APPENDIX B. MODELING THE POTENTIAL EFFECTS OF CHANGED WATER AVAILABILITY AND WATER TEMPERATURE ON PACIFIC SALMON CULTURE PROGRAMS AT WARM SPRINGS NATIONAL FISH HATCHERY

Kyle C. Hanson[1] and Douglas P. Peterson[2]

[1]US Fish and Wildlife Service, Columbia River Fish and Wildlife Conservation Office,
1211 SE Cardinal Court, Suite 100, Vancouver, WA 98683

[2]US Fish and Wildlife Service, Abernathy Fish Technology Center,
1440 Abernathy Creek Road, Longview, WA 98632

Original draft: March 2, 2018
Previous revision date: October 23, 2019
Current revision date: June 1, 2021

[1] Email: Kyle_Hanson@fws.gov
[2] Email: Doug_Peterson@fws.gov

ABSTRACT

Future climate conditions may inhibit the ability of salmon hatcheries in the Pacific Northwest to operate under existing paradigms where those programs adhere to long-established rearing schedules and fish production targets. Here, we evaluate the vulnerability of the current Spring Chinook Salmon (*Oncorhynchus tshawytscha*) program at Warm Springs National Fish Hatchery (NFH) to future climates expected by the 2040s under a suite of 10 general circulation models (GCMs) and a 'middle-of-the-road' (A1B) greenhouse gas emissions scenario (IPCC 2007). We summarize projected environmental conditions in the Warm Springs River basin in Oregon – the location and water source for the hatchery – and then use those data to implement a temperature-driven growth model for hatchery-reared Spring Chinook Salmon that allowed us to evaluate monthly changes in mean fish size, water flow index (FI), and fish density index (DI) in the hatchery. By the 2040s, surface water sources for Warm Springs NFH are expected to be warmer in all months with Chinook Salmon in the facility experiencing temperatures 1.0 – 1.7 °C greater than the historical average. During the summer months, all life-history stages of fish will be exposed to temperatures that exceed physiological thresholds. Juvenile Chinook Salmon reared in the facility are projected, on average, to be approximately 36.6% heavier and 10.8% longer at release because of faster growth rates. Concurrent with increased temperatures, the annual hydrograph in Warm Springs River will differ from present with mean river flows projected to be substantially higher in winter and spring with a higher risk for more extreme winter floods. Conversely, surface water flows in summer are projected to be lower than the historic average with an increased risk of drought in the watershed. Higher water temperatures in the 2040 are projected to increase future FI and DI values, though after ponding neither are expected to exceed fish health guidelines (FI < 1.0; DI < 0.2). Under these future conditions, physiological stress, disease risks, and mortality of Chinook Salmon reared at Warm Springs NFH will likely increase if current culture practices and infrastructure remain unchanged.

INTRODUCTION

Pacific salmon (*Oncorhynchus* spp.) have a complicated life cycle and may be sensitive to the effects of climate change through a number of pathways. Changes in air temperature and precipitation patterns may cause freshwater rearing habitat to become unsuitable because of altered thermal and hydrologic regimes (Mantua et al. 2010). Increased fire frequency and duration in the western U.S. (e.g., Westerling et al. 2006) may alter disturbance regimes and influence the structure and function of some aquatic systems (e.g., Bisson et al. 2003; Isaak et al. 2010). Temperature increases in mainstem rivers can create seasonal thermal migration barriers that block adults from reaching spawning habitats (Mantua et al 2010). The establishment of new invasive species, spread of existing ones that compete with Pacific salmon, and their impact will depend, to some extent, on how freshwater habitats are affected by climate change (Petersen and Kitchell 2001; Rahel and Olden 2008; Carey et al. 2011). Changes in ocean temperature, upwelling (e.g., Scheuerell and Williams 2005) and acidification (e.g., Fabry et al. 2008) could dramatically alter the food webs in the marine ecosystems on which salmon depend during the ocean phases of their life cycle.

The viability of wild (naturally spawning) and propagated (hatchery-reared) populations of Pacific salmon could be affected by some or all of the aforementioned factors. A comprehensive analysis of all of those effects is highly desirable but is beyond the scope of the effort presented here. Rather, our intent is to focus in significant detail on one portion of the life cycle of hatchery-propagated salmon – that portion which takes place in the hatchery – and understand specifically how growth rates, mean size, and total biomass of the fish during that freshwater phase are affected by changes in water availability and temperature anticipated under future climates. This emphasis is based on two premises. First, the freshwater rearing phase of the salmon's life cycle could represent a population bottleneck if climatic changes result in conditions that meet or exceed a species' physiological tolerances. This premise should be valid whether the rearing phase occurs in a hatchery or in a natural setting. Second, hatchery managers have some ability to influence rearing conditions within a hatchery in response to environmental perturbations. The hatchery represents an environment, albeit artificial, over which the U.S. Fish and Wildlife Service (USFWS) Fish and Aquatic Conservation program has the scope to directly design and implement climate mitigation and adaptation strategies.

Given these premises, our overall goal is to understand whether hatchery programs can operate in a 'business as usual' paradigm following existing fish-culture schedules and production targets under future climatic conditions, focusing specifically on changes in water temperature and water availability at the hatchery. Specific objectives are to: (a) determine if future environmental conditions are likely to altogether preclude propagation of certain species or populations, (b) identify the magnitude and timing of sub-lethal effects that may affect freshwater growth and survival, including the incidence of disease, and (c) suggest general mitigation and adaptation strategies given the sensitivities detected in (a) and (b). To achieve these objectives, we collated physiological tolerance data for Pacific salmon species, adapted a temperature-driven growth model to predict fish growth, and developed a modeling framework using flow index and density index parameters (Piper et al. 1982; Wedemeyer 2001) which integrate the effects of changing water temperatures and availability with fish growth, physiological stress, and disease risks.

Here, we apply our methodology to the Spring Chinook Salmon (*O. tshawytscha*) program at Warm Springs NFH, which is located in north-central Oregon (Figure B1). We briefly summarize the important hydrologic changes anticipated for the Warm Springs River basin upstream from the hatchery, the primary water source for the hatchery. We then use empirical data on recent fish rearing conditions within the hatchery to assess the future growth, mean size and total biomass of Spring Chinook Salmon by (a) implementing the growth model and (b) modeling flow and density indices based on in-hatchery environmental conditions projected for the 2040s under a moderate, future greenhouse gas emission scenario (A1B scenario; IPCC 2007).

METHODS

Salmon thermal tolerances

In August 2011, we reviewed the peer-reviewed scientific literature of thermal tolerances of five focal species of Pacific salmon and trout (Chinook, Coho [*O. kisutch*], Chum [*O. keta*], and Sockeye [*O. nerka*] Salmon, and Steelhead [*O. mykiss*]) reared at National Fish Hatcheries (NFH's) in the Pacific Northwest to determine the thermal tolerances for multiple life-history stages. This information was acquired through two general approaches. First, to identify relevant primary literature ISI's Web of Science (1945 – 2011) was searched for variations on the following key terms: *thermal tolerance*, *critical thermal maximum* (CTM), *incipient lethal temperature* (ILT), *temperature maximum* (TM), and *ultimate lethal incipient temperature* (UILT). Second, bibliographies from several reviews of thermal tolerance in fishes (Beitinger et al. 2000; Becker and Genoway 1979; Paladino et al. 1980; Beitinger and McCauley 1990; Lutterschmidt and Hutchinson 1997) were surveyed to locate additional information on each focal species. Results were then screened for relevance before inclusion in the literature review, and studies that did not specifically contain information on the thermal tolerance of the focal species were excluded from further synthesis. We attempted to extract the following thermal tolerance data (Elliott 1981) from results, tables and figures:

1. *Optimal temperatures*: the temperature range that allows for normal physiological response and behavior without thermal stress symptoms;
2. *Optimal growth temperatures*: the temperature range that provides the highest growth rates given a full food ration;
3. *Optimal spawning temperatures*: the temperature range that results in lowest pre-spawn mortality and the highest fertilization rates and egg/embryo survival;

4. *Upper smoltification temperature limit*: the minimum, upper temperature at which the smoltification process is inhibited;
5. *CTM, ILT, or UILT*: the maximum temperature that induces 50% mortality in the fish previously acclimated to a given constant temperature.

Meta-data available varied among publications, but, to the extent possible, the following variables were recorded for each datum: species, life-history stage, fish length (mean ± SD or range in mm), fish weight (mean ± SD or range in g). The following supplemental meta-data from published values of CTM, ILT, or UILT tests was also recorded, when provided, to facilitate proper interpretation of results: acclimation temperature (°C), maximum temperature from CTM, ILT, or UILT tests (°C), and test endpoint criterion. Thermal tolerance data for each species analyzed were categorized by the following three life-history stages[3]: (1) *egg/fry* (eggs, sac fry, and fish less than 70 mm in length that are maintained in small, early rearing containers); (2) *juvenile* (sexually immature fish that are maintained in large rearing containers [e.g., raceways] prior to release), and (3) *adult broodstock* (sexually mature fish that have returned to a facility during the spawning migration and represent the pool of potential parents for the offspring generation). Data were averaged for each of the three life-history stages to determine representative thermal tolerances for each life-history stage of Spring Chinook Salmon at Warm Springs NFH (Table B1).

Disease thermal tolerances

In August 2011, we reviewed the peer-reviewed scientific literature on thermal tolerances of common pathogens that infect salmon at aquaculture facilities in the Pacific Northwest to determine the range of temperatures at which each species of pathogen is known to cause disease in salmon. The literature review followed the same protocols as described above, but with the common name or Latin binomial name of each pathogen added to the following search terms: *thermal tolerance*, *outbreak temperature*, and *transmission temperature*. Results were then screened for relevance before inclusion in the literature review, and studies that did not specifically contain information on the thermal tolerance of the focal species were excluded from further synthesis. Four citations (McCullough et al. 2001; Piper et al. 1982; Post 1987; Wedemeyer and McLeary 1981) provided detailed information on the following two variables (Table B2):

1. *Disease outbreak temperatures*: The pathogen-specific temperature range at which disease and mortality are most likely in Pacific salmon and Steelhead; and
2. *Minimum disease temperatures*: The lowest temperature (or range) at which the pathogen-specific disease occurs in Pacific salmon and Steelhead.

---

[3]These three life-history stages are the principle ones addressed by salmon hatcheries in the Pacific Northwest.

The Columbia River Information System (CRiS) database[4] was queried for rearing parameters from Warm Springs NFH for production lots[5] of salmon raised between 1992 and 2012.

Historical and modeled surface water temperatures in the Warm Springs River adjacent to Warm Springs National Fish Hatchery

The primary water source for Warm Springs NFH is water diverted from the Warm Springs River (see Figures B1 and B2; Appendix C), and we assumed that surface water temperatures at that diversion location were representative of the thermal conditions experienced by salmon reared within the hatchery. We obtained historical surface water temperatures by conducting data calls with staff from Warm Springs NFH and the USFWS Water Resource Branch. The Water Resources Branch has maintained a temperature logger at the intake diversion from the Warm Springs River to the hatchery and provided continuous river water temperature data from 2012 – 2017.

We established a regression relationship between air temperature and water temperature (at the diversion location) using the method of Mohseni et al. (1998) following the approach of Mantua et al. (2010). This relationship was used to simulate both historical and future water temperatures. The non-linear regression model of Mohseni et al. (1998) is intended for use with weekly time-series data and takes the form (equation 1a),

$$T_{sw} = \mu + \frac{\alpha + \mu}{1 + e^{\gamma(\beta - T_{air})}}$$

where T_{sw} = surface water temperature, μ = estimated minimum stream temperature, α = estimated maximum stream temperature, γ = a measure of the steepest slope of the function, β = the air temperature at the inflection point of the function, and T_{air} = measured air temperature. Mean weekly air temperature for the Warm Springs River watershed (upstream from Warm Springs NFH) was estimated from historic air temperatures downscaled from global climate models (flux files from: http://warm.atmos.washington.edu/2860) by aggregating the daily mean air temperatures within the area of overlap between the 1/16° grid cells (scale of the downscaled historic climate data) and the Warm Springs River watershed boundary upstream from the Warm Springs NFH, as delineated by a Geographic Information System (GIS; see Figure B3). Consequently, we refer to the historic air temperatures as *area-weighted values*.

