sectors (mainstem and tributary), with a correlation as high as 0.94 (Table S2). Discharge was generally negatively correlated with LST and not surprisingly, day of year was strongly correlated with both LST and stream temperature in most years. Elevation improved the proportion of variance explained by the mainstem model (r^2) by almost 40% (Tables S3 and S4). Elevation was strongly correlated to distance from Lake Almanor (Pearson's $r = 0.94$), and it is unclear whether the strong contribution of elevation is due to cooling effects from Lake Almanor, discharge impacts, or elevation per se (i.e. the influence of the temperature lapse rate). The latter seems unlikely because the correlation is negative, while influence of lapse rate is expected to be positive. The cooling effect of Lake Almanor would tend to produce a negative correlation with elevation during the warm season, when reservoir releases are cooler than ambient climate and warm up as water flows to lower elevations. Although distance from Lake Almanor was explored, it was not considered in model selection due to the strong confounding with elevation.

Relatively few logger sites (maximum of 9, depending on the year) were available for the mainstem sector, but even so these models performed well, with r^2 consistently above 0.75. This was comparable to models calibrated with high densities of loggers in interior Columbia watersheds, where r^2 were 0.88-0.95 (McNyset et al. 2015) (Table S5). For consistency, to make predictions we retained the same set of terms across sectors and years: LST was included as a first- and second-order term, along with day-of-year and elevation even though these predictors were not statistically significant in all years in both sectors. On average, discharge and interaction terms improved models by less than 2% (Table S3 and S4). We prioritized consistency and parsimony over such minor model improvements, and did not use models with terms for discharge and interactions in making the final predictions.

RMSE of the overall tributary and mainstem sectors ranged from 1.47 to 3.09° C (Table S3). In comparison, RMSE for MODIS-based models developed by McNyset et al. (2015) for Pacific NW river systems (John Day, Wenatchee, Upper Grande Ronde, Tucannon and Lemhi) ranged from 1.2 to 2.74°C. Better model fit in the tributary sector relative to the mainstem sector agrees with our general expectation that model performance would be lower in reaches where flows are highly managed.

Focusing in on spatial domains, average model error varied widely among years and spatial domains and could not be estimated for some spatial domains due to lack of logger data (Tables S6 and S7). In the Seneca and Lower NFFR domains, average error was less than 2°C, while the Belden Reach had greater variability with average error nearly 5°C in 2015 and 2017. Conclusions about life-stages whose season and domain had higher error should be treated as less certain. Model error was particularly high in the Belden reach for late season Chinook salmon holding (October) and early spawning steelhead. In contrast, the Upper Tributaries of the East Branch NF fit particularly well, with consistently low average error of less than 0.5° C across all years. Table S6 shows that models tend to over-predict temperatures for the life-stages occurring in the Belden domain in summer and fall, suggesting the managed flow regime there may be more thermally suitable than we predict.

For steelhead, model error in Belden was greatest for the dry-season rearing and late incubation, and averaged 3.4°C across years, including a high of 5.3°C in 2015 (Table S7). Seneca also had high error in the early incubation period, although the error during late and peak temperatures were almost always less than 2°C. Model error within tributaries tended to be lower than model error within the mainstem, and was generally lower for steelhead than Chinook salmon life histories.

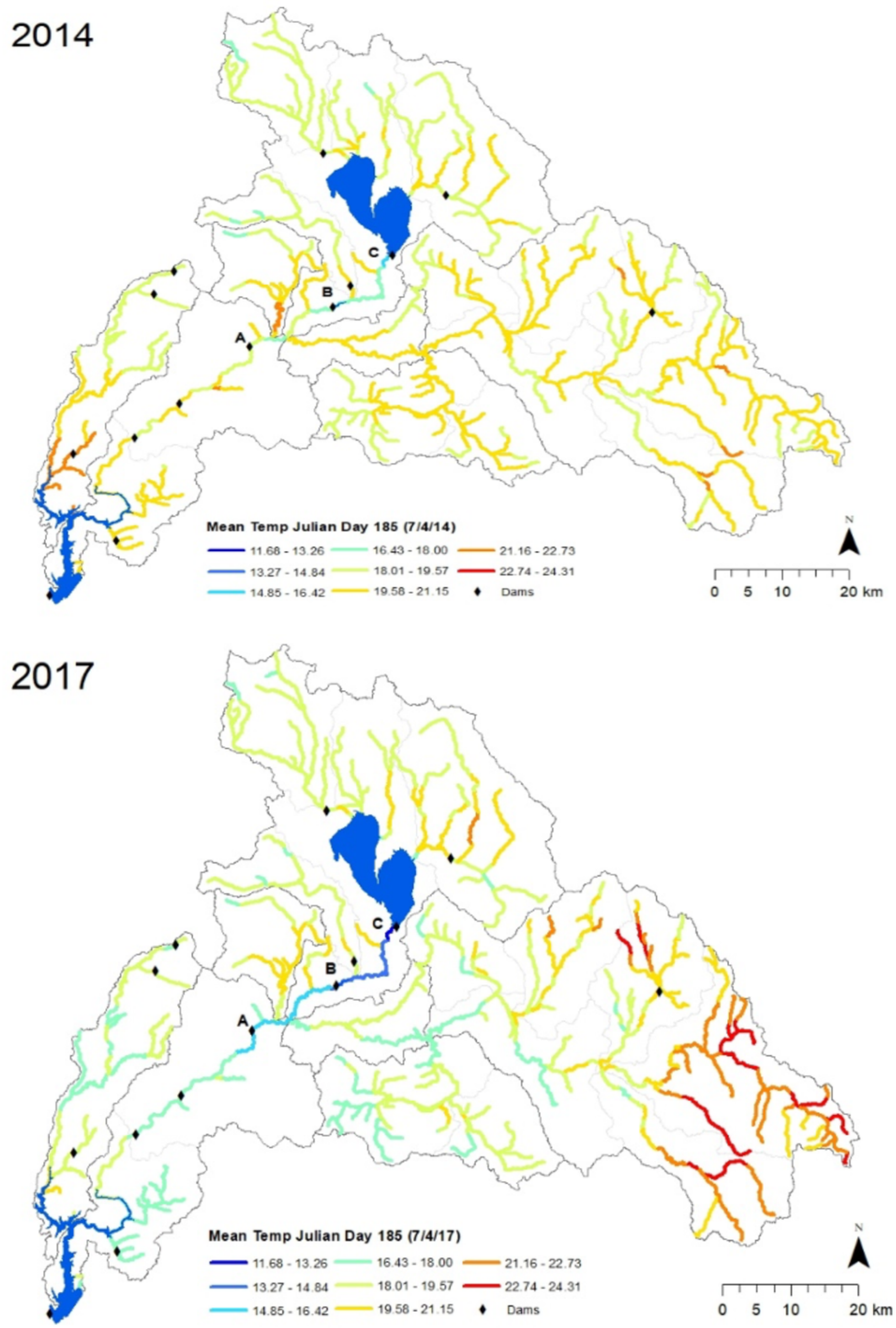

Figure 3. 8-day temperature estimate for July 1 (day of year 184) in dry year (2014) and a wet year (2017). A=Rock Creek Dam, B=Caribou Afterbay Dam, and C=Canyon Dam impounding Lake Almanor. Note that colors of Lakes Almanor and Oroville (shown in deep blue) do not represent modeled temperature predictions.

Thermal Landscape

Based on average summer water temperatures, the modeling period included heterogeneous conditions with no clear warmest or coolest year. The range of thermally diverse years provided context for annual temporal variation, and insight into how this variation may impact the life-stages of each species. The multi-year dataset was also helpful for understanding the consistency of spatial patterns in temperature over time.

Tributary temperatures tended to be spatially homogeneous within small watersheds such as Yellow Creek, whereas markedly cool or hot patches tended to be more prevalent in large domains, such as Indian Creek (Figure 3). The large Indian Creek domain has diverse topography so the potential for thermal heterogeneity was high. The downstream reaches of the West Branch NF and eastern edge of Indian Creek were both consistently warmer than other domains due to regional weather patterns; this is highlighted in a particularly warm week in July 2017, where temperatures in both domains averaged 3°C higher than other domains (Figure 3). Interestingly, the far eastern section of the Indian Creek domain near the Great Basin of Nevada was markedly warmer than the rest of the watershed in this week.

In the potential reintroduction area around Belden, the dry (2014) and wet (2017) years both showed that Seneca and Belden were both consistently cooler than the Lower NFFR below Rock Creek Dam. This is consistent with prior water temperature modeling (FERC 2005). Our predictions of the Lower NFFR are particularly uncertain as there are very few (1-2) temperature loggers in this domain and there is likely a strong influence of the numerous dams and hydroelectric tunnels (Figure 3).

The timing and magnitude of peak temperatures among years was highly variable. Tributary domains, such as Indian Creek, Spanish Creek, Above Dam, Lower NF Feather Tributaries, and Upper Tributaries (shown in Figure 1d) had less year-to-year variation in monthly mean temperatures (Δ 2.65°C) than the Lower NFFR below Seneca (Δ 5.39°C). However, the *rate* of temperature change of the mainstem was lower than in tributaries, suggesting the mainstem is slower to heat and cool relative to smaller streams. This may be due to the thermal buffering provided by upstream reservoirs and hydroelectric tunnels. Patterns in winter temperatures were consistent between across years, when temperatures reached as low as 1°C. Note that winter temperatures did not exceed any thermal criteria for Chinook salmon or steelhead.

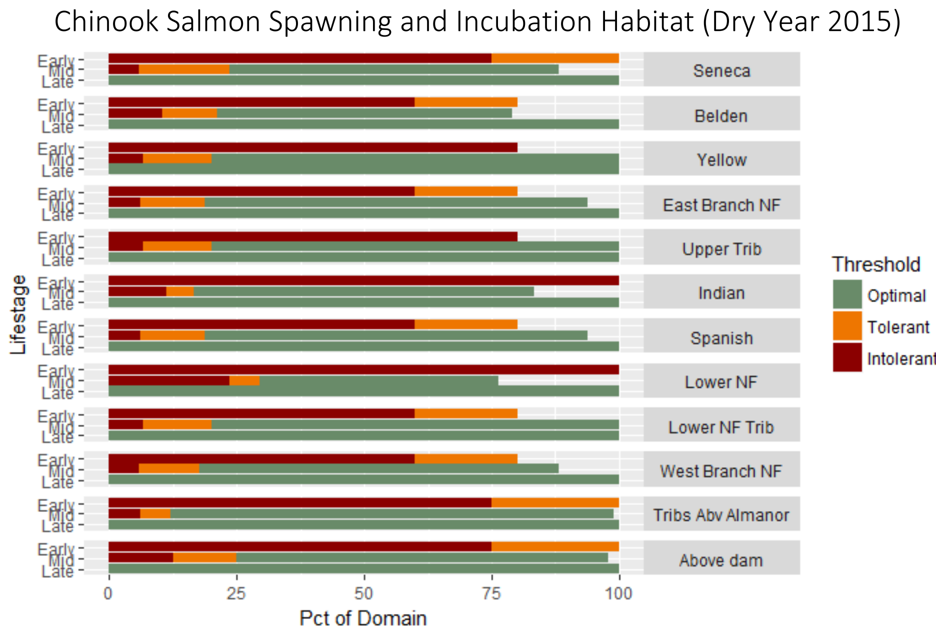

Figure 4. Spawning and incubation habitat for Chinook salmon in 2015. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

Chinook Salmon Thermal Habitat

When 8-day temperatures were summarized by species and life-stage, we found thermal limitations for Chinook salmon were consistent across years but differed by life-stage and spatial domain. To present these findings, we graph summaries by life stage, season (e.g. early, mid, late), and spatial domain, giving the percent of days that a given thermal condition predominates spatially (defined as at least half the stream kilometers meeting the thermal criterion[1]). Here we focus on three illustrative examples (Figures 4 – 6); other findings are in the Supplementary Material (Figures S7 – S15, Table S8).

Focusing on the relatively dry year of 2015, we find that the thermal suitability of spawning and incubation habitat depended greatly on seasonality (compare early, mid and late in Figure 4). For early-spawning Chinook salmon, intolerable conditions predominated more than half the time in all spatial domains, with the majority of domains having tolerable conditions predominate only 10 to 30 % of the time. During the mid-season, in contrast, optimal or tolerable conditions generally predominated, over 90% of the time in most domains but only ~75% of the time in the Lower NF Feather (Figure 4). For late-spawning Chinook salmon, optimal thermal conditions predominated the entire season in all spatial domains.

Thermal conditions for holding adult Chinook salmon were more suitable than for spawning and incubation (Figure 5). For early and mid-season holding, tolerable conditions predominated at most only 30 to 40% of the time and intolerable conditions predominated less than 10% of the time across all domains; otherwise optimal conditions predominated (Figure 5). Notably, only Belden and Seneca had optimal temperatures predominating at all times in all seasons. Similar to spawning and incubation, optimal temperatures in the late season predominated at all times in all spatial domains.

Rearing conditions for Chinook salmon are divided into subyearling and yearling seasons. Subyearling season covers winter and spring, when all juvenile Chinook salmon begin freshwater rearing and those with the subyearling life-history complete it and emigrate. Yearling season covers the summer and fall, when yearlings remain in the river system through the summer and emigrate the following fall.

[1] This means that when tolerable conditions are said to predominate, it really means tolerable + optimal conditions predominate, but optimal conditions alone do not predominate.

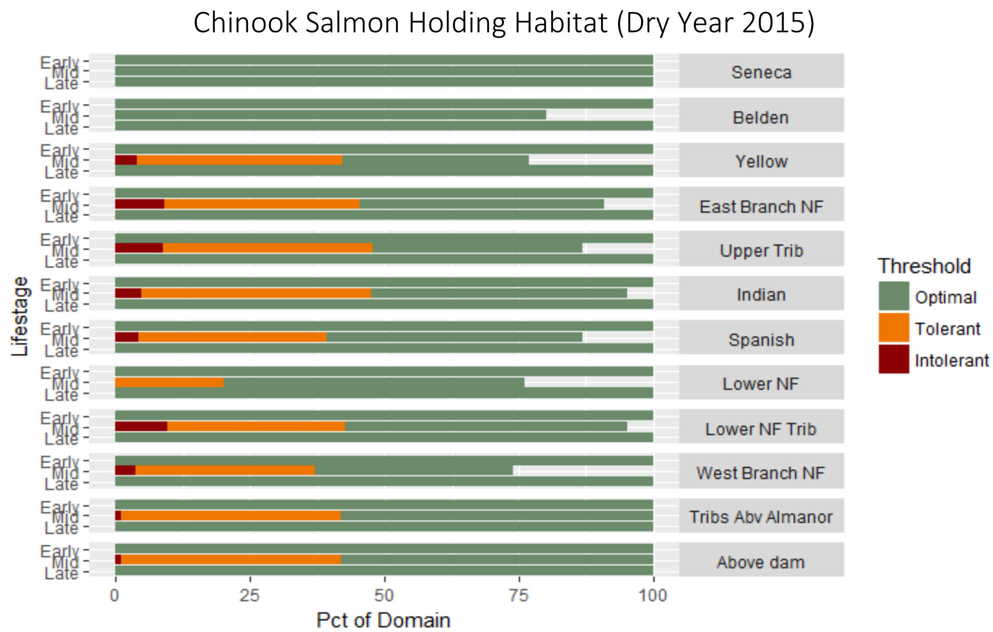

Figure 5. Holding habitat for Chinook salmon in 2015. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

In the dry year of 2015, the entire subyearling and yearling seasons saw optimal temperatures predominating in Belden and Seneca (Figure 6). Elsewhere optimal temperatures always predominated during the subyearling season, but only ~60% of the time during the yearling season. The large size of yearlings at ocean entry can increase survival and contribute disproportionately to adult returns. As a result, the presence of any thermally tolerable habitat for yearlings likely benefits the population.

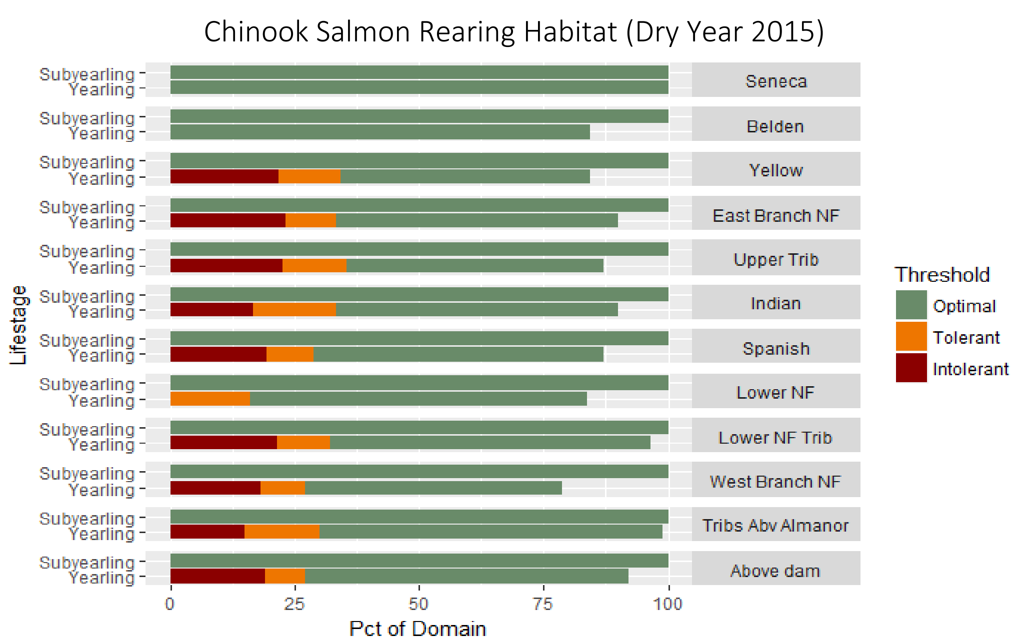

Figure 6. Rearing habitat for Chinook salmon in 2015. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

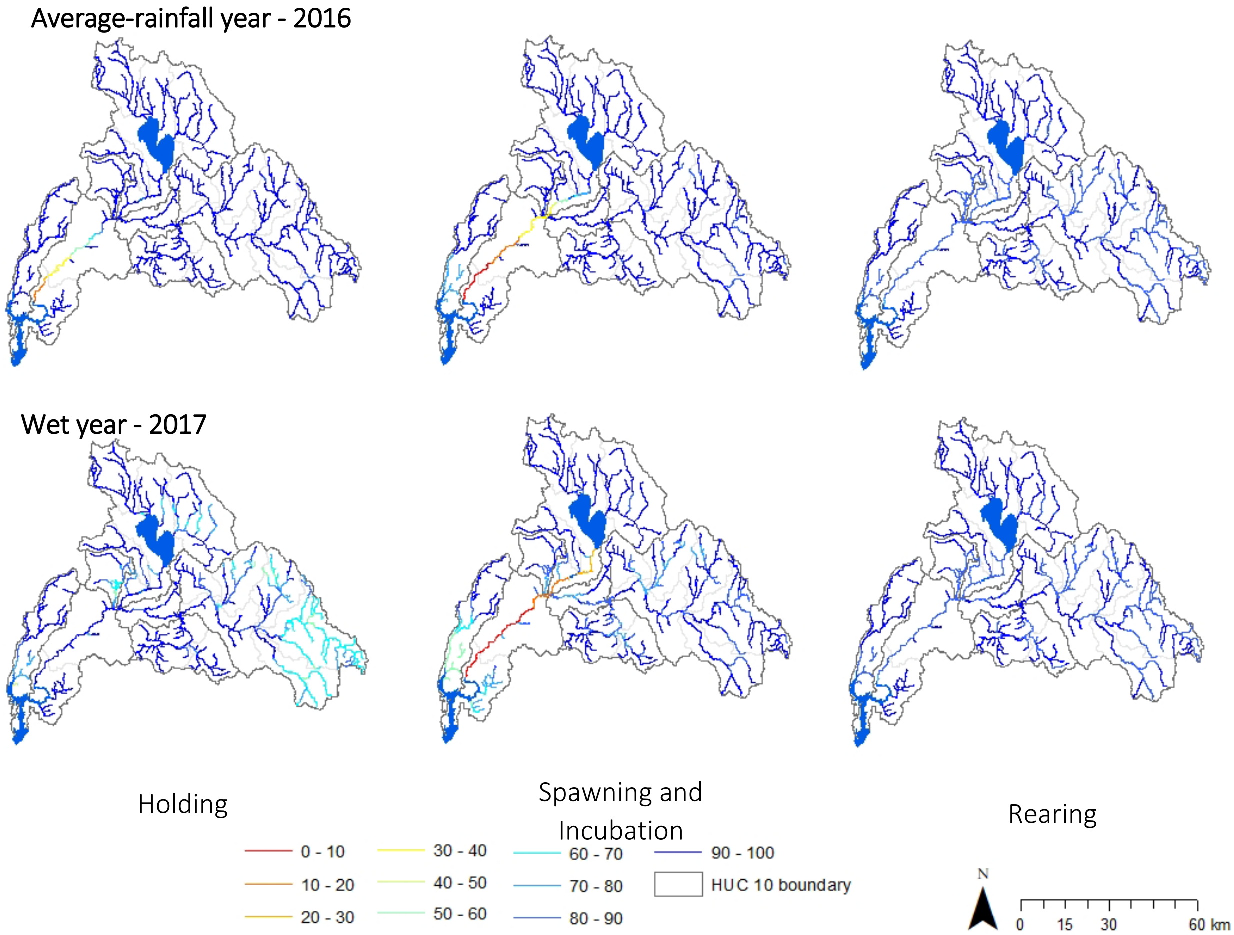

Figure 7. Percent of time habitat had optimal or tolerable thermal conditions for three life-stages of Chinook salmon: the mid-season of holding adults (May – Sep, left column), the mid-season of spawning and incubation (Sep – Dec, middle column), and the subyearling season for rearing juveniles (Dec – Apr, right column). Shown are an average-rainfall year (top) and a wet year (bottom). Note that Lakes Almanor and Oroville (shown in blue) are for reference, and do not represent model predictions.

For the most part, the year of average rainfall 2016 showed more limiting thermal conditions than the dry years 2014 and 2015, or the wet year 2017 (Figures S7 – S15). For example, in 2016 the percent of suitable Chinook salmon holding habitat was lower in the Lower NFFR than in the wet year 2017 (Figure 7, left column). But we see some exceptions, such as thermal holding conditions along the eastern edge of Indian Creek domain, which were 40% *less* suitable in the wet year than in 2016. This indicates thermal suitability can be spatially diverse; cooler areas may be interspersed with warmer areas, which may benefit Chinook salmon if the diversity is accessible to migrants. For both 2016 and 2017, thermal suitability for spawning and incubation was higher in Belden and Seneca than in the Lower NF Feather (Figure 7, middle column). Rearing conditions for subyearlings were generally suitable for all spatial domains in dry and wet years, suggesting this life-stage is not limited by temperatures (Figure 7, right column).

Steelhead Thermal Habitat

Thermal suitability for steelhead spawning and incubation declined from early to late seasons (Figure 8). In the early season (Oct – Nov), the East Branch was the only domain where optimal temperatures predominated the entire time; most domains had tolerable conditions ~15% of the time, and a few key domains (Belden, Lower NFFR) had intolerable conditions ~15% of the time. By the late season (Jul - Aug), intolerable temperatures predominated the entire time in all spatial domains except Seneca, where it was still high (70%).

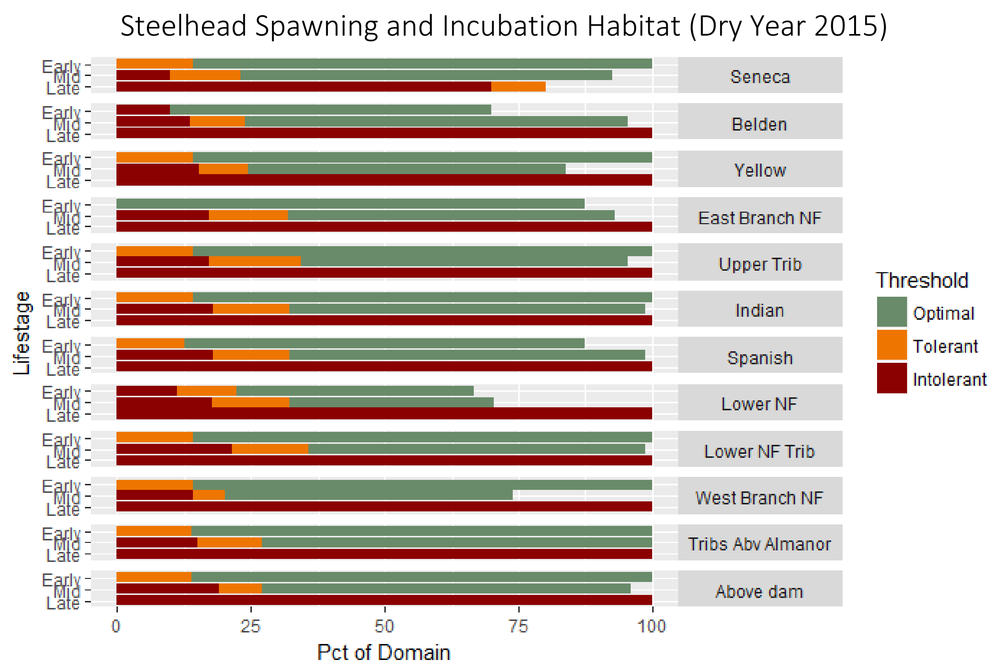

Figure 8. Spawning and incubation habitat for steelhead in 2015, Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

Thermal suitability for steelhead rearing was optimal across all spatial domains and is likely not limiting for dry or wet seasons (Figure 9). These thermal patterns of suitability for both spawning and rearing were consistent across 2014 to 2017 (Figures S16-S21, Table S9).

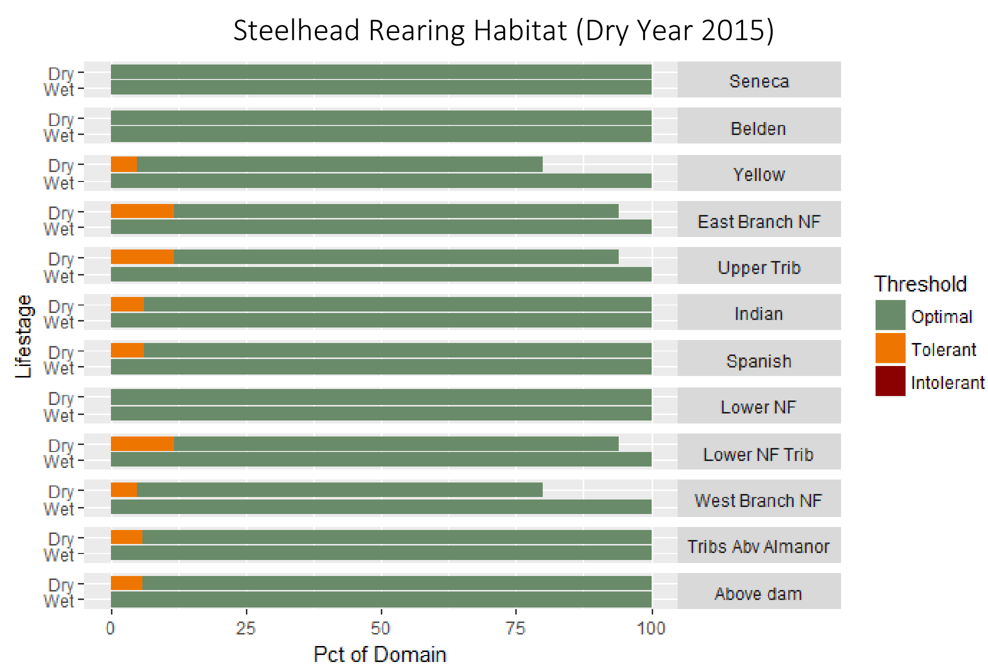

Figure 9. Rearing habitat for steelhead in 2015. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

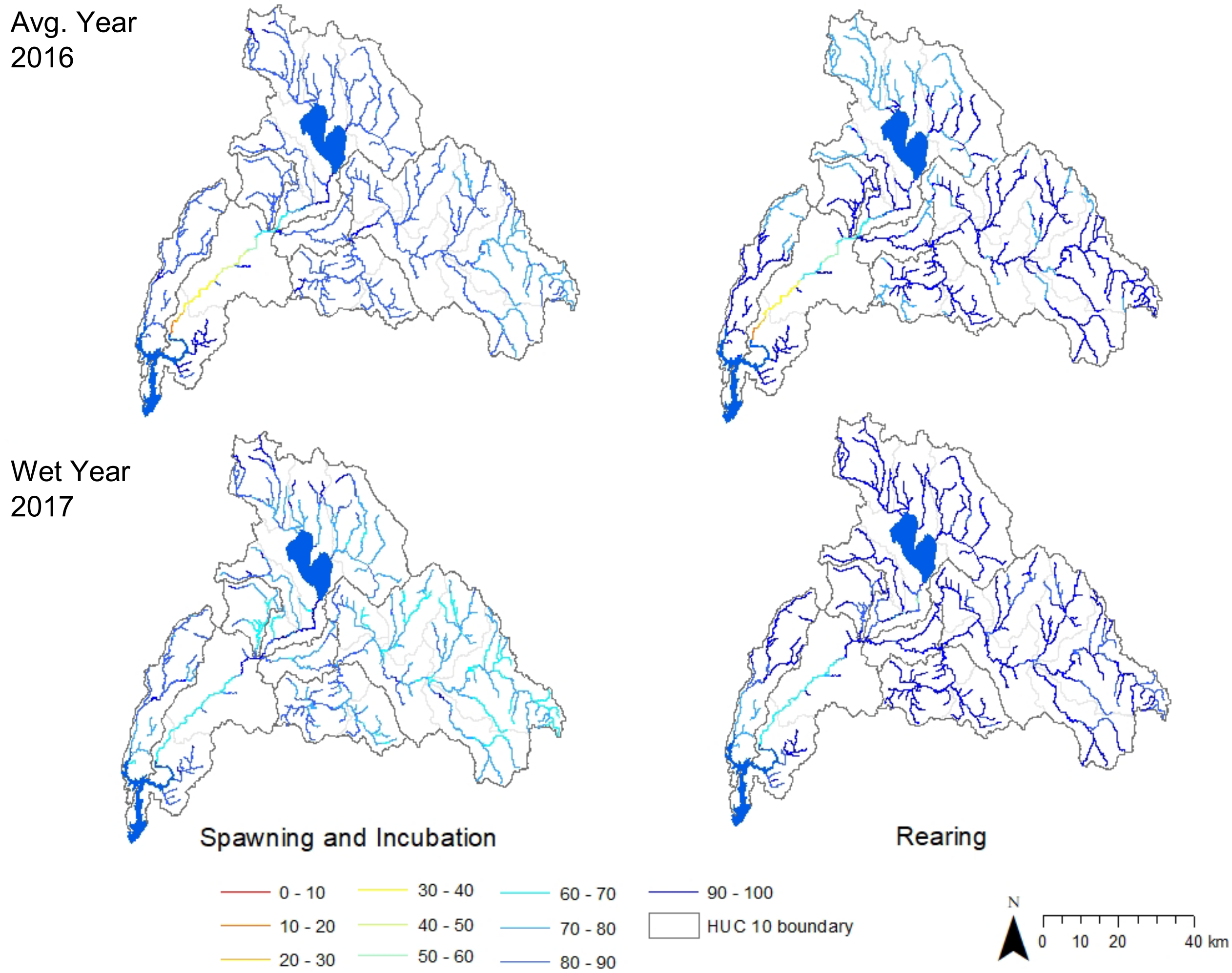

Figure 10. Percent of time with optimal or tolerable thermal conditions for two life-stages of steelhead: the mid-season of spawning and incubation (Dec – Jun, middle column), and the full year for rearing juveniles dry + wet season, right column). Shown are an average-rainfall year (top) and a wet year (bottom). Note that Lakes Almanor and Oroville (shown in blue) are for reference, and do not represent model predictions.

Comparing spatial patterns in an average-rainfall year and a wet year (Figure 10), we see that the percent of habitat suitable for steelhead spawning and incubation was lower in the Lower NFFR in the wet year 2017 (Figure 10, left column), dipping below half the time in much of the domain. Interestingly, the reverse pattern was observed in many other spatial domains (e.g. northern and eastern portions of Figure 10, left column), with suitable conditions for spawning and rearing being more prevalent in the average year of 2016. Even so in 2017 suitable conditions were generally present half the time or better. For rearing steelhead (Figure 10, right column), the patterns better matched expectations, with suitable conditions either similar among the two years or less frequent in the average year (especially in the Lower NFFR and Tributaries above Almanor, Figure 10 top right). The difference in which year is better for spawning and incubation versus rearing suggests that individual weather patterns can temporarily reverse the annual pattern of temperature, in a way that affects thermal suitability for a particular life-stage.

Physical Habitat

The distribution and abundance of channel types varied by spatial domain (Figure 11; see also Table S10). High-gradient cascade reaches with slopes >7.5% were rare, and comprised less than 5% of each spatial domain except in the Upper Tributaries (14%). Step-pool habitat (3-7.5% slope) was prevalent in the tributary sector (31-61%). On the mainstem sector below Lake Almanor, river bed gradient declined with distance from Canyon Dam, with Seneca having the highest percentage of step-pools at 17% (Figures 11 and 12). The Lower NFFR and East Branch consisted mostly of low-gradient pool-rifle systems, while adjacent tributaries had predominately step-pool and cascade habatat (i.e. Lower NF Tributaries and Upper Tributaries in Figures 11 and 12). Other pool-riffle habitat was available in domains thought to be physically inaccessible to fish reintroduced at Rock Creek Dam (Spanish Creek, Indian Creek, and Above Dam). Almost a quarter of the watershed was classified as plane-bed habitat (21%). As expected, sub-watersheds with larger numbers of tributaries had more higher-gradient reaches (e.g. Indian and Spanish Creeks).

Consider for a moment the channel types that would be immediately accessible to fish reintroduced at Rock Creek Dam (near the top of the Lower NF domain in Figure 12). Pool-riffle channels are the most valuable type for spawning due to their typical grain size, and a morphology conducive to redd construction and through-gravel flow. But steeper channels (plane-bed, step-pools) are also expected to contain spawning habitat at lower prevalence. Within the accessible domains with larger channels (Belden, Seneca, East Branch NF Feather River), the habitat was predominantly pool-riffle and plane-bed habitat (82 - 100%), with almost all of the pool-riffle habitat in East Branch NF Feather River. Yellow Creek is comprised of only 38% of these lower-gradient channel types, separated from the mainstem by a long section of step-pools (Figure 12). The Upper Tributary domain is almost entirely step-pools and cascades (91%).

Although the largest amount of accessible pool-riffle habitat is in the East Branch, even larger amounts are in some of the inaccessible domains. The Lower NFFR has twice the stream kilometers of pool-riffle channel as the East Branch, mostly downstream of Rock Creek Dam within the Stairway of Power. The large Indian Creek domain has extensive sections of pool-riffle channel (Figure 12), nine times more stream kilometers than the East Branch (Table S10). Unfortunately, nearly all of it is upstream of Indian Falls, a 5 m high waterfall near the confluence that is thought to be impassable (Yoshiyama et al. 2001). Similarly, the Spanish Creek domain also has extensive pool-riffle habitat, comparable in amount to the East Branch but upstream of a rapids near the confluence that is thought to be impassable (Yoshiyama et al. 2001). Finally, the domain of Tributaries above Almanor also has extensive pool-riffle habitat, over four times the stream kilometers as the East Branch.

The continuous habitat surveys from PG&E provided valuable field data in the Seneca and Belden domains (Table 5). In this dataset, Seneca had a slightly higher percentage of pools than Belden, but the percent of riffles and runs were similar. This similarity supported our decision to combine the two in our summary of channel unit composition by gradient class (not shown), which we used to estimate composition in Yellow Creek, East Branch NF Feather, and Upper Tributary domains (see methods). Although Seneca and Belden had similar means for bankfull width and depth, channel gradient was 2 - 2.5 times higher in Seneca (Table 5). Reach-averaged median grain size (D_{50}) were 10% higher in Seneca, likely due to the higher bed slope. The range in grain size, bankfull widths and bankfull areas were twice those of Belden.

Table 6. Summary of Belden and Seneca habitat metrics. BF = Bankfull; Other = cascades, pocket water.

Statistic	Reach	Slope	D_{50} (mm)	BF width (m)	BF depth (m)	BF area (m^2)	BFW:BFD	Pool %	Riffle %	Run %	Other %
Mean	Belden	1.1	99.7	20.3	0.6	10.9	48.7	16.3	16.7	34.5	32.6
	Seneca	2.4	117.3	25.2	0.6	15.5	45.0	25.4	12.1	30.7	31.9
Range	Belden	1.0	84.0	14.3	0.7	13.7	87.0	-	-	-	-
	Seneca	2.8	198.0	23.5	0.6	22.7	76.0	-	-	-	-

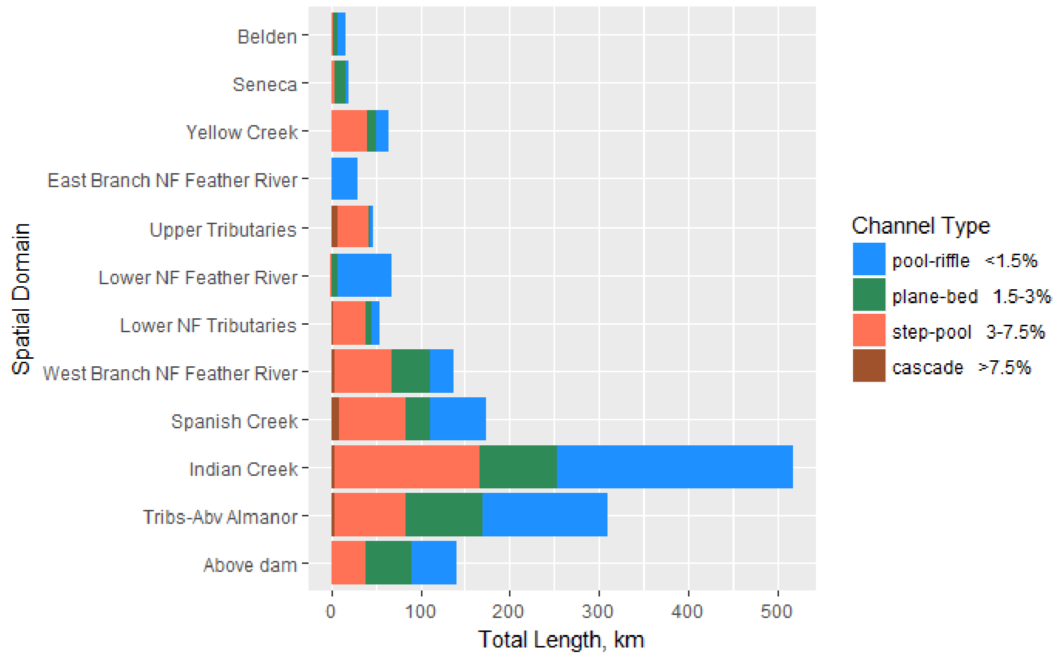

Figure 11. Channel type classification of the North Fork Feather River.