The modeled historical air temperature data covers 1915 – 2006, but we only had a continuous, reliable water temperature data record at the diversion that spanned the 6-year period 2012 – 2017. We explored two approaches to fitting the model given the data in hand: (a) mean weekly

---

[4] Maintained by the USFWS Columbia River Fish and Wildlife Conservation Office (FWCO), Vancouver, Washington.

[5] A production lot is a cohort of families – represented by fertilized eggs, fry and juveniles – whose parents were all spawned on the same day.

historical air temperature over 1915 – 2006 and mean weekly Warm Springs River water temperature over 2012 – 2017 (model fit 'a'), and (b) mean weekly historical air temperatures for the most recent 6-year period 2001 – 2006 and mean weekly Warm Springs River water temperature over 2012 – 2017 (model fit 'b'). We fit the models with the non-linear regression package 'nls' in R version 3.2.3 (R Core Team 2015), and assumed a stable mathematical relationship (i.e., with fixed-value parameters) between weekly average air and surface water temperatures.

After inspecting parameter estimates and calculating model fits (Nash-Sutcliff coefficient, Nash and Sutcliffe 1970), we selected model fit 'a'. Model fits 'a' and 'b' had similar Nash-Sutcliff values (0.974 and 0.957, respectively). Model fit 'a' yielded slightly higher predictions for historical water temperatures than model fit 'b', and fit 'a' predictions were closer to the recent empirical observations. Model fit 'a' thus yielded the following equation to predict water temperatures (T_{sw}) at the hatchery diversion point in the Warm Springs River as a function of mean air temperature over the watershed upstream of the hatchery (equation 1b):

$$T_{sw} = 0 + \frac{20.19+0}{1+e^{0.2(7.03-T_{air})}}$$

Predicted weekly historic surface water temperatures at the diversion point were generated from the preceding equation by entering the downscaled historic air temperatures (1915 – 2006), whereas the weekly surface water predictions for the 2040s were generated by entering the statistically downscaled[6] air temperature predictions from an ensemble of 10 general circulation models (aka global climate models; GCMs) – ccsm3, cgcm3.1_t47, cnrm_cm3, echam5, echo g, hadcm, hadgem1, ipsl_cm4, miroc_3.2, and pcm1 – forced by the A1B emissions scenario (Hamlet et al. 2010a, b). The A1B scenario is often referred as "middle-of-the-road" in terms of emissions levels and projected warming, and has been utilized as a reference in a number of studies (e.g., Mantua et al. 2010; Wenger et al. 2011). The A1B scenario assumes that some global efforts are undertaken in the 21st Century to reduce the rate of increase in greenhouse gas emissions compared to the 1980 – 1999 baseline established in the 4th IPCC Assessment Report (IPCC 2007).[7] Weekly simulated historic and 2040s surface water temperatures were then aggregated by month.

---

[6] Data were downscaled using the hybrid delta method (see Hamlet et al. 2010b).

[7] The A1B scenario and other global model outputs of the 4th IPCC (IPCC 2007) have recently been supplanted by a new set of scenarios and modeled outputs from the 5th IPCC (IPCC 2014). The A1B is referred to as a SRES scenario described in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (IPCC 2000), and is one among a family of scenarios used in fourth global climate assessment (AR4) that describe greenhouse gas emissions under alternative developmental pathways with different expectations for demographic, economic, and technological factors that assume no additional climate policies (IPCC 2007). The most recent IPCC global climate assessment (AR5) uses a different methodology to describe global climate forcing, called Representative Concentration Pathways or RCPs (IPCC 2014). The RCPs represent trajectories for emissions and other atmospheric elements that affect the radiative forcing of the earth's climate through time, and that assume possible mitigation actions (van Vuuren et al. 2011). The AR5 assessment uses four representative RCPs: RCP2.6, RCP4.5, RCP6, and RCP8.5, in rank order of their radiative forcing and emission levels (van Vuuren et al. 2011;

Growth Model Simulation

We used the fish growth model of Iwama and Tautz (1981) to estimate how the growth of hatchery-reared Spring Chinook Salmon in Warm Springs NFH might change in response to future climate. This model has been widely applied to evaluate growth of captive salmonids (Dumas et al. 2007; Good et al. 2009; Jobling 2010), and we used it here to estimate mean fish size at age (month of year) as a function of water temperature assuming unlimited food ration. We solved the equation to estimate mean fish weight at time-step *i* (W_i) as (equation 2):

$$W_i = \left[W_0^b + \left(\frac{T_i}{10^3} \right) \bullet d_i \right]^{\frac{1}{b}}$$

where W_0 is initial weight (g), and T_i and d_i are the average temperature and number of days in time-step "*i*". Iwama and Tautz (1981) analyzed growth data for three species of salmonid fishes and proposed that $b = 0.33$ provided a reasonable approximation that balanced model accuracy and simplicity; consequently, we applied that exponent in our analyses. To estimate mean fish length (L_i) by time-step, we rearranged an equation for Fulton-type fish condition factor (Anderson and Gutreuter 1983) to solve for fish fork length (L_i in mm) as (equation 3):

$$L_i = \left(\frac{W_i}{K/10^5} \right)^{1/3}$$

where K is the condition factor which was held constant at $K = 1.0$ to represent fish in a healthy condition.

To characterize historical rearing conditions, we queried the Columbia River Information System (CRiS) database[8] for water use, number of fish reared, total fish weight, fish per unit weight, flow index (FI)[9], density index (DI), and mortality of for production lots of Spring Chinook Salmon reared at Warm Springs NFH during 1992 and 2012. In general, we relied on values averaged over the 2000 – 2004 and 2008 brood years for the historical baseline as data from these years were the most complete in the dataset (see Table B8).

IPCC 2014). The SRES A1B scenario falls roughly between the RCP6 and RCP8.5 (though closer to RCP6) in terms of CO_2 concentration, radiative forcing, and expected increases in mean global temperatures (van Vuuren and Carter 2014). We acknowledge the updated and improved assessments of AR5 (IPCC 2014) but have relied here on the outputs of the A1B scenario of AR4 (IPCC 2007) for our vulnerability assessment of Warm Springs NFH to maintain quantitative consistency with our previous and other ongoing vulnerability assessments of NFHs in the Pacific Northwest.

[8] Maintained by the USFWS Columbia River Fish and Wildlife Conservation Office (FWCO), Vancouver, Washington.

[9] Flow index (FI) and density index (DI) are defined and explained in more detail later in subsequent paragraphs of this report.

We applied the growth model to estimate mean monthly fish sizes of Spring Chinook Salmon for two months when fish are reared inside hatchery buildings and then from "ponding" (transfer) to outside raceways (in April) through release as smolts the following April. The initial weight at ponding was the input for the first month in the growth simulation, and subsequent months were initialized using the predicted final weight of the fish from the preceding month. The growth model was implemented with hatchery thermal environments consistent with recent historical conditions and those projected for the 2040s, and we compared cumulative differences in size between those thermal regimes.

Projected water availability at Warm Springs NFH during the 2040s

To generate estimates for water availability at Warm Springs NFH under the A1B emissions scenario, we used simulated streamflow data from the variable infiltration capacity (VIC) hydrologic model (Liang et al. 1994). In this instance, we used VIC data forced by output from the same 10 GCM ensemble used to derive water temperatures (e.g., Mantua et al. 2010). Streamflow data were summarized as mean monthly surface water discharge in the Warm Springs River routed to the location of Warm Springs NFH (A. Hamlet, Climate Impacts Group, University of Washington, unpublished data). Our baseline assumption was that the water available to the hatchery from all sources would change in direct proportion to the change in mean monthly flow estimated by the VIC model for the 2040s, with the exception that the facility could not utilize additional water (above the mean historical use) for months where an increase in mean flow is projected (Scenario A). Under this scenario, predicted flow of water into the hatchery during the 2040s was estimated by multiplying (a) the modeled change in mean monthly flow, calculated as the ratio of VIC modeled historical and 2040s flows, and (b) the average monthly water used by the hatchery during to rear the 2000 – 2004 and 2008 brood years. For example, if the Chinook Salmon program uses 15 cfs of water on average during a hypothetical month, and the hydrologic model predicted that the mean monthly discharge would decline by 40% in the 2040s, then the estimated water available to the hatchery from all sources would be 9 cfs (15 cfs × 0.60). If the hydrologic model predicted an increase in mean monthly discharge, then the hatchery would still use 15 cfs to rear the salmon. For Warm Springs NFH, we also considered two additional scenarios that would affect water use at the hatchery and fish culture parameters: (1) water use would decrease *and* increase proportionally to the predicted future river flows (Scenario B, cf. Scenario A where the hatchery would not use additional water when streamflow was predicted to increase), and (2) water use would not change in future years relative to current historical levels despite projected changes in surface water flow (Scenario C).[10]

[10] Our projections for future water flows of the Warm Springs River were never less than the quantities of water currently used at the hatchery.

Flow index and density index: critical fish-culture parameters

Hatcheries typically operate to achieve a production target (mean weight and total number of fish at release) while remaining below threshold flow and density index values established as fish health guidelines based on empirical observations of fish disease, mortality, or poor growth. These indices function as general rules of thumb based on oxygen saturation for different water temperatures and elevation (e.g., Piper et al. 1982) and act as surrogates for carrying capacity within the facility. Conceptually, these indices are the total fish biomass divided by the product of mean fish length and either (a) water use (flow index, equation 4) or (b) total rearing volume or capacity (density index, equation 5):

$$FI_i = \frac{N_i \bullet W_i}{L_i \bullet GPM_i}$$

$$DI_i = \frac{N_i \bullet W_i}{L_i \bullet C_i}$$

where FI_i and DI_i are flow and density indices, respectively, N_i is the total number of fish (abundance), W_i is mean fish weight (lb.), L_i is mean fish length (in), GPM_i is water use rate by the hatchery (gallons per min), and C_i is the rearing capacity (ft^3) at monthly time-step i. In this formulation, mean fish length (L_i) and weight (W_i) are forced by water temperature (T_i), which thus links temperature (and climate) changes to variation in FI_i and DI_i. Flow index also changes in response to water availability (GPM_i). Rearing capacity (C_i) does not necessarily change in response to climate, but operationally, it could be adjusted by managers to compensate for the effect of increased fish growth on DI_i.