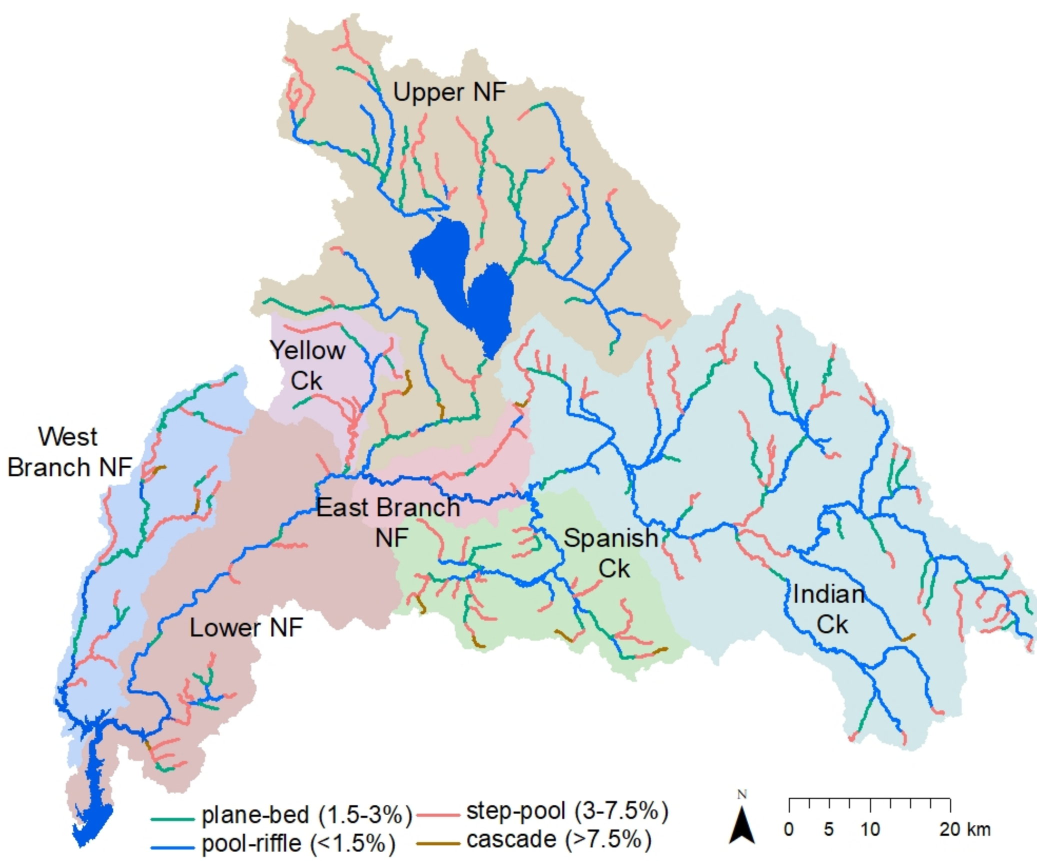

Figure 12. Channel types within the NF Feather River. Note that Lakes Almanor and Oroville (shown in blue) are for reference, and do not represent channel types.

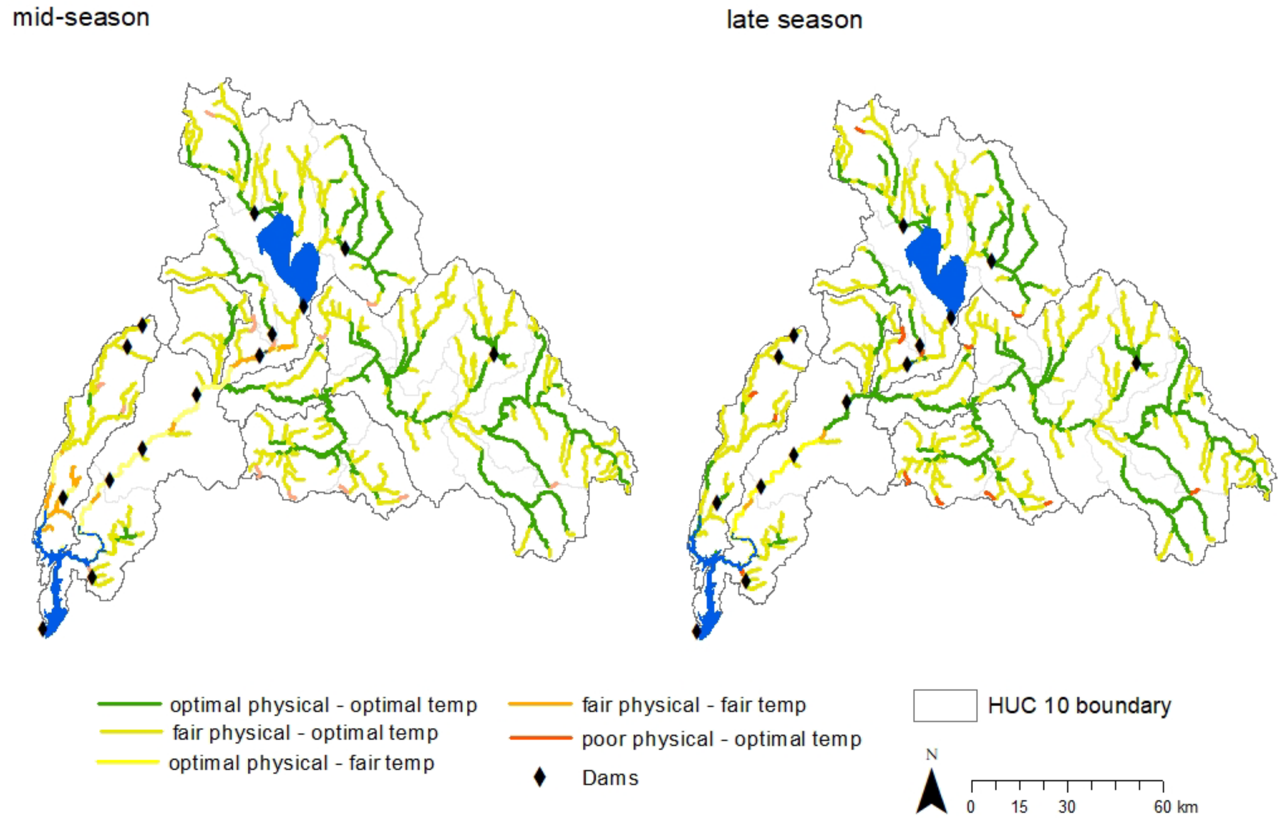

Figure 13. Comprehensive suitability for Chinook salmon in 2016. Pool-riffle (<1.5% gradient) habitat was considered optimal habitat while step-pool and plane-bed habitat were fair. A criterion of 80% thermal suitability defined optimal thermal habitat (all other areas were fair).

Comprehensive Suitability

Since physical and thermal factors impact fish simultaneously, we overlaid physical habitat and thermal suitability to determine areas that were likely suitable across lifestages. Domains with such overall suitability would be especially valuable for pursuing reintroductions. For this overlay we focused on the average-rainfall year 2016. Thermal habitat was classed as optimal if temperatures were tolerable at least 80% of the time for each lifestage; otherwise it was classed as fair. Physical habitat was classed as optimal for pool-riffle morphology, fair for plane-bed and step-pool morphology, and poor for cascades.

For mid- and late-season Chinook salmon (Figure 13), the most promising domains with comprehensive suitability were the East Branch, Spanish Creek, and Indian Creek domains, where about 50% of the area was optimal for both physical and thermal conditions for all lifestages (the three southeastern domains in Figure 13). The domain of Tributaries above Almador was also very promising. Belden was less thermally suitable than Seneca for mid-season, but both reaches had more favorable thermal conditions than the Lower NFFR. The West Branch NF Feather had fair thermal and physical conditions in the downstream reaches, which may serve as a barrier to upper reaches that have fair habitat and optimal temperatures. For early season Chinook salmon, there were no areas that met thermal and habitat criteria (not shown).

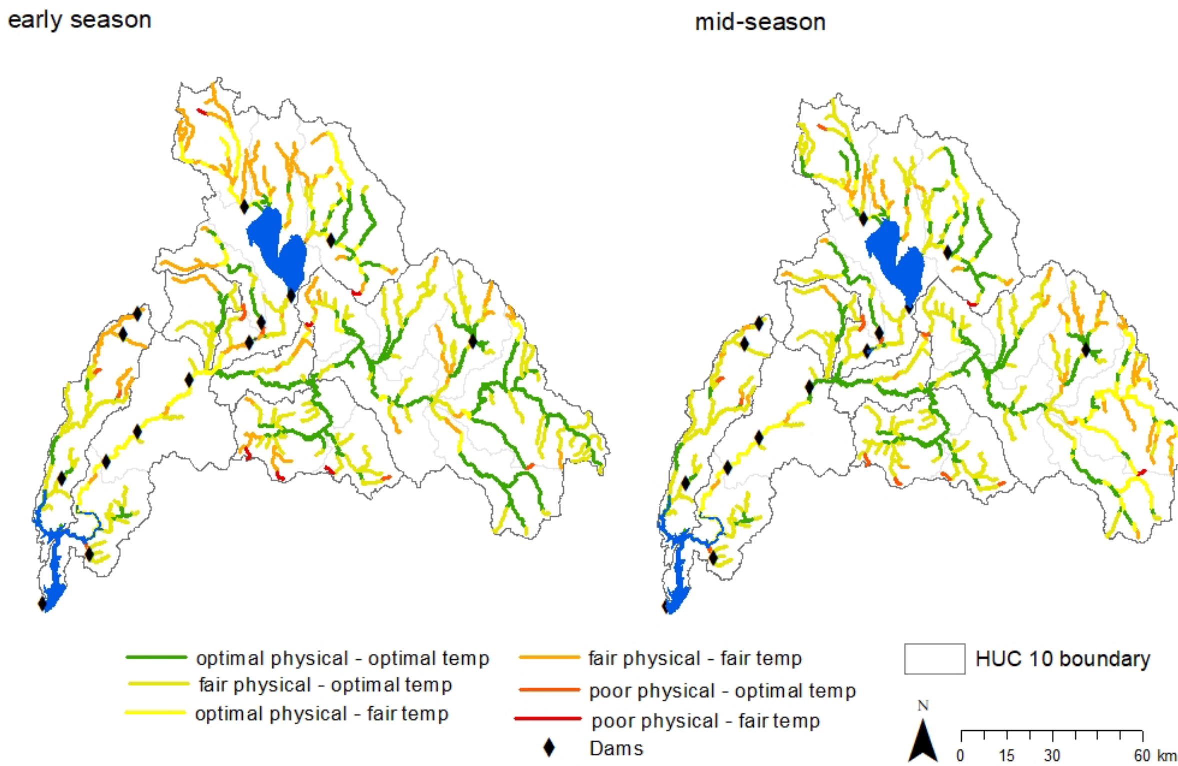

Figure 14. Comprehensive suitability for steelhead in 2016. Pool-riffle (<1.5% gradient) habitat was considered optimal habitat while step-pool and plane-bed habitat were fair. A criterion of 80% thermal suitability defined optimal thermal habitat (all other areas were fair).

Similar to Chinook salmon, for steelhead the most promising domains in terms of comprehensive suitability were East Branch, Spanish Creek, and Indian Creek (Figure 14, the three southeastern domains). Thermal suitability of Seneca was slightly better than Belden. Yellow Creek could potentially provide fair habitat with optimal thermal suitability that would supplement habitat available in Belden and Seneca. The largest areas of fair thermal and physical habitat suitability were in the upper reaches of the West Branch, Upper Tributaries, and Indian Creek, while the majority of the remaining NF Feather watershed was either physically or thermally optimal. Thermal conditions were unsuitable for late steelhead and are not shown.

Capacity Estimates

For Chinook salmon, the total geomorphic capacity (omitting thermal constraints) for the Belden, Seneca, East Branch, and Yellow Creek domains was 10 times lower than the holding capacity and up to 1000 times lower than the rearing capacity, suggesting a viable Chinook salmon population would most likely be limited by redd abundance (Figure 15 and Table 7). We estimated the combined capacity for female spawners in Belden and Seneca reaches was about 700 fish per year, with about 66% and 34% coming from Belden and Seneca, respectively. Yellow Creek could supply an additional approximately 500 females, nearly doubling the capacity above Rock Creek Dam. The East Branch increases female capacity by 2,500 fish, due to the large extent of this spatial domain.

Geomorphic holding capacities for Chinook salmon were greater than spawning capacities in all five spatial domains, and along the mainstem NFFR, Seneca had double the holding habitat of Belden (Figure 15). With an estimate of almost 17,000 fish, Yellow Creek had the most abundant holding habitat above Rock Creek Dam, exceeding that of the East Branch and almost tripling the combined capacities of Seneca and Belden. Modeled rearing capacities in Belden were almost twice that of Seneca and likely a

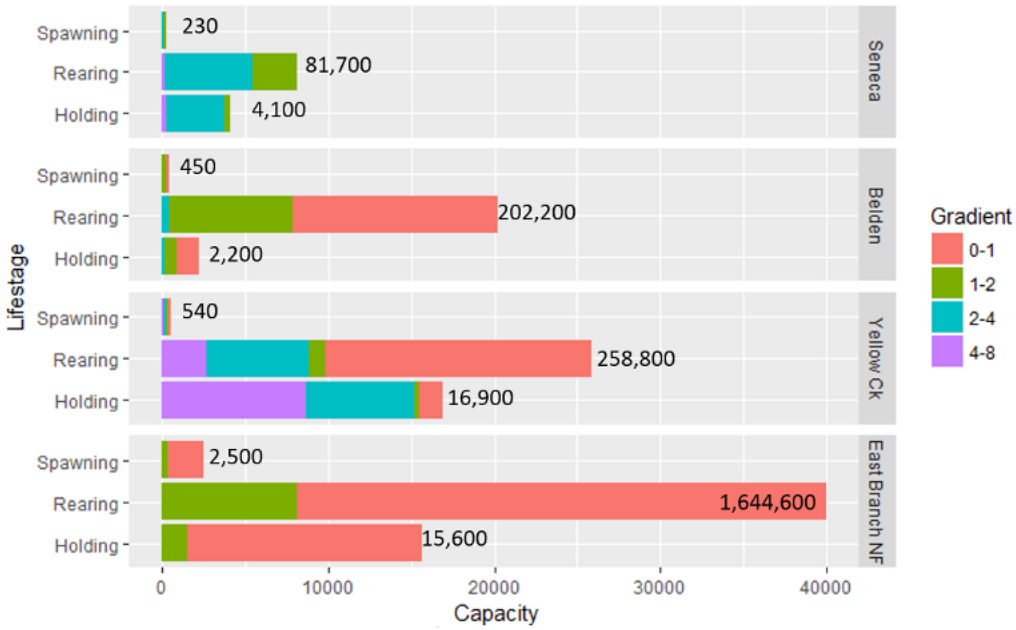

Figure 15. Geomorphic capacity for Chinook salmon (omitting thermal constrants) within domains accessible upstream from Rock Creek Dam. Units of capacity are adults for holding; redds or female adults for spawning; and 10s of juveniles for rearing (East Branch rearing extends off the chart by about 4X).

reflection of the lower gradient; rearing fish densities for habitats with gradients of 0 - 1% were at least twice that of higher-gradient reaches (Table 5). Similarly, the low gradient and large area of the East Branch NF Feather produced rearing capacity estimates of over 1.5 million. The diversity of gradients across Seneca, Belden, and Yellow Creek may provide a beneficial array of habitat that can be leveraged in reintroduction efforts; this can be seen in Figure 15 with the dominance of 0 - 2%, 2 - 4%, and 4 - 8% gradient classes in Belden, Seneca, and Yellow Creek, respectively.

If we extrapolate the geomorphic capacity of spawning adults to a full generation across 3-4 years, we would expect a Chinook salmon population of about 2,700 - 3,600 adults for Belden and 1,400 - 1,800 adults for Seneca, assuming no thermal constraints (Table 7). If viability is defined as a long-term average of 2,500 adults per generation, the combined capacity for Belden and Seneca to support Chinook salmon is potentially feasible. The addition of Yellow Creek habitat could double the population estimate and capacity estimates are increased almost five times if the East Branch NF Feather is included. Since capacities were estimated using only physical habitat characteristics (gradient and channel unit composition, Table 5), we applied a thermal filter to the per-generation capacities based on the proportion of each domain that was thermally suitable for at least 80% of the time during the mid-season of each life-stage (Table 7). This filter reduced per-generation estimates in Seneca by about half and Belden down to zero, but other domains were not affected. It should be noted that temperature estimation was more uncertain for Seneca and Belden, and may also be amenable to temperature management via releases from Lake Almanor, Butt Valley Reservoir or other parts of the hydroelectric infrastructure.

Although capacity estimates are promising for reintroductions above Rock Creek Dam, there are high uncertainties in the capacity contributions from Yellow Creek and East Branch NF Feather, and we suggest additional validation of physical and thermal suitability of these areas to confirm results.

For steelhead, spawner capacity in Belden and Seneca is about 1,250 females, nearly double the estimate of Chinook salmon for these same domains (Figure 16). If Yellow Creek and the East Branch are considered, an additional 6,000 fish could be sustained in the domains accessible above Rock Creek Dam. Rearing capacities are high for all domains and this habitat is not likely limiting for steelhead, which is

Table 7. Estimated capacity for potential reintroduction domains. Spawner capacity is number of females while other lifestages are number of fish. Comprehensive capacity considers percent of domain that is thermally available 80% of the time during the mid-season of each lifestage.

Spatial Domain	Geomorphic Capacity[1] Spawning	Rearing	Holding	Per Generation	Comprehensive Capacity[2] Thermal Score (%)[3] Early	Mid	Late	Per Generation
Spring-Run Chinook Salmon								
Seneca	229	81,663	4,089	1,370-1,830	12	53	100	730-970
Belden	446	202,213	2,214	2,670-3,570	0	0	100	0
Yellow Creek	539	258,767	16,907	3,230-4,310	0	100	100	3,230-4,310
East Branch	2494	1,644,558	15,615	14,960-19,950	0	100	100	14,960-19,950
Upper Tribs	153	46,005	8,008	920-1,220	0	100	100	920-1,220
Total	3861	2,233,206	46,833	23,166-30,888				19,840-26,450
Steelhead								
Seneca	463	18,552	-	2,778-3,704	75	94	0	2,610-3,480
Belden	794	38,313	-	4,764-6,352	0	100	0	4,760-6,350
Yellow Creek	1161	38,741	-	6,966-9,288	82	91	0	6,340-8,450
East Branch	4942	141,869	-	29,652-39,536	100	100	0	29,650-39,540
Upper Tribs	342	13,941	-	2,052-2,736	72	86	0	1,760-2,350
Total	7,702	251,416	-	46,212-61,616				45,120-60,170

[1] Capacity of stream channels omitting thermal constraints or increase in wetted area at higher flows. Units of capacity: spawning = number of adult females or redds; rearing = number of juveniles; holding=number of adults; per-generation=number of spawning females times 2 to account for males, times 3 or 4 years per generation.

[2] Geomorphic capacity adjusted by thermal score during mid-season for holding and spawning (rearing was not thermally constrained in any reach that was not already thermally constrained by holding or spawning).

[3] Percent of physical habitat thermally suitable at least 80% of time for each life stage in 2016, during early, mid and late seasons of each life-stage as defined in Table 2.

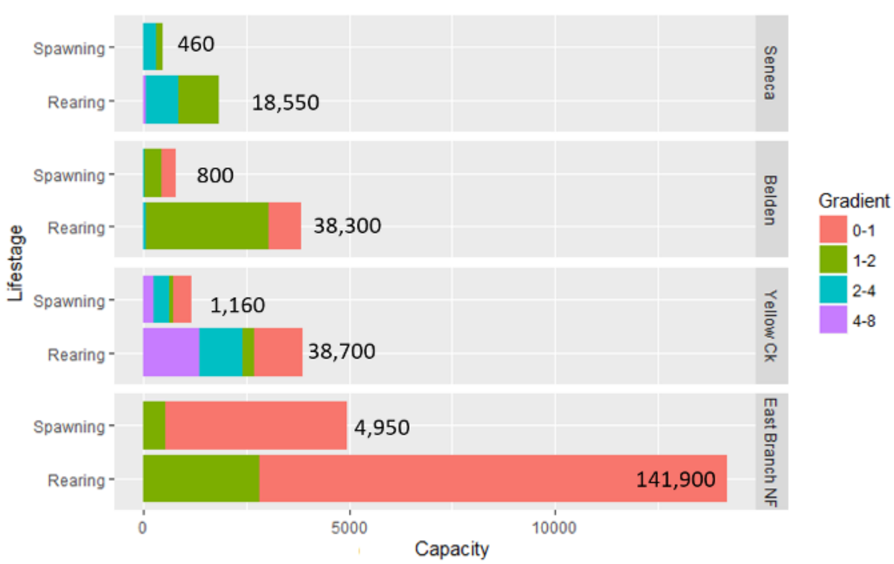

Figure 16. Steelhead capacity within domains accessible upstream from Rock Creek Dam. Units of capacity are redds or female adults for spawning; and 10s of juveniles for rearing.

similar to Chinook salmon results. Since steelhead do not have a strong use preference for low-gradient habitat, the differences in capacity contributions from different gradient classes is not as prevalent as Chinook salmon results.

Steelhead capacity estimates have a similar story to Chinook salmon and are likely a stronger candidate for reintroduction; Belden, Seneca and Yellow Creek potentially have the capacity to support a viable population but the addition of East Branch NF Feather improves this likelihood even further. With annual adult capacity estimates of roughly 800 and 500 fish for Belden and Seneca, respectively, a population of 4,700 - 6,350 fish is estimated for Belden and 2,750 - 3,700 adults for Seneca (Table 7). Yellow Creek provides an additional 7,000 - 9,200 fish to these estimates, suggesting that establishment of a viable population above Rock Creek Dam may be possible. When thermal suitability is considered, steelhead still have per-generation capacity estimates well above a threshold of 2,500 fish (Table 7).

The approach to estimating habitat capacity for the NF Feather River was conservative, as quantitative measures of area from existing field surveys were utilized for the Seneca and Belden reaches and results were not extrapolated beyond Yellow Creek and East Branch NF Feather River. Parts of the network upstream of barriers, notably Above Lake Almanor, Indian Creek, and Spanish Creek domains all would likely have high capacity but we do not estimate it here.

Domain Summary

For a map of spatial domains see Figure 2 on page 10.

Lower NF Feather River

The Lower NF Feather River is the reach directly upstream of Lake Oroville, to just above the top of PG&E's highly-managed Stairway of Power at the confluence of Yellow Creek. Thermally, it is predominantly unfavorable for both Chinook salmon and steelhead during the summer months and has limited value for reintroduction between dams along the Stairway of Power. Temperatures peaked in August at about 21°C in 2014 and 2016 and at about 19°C in 2015 and 2017, and averaged 10 - 11°C from November to February across all years. Although there is some pool-riffle habitat that may be valuable physical habitat, the thermal limitations for Chinook salmon holding and incubation lifestages reduces the overall habitat value.

Seneca and Belden

The Seneca and Belden reaches of the NF Feather River extend downstream from Lake Almanor to Yellow Creek confluence near the top of the Stairway of Power. Both Chinook salmon and steelhead capacity estimates suggest these domains may have the potential to support viable populations, particularly for steelhead. As expected, Belden and Seneca reaches were markedly cooler than the Lower NF Feather River domain by about 3°C in summer months (~17°C). Similarly, mean modeled August temperatures of Belden and Seneca were often 2°C lower than tributaries (e.g. 2015 and 2017). Cooler temperatures make these domains attractive for both steelhead and Chinook salmon reintroductions. When model error and bias was considered, Belden temperatures are likely to be more favorable than expected (up to 5°C reduction). Trends in unsuitable habitat for egg incubation would not change, but impacts to Chinook salmon holding and rearing are likely most sensitive and could experience intolerable temperatures more frequently.

Although Belden and Seneca have higher reach-averaged gradients than the Lower NF Feather, model predictions indicate that these domains still offer some spawning habitat and plenty of rearing habitat for Chinook salmon and steelhead; about 80% of both reaches (~15 km) are <3%, which is useable habitat for both rearing and holding. Due to their relatively short lengths (Figure 11) and steep gradients that tend to export gravel, the Seneca and Belden reaches do not offer abundant spawning habitat and capacities are likely limited by this. However, recent work by Riebe et al. (2014) suggests that salmon can spawn in coarser substrates than previously assumed, suggesting our geomorphic capacity estimates may be too conservative.

Yellow Creek

Yellow Creek is a substantial tributary just above Rock Creek Dam, and drains an open wet meadow that connects to the North Fork via a steep section of step pools. It potentially provides capacity for both Chinook salmon and steelhead that would complement habitat available in Seneca and Belden. Predicted summer temperatures in Yellow Creek averaged 18°C in August for warmer years and 16.5°C in cooler years. Unlike other spatial domains, such as Seneca and Belden, Yellow Creek offered tolerable thermal conditions during early season Chinook salmon incubation periods (holding and rearing periods were still intolerable). With 24 km of low-gradient, pool-riffle and plane-bed habitat in the wet-meadow area, Yellow Creek nearly doubles the predicted availability of this habitat type relative to the combined available habitat in Seneca and Belden. The remaining 40 km of habitat in Yellow Creek is higher-gradient, step-pool habitat (60% of domain) and although abundant, this is less preferred for all lifestages of Chinook salmon and steelhead.

For Chinook salmon, the three domains summarized so far (Lower NF, Seneca and Belden Reaches, Yellow Creek) are complementary, in that Yellow Creek appears to have substantial spawning, incubation, and subyearling habitat; Seneca and Belden have substantial holding, subyearling, and yearling habitat; and the lower North Fork has thermal conditions suitable for subyearlings but suffers from a highly altered flow regime and movement barriers along the Stairway of Power. Viability is likely to depend sensitively on the ability of the fish to move appropriately between these different domains during the life-cycle. For example, the ability of a spring-run population to fully exploit Yellow Creek would likely depend on whether adults holding in Belden or Seneca would ascend the steep lower portion of Yellow Creek in September or October during low flows, to spawn in the suitable upper portion. Depending on how limiting the spawning habitat is in Seneca and Belden, the ability of the population to fully exploit the rearing habitat in these reaches may depend on whether fry or subyearlings emigrating from Yellow Creek in the winter are able to move up into Belden and Seneca for rearing. It seems more likely that emigrant fry from Yellow Creek would move downstream with the current into the lower North Fork, where they may or may not be able to exploit the infrastructure of the Stairway of Power for rearing during the subyearling season. Expression of the yearling life-history may then depend on whether these fish are able to move upstream in late spring to exploit the suitable thermal conditions in Belden and Seneca.

East Branch NF Feather

The East Branch NF Feather extends easterly upstream from its confluence in the Belden Reach to its formation at the confluence of Indian and Spanish Creeks. The East Branch drains a large eastern portion of the watershed via these two creeks. It had a substantial capacity contribution relative to the other accessible domains above Rock Creek Dam, due primarily to the high abundance of pool-riffle habitat (29 km) and a generally suitable thermal regime. Due to the small number of available temperature loggers and lack of field-surveyed channel type data in this spatial domain, we recommend placement of temperature loggers within this reach and a review of physical habitat to confirm that this domain provides the high thermal and physical capacity for both Chinook salmon and steelhead that is predicted in our results.

Spanish and Indian Creeks

The majority of the eastern North Fork Feather watershed is comprised of the Spanish and Indian Creek drainage networks, which converge to form the East Branch. With over 600 km of streams in these two tributaries, reach types are diverse but over 90% of each of these domains has a gradient of <7.5%. 50 - 66% of these domains were classified as pool-riffle or plane-bed habitat, suggesting that these domains may have been valuable for historic Chinook salmon and steelhead populations. Similar to Yellow Creek, summer temperatures in Spanish and Indian Creeks averaged 18°C in August for warmer years and 16.5°C in cooler years, although the upper reaches of the Indian Creek domain had modeled temperatures that were up to 4°C higher than tributaries in the rest of the NF Feather River watershed. There were several notably cool reaches in lower Indian Creek that were pronounced in warmer years. The extent of thermal extremes in Indian Creek was much higher in 2017 than 2014.

Potential fish passage barriers exist on both Spanish and Indian Creeks near their confluences (Yoshiama et al., 2001), and these potential migration barriers would need to be carefully evaluated before reintroductions to either Spanish or Indian Creeks. The migration barrier on Spanish Creek is a "substantial waterfall" near the confluence (Yoshiyama et al., 2001), whereas the barrier on Indian Creek is a well-known 5-meter waterfall about 6 km from the confluence. The historic passability of each is described rather ambiguously by Yoshiyama et al. (2001) and it would be useful to assess each for passage at high flows (spring snowmelt), given the substantial amount of habitat that would be available to spring-run Chinook salmon if they could ascend either falls.

Tributaries Above Lake Almanor, and Above Dams

The tributaries above Lake Almanor and the large wet meadow system that used to exist on the site of Lake Almanor were at one time accessible to anadromous fish (Yoshiyama et al. 2001). In our study, the tributaries above Lake Almanor had one of the highest network densities of cool temperatures in the tributary domains, and should perhaps be more closely investigated for capacity and reintroduction scenarios. However, the reaches above Lake Almanor are currently isolated from the rest if the North Fork watershed by the lake and its Canyon Dam. The Above Dam domain describes tributaries isolated by other dams in the North Fork drainage, and is comprised of a mixed combination of pool-riffle, plane-bed, and step-pool habitat (~35% each), also with a substantial proportion of thermally suitable habitat.

Upper Tributaries, Lower NFFR Tributaries,

These two domains consist of various minor tributaries to the North Fork mainstem and East Branch. The majority (66 - 76%) of physical habitat in the two domains is higher-gradient, step-pool habitat, making these areas useable for steelhead but of little value to Chinook salmon. Although the Upper Tributaries are accessible from Rock Creek Dam, our modeling suggests that the high-gradient habitat provides limited capacity for Chinook salmon or steelhead relative to other domains.

West Branch NF Feather

The West Branch is the westernmost tributary of the watershed and drains directly into Lake Oroville from the north. Since 64% of the West Branch NF Feather is high gradient, step-pool habitat (3 - 7% slope), a large portion of this watershed is useful mainly for steelhead. However, the remaining 68 km of channel in this domain is comprised of pool-riffle and plane-bed reaches and the lower 16 km was likely historically useful for both species (Yoshiyama et al. 2001). Currently, the downstream end of the West Branch NF likely has a thermal barrier that may be difficult for fish passage, especially in warmer years, and Lake Oroville and the Stairway of Power isolate it from fish in the rest of the watershed. Use of the West Branch by a reintroduced population would depend on the ability of adults and juveniles to move appropriately through the lower branch and reservoir. This questionable accessibility and the likelihood of thermal constraints in the West Branch make this domain an unfavorable reintroduction area. However, the upper reaches of the West Branch did have one of the highest network densities of cool temperatures in all the tributary domains.

Conclusions

Results from this study indicate that the Upper Feather River watershed could probably support a viable steelhead population, and possibly a spring-run Chinook salmon population, in the Seneca, Belden and Yellow Creek domains. The adjacent West Branch appears to expand capacity considerably, but its predicted thermal suitability was based solely on the regression models, without any logger data from the West Branch itself to confirm. Although we did not explicitly estimate capacity in other spatial domains, it seems likely that the tributaries above Lake Almanor and the Spanish and Indian Creek drainages all have substantial capacity for both species, but are upstream of migration barriers. An array of explicit reintroduction scenarios are worth considering in greater detail in future work, including a more detailed scenario for reintroduction just above Rock Creek Dam, a scenario for reintroduction above Lake Almanor, more detailed field data on the West Branch, and an evaluation of the possibility that the natural barriers on Spanish and Indian Creeks are passable by Chinook salmon during high flows associated with snowmelt.

Key limiting factors for both species included cool waters for spawning and incubation, and limited low-gradient spawning habitat where gravel accumulates (but see Riebe et al. 2014). In the Yellow Creek and East Branch domains, physical habitat is likely limiting Chinook salmon and steelhead capacity more than thermal regimes, but in Seneca and especially Belden, thermal constraints during the spawning and incubation stage appeared to reduce capacity by about 50% and 100% respectively. Our analysis of thermal constraints was very simple and coarse, however, and more detailed analysis of reintroduction scenarios, as well as the effect of water management on temperatures, would be valuable. This is especially true in the cooler waters of the Seneca reach, where spawning habitat is more limited than rearing and holding habitat, due to the steep gradient and coarse sediment texture. If salmon reintroductions were pursued in the Seneca and Belden reaches, periodic gravel additions could be used to enhance spawning habitat, but it is also worth evaluating whether salmon would successfully use the coarser substrates to spawn, as predicted by Riebe et al. (2014). The addition of Yellow Creek and East Branch NF Feather habitat to Seneca and Belden domains improves the potential likelihood of reintroduction success of both species.

Our overall capacity estimates were smaller for Chinook salmon than steelhead; Chinook salmon capacity estimates were closer to the minimum recommendation of 2,500 adults for reintroduction success. In Belden, Seneca, and Yellow Creek domains, adult steelhead capacity is higher than adult Chinook salmon capacity, likely due to the limited amount of low-gradient habitat suitable for spawning adult Chinook salmon. As a result, steelhead reintroduction may be more successful than Chinook salmon reintroduction, especially since both spawning ground and adult holding habitat appear to be in short supply within the potential reintroduction domain.

Future work could focus on collection of habitat type data in Yellow Creek and the East Branch to verify the gradient-based channel typing approach used here. The water temperature modeling could also be improved through the addition of full-year temperature monitoring and additional loggers in the East Branch NF Feather to verify its predicted thermal suitability and large capacity. It would also be valuable to consider other reintroduction scenarios more fully, such as introduction above Lake Almanor, in Indian Creek, or in Spanish Creek, and also conduct a detailed assessment of passability during spring snowmelt at the migration barriers on Indian Creek and Spanish Creek. Although our thermal modeling was relatively successful in the unmanaged sections of the stream network, it was less successful in the highly-managed flow regime on the mainstem of the North Fork between Lakes Almanor and Oroville. Impacts from water supply diversions and returns were not explicitly considered in this study. Future work could consider all water return locations, as these locations may be differentially warmer or cooler than the mainstem Feather, depending on the source and the transport of the water, the season, and the amount of precipitation in the water year.

Acknowledgements

Many thanks to PG & E for providing habitat type data for the Seneca and Belden Reaches of the NF Feather River and mainstem temperature data (Rohit Salve, Matthew Joseph and Catalina Reyes). Observational stream temperature data provided by the USFS (James Johnson), California Department of Water Resources (Patrick Jarrette), and the Plumas Corporation (Terri Rust) greatly improved spatial accuracy of the model. The development of the LST model code was essential to this project and Kris McNyset is credited with this as a product developed for the Integrated Status and Effectiveness Monitoring Program. We thank Rachel Johnson, Tom Holley, and Alyssa Fitzgerald for providing detailed and useful review of the report, Nate Mantua and Steve Lindley for carefully reading the final manuscript, and Kit Johnston for performing the final formatting of the Technical Memorandum.

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Supplemental Material

LST Data

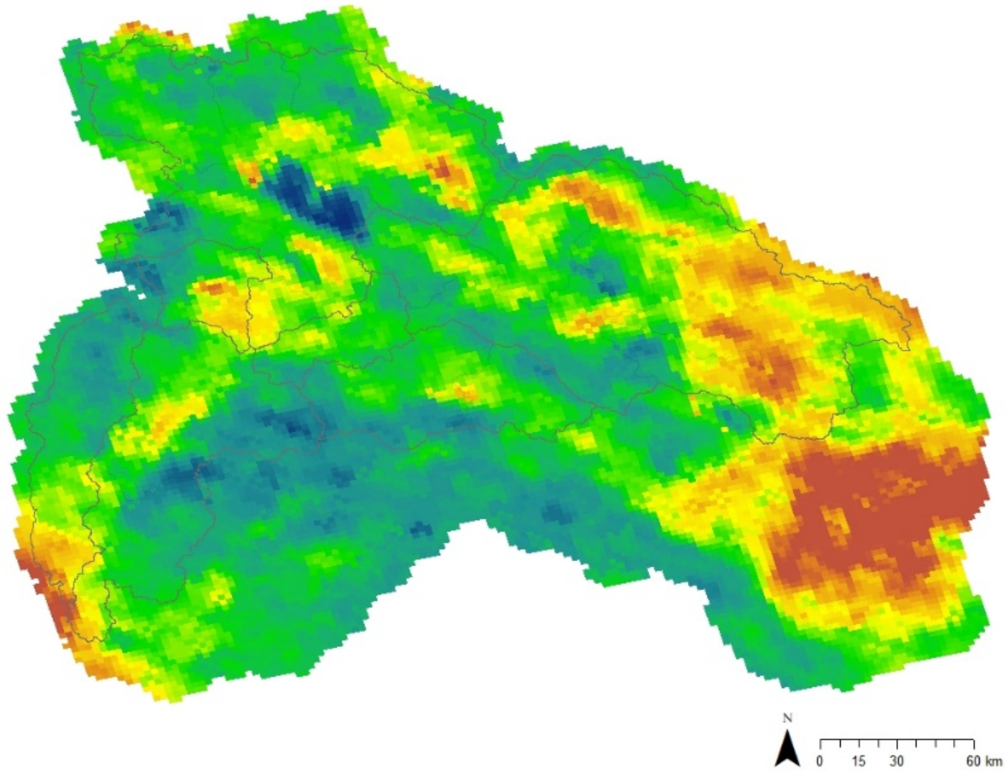

Figure S1. Example of raw MODIS dataset for a single-day time point. Cooler temperatures are depicted in greens and blues with warmer colors indicating higher LST.

The MODIS land surface temperature (LST) data are freely available from NASA in both daily and 8-day time steps and are 1-km rasters that are spatially continuous throughout the US. An example is shown in Figure S1. Eight-day data between January 1, 2014 and December 31, 2017 were downloaded from the EarthData Portal (https://earthdata.nasa.gov). The data product is MOD11A2: MODIS/Terra Land Surface Temperature/Emissivity 8-Day L3 Global 1km SIN Grid V005. The MODIS granule naming convention includes horizontal and vertical tiling information. Complete coverage of the Feather River requires swath 8, vertical tiles 4 and 5. For example, an hdf name is interpreted as follows:

Full hdf name: MOD11A2.A2014041.h09v04.005.20140581411909.hdf

Year + Day of Year: A2014041

Swath ID: h09v04

Version: 005

The HDFs were batch imported to Arc rasters using the **Find HDFs and Convert SDS To ArcGIS Rasters** function in the ArcGIS Marine Geospatial Ecology toolbox (https://mgel.env.duke.edu/mget/). We used the following parameters:

SDS name: LST_Day_1km
Cell size => 926.6254331
Wildcard: *.hdf
Min Size: 40 (no max)
Projection: MODIS_sin.prj
Naming convention code:
os.path.join(outputWorkspace, os.path.dirname(inputFile[len(directoryToSearch)+1:]), 'LST_s1' + os.path.basename(inputFile)[11:16])

The ArcGIS rasters from each time point within the timeframe were mosaicked together for continuous coverage of the Feather, reprojected (Albers), and clipped to the NF Feather River watershed. A custom python script was then used to extract LST grid values for each year into a grid cell point shapefile (multi_value_pts_Loop.py).

LST for individual RCAs (reach catchment areas) were calculated using a weighted mean of LST values from the 1km grid. To do this, a master file of grid cell weights within each RCA was created from area (area of grid cell within the RCA divided by area of the whole grid cell). A scaling factor (0.02) used in the hdf storage format was backed out, and temperatures were converted to Celsius during post processing. Any gaps in LST coverage for RCAs due to equipment failure or cloud cover were filled via splining. All values below 0.5 were filled with 0.

The core relationship between land surface temperature and in-stream temperature had an R^2 of 0.76 for the NFFR (Figure S2 and Table S2).