Integrating the effect of water temperature and water availability on hatchery operations

We used flow index and density index as response variables to integrate and evaluate the combined effects of changing water temperatures, water availability, and physical rearing capacity at Warm Springs NFH (and more generally, as surrogates for carrying capacity under historical and future conditions). To do this, we used both recent historical conditions and climate model output for the 2040s to drive the salmon growth model and to simulate flow and density indices for Chinook Salmon at Warm Springs NFH in each monthly time-step after initial ponding. This produced monthly values for each index at each time-step (modeled historical and modeled future values). The modeled historical and empirical FI_i and DI_i values recorded in the hatchery could differ because of real-time changes implemented by hatchery managers, such as reducing feed rations or increasing hatchery water use in response to environmental conditions. We could not explicitly represent those variable factors in the analyses, so we adjusted the future simulated values based on the ratio between the empirical and modeled historical values (rFI_i and rDI_i) as (equations 6a and 6b):

$$rFI_i = \frac{FI_i \ mean\ empirical\ historical}{FI_i \ modeled\ historical}$$

$$rDI_i = \frac{DI_i \ mean\ empirical\ historical}{DI_i \ modeled\ historical}$$

Thus, the future bias-corrected index values were (equations 7a and 7b):

$$FI_i \ future\ corrected = rFI_i \bullet FI_i \ modeled\ \ future$$

$$DI_i \ future\ corrected = rDI_i \bullet DI_i \ modeled\ \ future$$

A complete description of the model formulation and underlying equations are presented in Hanson and Peterson (2014).[11]

RESULTS

Projected future climate in the Warm Springs River basin and at Warm Springs NFH under the A1B emissions scenario

Under the A1B emissions scenario, the Warm Springs River basin was projected to experience, by the 2040s, (a) warmer air and stream temperatures, (b) reduced snowpack and earlier snowmelt runoff, (c) lower base flows in summer, and (d) higher flows and larger floods in winter (Table B3; Figures B4 – B15). Mean air temperature over the entire watershed was expected to increase in every month (mean increase = 1.96 °C, SD = 0.63 °C) with the largest absolute increases predicted for July – September (range 2.7 – 3.1 °C; Table B3 and Figure B4). Total annual precipitation was projected to be within about 2% of the historical baseline (historical: 66 mm, 2040s: 67 mm), and small seasonal differences may be possible, but the monthly historical precipitation generally fell within the range of predictions from the 10 GCMs (Table B3; Figure B5). Maximum snow water equivalent (SWE, aka snow pack) was predicted to decline by nearly 62 %, from 65 mm to 25 mm and occur in February instead of March (Table B3; Figure B6). Overall, the mean monthly SWE for the entire year was predicted to decline by 65 % in the 2040s compared to the historic baseline values (mean historical monthly mean = 23 mm, 2040s monthly mean = 8 mm; Table B3; Figure B6).

Based on the VIC modeling, mean *annual* flows projected for the Warm Springs River in the 2040s were slightly higher than modeled historical values (historical = 520 cfs, 2040s ensemble

[11] Note: $rDI_i = rFI_i$ (= r_i) at each time step because (a) the value of N_iW_i/L_i is the same for calculating DI_i and FI_i at each time step for each scenario (i.e., N_iW_i/L_i differs between modeled historical and empirical scenarios but not between DI_i and FL_i for each scenario), and (b) the values for GPM_i and C_i, respectively, at each time step were the same in both scenarios (i.e., the modeled historical scenario used the same values of GPM_i and C_i, respectively, as those measured empirically).

mean = 553 cfs) and within the range of projections from each of the 10 GCMs (Table B4). The same pattern is apparent when the flow data are plotted by stream segment across the contributing basin (Figure B7). Although mean annual flows of the Warm Springs River in the 2040s will be comparable to historic averages, the shape of the modeled hydrograph for the 2040s differs considerably from the historic average (Figure B8). The projected hydrograph at the location of the hatchery shows lower flows May through July (Figure B8) which extend into August (Figure B9) with an average flow decrease of 25.8% (ensemble range -18.9% to -34.9%) compared to the historic average. In contrast, mean flows of the Warm Springs River in the 2040s at the hatchery in winter (December – February) were projected to increase by an average of 24.6% (ensemble range 5.3 – 63.9%) with a shift in the month of peak flow from March to January (Figures B8 and B9).

The date at which half the annual discharge passes a particular point was projected to be more than at least 11 days earlier in the 2040s for the main stem Warm Springs River basin (Figure B10). In general, summer low flow events (7Q10) were not predicted to be consistently more severe across the basin, although considerable variability existed among the 10 GCMs (Figures B11 and B12). In winter, the number of *W95* days – defined as the number of days in a calendar year when surface flows are in the top 5% of annual daily flows – were projected to increase by at least one day within the main stem Warm Springs River (Figure B13). The magnitude of high flows with recurrence intervals of 20, 50 and 100 years was expected to increase, on average by the 2040s, with largest floods (100 year recurrence interval) projected to increase from about 8,800 cfs to 10,300 cfs, on average (Figure B14)

Water temperature in Warm Springs River at the intake to Warm Springs NFH was projected to be warmer in every month in the 2040s compared to the historical period (Table B5; Figure B15). The mean annual water temperature was projected to increase by an average of 1.3 °C (range of monthly increase = 1.0 – 1.7 °C), and mean monthly temperatures in July and August were projected to exceed 18.4 °C.

Chinook Salmon program

Adult Chinook Salmon returning to Warm Springs NFH are typically captured for broodstock starting in April and retained in holding ponds prior to spawning through early September. These ponds are supplied with surface water from the Warm Springs River. By the 2040s, the water temperatures in holding ponds between May and September are projected to increase by 1.2 – 1.7 °C, and the highest mean monthly water temperature during the broodstock holding period is predicted to be 18.5 °C (Table B6; Figure B16). Projected water temperatures in the 2040s during June–September exceed the optimal spawning temperatures for Chinook Salmon (5.7 – 11.7 °C; Table B1), and it is highly likely that adult Chinook will experience physiological stress during holding and spawning due to temperature alone.

Juvenile Chinook Salmon reared in Warm Springs NFH will be exposed to warmer rearing conditions by the 2040s, with projected increases ranging between 1.0 °C and 1.7 °C across the rearing periods (September year 1 to March year 2; Table B6, Figure B17). Projected water temperatures for the 2040s at Warm Springs NFH exceed the optimal temperature upper threshold (Table B1) for eggs/fry in September and for juveniles June – September, with projected temperatures in July and August exceeding the optimal upper growth temperature of 18.4 °C for Chinook Salmon (Table B6; Figure B17). Water temperatures greater than 18.0 °C are well within the disease outbreak temperatures for Bacterial Kidney Disease and Ceratomyxsosis (Table B2). At the time of smolt release in April, water temperature within the hatchery (9.6 °C) is projected to remain well below the upper limit for proper smoltification (14.0 °C, Table B1).

Warmer water temperatures projected for the 2040s will increase the growth rates of juvenile Chinook Salmon throughout the rearing period (Table B7). Chinook Salmon smolts from Warm Springs NFH are predicted to be, on average, 36.6% heavier and 10.8% longer at release compared to historical sizes (Table B7) assuming no culture modifications or compensatory biological responses (e.g., precocious sexual maturation that reduces growth).

Assuming recent historical average rearing densities (Table B8, Part A), flow index values for Spring Chinook Salmon are expected to increase if the hatchery's water availability and use decline in proportion to projections for lower flow in summer (Scenario A, Table B8, Part B; Figure B18a). If the hatchery can utilize more water when river flows are projected to increase (Scenario B), then flow index values may be the same or slightly lower than the historical average during the winter before smolts are released (Table B8B, Figure B1a). Even if the hatchery's water use does not change relative to projected future river flows, flow index values would still increase in all months (Scenario C) because higher water temperatures would be forcing substantially greater growth rates of juvenile salmon. Under all three modeled scenarios, flow index values after ponding are projected to remain below the maximum threshold value of 1.0 recommended by the USFWS's fish health staff (USFWS 2013).

Density index values for Spring Chinook Salmon at Warm Springs NFH were also projected to increase by the 2040s but would not exceed – after ponding in outdoor raceways – the upper limit fish health guideline value of 0.2 (Table B8, Part B; Figure B18b).

DISCUSSION

Our analyses suggest that by the 2040s projected warming and hydrologic changes are likely to produce a different set of environmental conditions in the Warm Springs River basin. Most significantly, warmer air and water temperatures are projected for every month. Warming can have direct effects on fish growth, disease outbreaks, and perhaps even lead to mortality. Warming may indirectly, but significantly, influence hydrologic conditions in the basin. For example, *mean* annual flow in the Warm Springs River during the 2040s is predicted to be slightly higher than the historic baseline, but the *shape* of the annual hydrograph should be quite different presumably because of an increase in winter precipitation falling as rain instead of snow and less precipitation retained in higher-elevation snowpack.

Effects of stream warming and hydrologic alterations on salmon rearing

By the 2040s, Spring Chinook Salmon reared at Warm Springs NFH are projected to experience consistently higher water temperatures compared to the historical period 1915 – 2006. Water temperatures are projected to exceed the physiological thresholds for Chinook Salmon at multiple life history stages (Table B6). Taken together, the projections for the thermal environment within Warm Springs NFH suggest that all life stages of Spring Chinook Salmon may experience substantial physiological stress in summer when water temperatures exceed 16 °C. Increased thermal stress may compound the effects of other stressors related to common hatchery practices (e.g., cleaning raceways, crowding, fish marking and transfer), thereby increasing mortality.

Notwithstanding thermal stress inducing mortality, potential decreases in immune function due to high water temperatures would increase susceptibility to pathogens and disease risks. For example, juvenile Chinook Salmon at Warm Springs NFH have previously experienced outbreaks of bacterial diseases such as bacterial kidney disease (*Renibacterium salmoninarum*), and columnaris (*Flavobacterium columnaris*), as well as infestation by parasites such as Ich (*Ichthyophthirius multifiliis*), and ceratomyxosis (*Ceratonova shasta*). All of these diseases tend to be associated with higher than normal water temperatures, and some outbreaks have resulted in mortality of juvenile Chinook Salmon reared at the hatchery. Projected water temperatures during June – September in the 2040s are near the optimal temperatures for several pathogens common to salmonids in the Columbia River Basin (Table B2), suggesting that the frequency and types of disease outbreaks may increase.

Water temperatures at Warm Springs NFH have approached or exceeded historic temperatures in recent years, and hatchery staff have had to take emergency measures to reduce thermal stress to Chinook Salmon. In the summer of 2015 during the adult broodstock capture and holding period, mean daily water temperatures of the Warm Springs River exceeded 21 °C with daily fluctuations of 17 – 26 °C. Although Warm Springs NFH can chill water in the adult holding pond by ~11 °C below ambient, adult Chinook Salmon frequently experienced temperatures exceeding 13 °C. Because this latter temperature is a threshold at which fish infected with *C. shasta* have experienced increased pre-spawn mortality, adult broodstock were transferred to a separate facility (Little White Salmon NFH) that has cooler water for holding and spawning adult broodstock. Despite that transfer, post-spawn mortality of fertilized eggs in 2015 was approximately 53%, far exceeding the long-term average of 5 – 10% mortality (USFWS 2006; USFWS 2016). While increased egg mortality could not be definitively linked to thermal stress of the adults during gamete maturation (e.g., versus physical crowding and transfer of gravid females to another hatchery), it was a potential aggravating factor. While post-spawn mortality of eggs can occur due to transfers such as this, this situation was deemed less undesirable than total broodstock loss due to an anticipated disease outbreak at Warm Springs NFH. In addition, mean daily water temperatures for juvenile Chinook Salmon at Warm Springs NFH exceeded 21 °C for multiple days during the summer of 2015. Increased mortality of juveniles was noted, and all juvenile fish were moved to a different hatchery with colder water (N. Wiese, USFWS, personal communication). In the aftermath of these emergency fish transfers and in recognition that similar actions may be required in the future, a management plan was developed for Warm Springs NFH that dictated that juvenile salmon would be moved to another facility whenever daily mean water temperatures in raceways exceeded 19 °C for three consecutive days. This management plan was first implemented in 2016 when construction at Warm Springs NFH reduced the capacity to chill water. When weather forecasts predicted conditions that would lead to water temperatures exceeding 19 °C for multiple days in the summer of 2016, fish were again moved to another facility prior to the onset of any mortality (Michael Clark, USFWS, personal communication).

The negative consequences of future climate condition to juvenile Chinook Salmon at Warm Springs NFH appear to be largely driven by increased water temperatures rather than hydrologic alternations of water availability or decreases in summer flows. For example, fish health guidelines for upper flow and density index values were not exceeded in our modeled scenarios for the 2040s although the mean length and weight of Chinook Salmon smolts at release were predicted to be approximately 11% and 36% greater than the modeled historic values. Index values that integrate total fish biomass, mean fish length, and either (a) water flow (flow index) or (b) total rearing volume (density index) are proxies for the carrying capacity of a hatchery based on dissolved oxygen levels, removal of metabolic waste, and the ecological and physiological consequences of fish interactions or "crowding" (Wedemeyer 2001). The guideline threshold values for these indices in a hatchery are derived through a combination of fundamental abiotic considerations (e.g. oxygen saturation levels) and empirical experience with a particular stock or species relative to the infrastructure of a particular hatchery. Despite the significant increase predicted for individual fish length and weight after ponding, the modeled flow index values during the rest of the juvenile rearing cycle never exceeded the fish health guideline of 1.0. This was true across a range of water availability scenarios, including the worst-case scenario (Scenario A) where water available to the hatchery would decline in proportion to reduced surface flows in the Warm Springs River. Flow index values were comparatively high during February and March when fry were maintained in nursery tanks in the hatchery building before ponding, but those values never exceeded the guideline value of 1.0 after ponding. Similarly, the density index exceeded (in February) or approached (in March) the fish health guideline value of 0.2 only prior to outside ponding when fish were still in nursery tanks inside the hatchery building. Based on the two index values (and their thresholds), the ecological capacity of the Warm Springs NFH during most of the rearing cycle would be judged sufficient given the future flow and temperature conditions considered in this analysis. This interpretation runs counter to the fact that Chinook Salmon in the hatchery have experienced outbreaks of disease and parasite infestations leading to mortality and have even been moved to other hatcheries to avoid mass mortality from acute thermal stress.

Assumptions and uncertainties

Our modeled results for Spring Chinook Salmon at Warm Springs NFH coupled with recent empirical observations illustrate the biological complexities of fish health related to thermal stress, pathogen prevalence, rearing densities and water flows. Fish health specialists have established upper-limit density and flow index guidelines of 0.2 and 1.0, respectively, to reduce disease risks for endogenous pathogens when water temperatures are within the optimal temperature range for Chinook Salmon (Table B1). During crowded or low flow conditions when density and/or flow index values exceed fish health guidelines - even when water temperatures are within optimal ranges for the fish - disease outbreaks are more likely because of compromised immunity associated with physiological stress (due to crowding) and the greater likelihood of pathogen transfer between infected fish. Conversely, even when density and flow indexes are maintained within fish health guidelines, higher-than-desired water temperature for the fish (Table B1) can cause (a) thermal stress and reduced immunological competence and (b) more optimum growth conditions for endogenous pathogens (Table B2). Consequently, the current flow and index values should be considered as two of many possible metrics to assess future impacts. Empirical observations of fish behavior, disease, and mortality in response to perturbed environmental conditions (e.g., temperature spikes) should also help form the basis for evaluating future impacts to more prolonged, frequent, or intense environmental perturbations. In that context, the ability of Warm Springs NFH to maintain a Spring Chinook Salmon program year-round in the 2040s should be questioned.

We caution also that our predictions for flow index values in the 2040s may be conservative (i.e., an underestimate) with respect to water availability, especially during summer when availability is expected to decrease. We assumed that the hatchery would be able to utilize its existing surface water right from the Warm Springs River. If other existing surface water rights holders have priority over the water rights held by Warm Springs NFH and choose to execute a call on that right, then the water available for salmon culture may be significantly less than we assumed. Hydrologic modeling suggested that higher winter flows will occur in the Warm Springs River during the 2040s, and the magnitude of floods with a given recurrence interval would increase. We did not evaluate the potential for these conditions to damage the hatchery's infrastructure or otherwise disrupt the capture of broodstock or the rearing of Spring Chinook Salmon.

We emphasize that our analysis of climate vulnerability for the Chinook Salmon program at Warm Springs NFH focused on the quality (temperature) and quantity (availability) of surface water within the Warm Springs River basin. We did not evaluate any potential groundwater utilization or water reuse by the hatchery, as we are not aware of any such measures under the facility's current salmon production protocols. Additionally, we did not investigate how a changing climate might affect the ability of adult salmon or smolts to migrate upstream or downstream, respectively, in the migration corridor of the Columbia and Deschutes rivers, as that was beyond the geographic scope of our analysis. Consequently, we caution that our assumptions and the uncertainties associated with the modeling approach and available data limit our ability to make precise and accurate *predictions* about the future vulnerabilities of the Chinook Salmon program and hatchery to climate change. Despite these uncertainties, we believe the outputs of our analyses are consistent with recent observations at Warm Springs NFH and can be helpful for gauging relative threats and risks in the next 2 – 3 decades.

Mitigating the effects of climate change at Warm Springs NFH

Warm Springs NFH already has to contend with thermal stress to their stock of Spring Chinook Salmon as exhibited by fish mortality and disease outbreaks. By the 2040s, we project that mean daily stream temperatures in the Warm Springs River will rise by an average of 1.3 °C, which would be expected to exacerbate these fish culture issues. Additionally, the effect of higher water temperatures may be compounded by lower stream flows in summer. Although we cannot discount the impacts to salmon culture to reduced stream flows alone, we infer that elevated water temperatures will present the most significant challenge to rearing Spring Chinook Salmon at Warm Springs NFH during the next 2 – 3 decades. Without some mechanism to compensate for higher water temperatures in summer, we speculate that by the 2040s rearing 700,000+ Chinook Salmon may present a persistent challenge to hatchery managers. There are a few general approaches by which a facility like Warm Springs NFH might seek to develop a colder salmon holding and rearing environment to buffer against anticipated warming.

First, some hatcheries use a source of cold groundwater entirely or mixed with surface flows to reduce high temperatures of surface water sources. Currently, we are unable to evaluate whether this potential strategy is feasible as the Warm Springs NFH has no experience of using groundwater for rearing.

Second, electro-mechanical chilling of surface water is theoretically possible as a mitigation strategy, although cooling the large volume of water (up to 13,700 GPM) needed for the full production of ~700,000 Spring Chinook Salmon for multiple months by just a few degrees Celsius presumably would be energy intensive and expensive. Warm Springs NFH currently has the infrastructure to chill water entering the adult holding pond by ~11 °C from ambient. Although ~11 °C is admittedly a considerable change, the hatchery was still not able to keep water temperatures below the optimal spawning temperature for Spring Chinook Salmon during high temperature events in 2015. Thus, it is unknown whether this chilling capacity will be sufficient given the predictions for warming surface waters. We do not know whether the hatchery's current infrastructure could be used to chill water to the rearing units holding fry and juveniles, although mechanical chilling of egg incubation water is relatively easy and common. Chilled water could be used at key times in the rearing cycle – e.g., during the first spring and summer to slow fish growth and, thus reduce flow and density indexes (surrogates for habitat capacity, crowding, and stress) – at lower energy cost than chilling water in every month. However, we do not know whether decreasing growth early in the rearing cycle would be offset by increased compensatory growth later in the rearing cycle or whether chilling of water will be able to sufficiently lower juvenile rearing temperatures below critical physiological thresholds.

Growth modulation could also be achieved through reduced rations, although ration levels would need to be maintained at a level sufficient to ensure adequate physiological condition and health. Although hatchery capacity did not appear to be as significant a risk factor as elevated stream temperatures, reducing the number of fish reared could reduce the likelihood of fish transferring pathogens and the potential disease outbreak when water temperatures are elevated.

Fourth, mechanical chilling within a recirculating aquaculture system (RAS) could reduce the electrical costs of chilling larger volumes of water because up to 90% of outflow culture water can be filtered, aerated, and mixed with smaller volumes of ambient surface water. This small volume of surface water can be conditioned for temperature and pathogen load at a lower cost than the volume required in the current flow-through system. However, this process requires substantial capital expenditures for new rearing tanks, plumbing, and filtering – typically millions of dollars for a culture program the size of Warm Springs NFH – as well as annual expenditures for operation and maintenance.

Finally, the hatchery could continue to pursue the adaptive management strategy of transferring fish to other hatcheries when conditions at Warm Springs NFH were deemed too stressful or when the probability of mortality or disease outbreak was judged unacceptably high. However, the effect of moving fish in this manner on homing and adult returns (to Warm Springs NFH) is unknown, and we do not know whether this would be financial and logistically approach if was to be implemented in perpetuity.

Overall, the mitigation strategies described above are theoretically possible to help climate-related threats and impacts on the salmon culture program at Warm Springs NFH. However, each has obvious drawbacks and trade-offs, so a targeted consideration of efficacy, feasibility, and cost-benefit should be conducted before making a long-term commitment to one or more of these approaches.

ACKNOWLEDGEMENTS

We thank Mary Bayer, Terry Freije and the staff at the Warm Springs NFH for providing data and comments during the modeling process, David Hand with the USFWS Columbia River FWCO for help interpreting historical salmon rearing data, and Tim Mayer with USFWS Columbia-Pacific Northwest Region Water Resources Branch for water temperature data in Warm Springs River. The Columbia-Pacific Northwest Region's NFH Climate Change Vulnerability Assessment Team of Chris Pasley, Bill Gale, Patty Crandell and Don Campton provided general guidance on the scope and content of this project and also contributed useful comments on this report. Ingrid Tohver (University of Washington, Climate Impacts Group) provided the modeled flow data generated by the distributed hydrologic (VIC) model and R code that we modified to predict water temperatures based on forcing data from global climate models.

REFERENCES

Anderson, R. O., and S. J. Gutreuter. 1983. Length, weight, and associated structural indices. Pages 283-300 in L. A. Nielson and D. L. Johnson, editors. Fisheries techniques. American Fisheries Society, Bethesda, Maryland.

Becker, C. D., and R. G. Genoway. 1979. Evaluation of the critical thermal maximum for determining thermal tolerance of freshwater fish. Environmental Biology of Fishes 4:245-256.

Beitinger, T. L., W. A. Bennett, and R. W. McCauley. 2000. Temperature tolerances of North American freshwater fishes exposed to dynamic changes in temperature. Environmental Biology of Fishes 58:237-275.

Beitinger, T. L., and R. W. McCauley. 1990. Whole-animal physiological processes for the assessment of stress in fishes. Journal of Great Lakes Research 16:542-575.

Bisson, P. A., B. E. Rieman, C. Luce, P. F. Hessburg, D. C. Lee, J. L. Kershner, G. H. Reeves, and R. E. Gresswell. 2003. Fire and aquatic ecosystems of the western USA: current knowledge and key questions. Forest Ecology and Management 178(1-2):213-229.

Carey, M. P., B. L. Sanderson, T. A. Friesen, K. A. Barnas, and J. D. Olden. 2011. Smallmouth bass in the Pacific Northwest: a threat to native species; a benefit for anglers. Reviews in Fisheries Science 19:305-315.

Dumas, A., J. France, and D. P. Bureau. 2007. Evidence of three growth stanzas in rainbow trout (*Oncorhynchus mykiss*) across life stages and adaptation of the thermal-unit growth coefficient. Aquaculture 267(1-4):139-146.

Elliott, J. M. 1981. Some aspects of thermal stress on freshwater teleosts. Pages 209-245 in: A. D. Pickering, editor. Stress and Fish. Academic Press, New York, NY.

Fabry, V. J., B. A. Seibel, R. A. Feely, and J. C. Orr. 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. ICES Journal of Marine Science 65:414-432.

Hamlet, A. F., E. P. Salathé, and P. Carrasco. 2010a. Statistical downscaling techniques for global climate model simulations of temperature and precipitation with application to water resources planning studies. Chapter 4 in Final Report for the Columbia Basin Climate Change Scenarios Project, Climate Impacts Group, Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle.

Hamlet, A. F., P. Carrasco, J. Deems, M. M. Elsner, T. Kamstra, C. Lee, S.-Y. Lee, G. Mauger, E. P. Salathé, I. Tohver, and L. Whitely Binder. 2010b. Final Project Report for the Columbia Basin Climate Change Scenarios Project, http://www.hydro.washington.edu/2860/report/.