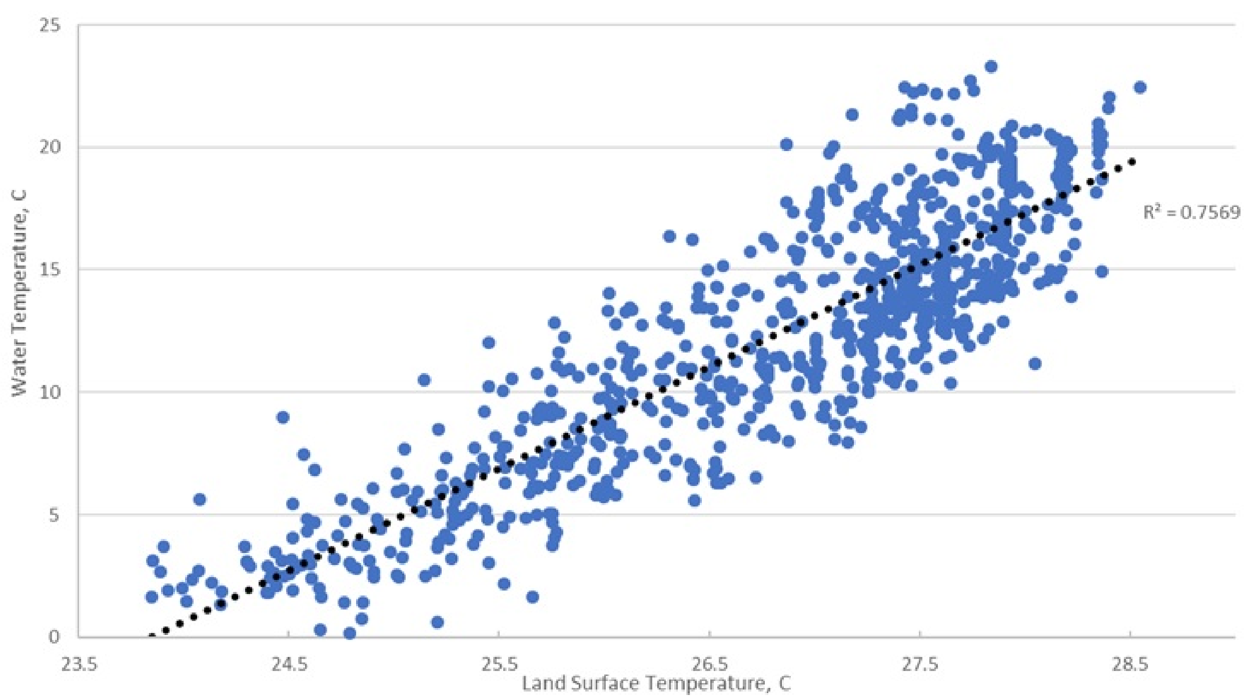

Figure S2. Land surface relationship to 8-day mean water temperature in the Feather River (2016)

Temperature Models

The number and location of loggers varied by year (Figure S3 to S6 for 2014 – 2017). The largest number of loggers were available for 2015 and 2016 (Table S1). Table S2 shows correlations among the various predictors of stream temperature. A full set of model fits for the tributary (Table S3) and mainstem (Table S4) for 2017 show the relative impact of covariates on r^2.

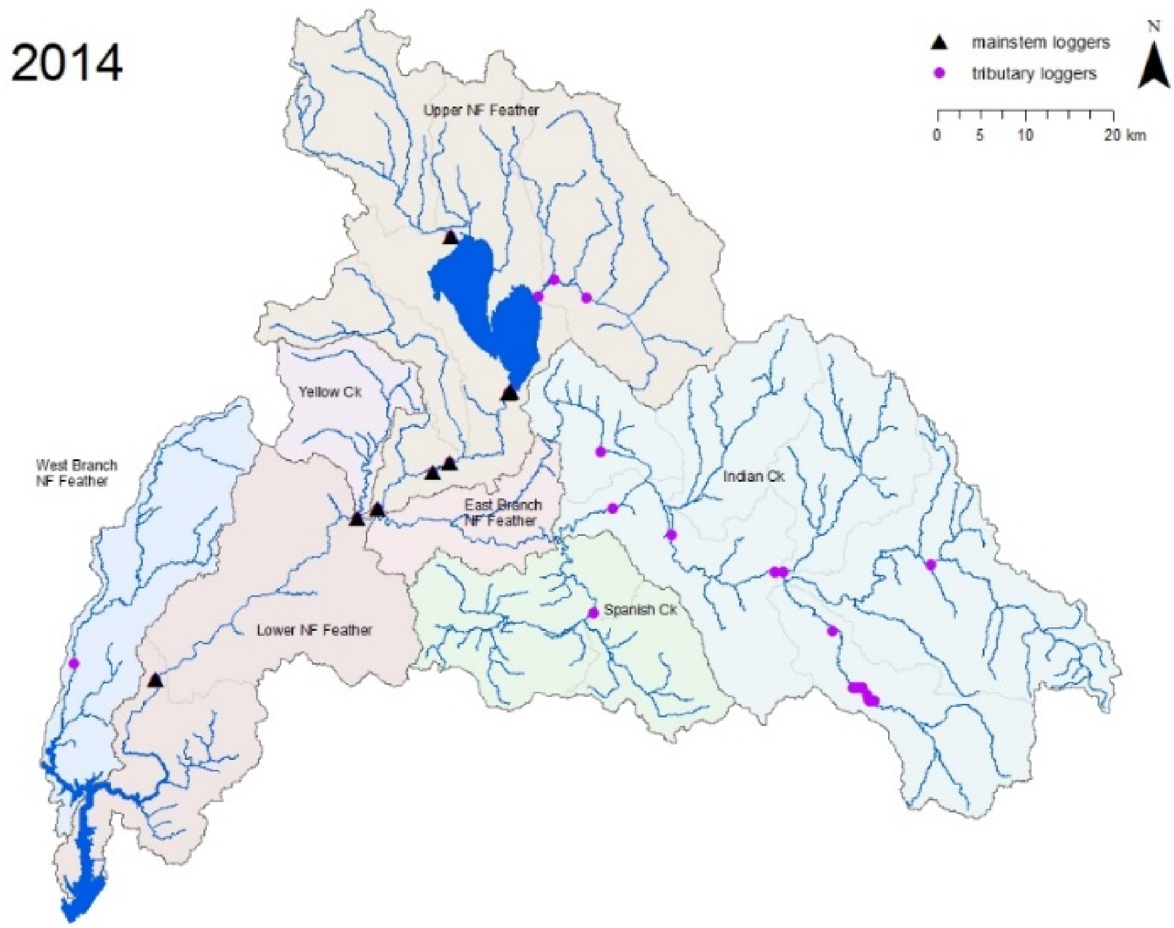

Figure S3. Locations of temperature loggers in 2014.

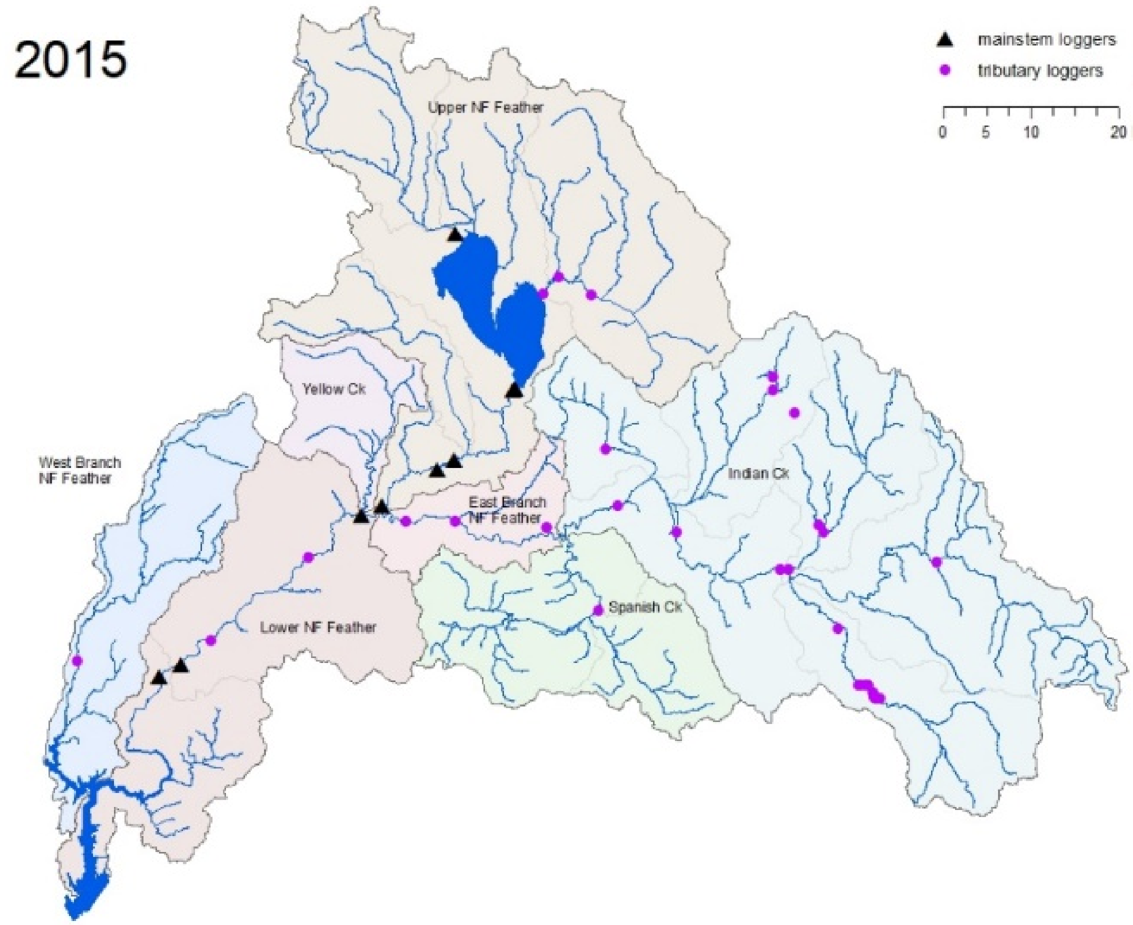

Figure S4. Locations of temperature loggers in 2015.

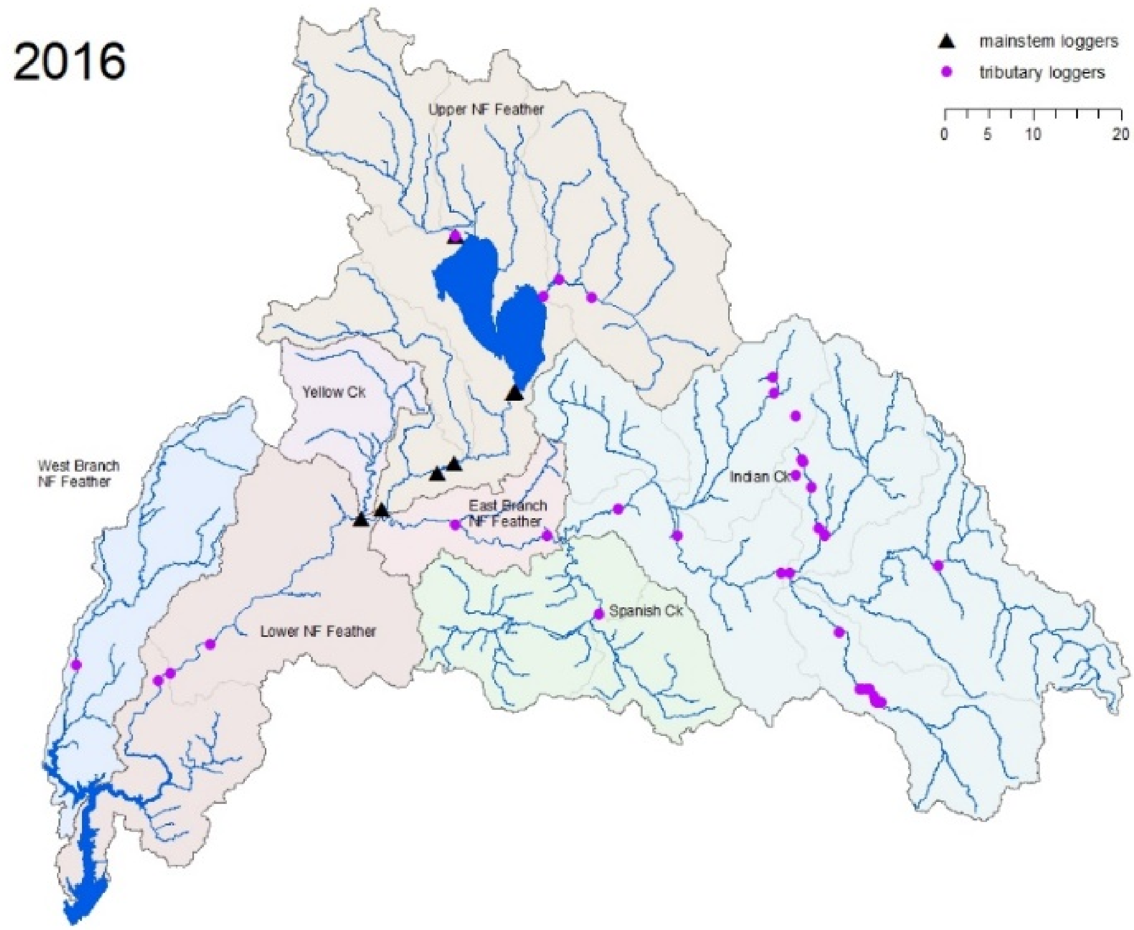

Figure S5. Locations of temperature loggers in 2016.

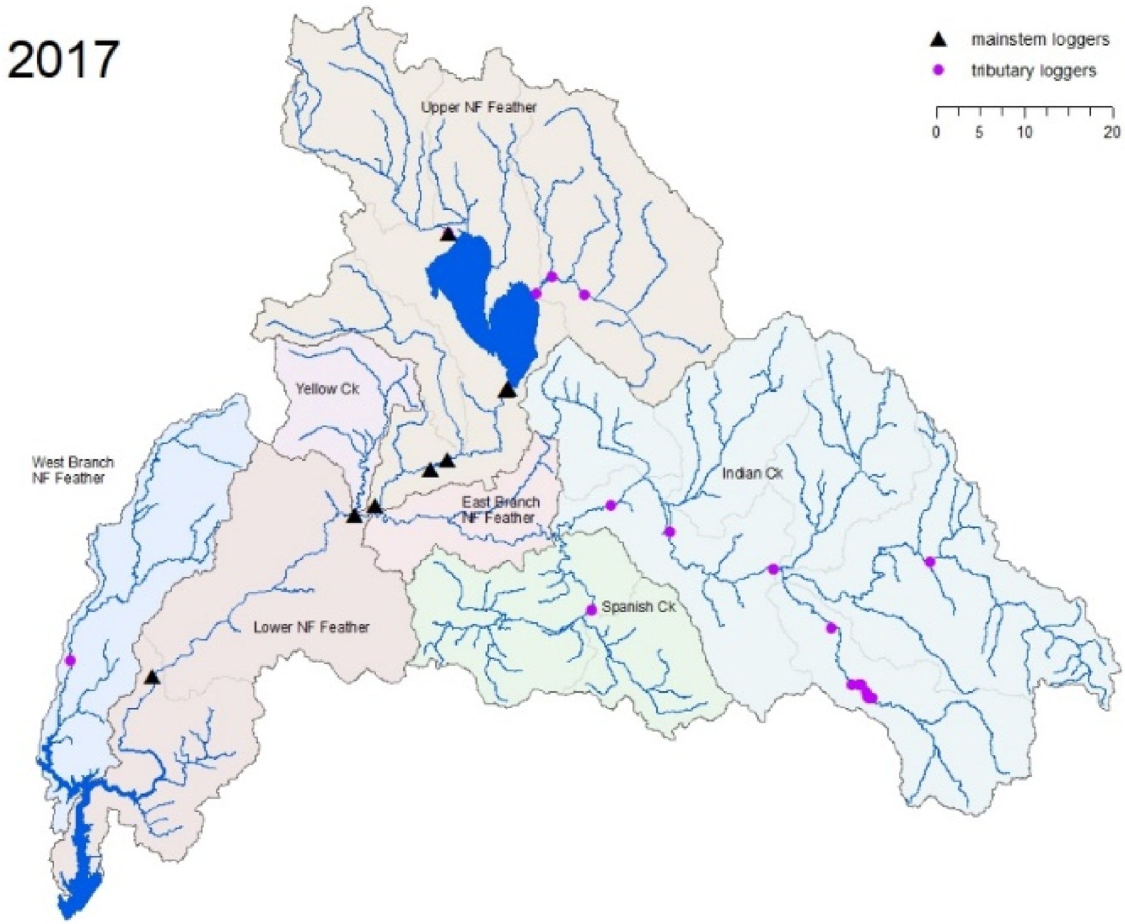

Figure S6. Locations of temperature loggers in 2017.

Table S1. Number of temperature logging sites per year.

	2014	2015	2016	2017
Tributary	25	33	38	19
Mainstem	7	9	7	8

Table S2. Covariate correlation matrix of 2017 spring tributary and full-year mainstem models. Dv8D refers to 8-day mean discharge; table entries are Pearson correlations. Some correlations such as between Elevation (Elev) and day-of-year are due to non-random patterns of missing data associated with timing of logger deployment.

		Stream Temp	LST	Day of Year	Elev	Dv8D
Tributary	**Stream Temp**	1.00				
	LST	0.94	1.00			
	Day of Year	0.45	0.46	1.00		
	Elev	0.21	0.18	0.34	1.00	
	Dv8D	-0.60	-0.60	-0.71	-0.25	1.00
Mainstem	**Stream Temp**	1.00				
	LST	0.76	1.00			
	Day of Year	0.74	0.75	1.00		
	Elev	-0.80	-0.35	-0.46	1.00	
	Dv8D	-0.68	-0.71	-0.73	0.47	1.00

Table S3. Example of a full suite of model fits for the 2017 tributary sector. R^2 is the proportion of variance explained by each model (aka model fit). Final models are in bold.*

	Full Year		Spring		Fall	
Model	**Sig > 0.05**	**R^2**	**Sig > 0.05**	**R^2**	**Sig > 0.05**	**R^2**
LST+LST^2+DoY+Elev+d+d*DoY	I,LST,LST^2,d	0.89	I,LST,LST^2,DoY,Elev	0.93	DoY,Elev,d,DoY*d	0.85
LST+LST^2+DoY+Elev+d+d*Elev	LST,LST^2,d	0.89	I,LST,LST^2,DoY,Elev,d,Elev*d	0.94	DoY	0.84
LST+LST^2+DoY+Elev+d+DoY*Elev	LST,LST^2,DoY,Elev, d,Doy*Elev	0.90	I,LST,LST^2,DoY,Elev, DoY*Elev	0.95	Elev,DoY*Elev	0.84
LST+LST^2+DoY+Elev+d	LST,LST^2,d	0.89	I,LST,LST^2,DoY,Elev	0.93	DoY,Elev	0.84
LST+LST^2+DoY+Elev	LST,LST^2,DoY	0.89	**I,LST,LST^2,DoY,Elev**	**0.93**	**DoY,Elev**	**0.84**
LST+LST^2+DoY	I,LST,LST^2,DoY	0.89	I,LST,LST^2,DoY	0.92	DoY	0.83
LST+LST^2+DoY+d	I,LST,LST^2,d	0.89	I,LST,LST^2,DoY	0.92	DoY	0.84
LST+LST^2+d	LST,LST^2,d	0.89	I,LST,LST^2,d	0.90	I	0.81
LST+LST^2	I,LST,LST^2,d	0.89	I,LST,LST^2	0.89		0.81
LST+LST^2+Elev	LST^2,Elev	0.89	I,LST,LST^2,Elev	0.91	Elev	0.82
LST+Elev	LST,Elev	0.89	I,LST,Elev	0.90	I,LST,Elev	0.82
LST+DoY	I,LST	0.89	I,LST,DoY	0.91		
LST+DoY+Elev	I,LST,Elev	0.89	I,LST,DoY,Elev	0.92	I,LST,DoY,Elev	0.84
LST	I,LST	0.89	I,LST	0.88	I,LST	0.81

* LST=Land Surface Temperature as linear effect; LST^2 = Land Surface Temperature as second-order polynomial; DoY=Day of Year; Elev=elevation of reach; d=discharge at representative gauging station. I =y-intercept; * = interaction effect.