Hanson, K. C. and D. P. Peterson. 2014. Modeling the potential impacts of climate change on Pacific salmon culture programs: an example at Winthrop National Fish Hatchery. Environmental Management 54: 433-448. Online Resource 2 available at: http://link.springer.com/article/10.1007/s00267-014-0302-2.

Hawkins, S. W., and J. M. Tipping. 1999. Predation by juvenile hatchery salmonids on wild fall Chinook salmon fry in the Lewis River, Washington. Calif. Fish Game 85:124–129.

IPCC (Intergovernmental Panel on Climate Change). 2007. Climate Change 2007, Fourth Assessment Report. Available at: http://www.ipcc.ch/report/ar4/.

Isaak, D. J., C. H. Luce, B. E. Rieman, D. E. Nagel, E. E. Peterson, D. L. Horan, S. Parkes, and G. L. Chandler. 2010. Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. Ecological Applications 20:1350-1371.

Iwama G. K. and A. F. Tautz. 1981. A simple growth model for salmonids in hatcheries. Canadian Journal of Fisheries and Aquatic Science 38:649-656.

Jobling, M. 2010. Are compensatory growth and catch-up growth two sides of the same coin? Aquaculture International 18(4):501-510.

Koseki, Y., and I. A. Fleming. 2007. Large-scale frequency dynamics of alternative male phenotypes in natural populations of coho salmon (*Oncorhynchus kisutch*): patterns, processes, and implications. Canadian Journal of Fisheries and Aquatic Sciences 64:743–753.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges. 1994. A simple hydrologically based model of land-surface water and energy fluxes for general-circulation models. Journal of Geophysical Research 99(D7):14,415-14,428.

Luttershmidt, W. I., and V. H. Hutchinson. 1997. The critical thermal maximum: history and critique. Canadian Journal of Zoology 75:1561-1574.

Mantua, N., I. Tohver, and A. Hamlet. 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. Climatic Change 102:187-223.

McCullough, D., S. Spalding, D. Sturdevant, and M. Hicks. 2001. Issue Paper 5: Summary of technical literature examining the physiological effects of temperature on salmonids. U.S. Environmental Protection Agency, Region 10. 119pp.

Mohseni, O., H. G. Stefan, and T. R. Erickson. 1998. A nonlinear regression model for weekly stream temperatures. Water Resource Research 34:2685–2692.

Namen, S. W., and C. S. Sharpe. 2012 Predation by hatchery yearling salmonids on wild subyearling salmonids in the freshwater environment: A review of studies, two case histories, and implications for management. Environmental Biology of Fishes 94:21-28.

Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models. Journal of Hydrology 10:282-290.

Paladino, R. V., J. R. Spotila, J. P. Schubauer and K. T. Kowalski. 1980. The critical thermal maximum: a technique used to elucidate physiological stress and adaptation in fishes. Revue Canadienne de Biologie 39:115-122.

Petersen, J. H., and J. F. Kitchell. 2001. Climate regimes and water temperature changes in the Columbia River: bioenergetic implications for predators of juvenile salmon. Canadian Journal of Fisheries and Aquatic Sciences 58:1831–1841.

Piper, R. G., I. B. McElwain, L. E. Orme, J. P. McCraren, L. G. Fowler, and J. R. Leonard. 1982. Fish hatchery management. U.S. Fish and Wildlife Service, Washington, D.C.

Post, G. 1987. Textbook of fish health, Second Edition. T.F.H Publications Inc. Ltd., Neptune, New Jersey.

R Core Team. 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Rahel, F. J., and J. D. Olden. 2008. Assessing the effects of climate change on aquatic invasive species. Conservation Biology 22(3):521-533.

Scheuerell, M. D., and J. G. Williams. 2005. Forecasting climate-induced changes in the survival of Snake River spring/summer Chinook salmon (*Oncorhynchus tshawytscha*). Fisheries Oceanography 14(6):448-457.

Simpson, W. G., B. M. Kennedy, and K. G. Ostrand. 2009. Seasonal foraging and piscivory by sympatric wild and hatchery-reared steelhead from an integrated hatchery program. Environmental Biology of Fishes 86:473-482.

U.S. Fish and Wildlife Service (USFWS). 2006. Warm Springs National Fish Hatchery assessments and recommendations: final report. U.S. Fish and Wildlife Service, Columbia River Basin Hatchery Review Team, Portland, OR. 50 pp. Available at: http://www.fws.gov/Pacific/fisheries/Hatcheryreview/reports.html.

U.S. Fish and Wildlife Service (USFWS). 2013. Review of U.S. Fish and Wildlife Service hatcheries in Washington, Oregon, and Idaho: region-wide issues, guidelines and recommendations. Hatchery Review Team, Pacific Region. U.S. Fish and Wildlife Service, Portland, OR. 44 pp. Available at: http://www.fws.gov/Pacific/fisheries/Hatcheryreview/reports.html.

U.S. Fish and Wildlife Service (USFWS). 2016. An investigation into the cause of egg mortality at Warm Springs National Fish Hatchery during the fall of 2015. Pacific Region Fish Health Program, Pacific Region, U.S. Fish and Wildlife Service, Portland, OR. 17 pp.

Weber, E. D., and K. D. Fausch. 2003. Interactions between hatchery and wild salmonids in streams: differences in biology and evidence for competition. Canadian Journal of Fisheries and Aquatic Sciences 60:1018–1036.

Wedemeyer, G. A., editor. 2001. Fish hatchery management, second edition. American Fisheries Society, Bethesda, MD.

Wedemeyer, G. A., and D. J. McLeay. 1981. Methods for determining the tolerance of fishes to environmental stressors. In: Pickering, A.D. (ed.). Stress and fish. London: Academic Press, pp. 247-275.

Wenger, S. J., D. J. Isaak, J. B. Dunham, K. D. Fausch, C. H. Luce, H. M. Neville, B. E. Rieman, M. K. Young, D. E. Nagel, D. L. Horan, and G. L. Chandler. 2011. Role of climate and invasive species in structuring trout distributions in the interior Columbia River Basin, USA. Canadian Journal of Fisheries and Aquatic Sciences 68(6):988–1008.

Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam. 2006. Warming and earlier spring increases Western U.S. forest wildfire activity. Science 313:940-943. DOI:10.1126/science.1128834

Table B1. Thermal tolerances (°C) of Pacific salmon species (*Oncorhynchus* sp.) reared at Warm Springs NFH.

Species	Latin Binomial	Life-History Stage	Optimal Temp. Range	Optimal Temp. Growth Range	Spawn Range	Smoltification Threshold
Chinook Salmon	*O. tshawytscha*	adult	6.0 – 14.0 °C		9.0 – 12.3 °C	
		egg/fry	8.4 – 12.4 °C			
		juvenile	8.6 – 15.9 °C	14.0 – 18.4 °C		14.0 °C

Table B2. Thermal ranges (°C) at which common salmon pathogens cause disease in Pacific salmon and Steelhead.

Disease Name	Pathogen Name (causative agent)	Disease Outbreak Temperatures	Minimum Disease Temperatures
Bacteria diseases			
Furunculosis	*Aeromonas salmonicida (A.sal)*	20.0 – 22.0 °C	12.0 °C
Vibriosis	*Vibrio anguillarum*	18.0 – 20.0 °C	14.0 °C
Enteric redmouth disease	*Yersinia ruckeri*	22.0 °C	11.0 – 18.0 °C
Columnaris disease	*Flavobacterium columnaris*	28.0 – 30.0 °C	15.0 °C
Coldwater disease (fin rot)	*Flavobacterium psychrophilum*	4.0 – 10.0 °C	4.0 – 10.0 °C
Bacterial kidney disease	*Renibacterium salmoninarum*		15.0 °C
Fungal diseases			
Saprolegniasis	*Saprolegnia parasitica, Achyla hoferi, Dictyuchus* spp.	15.0 – 30.0 °C	
Parasitic diseases			
Parasitic ichtyobodiasis (Costiasis)	*Ichthyobodo necatrix, I. pyrifornis*	10.0 – 25.0 °C	
White spot disease (Ich)	*Ichthyophthirius multifiliis*	24.0 – 26.0 °C	12.0 – 15.0 °C
Proliferative kidney disease	*Tetracapsuloides bryosalmonae*	16.0 °C	
Ceratomyxosis	*Ceratonova shasta*	15.0 – 25.0 °C	10.0 – 15.0 °C
Viral diseases			
Infectious pancreatic necrosis virus (IPNV) disease	*Aquabirnavirus* sp.	20.0 – 23.0 °C	
Infectious hematopoietic necrosis (IHN) disease	*Novirhadovirus* sp.	13.0 – 18.0 °C	15.0 °C

Table B3. Historical and future mean monthly water temperatures (°C) for the Warm Springs River based on three analyses: (1) historical values measured empirically, (2) historical modeled values derived as outputs from the regression relationship between air and water temperature, and (3) projected future temperatures for the 2040s. Historical empirical values for Warm Springs River (°C ± S.D.) are for 2012 – 2017 and were collected by USFWS Columbia-Pacific Northwest Region Water Resources Division, at the hatchery diversion. Predictions for the 2040s represent the mean and range of surface water temperatures derived from statistically downscaled air temperatures from 10 general circulation models (GCMs) under the A1B emissions scenario (IPCC 2007) and regression relationships between air and surface waters (see text for additional details). The historical modeled values are predictions from the air-water regression across the 1915 – 2006 period, and the SD shows the variability across that period.

Month	Historical empirical (± S.D.)	Historical modeled (± S.D.)	2040s A1B ensemble (Min. – Max.)
January	2.7 ± 1.7	3.4 ±1.8	4.4 (3.7 – 5.0)
February	4.2 ± 1.7	4.5 ± 1.8	5.6 (4.8 – 6.3)
March	6.6 ± 1.6	6.1 ± 1.8	7.4 (6.4 – 8.6)
April	9.3 ± 1.6	8.4 ± 2.3	9.6 (9.1 – 10.3)
May	13.0 ± 1.9	12.0 ± 2.5	13.4 (12.7 – 14.0)
June	16.2 ± 2.1	15.3 ± 1.8	16.8 (16.1 – 17.4)
July	18.3 ± 1.3	17.5 ± 1.1	18.5 (18.2 – 19.2)
August	17.1 ± 1.1	17.2 ± 1.1	18.4 (17.9 – 19.0)
September	13.4 ± 1.7	15.0 ± 2.0	16.7 (16.3 – 17.6)
October	9.3 ± 1.6	10.4 ± 2.8	12.1 (11.7 – 12.6)
November	5.6 ± 2.7	5.5 ± 1.9	6.8 (6.3 – 7.2)
December	2.9 ± 1.9	3.8 ± 1.8	4.8 (4.4 – 5.3)

Table B4. Modeled historical and future monthly average air temperatures (T_{ave}), precipitation (PPT), and snow water equivalent (SWE) for the drainage area of Warm Springs River upstream from Warm Springs NFH. Modeled projected future values are ensemble means based on 10 GCMs extracted from daily flux files and weighted by the intersection of the delineated watershed and the 1/16° grid cells underlying the flux files. The historical period is based on the 1915 – 2006 meteorological record, and the 2040s represents a 30-year period (2030 – 2059) centered on the decade of the 2040s. Standard deviation (SD) values represent the variability in monthly estimates among the 10 GCMs. Differences (Diff.) are calculated as the 2040s ensemble mean minus the historical mean. An example of the file location for a flux file is: http://warm.atmos.washington.edu/2860/r7climate/hb2860_hybrid_delta_runs/echam5_A1B_2030-2059/fluxes_monthly_summary/fluxsumm_47.78125_-122.90625 .