Table S4. Example of a full suite of model fits for the 2017 mainstem model domain. Final model is in bold.*

	Full Year	
Model	**Sig > 0.05**	***R^2***
LST+LST^2+DoY+Elev+d+d*DoY	I,LST,LST^2,DoY,Elev,d*DoY	0.92
LST+LST^2+DoY+Elev+d+d*Elev	I,LST,LST^2,DoY,Elev	0.92
LST+LST^2+DoY+Elev+d+DoY*Elev	I,LST,LST^2,Elev,d	0.92
LST+LST^2+DoY+Elev+d	I,LST,LST^2,DoY,Elev,d	0.92
LST+LST^2+DoY+Elev	**DoY.Elev**	**0.92**
LST+LST^2+DoY	DoY	0.64
LST+LST^2+DoY+d	DoY,d	0.65
LST+LST^2+d	LST,LST^2,d	0.63
LST+LST^2	I,LST,LST^2	0.58
LST+LST^2+Elev	LST^2,Elev	0.91
LST+Elev	I,LST,Elev	0.91
LST+DoY	I,LST,DoY	0.64
LST+DoY+Elev	I,LST,Elev,DoY	0.91
LST	I,LST	0.58

* LST=Land Surface Temperature as linear effect; LST^2 = Land Surface Temperature as second-order polynomial; DoY=Day of Year; Elev=elevation of reach; d=discharge at representative gauging station. I =y-intercept; * = interaction effect.

Table S5. Final model fits for NF Feather River network. Bold indicates covariate was significant ($p<0.05$).

Year	Model Sector	Model Type	Model	*R^2*	RMSE
2014	Tributaries	Spring	LST+LST^2+**DoY+Elev**	0.92	1.68
2014	Tributaries	Fall	**LST+LST^2+DoY+Elev**	0.89	1.89
2014	Mainstem	Full-year	LST, LST^2+**DoY+Elev**	0.82	2.28
2015	Tributaries	Spring	LST+LST^2+**DoY+Elev**	0.86	2.01
2015	Tributaries	Fall	**LST+LST^2+DoY+Elev**	0.85	2.28
2015	Mainstem	Full-year	LST+LST^2+DoY+**Elev**	0.76	3.09
2016	Tributaries	Spring	LST+LST^2+**DoY+Elev**	0.82	2.27
2016	Tributaries	Fall	**LST+LST^2+DoY+Elev**	0.78	2.25
2016	Mainstem	Full-year	LST+LST^2+**DoY+Elev**	0.90	1.68
2017	Tributaries	Spring	**LST+LST^2+DoY+Elev**	0.93	1.47
2017	Tributaries	Fall	LST+LST^2+**DoY+Elev**	0.84	2.19
2017	Mainstem	Full-year	LST+LST^2+**DoY+Elev**	0.91	2.80

* LST=Land Surface Temperature as linear effect; LST^2 = Land Surface Temperature as second-order polynomial; DoY=Day of Year; Elev=elevation of reach.

Table S6. Average model error (C°) for Chinook salmon life-stages within spatial domains.

Spatial Domain	Period	Subperiod	2013	2014	2015	2016	2017
Belden	Holding	Early					
		Middle		2.36	4.39	0.77	3.69
		Late					
	Incubation	Early		2.35	4.91	1.16	4.56
		Middle		1.28	3.02	0.52	3.11
		Late					
	Rearing	Subyearling					
		Yearling		2.36	4.39	0.77	3.69
Seneca	Holding	Early		1.41	-1.50	0.00	-0.10
		Middle		-1.64	-0.83	-1.39	-0.20
		Late		3.40	3.52	2.88	
	Incubation	Early		-1.89	-0.96	-2.45	-0.81
		Middle		0.39	1.53	0.66	0.49
		Late				-0.19	-0.08
	Rearing	Subyearling	1.41	-1.50	0.79	0.51	
		Yearling		-1.16	-0.33	-0.79	-0.20
East Branch NF Feather River	Holding	Early					
		Middle			-1.19		
		Late					
	Incubation	Early			-0.60		
		Middle			1.04		
		Late					
	Rearing	Subyearling					
		Yearling			-1.19		
East Branch NF Tributaries	Holding	Early		-0.04	0.08	-0.03	-0.36
		Middle		0.09	-0.18	0.06	-0.61
		Late		0.05	0.69	-0.30	-1.94
	Incubation	Early		0.13	-0.05	0.06	-0.47
		Middle		0.09	0.07	-0.34	-0.40
		Late		-0.06	-0.22	0.02	0.09
	Rearing	Subyearling		0.13	0.29	-0.53	
		Yearling		0.00	-0.11	0.01	-0.76
Lower NF Feather	Holding	Early		-0.95			
		Middle		0.98	-0.89		
		Late		-3.20	-0.05		
	Incubation	Early		1.04	-0.81		
		Middle		-1.32	-0.43		
		Late		-0.86			
	Rearing	Subyearling	-1.13				
		Yearling		0.78	-0.83		
Lower NF Tributaries	Holding	Early					
		Middle			-2.14	-1.04	
		Late			1.04	0.47	
	Incubation	Early			-1.84	-1.29	
		Middle			0.11	-0.56	
		Late					
	Rearing	Subyearling					
		Yearling			-1.91	-0.85	
Tributaries above Almanor	Holding	Early		0.84	-0.99	-0.65	0.14
		Middle		-1.32	-1.59	0.25	1.55
		Late		-0.87	-1.52	0.11	-0.93
	Incubation	Early		-2.01	-1.83	0.50	2.44
		Middle		-1.04	-1.22	-0.26	0.57
		Late				-0.32	-0.51
	Rearing	Subyearling	0.84	-0.99	-0.88	-0.49	1.07
		Yearling		-1.15	-1.41	0.15	1.11

Table S7. Average model error (C°) for steelhead life-stages within spatial domains.

Spatial Domain	Period	Subperiod	2013	2014	2015	2016	2017
Belden	Incubation	Early					
		Late		2.72	5.32	1.18	4.47
		Middle	2.73	3.87	0.20	2.73	
	Rearing	Dry		2.36	4.39	0.77	3.69
		Wet					
Seneca	Incubation	Early		3.03	3.33	2.82	
		Late		-2.31	-1.02	-2.30	-0.80
		Middle	-0.89	-1.50	0.58	1.02	0.16
	Rearing	Dry		-1.86	-0.84	-1.54	-0.46
		Wet	1.12	1.06	1.39	1.35	
East Branch NF Feather River	Incubation	Early					
		Late			-1.97		
		Middle		-2.53			
	Rearing	Dry			-1.19		
		Wet					
East Branch NF Tributaries	Incubation	Early		-0.22	0.15	-0.26	-1.94
		Late		-0.33	-0.64	-0.19	-1.14
		Middle	0.15	0.29	0.51	-0.96	-0.21
	Rearing	Dry		-0.02	-0.29	-0.03	-0.65
		Wet	0.14	0.09	0.29	-0.27	-1.94
Lower NF Feather	Incubation	Early		-3.20	-0.05		
		Late		1.56	-1.08		
		Middle	-0.28	-0.86			
	Rearing	Dry		0.94	-0.89		
		Wet	-0.66	-3.20	-0.05		
Lower NF Tributaries	Incubation	Early			1.04	0.47	
		Late			-3.07	-1.18	
		Middle		-2.80	-0.41		
	Rearing	Dry			-2.14	-1.04	
		Wet			1.04	0.47	
Tributaries above Almanor	Incubation	Early		-0.64	-0.89	-0.12	-0.27
		Late		-2.02	-2.10	0.25	2.51
		Middle	-0.06	-0.99	-0.71	-1.01	0.75
	Rearing	Dry		-1.62	-1.78	0.19	1.72
		Wet	0.33	-0.77	-0.64	-0.05	0.14

Temperature Exposures

Table S8. Summary of Chinook salmon exposure to 8-day mean temperatures (table entries in °C), by accessible spatial domain, life-stage and season. Green indicates temperatures are within optimal ranges for species and life-stage; yellow indicates temperatures are within tolerable ranges; and pink indicates temperatures exceed tolerable ranges.

Spatial	Period	Subperiod		2013			2014			2015			2016			2017	
Domain			Min	Mn	Max	Min	Mn	Max	Min	Mn	Max	Min	Mn	Max	Min	Mn	Max
Belden	Holding	Early				1.8	6.9	10.8	6.5	10.1	13.1	9.4	11.6	13.9	7.1	9.3	11.7
		Middle				10.9	16.6	18.7	11.5	14.7	16.2	14.3	17.3	19.2	12.1	14.6	16.3
		Late				12.9	14.3	16.2	12.1	12.9	14.1	14.4	15.4	16.3			
	Incubation	Early				17.7	18.1	18.4	14.6	15.6	16.1	18.4	18.8	19.2	15.7	15.9	16.2
		Middle				9.5	13.3	18.3	6.4	10.5	15.5	10.1	14.3	18.0	13.4	14.1	15.3
		Late				1.8	3.2	5.6	5.9	7.4	8.7	7.7	9.1	10.4	4.6	6.8	8.1
	Rearing	Subyearling	2.3	2.7	3.3	7.7	8.5	9.3	7.1	7.4	7.9	10.1	10.9	11.8	4.6	6.0	6.8
		Yearling				10.5	15.7	18.7	7.0	13.6	16.2	12.1	16.5	19.2	12.1	14.6	16.3
Seneca	Holding	Early				0	4.7	8.6	5.6	9.2	12.2	6.2	8.4	10.6	4.5	7.0	9.5
		Middle				8.6	14.9	17.2	9.9	14.0	15.5	11.1	14.2	16.1	10.3	12.8	14.4
		Late				11.2	12.6	14.7	11.4	12.2	13.5	11.2	12.2	13.2			
	Incubation	Early				15.8	16.3	16.6	13.9	14.9	15.4	15.3	15.7	16.1	13.9	14.2	14.4
		Middle				7.7	11.7	16.6	4.9	9.6	14.8	6.8	11.1	14.9	11.4	12.1	13.2
		Late				0	1.3	3.3	5.1	6.5	7.7	4.6	6.0	7.3	3.2	4.6	5.7
	Rearing	Subyearling	0.6	0.9	1.4	6.4	7.2	8.2	4.8	5.2	5.6	6.8	7.6	8.5	3.2	4.0	4.6
		Yearling				8.6	14.0	17.2	6.1	12.9	15.5	8.4	13.4	16.1	10.3	12.8	14.4
East Branch NF Feather River	Holding	Early				3.6	8.1	11.8	5.6	9.1	13.1	4.3	7.5	10.6	2.4	5.5	9.7
		Middle				12.7	17.5	22.0	11.5	16.5	21.5	11.4	14.7	17.9	10.8	16.0	19.7
		Late				10.2	11.5	13.3	9.6	10.6	12.1	7.4	8.8	10.2	11.5	11.9	12.1
	Incubation	Early				17.7	18.7	20.5	14.4	16.5	19.2	14.7	16.5	17.9	18.6	19.1	19.7
		Middle				4.3	10.0	17.1	2.2	8.0	14.8	3.4	8.1	14.4	4.9	9.9	17.1
		Late				1.7	3.9	6.6	3.0	5.3	7.4	1.4	3.8	5.9	-0.1	1.8	3.5
	Rearing	Subyearling	1.7	2.6	3.4	3.7	4.7	5.7	1.8	2.8	3.9	1.7	2.4	3.2	4.9	5.4	6.0
		Yearling				7.0	15.5	22.0	3.9	14.3	21.5	5.3	12.8	17.9	6.7	14.4	19.7
Yellow Creek	Holding	Early				2.9	7.6	11.5	4.4	8.6	12.8	4.6	7.7	11.1	2.5	5.7	10.1
		Middle				12.3	17.2	21.7	11.8	16.5	21.4	11.2	15.1	18.5	12.2	16.8	21.3
		Late				9.2	10.7	12.8	9.9	11.1	12.7	7.1	8.5	10.1	11.4	11.6	11.8
	Incubation	Early				17.3	18.3	20.2	14.9	16.9	19.5	14.7	16.7	18.3	18.4	19.1	20.5
		Middle				2.9	9.2	16.8	1.3	8.1	15.4	2.9	7.9	14.4	4.3	9.3	16.7
		Late				1.4	3.4	6.0	2.5	4.7	6.9	1.3	4.0	6.0	0	2.1	3.7
	Rearing	Subyearling	1.4	2.3	3.2	2.7	3.7	4.8	1.3	2.5	3.7	1.5	2.4	3.1	4.3	4.9	5.2
		Yearling				6.2	15.1	21.7	3.7	14.3	21.4	4.8	13.0	18.5	5.9	14.7	21.3

Table S9. Summary of steelhead exposure to 8-day mean temperatures (table entries in °C), by accessible spatial domain, life-stage and season. Green indicates temperatures are within optimal ranges for species and life-stage; yellow indicates temperatures are within tolerable ranges; and pink indicates temperatures exceed tolerable ranges.

Spatial Domain	**Period**	**Subperiod**	**2013**			**2014**			**2015**			**2016**			**2017**		
			Min	**Mn**	**Max**	**Min**	**Mn**	**Max**	**Min**	**Mn**	**Max**	**Min**	**Mn**	**Max**	**Min**	**Mn**	**Max**
Belden	Incubation	Early				10.5	12.9	16.2	7.0	10.5	14.1	12.1	14.4	16.3			
		Middle	1.8	8.9	17.7	7.7	10.4	13.4	7.1	9.4	12.2	7.4	10.6	13.8	4.6	10.2	15.7
		Late				17.7	18.2	18.7	14.6	15.6	16.2	17.4	18.6	19.2	15.5	15.8	16.3
	Rearing	Dry				15.2	17.6	18.7	13.0	15.2	16.2	16.1	17.8	19.2	13.4	15.1	16.3
		Wet	1.8	7.2	14.4	7.7	10.9	14.9	7.0	10.2	14.7	7.4	11.3	14.9			
Seneca	Incubation	Early				8.8	11.2	14.7	6.1	9.7	13.5	8.4	11.2	13.2			
		Middle	0.0	6.9	16.1	6.4	9.3	12.4	4.7	7.2	10.0	5.0	7.9	11.1			
		Late				15.8	16.6	17.2	13.9	14.8	15.5	14.4	15.4	16.1	13.6	14.0	14.4
	Rearing	Dry				13.9	15.9	17.2	12.4	14.6	25.5	12.9	14.7	16.1	11.4	13.2	14.4
		Wet	0.0	5.2	12.6	6.4	9.6	13.8	4.7	8.1	12.8	5.0	8.6	12.4			
East Branch NF Feather River	Incubation	Early				7.0	9.6	13.3	3.9	7.9	12.1	5.3	7.7	10.2	6.7	9.6	12.1
		Middle	1.7	10.0	19.4	3.6	8.0	12.9	1.8	5.7	10.1	1.7	5.8	11.2	4.9	5.4	6.0
		Late				17.7	19.8	22.0	14.4	18.4	21.5	14.7	16.7	17.9	18.0	18.7	19.7
	Rearing	Dry				14.2	18.3	22.0	11.5	17.1	21.5	11.4	15.3	17.9	13.2	17.0	19.7
		Wet	1.7	8.3	16.0	3.6	8.6	14.5	1.8	6.6	12.4	1.7	6.1	11.8	4.9	8.1	12.1
Yellow Creek	Incubation	Early				6.2	8.8	12.8	3.7	8.1	12.7	4.8	7.4	10.1	5.9	9.0	11.8
		Middle	1.4	9.6	19.3	2.7	7.1	12.2	1.3	5.5	10.1	1.5	5.9	11.7	4.3	4.9	5.2
		Late				17.3	19.6	21.7	14.9	18.4	21.4	14.7	17.0	18.5	18.4	19.5	21.3
	Rearing	Dry				13.7	18.0	21.7	11.8	17.2	21.4	11.2	15.6	18.5	12.7	17.6	21.3
		Wet	1.4	7.8	15.7	2.7	7.8	14.0	1.3	6.7	13.0	1.5	6.2	12.3	4.3	7.5	11.8

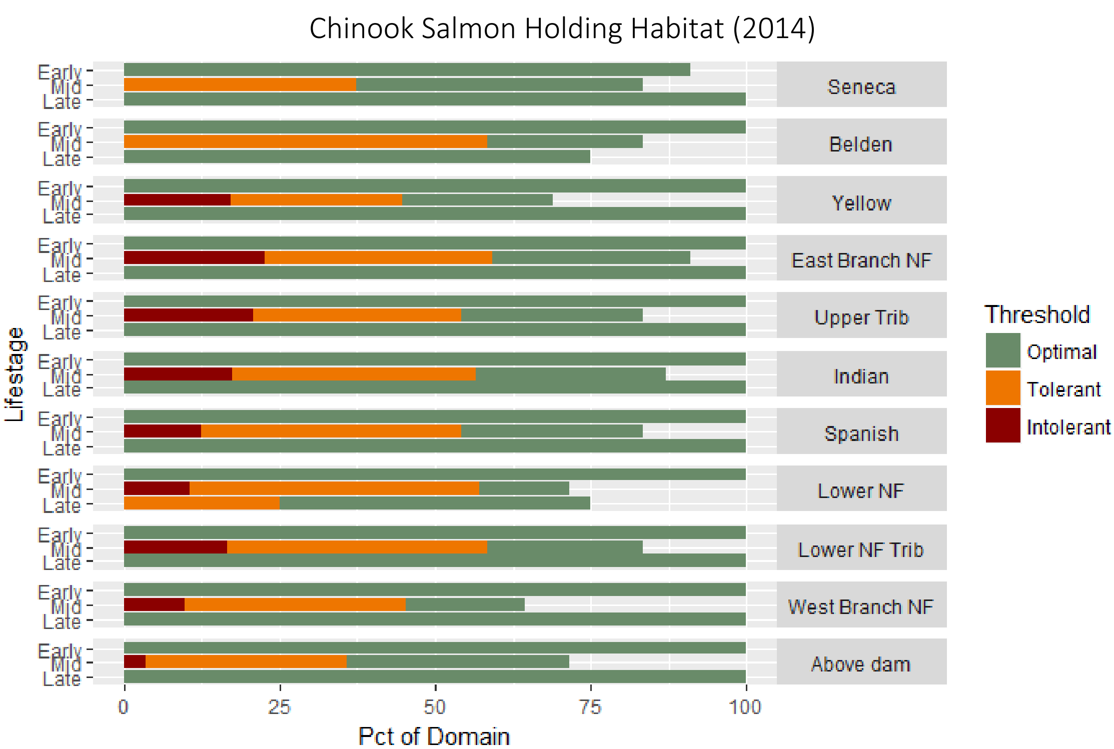

Figure S7. Holding habitat for Chinook salmon in 2015. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

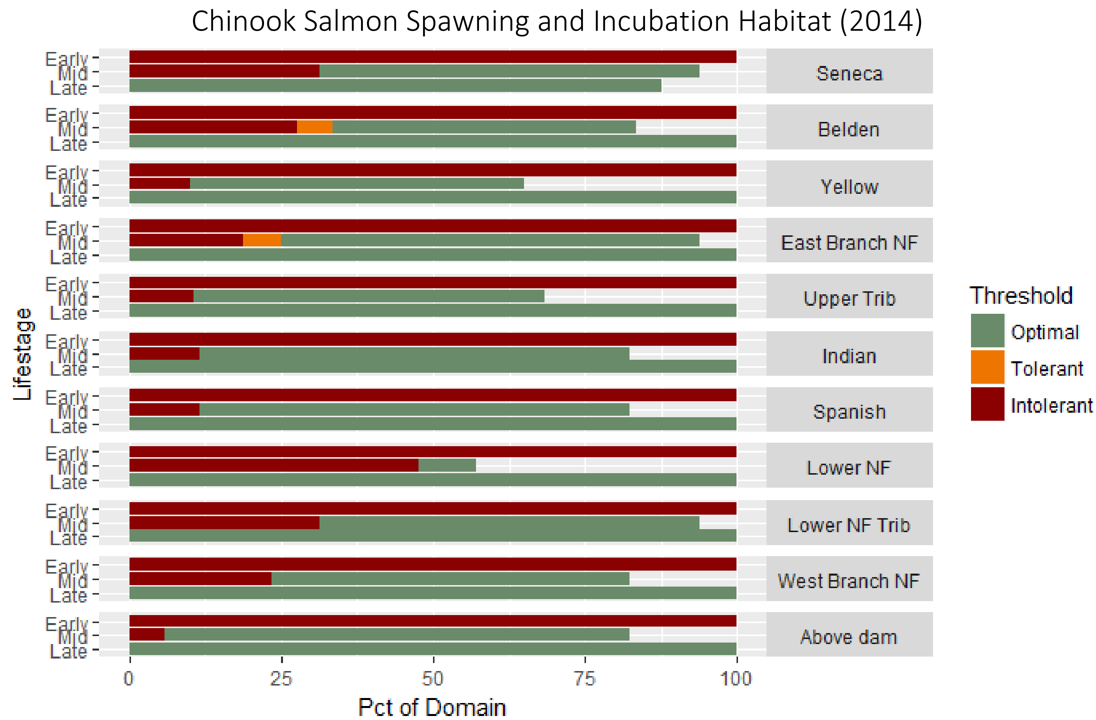

Figure S8. Spawning and incubation habitat for Chinook salmon in 2014. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