Month	T_{ave} (°C) Historical	T_{ape} (°C) Projected 2040s (± S.D.)	Diff.	PPT (mm) Historical	PPT (mm) Projected 2040s (± S.D.)	Diff.	SWE (mm) Historical	SWE (mm) Projected 2040s (± S.D.)	Diff.
January	-2.0	-0.4 ± 0.9	1.6	121	129 ± 20	8	28.5	9.2 ± 2.4	-19.3
February	0.1	-1.6 ± 0.9	1.5	91	92 ± 13	1	58.0	24.9 ± 10.4	-33.1
March	2.5	4.0 ± 0.9	1.5	91	97 ± 6	6	65.0	24.8 ± 14.1	-40.2
April	5.3	6.6 ± 0.4	1.3	49	52 ± 8	3	61.5	21.4 ± 13.6	-40.1
May	9.0	10.6 ± 0.5	1.6	41	35 ± 3	-6	40.9	11.2 ± 7.3	-29.7
June	12.9	15.2 ± 0.7	2.3	31	25 ± 6	-6	13.8	2.6 ± 1.8	-11.1
July	16.7	19.6 ± 1.1	2.9	9	6 ± 1	-3	2.5	0.2 ± 0.2	-2.2
August	16.2	19.2 ± 1.0	3.1	12	10 ± 4	-2	0.2	0.0 ± 0.0	-0.2
September	12.8	15.5 ± 0.9	2.7	28	22 ± 5	-6	0.0	0.0 ± 0.0	0.0
October	7.7	9.6 ± 0.3	1.9	75	78 ± 10	3	0.0	0.0 ± 0.0	0.0
November	2.2	3.7 ± 0.3	1.6	115	127 ± 17	12	0.9	0.2 ± 0.1	-0.7
December	-0.7	0.8 ± 0.4	1.5	125	132 ± 17	7	7.7	2.0 ± 0.6	-5.7

Table B5. Projected mean annual flows (cfs) of Warm Springs River near Warm Springs NFH in the 2040s derived from the VIC hydrologic model forced by output from 10 Global Climate Models (GCMs) under the A1B emissions scenario. The historical average (modelled) is based on the 1915 – 2006 period. Values do not account for irrigation withdrawals or any hydrologic alterations upstream from the hatchery.

GCM	**Mean annual flow in 2040s (cfs)**
ccsm3	494
cgcm3	580
cnrm_cm3	568
echam5	523
echo_g	498
hadcm	547
hadgem1	455
ipsl_cm4	638
miroc_3.2	599
pcm1	484
2040s AVERAGE	553
2040s RANGE	455 – 638
Historical AVERAGE	520

Table B6. Mean monthly water temperatures and water sources experienced by juvenile Chinook Salmon reared at Warm Springs NFH based on the historical baseline and projected values for the 2040s. Projected temperatures indicated by an asterisk (*) exceed the optimal temperature upper threshold for the corresponding life history stage.

Month	Life-History Stage	Mean water temperature, historical baseline (°C)	Mean water temperature in the 2040s (°C)
April	Broodstock	8.4	9.6
May	Broodstock	12.0	13.4
June	Broodstock	15.3	16.8*
July	Broodstock	17.5	18.5*
August	Broodstock	17.2	18.4*
September	Broodstock	15.0	16.7*
September	egg/fry	15.0	16.7*
October	egg/fry	10.4	12.1
November	egg/fry	5.5	6.8
December	egg/fry	3.8	4.8
January	egg/fry	3.4	4.4
February	egg/fry	4.5	5.6
March	juvenile	6.1	7.4
April	juvenile	8.4	9.6
May	juvenile	12.0	13.4
June	juvenile	15.3	16.8*
July	juvenile	17.5	18.5*
August	juvenile	17.2	18.4*
September	juvenile	15.0	16.7*
October	juvenile	10.4	12.1
November	juvenile	5.5	6.8
December	juvenile	3.8	4.8
January	juvenile	3.4	4.4
February	juvenile	4.5	5.6
March	juvenile	6.1	7.4
April	smolt	8.4	9.6

Table B7. End of month percent size difference of juvenile Chinook Salmon reared at Warm Springs NFH in the 2040s under a future temperature scenario relative to baseline historical water temperatures.

Month	Life-History Stage	Weight (g)	Length (mm)
February	fry	10.8%	3.4%
March	fry	21.2%	6.7%
April	fry	26.3%	8.0%
May	juvenile	29.1%	8.8%
June	juvenile	29.1%	8.8%
July	juvenile	26.8%	8.2%
August	juvenile	25.8%	7.9%
September	juvenile	27.1%	8.2%
October	juvenile	29.2%	8.8%
November	juvenile	31.0%	9.3%
December	juvenile	32.3%	9.7%
January	juvenile	33.6%	10.0%
February	juvenile	34.8%	10.4%
March	juvenile	36.2%	10.7%
April	smolt	36.6%	10.8%

Table B8, Part A. Mean historical, empirical and modeled, flow and density index values and constituent variables for Spring Chinook Salmon at Warm Springs NFH. Rearing (Rear.) parameters are listed in columns 3 – 5. Empirical historical values (Emp.) are listed in columns 6 – 10. Modeled historical values (Mod.) are listed in columns 11 – 14. Flow and density index values are shown graphically in Figure B18.

Time step (i)	Month[a]	Rear. N_i [b]	Rear. C_i(ft^3)[c]	Rear. d_i [d]	Emp. L_i [e]	Emp. W_i [f]	Emp. GPM_i[g]	Emp. DI_i [h]	Emp. FI_i [i]	Mod. L_i [j]	Mod. W_i [k]	Mod. DI_i [l]	Mod. FI_i[m]	r_i[n]
1	Feb	699,624	1,180	28	1.6	0.7	360	0.46	1.51	1.6	0.7	0.57	1.87	0.98
2	Mar	699,589	7,072	31	2.3	1.5	1,401	0.19	0.86	1.9	1.2	0.14	0.72	1.04
3	Apr	671,933	38,800	30	2.8	3.1	9,113	0.05	0.23	2.3	2.3	0.04	0.16	1.11
4	May	688,255	45,200	31	3.4	5.7	11,362	0.06	0.24	3.0	4.8	0.05	0.22	1.03
5	Jun	683,366	45,200	30	3.9	8.9	13,053	0.08	0.28	3.7	9.8	0.09	0.30	0.86
6	Jul	648,702	43,103	31	4.1	10.4	13,687	0.08	0.27	4.6	18.9	0.14	0.43	0.61
7	Aug	647,774	43,103	31	4.4	12.7	13,687	0.10	0.30	5.5	31.9	0.19	0.60	0.49
8	Sep	647,070	44,663	30	4.6	14.6	13,687	0.10	0.33	6.2	46.2	0.24	0.77	0.42
9	Oct	646,672	44,663	31	4.9	16.6	13,687	0.11	0.36	6.7	57.7	0.27	0.90	0.40
10	Nov	646,409	44,363	30	4.9	16.9	13,587	0.11	0.37	6.9	62.9	0.29	0.96	0.38
11	Dec	616,737	44,363	31	4.9	17.3	12,487	0.11	0.40	7.0	66.0	0.29	1.03	0.37
12	Jan	616,484	44,363	31	5.0	18.0	12,487	0.11	0.41	7.1	68.5	0.30	1.05	0.37
13	Feb	616,193	44,363	28	5.0	18.7	12,487	0.12	0.42	7.2	72.1	0.31	1.09	0.37
14	Mar	590,518	42,195	31	5.2	20.1	12,960	0.12	0.40	7.4	79.1	0.33	1.07	0.37
15	Apr	586,079	42,195	30	5.2	20.6	12,960	0.12	0.41	7.8	90.1	0.36	1.16	0.34

[a] Calendar month in rearing cycle.

[b] Numbers of post-hatch juvenile fish or abundance (N_i) based on hatchery averages over 2000 – 2004 and 2008 brood years. For some months, not all years were used to calculate the average; some values were excluded because they deviated substantially from the long-term averages and may either represent data entry errors or cases where the hatchery was rearing or holding fish in a manner that was very different than the generalized rearing cycle of approximately 700,000 salmon we sought to represent here.

[c] Mean hatchery capacity (C_i) used during 2000 – 2004 and 2008 brood years based on the number of raceways, their sizes, and water depth, with data exclusions described in footnote b.

[d] Number of days (d_i) in the monthly time-step i.

[e] Empirical mean fish length (L_i) in inches, at the end of each monthly time-step i averaged over the 2000 – 2004 and 2008 brood years, with exclusions described in footnote b.

[f] Empirical mean fish weight (W_i) in grams, at the end of each monthly time-step i averaged over the 2000 – 2004 and 2008 brood years, with exclusions described in footnote b.

[g] Empirical mean flow rates through the hatchery (GPM_i) in gallons per minute at each monthly time-step i averaged over the 2000 – 2004 and 2008 brood years, with exclusions described in footnote b.

[h] Empirical density index (DI_i) at time-step i averaged over the 2000 – 2004 and 2008 brood years, with exclusions described in footnote b.

[i] Empirical mean flow index (FI_i) at time-step i averaged over the 2000 – 2004 and 2008 brood years, with exclusions described in footnote b.

[j] Modeled historical mean fish length (L_i) in inches, at the end of each monthly time-step i.

[k] Modeled historical mean fish weight (W_i) in grams, at the end of each monthly time-step i.

[l] Modeled historical density index (DI_i) at time-step i.

[m] Modeled historical flow index (FI_i) at time-step i.

[n] Bias correction factors are the ratio between empirical mean index values and simulated historical values, (see footnote at bottom of page 10.

$$r_i = rFI_i = \frac{FI_i \text{ mean empirical historical}}{FI_i \text{ modeled historical}} = rDI_i = \frac{DI_i \text{ mean empirical historical}}{DI_i \text{ modeled historical}}$$

For additional details, see Online Resource 2 at Hanson and Peterson (2014).

Table B8, Part B. Bias-adjusted future (2040s) modeled mean length, mean weight, and flow and density index values for Spring Chinook Salmon at Warm Springs NFH under three future scenarios for the hatchery's use available water. **Scenario A:** rearing water availability decreases proportionally to predicted decreases in flow in the Warm Springs River but the hatchery does not utilize additional water in months the river flow is predicted to increase. **Scenario B:** rearing water availability decreases or increases proportionally to predicted changes in flow in the Warm Springs River. **Scenario C:** rearing water availability does not change despite predicted changes in flow in the Warm Springs River. For Scenarios B and C, only FI values are shown because (a) fish sizes do not vary between scenarios and (b) the differences between the future scenarios depend only on water availability. Flow and density index values are shown graphically in Figure B18.

Time step (*i*)	Month[a]	L_i [b]	W_i [c]	DI_i [d]	FI_i [e]	Scenario B FI_i [e]	Scenario C FI_i [e]
1	Feb	1.60	0.75	0.60	1.96	1.59	1.96
2	Mar	2.00	1.48	0.17	0.84	0.73	0.84
3	Apr	2.50	2.91	0.05	0.22	0.22	0.21
4	May	3.21	6.21	0.07	0.40	0.40	0.26
5	Jun	4.06	12.64	0.09	0.49	0.49	0.31
6	Jul	5.02	23.99	0.10	0.36	0.36	0.31
7	Aug	5.95	40.16	0.11	0.36	0.36	0.35
8	Sep	6.74	58.63	0.12	0.41	0.41	0.38
9	Oct	7.29	74.52	0.13	0.42	0.42	0.42
10	Nov	7.54	82.43	0.13	0.44	0.36	0.44
11	Dec	7.69	87.33	0.13	0.46	0.36	0.46
12	Jan	7.81	91.53	0.13	0.48	0.36	0.48
13	Feb	7.96	97.14	0.14	0.49	0.40	0.49
14	Mar	8.24	107.71	0.15	0.48	0.42	0.48
15	Apr	8.61	123.02	0.15	0.52	0.52	0.49

[a] Calendar month in rearing cycle.