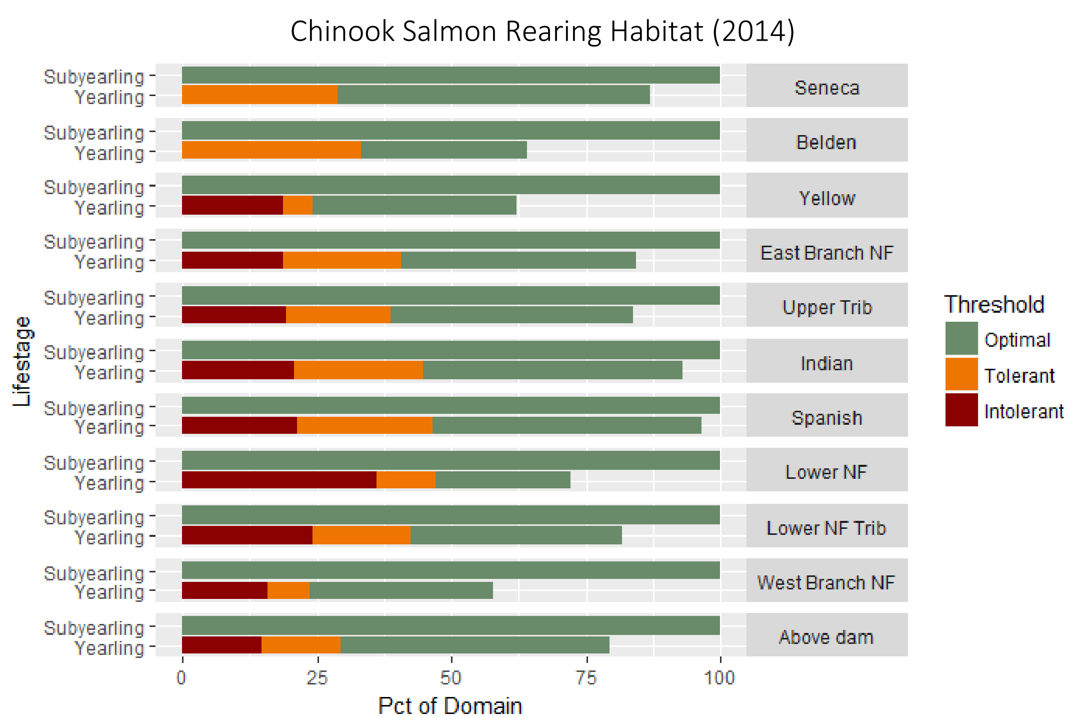

Figure S9. Rearing habitat for Chinook salmon in 2014. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

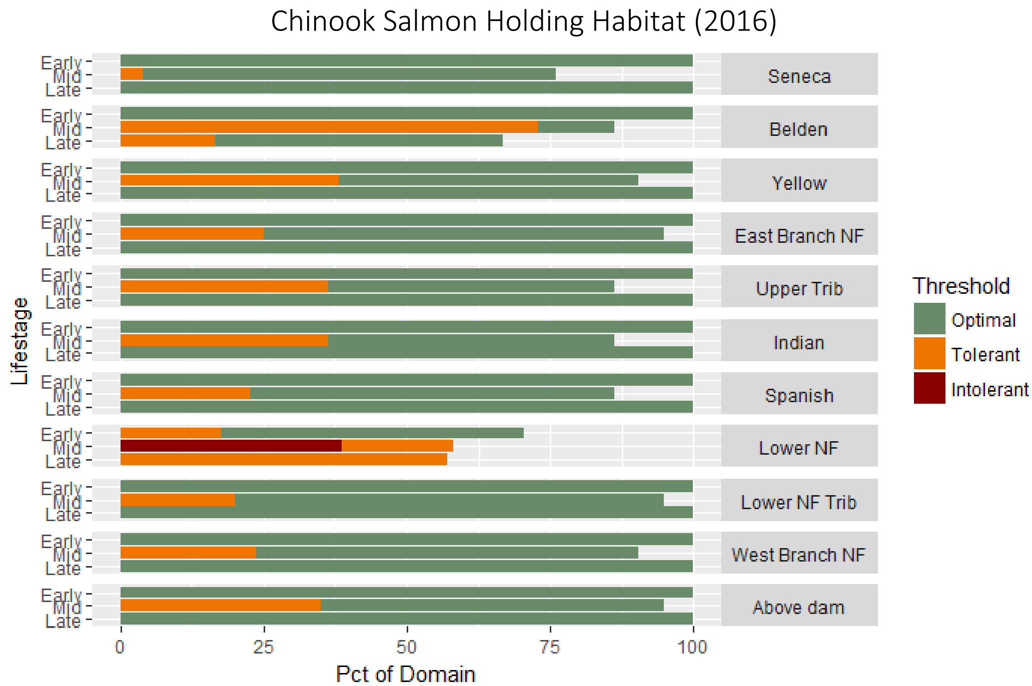

Figure S10. Holding habitat for Chinook salmon in 2016. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

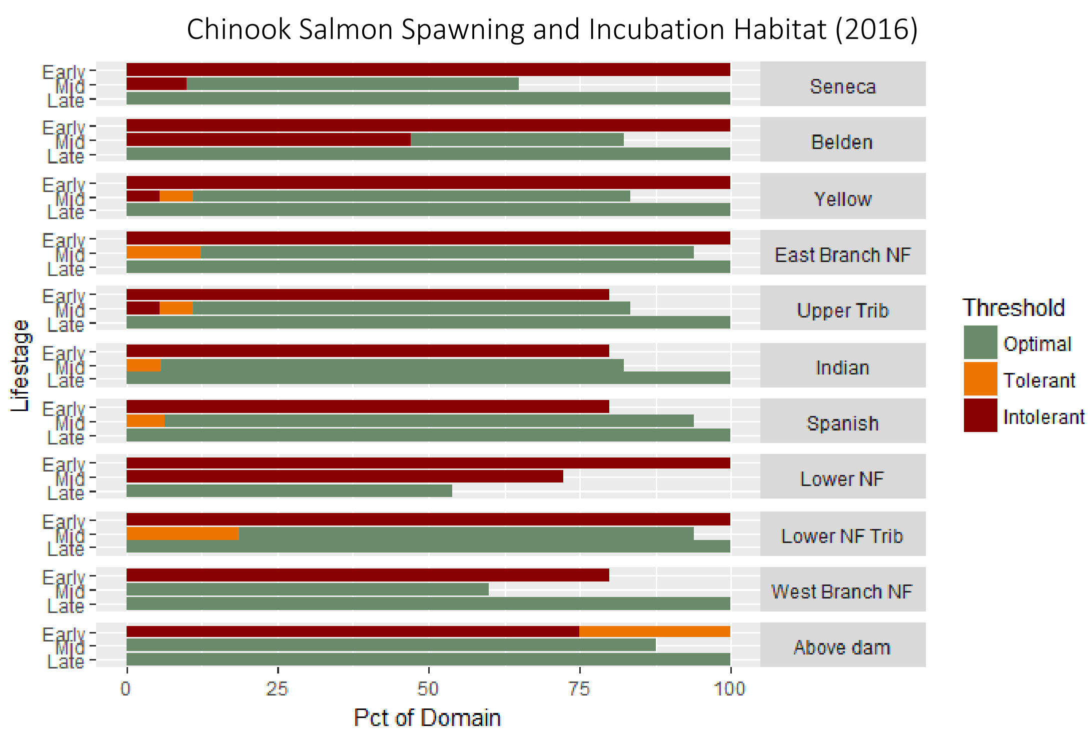

Figure S11. Spawning and incubation habitat for Chinook salmon in 2016. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

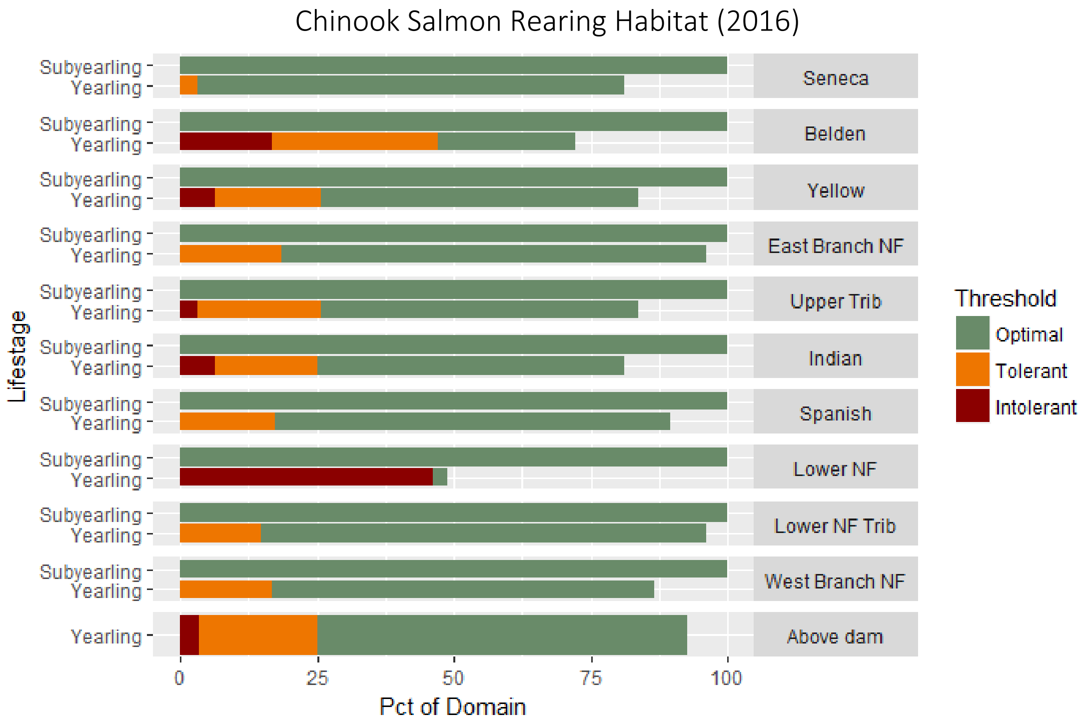

Figure S12. Rearing habitat for Chinook salmon in 2016. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

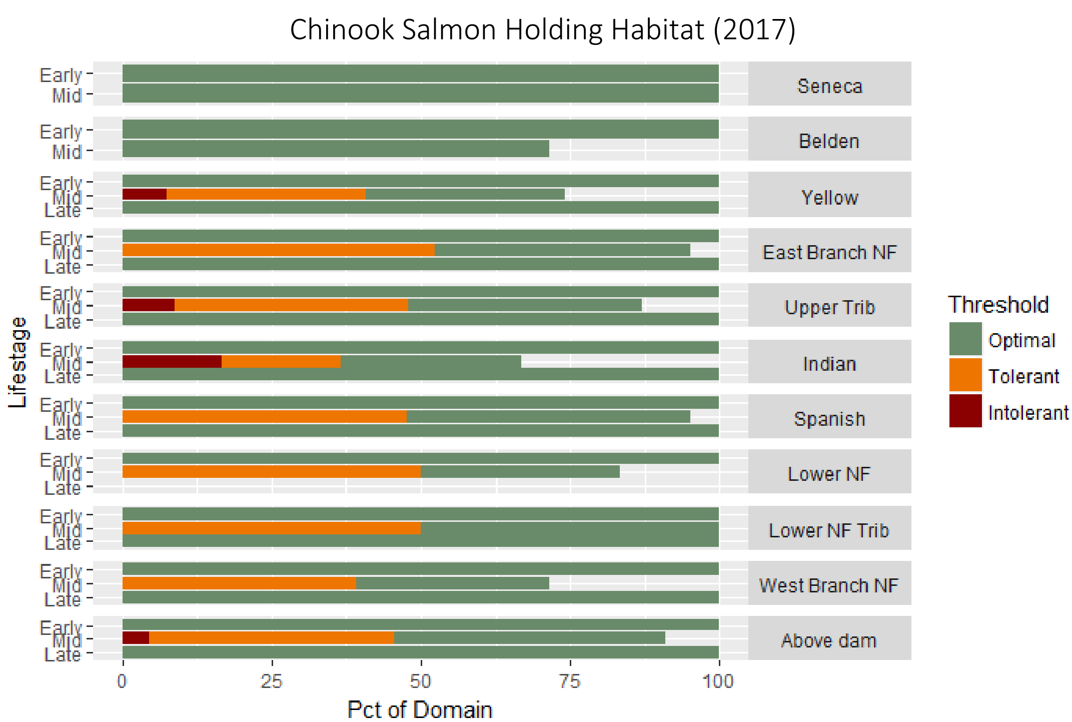

Figure S13. Holding habitat for Chinook salmon in 2017. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

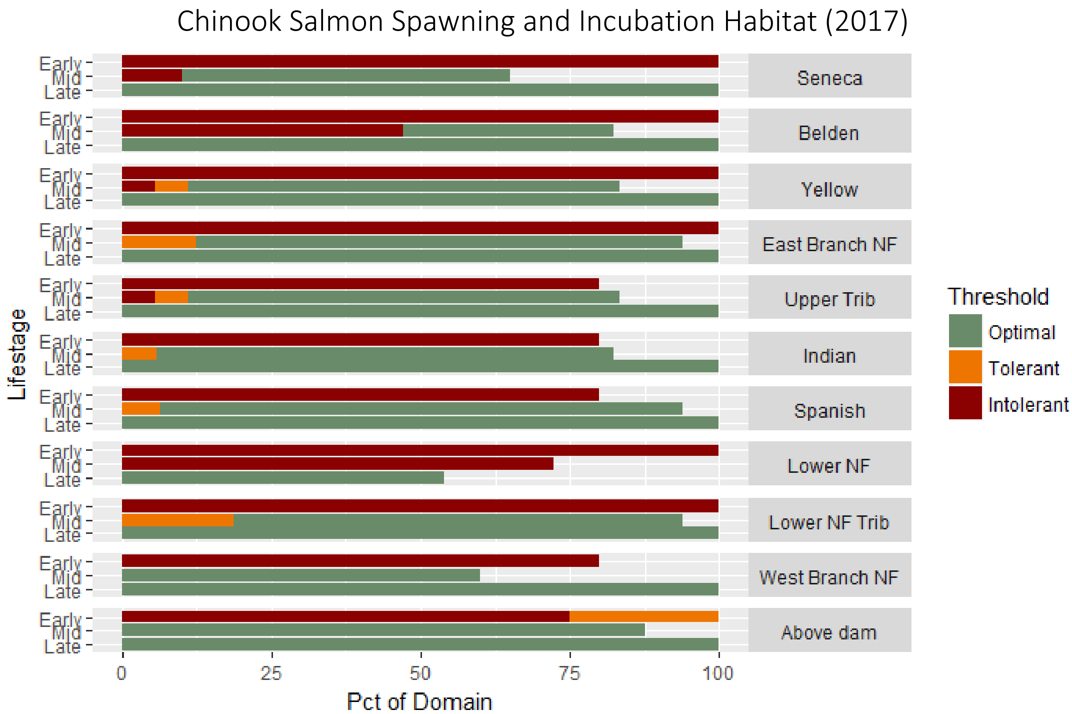

Figure S14. Spawning and incubation habitat for Chinook salmon in 2017. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

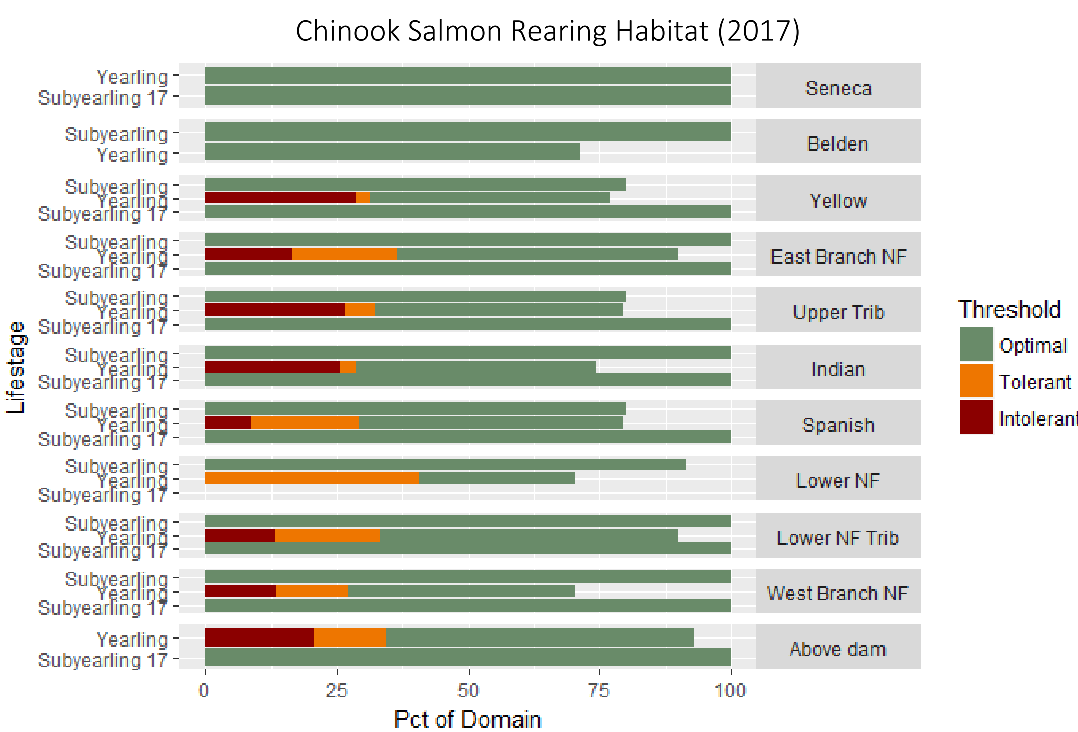

Figure S15. Rearing habitat for Chinook salmon in 2017. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

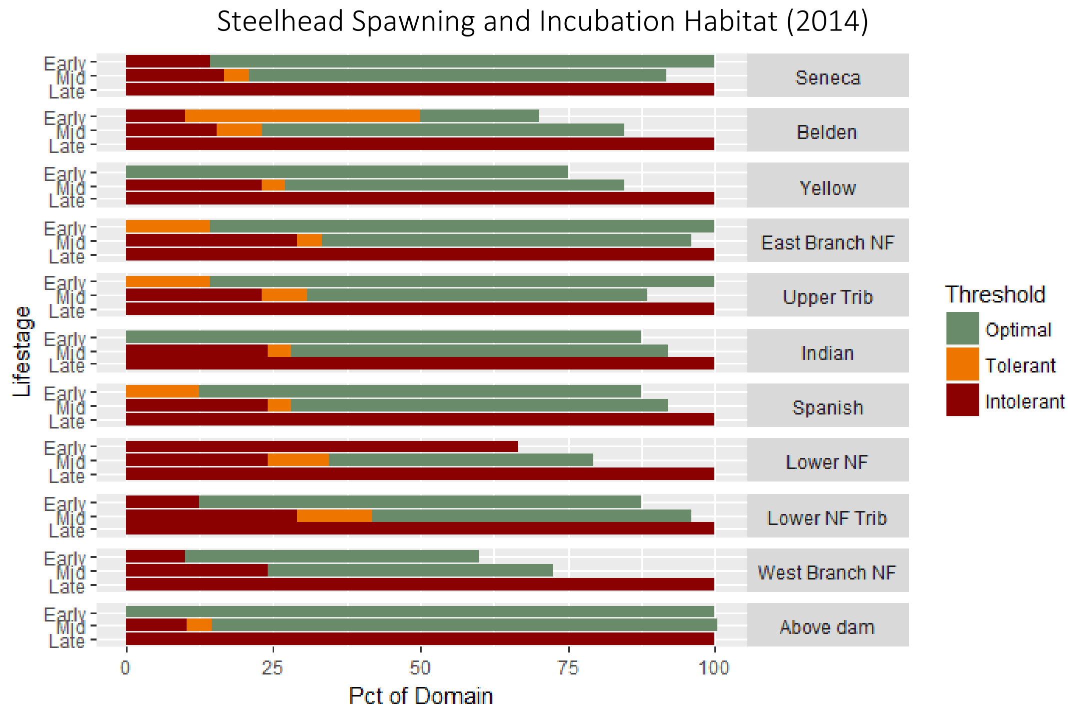

Figure S16. Spawning and incubation habitat for steelhead in 2014. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