[b] Projected mean fish length (L_i) in inches, at the end of each monthly time-step *i*.

[c] Projected mean fish weight (W_i) in grams, at the end of each monthly time-step *i*.

[d] Modeled future density index (DI_i) at time-step *i* adjusted using r_i.

[e] Modeled future flow index (FI_i) at time-step *i* adjusted using r_i.

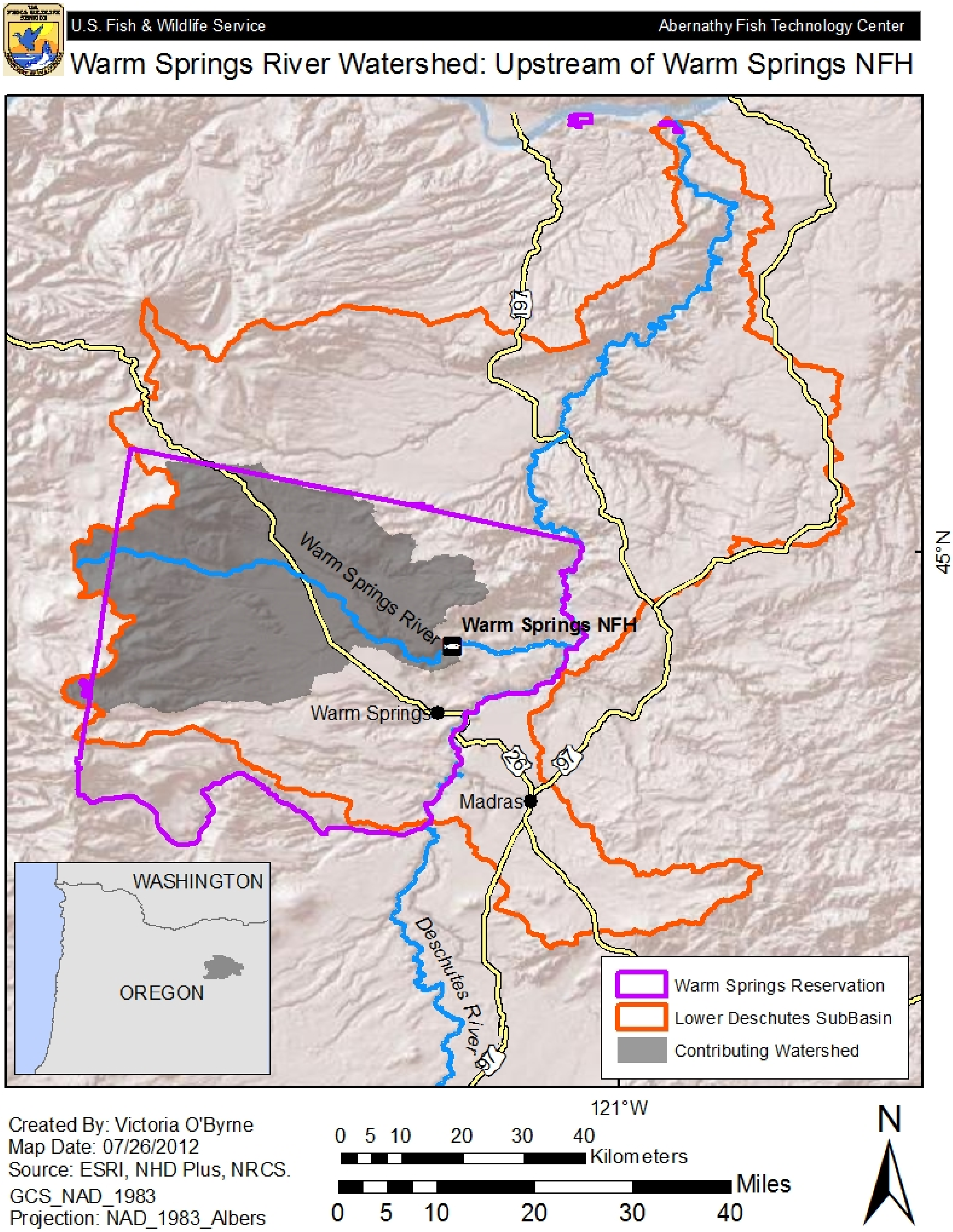

Figure B1. Warm Springs River contributing watershed (gray shaded area) and Warm Springs NFH in central Oregon.

d

Figure B2. Aerial view of Warm Springs NFH and Warm Springs River.

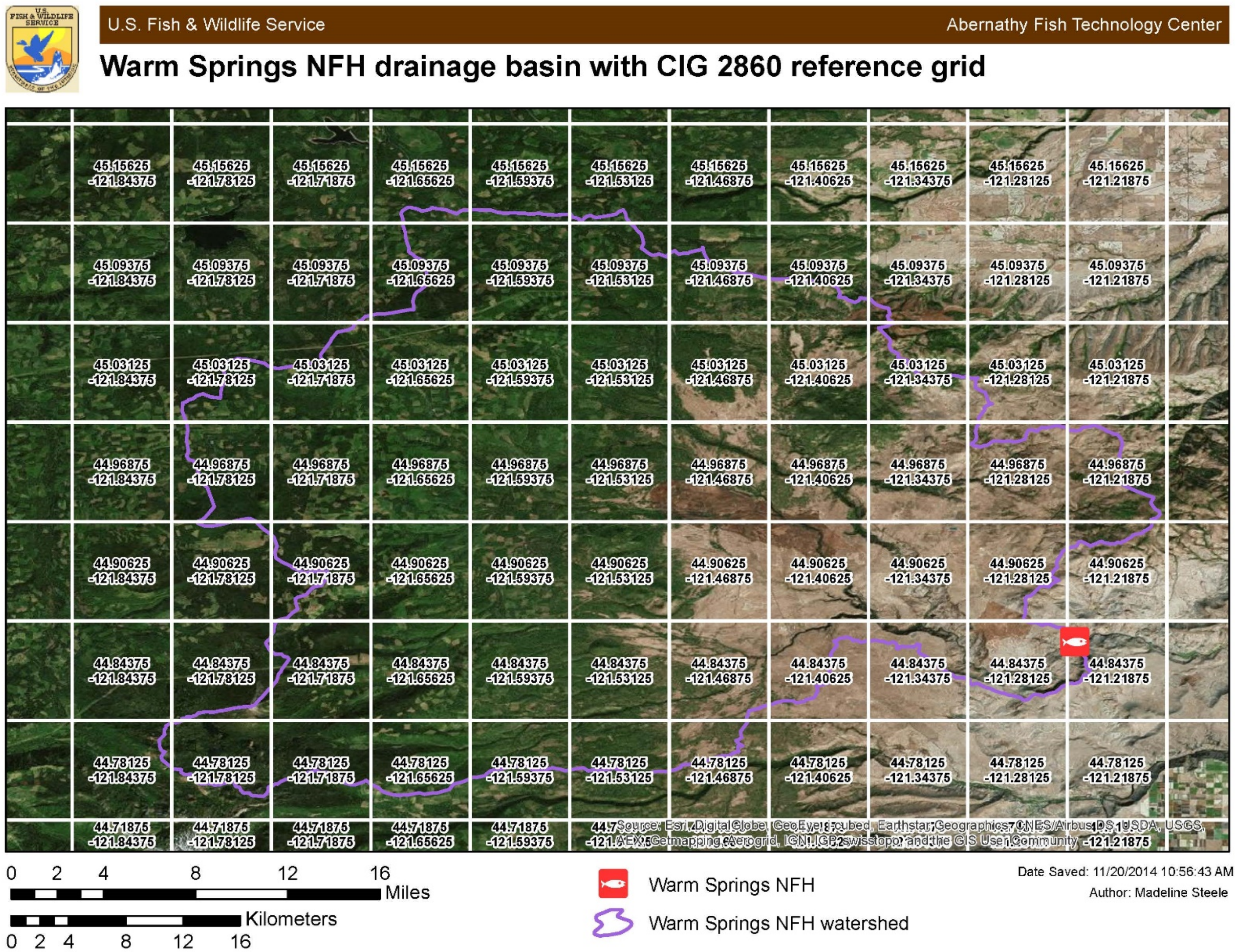

Figure B3. Warm Springs River watershed showing the intersection between the watershed delineation and the 1/16° grid cells to which the climate data were downscaled.

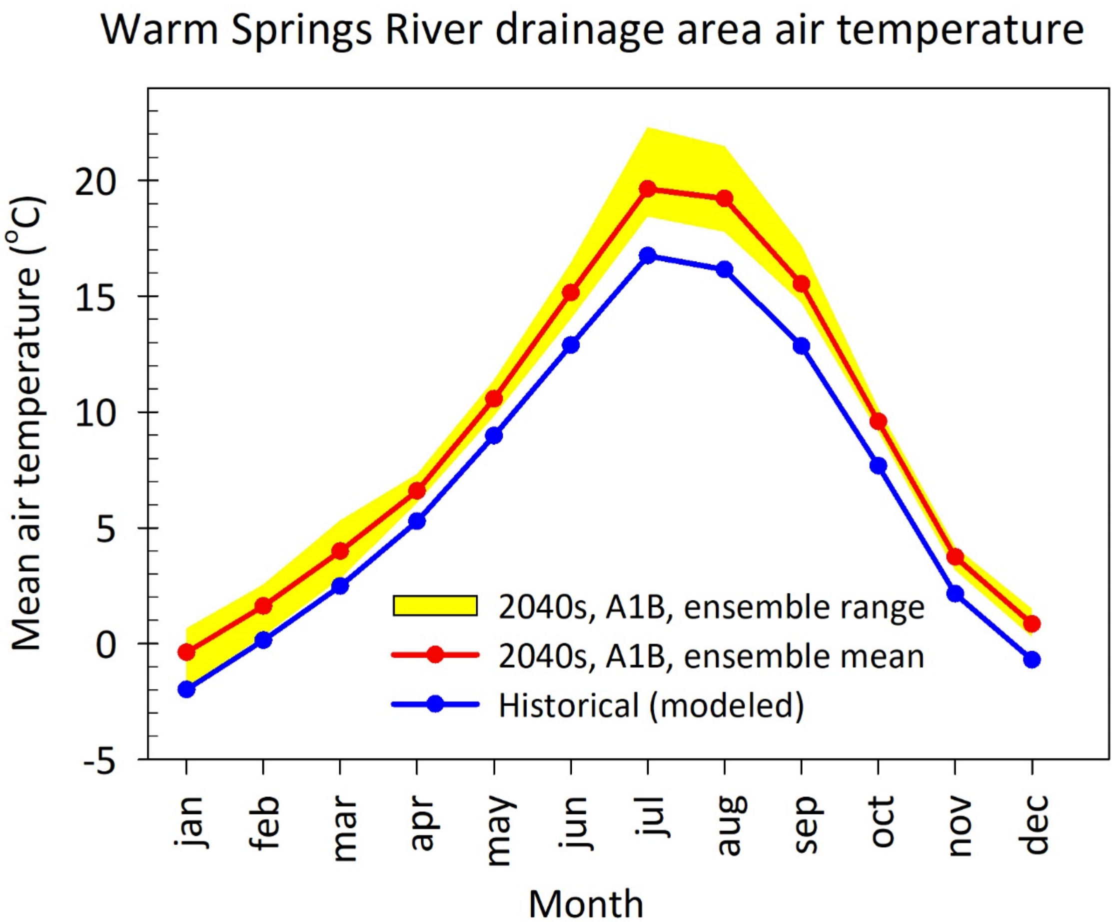

Figure B4. Modeled mean monthly air temperatures across the Warm Springs River watershed upstream from Warm Springs NFH based on an ensemble of 10 GCMs. Values are weighted by the intersection of the delineated watershed and the 1/16° grid cells underlying the flux files. The historical period is based on the 1915 – 2006 meteorological record, and the 2040s represents a 30-year period (2030 – 2059) centered on the decade of the 2040s.