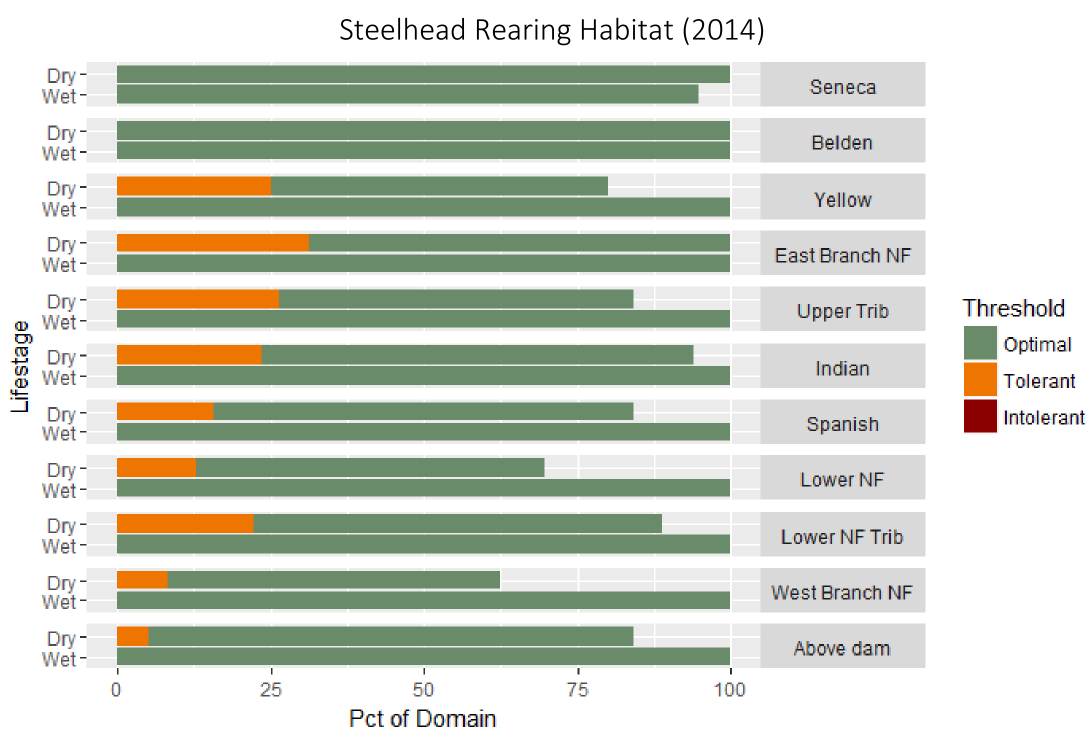

Figure S17. Rearing habitat for steelhead in 2014. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

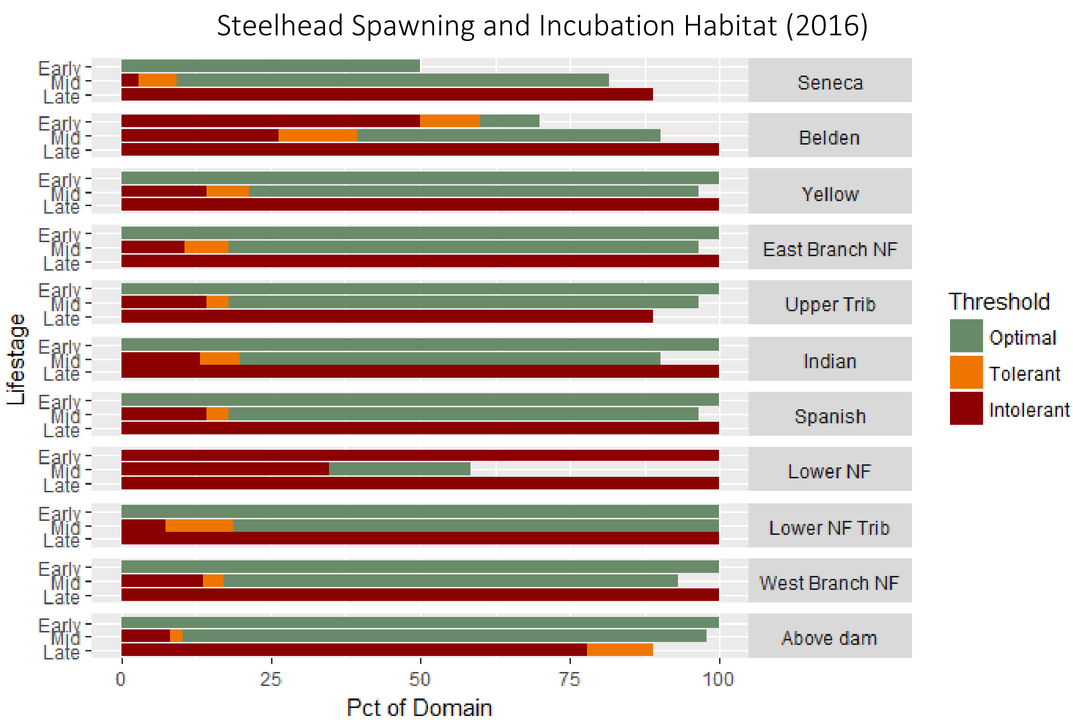

Figure S18. Spawning and incubation habitat for steelhead in 2016. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

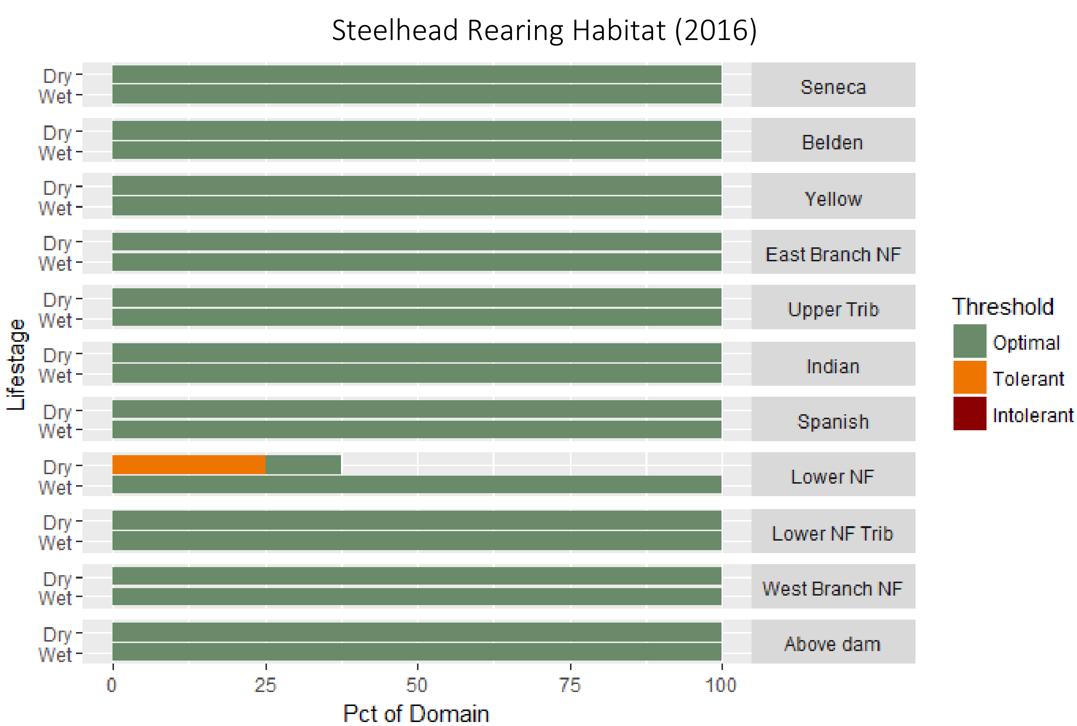

Figure S19. Rearing habitat for steelhead in 2016. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

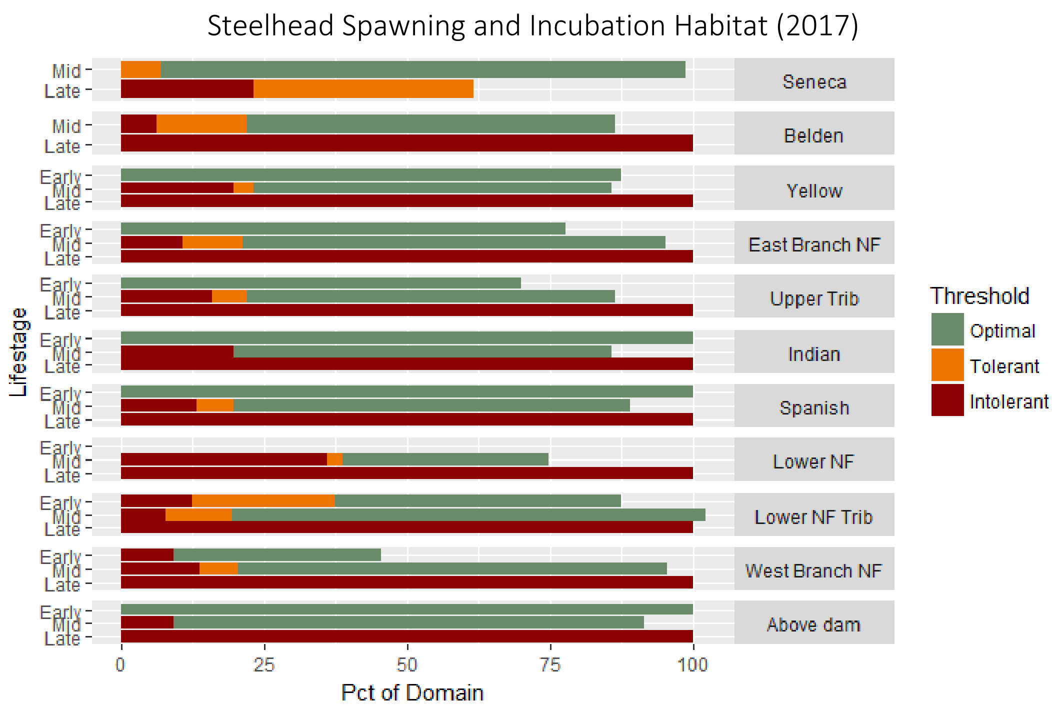

Figure S20. Spawning and incubation habitat for steelhead in 2017. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

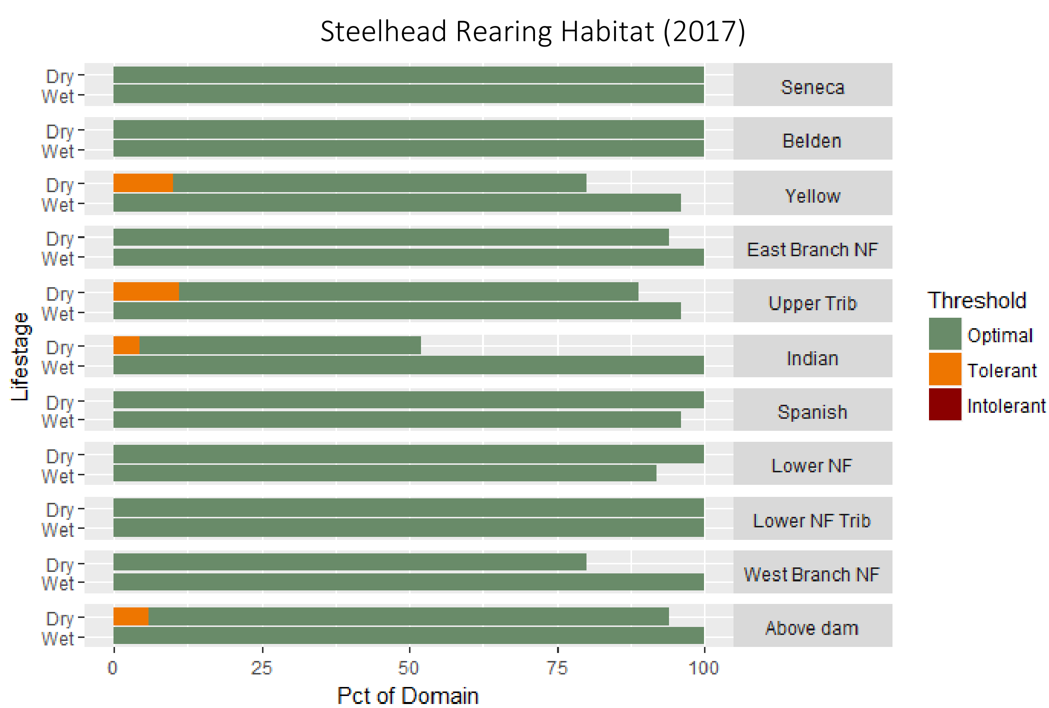

Figure S21. Rearing habitat for steelhead in 2017. Thermal habitat is expressed as percent of season that a given thermal condition predominated (at least half of stream kilometers met thermal criteria). Spatial domains as in Figure 1d.

Physical Habitat

Continuous PG & E survey data (Thomas R. Payne Associates 2002) for the Belden and Seneca reaches was translated to the 1:24k hydrography using the length measurements of each unit and a confirmed downstream start point of the survey (Belden bridge). A unique reach was then delineated upstream using linear referencing tools (ArcGIS) such that each surveyed habitat unit was represented. Survey notes regarding start and stop locations or key features, such as forebays and confluences were used to validate translation accuracy of field surveys to geospatial referenced locations. The Seneca habitat survey was shifted upstream during translation to adjust for differences in 1:24k hydrography and field survey space.

Montgomery-Buffington channel type summaries are included for all spatial domains (Table S10).

Table S10. Montgomery-Buffington channel types within the NF Feather River watershed.

Domain	**Pool-Riffle (<1.5%)**		**Plane-Bed (1.5-3%)**		**Step-Pool (3-7.5%)**		**Cascade (>7.5%)**		**Total km**
	km	**%**	**km**	**%**	**km**	**%**	**km**	**%**	
Belden	7.3	47.7	6.5	42.2	1.5	10.1	0.0	0.0	15.3
Seneca	2.1	11.3	13.6	71.3	3.3	17.5	0.0	0.0	19.1
Yellow Creek	13.7	21.0	11.5	17.7	39.9	61.3	0.0	0.0	65.1
East Branch NF Feather River	29.3	100.0	0.0	0.0	0.0	0.0	0.0	0.0	29.3
Upper Tributaries	2.1	4.6	2.1	4.5	35.6	76.5	6.8	14.5	46.5
Lower NF Feather River	60.8	89.6	5.8	8.6	1.3	1.8	0.0	0.0	67.8
Lower NF Tributaries	7.1	13.3	7.8	14.7	35.6	66.6	2.9	5.4	53.4
Indian Creek	264.3	51.1	87.0	16.8	162.1	31.3	4.0	0.8	517.3
Spanish Creek	61.0	35.3	28.9	16.7	73.2	42.4	9.4	5.5	172.6
West Branch NF Feather River	26.5	19.3	42.0	30.6	64.5	47.1	4.1	3.0	137.1
Tribs Above Almanor	139.4	45.0	86.4	27.9	79.6	25.7	4.6	1.5	310.0
Above Dam	51.2	36.2	52.1	36.9	37.9	26.8	0.0	0.0	141.2

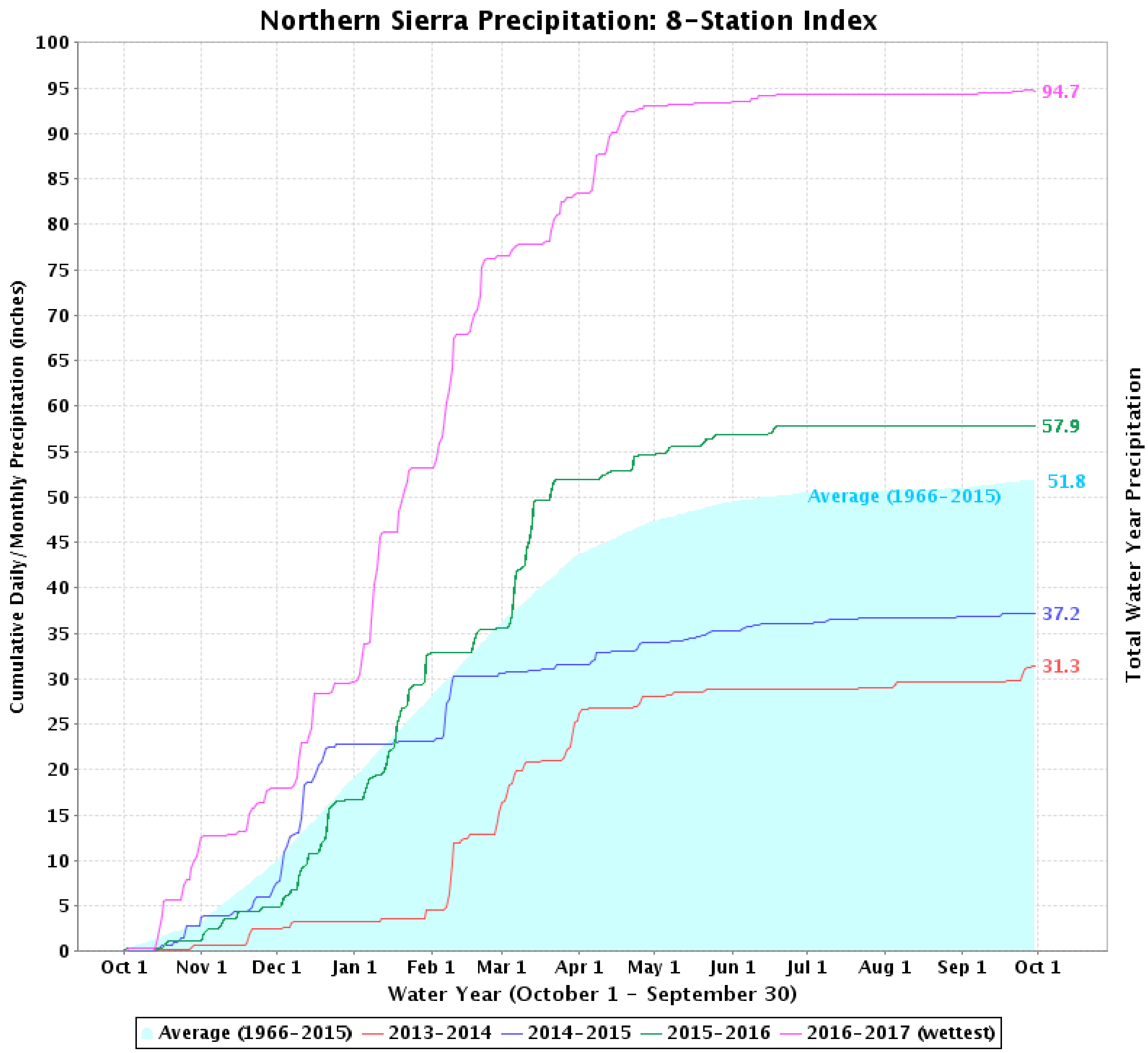

Figure S22. Precipitation in the northern Sierra Nevada during the four years of the analysis (Northern Sierra Precipitation 8-Station Index, from https://cdec.water.ca.gov/precipapp/get8SIPrecipIndex.action).