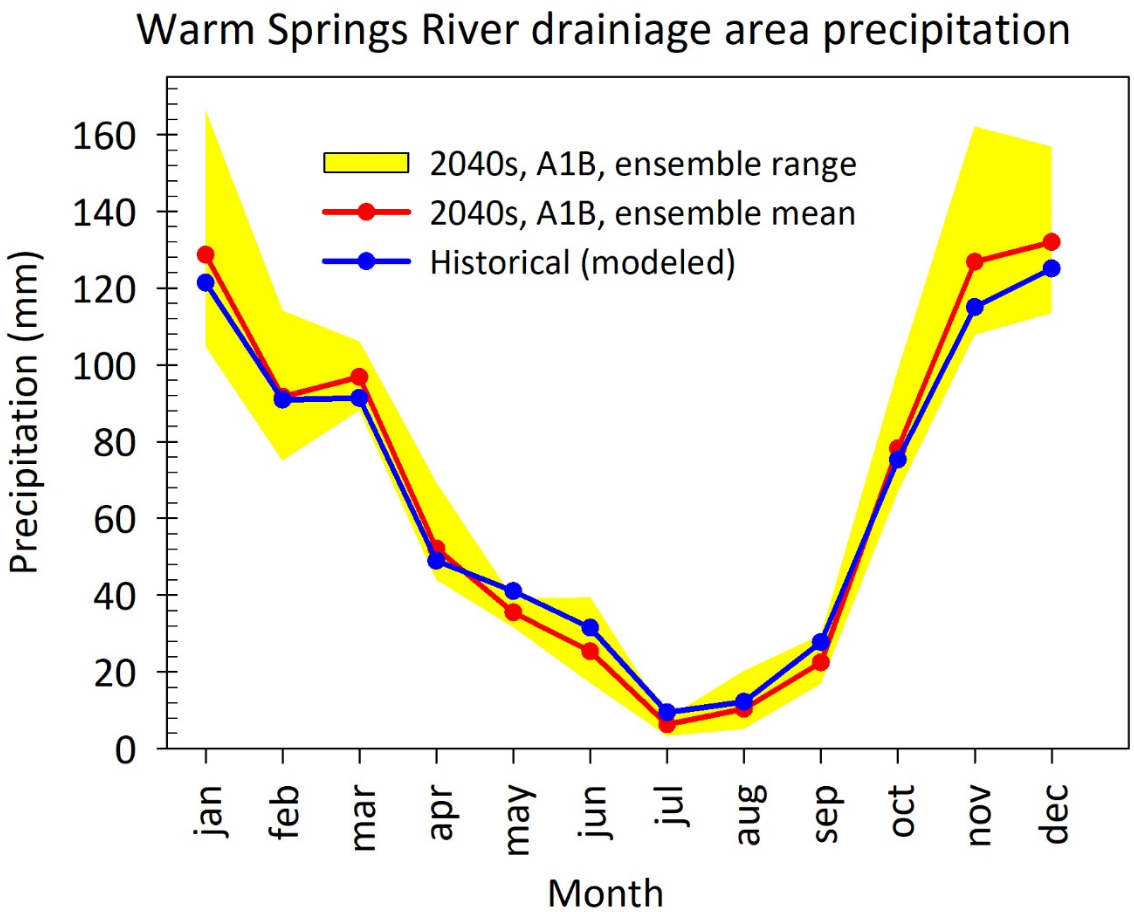

Figure B5. Modeled mean monthly precipitation across the Warm Springs River watershed upstream from Warm Springs NFH based on an ensemble of 10 GCMs. Values are weighted by the intersection of the delineated watershed and the 1/16° grid cells underlying the flux files. The historical period is based on the 1915 – 2006 meteorological record, and the 2040s represents a 30-year period (2030 – 2059) centered on the decade of the 2040s.

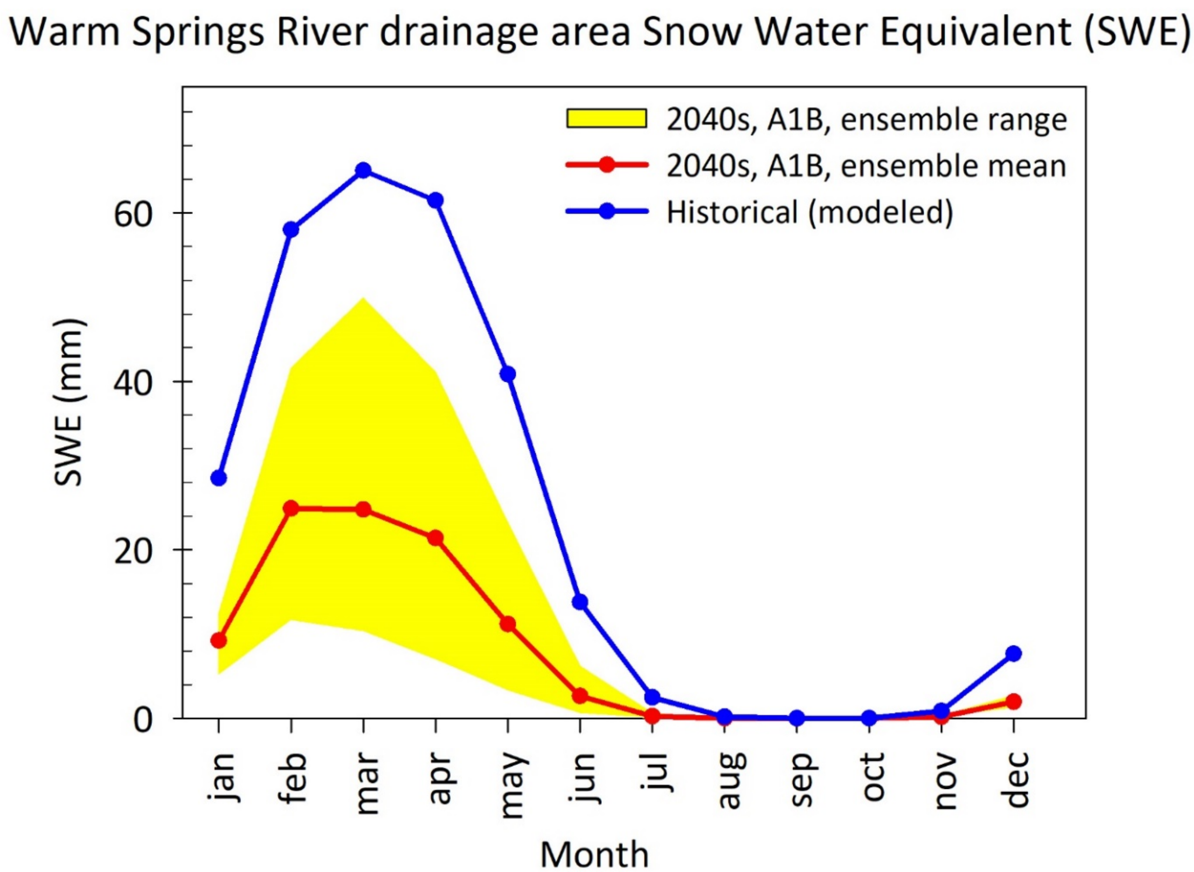

Figure B6. Modeled mean monthly snow water equivalent (SWE) across the Warm Springs River watershed upstream from Warm Springs NFH based on an ensemble of 10 GCMs. Values are weighted by the intersection of the delineated watershed and the 1/16° grid cells underlying the flux files. The historical period is based on the 1915 – 2006 meteorological record, and the 2040s represents a 30-year period (2030 – 2059) centered on the decade of the 2040s.

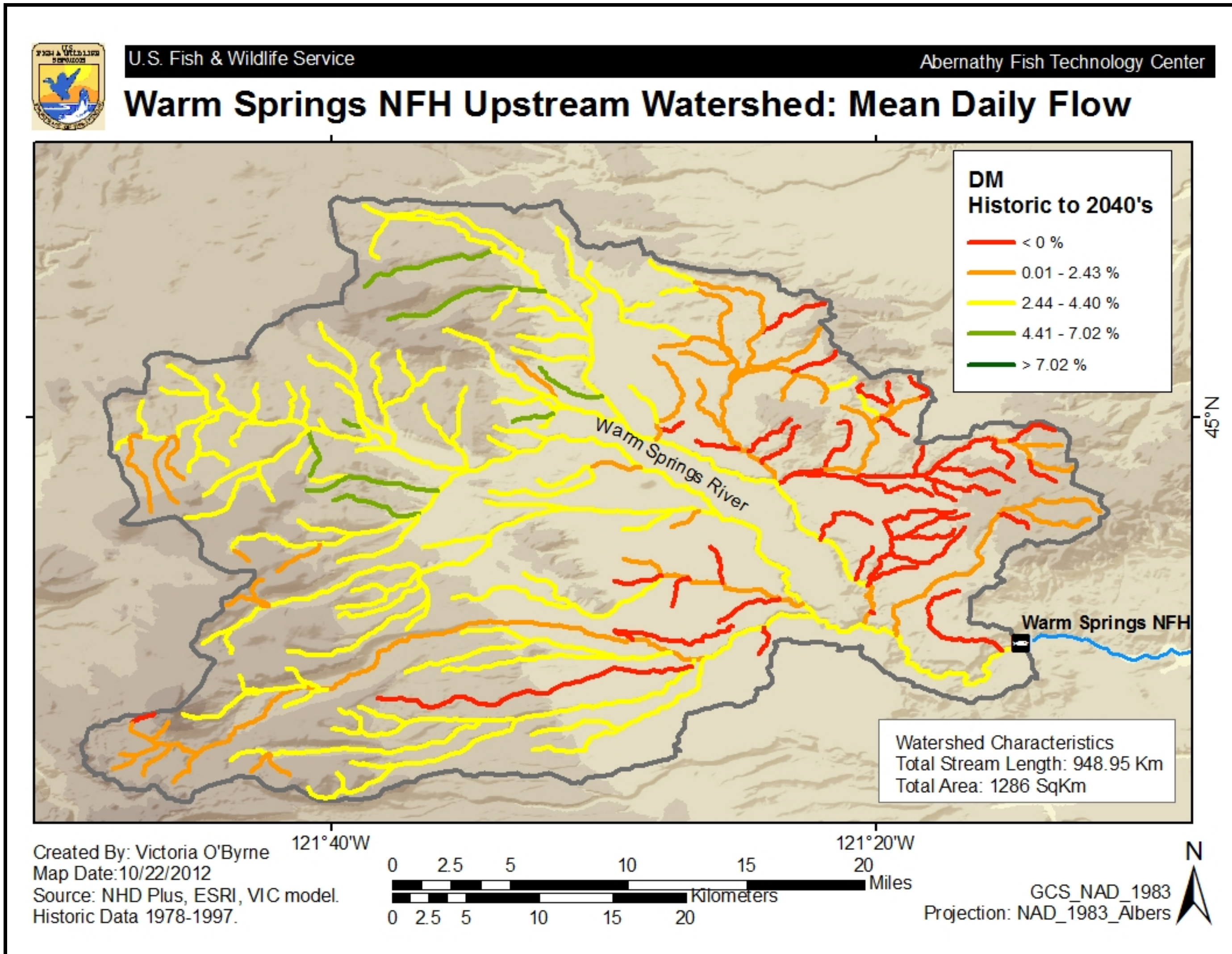

Figure B7. Projected change in mean daily flow (DM, in %) for the Warm Springs River basin upstream from Warm Springs NFH between the 1980s and 2040s time periods. Data are from VIC hydrologic model (Wenger et al. 2011), and the historical reference period is 1978 – 1997.

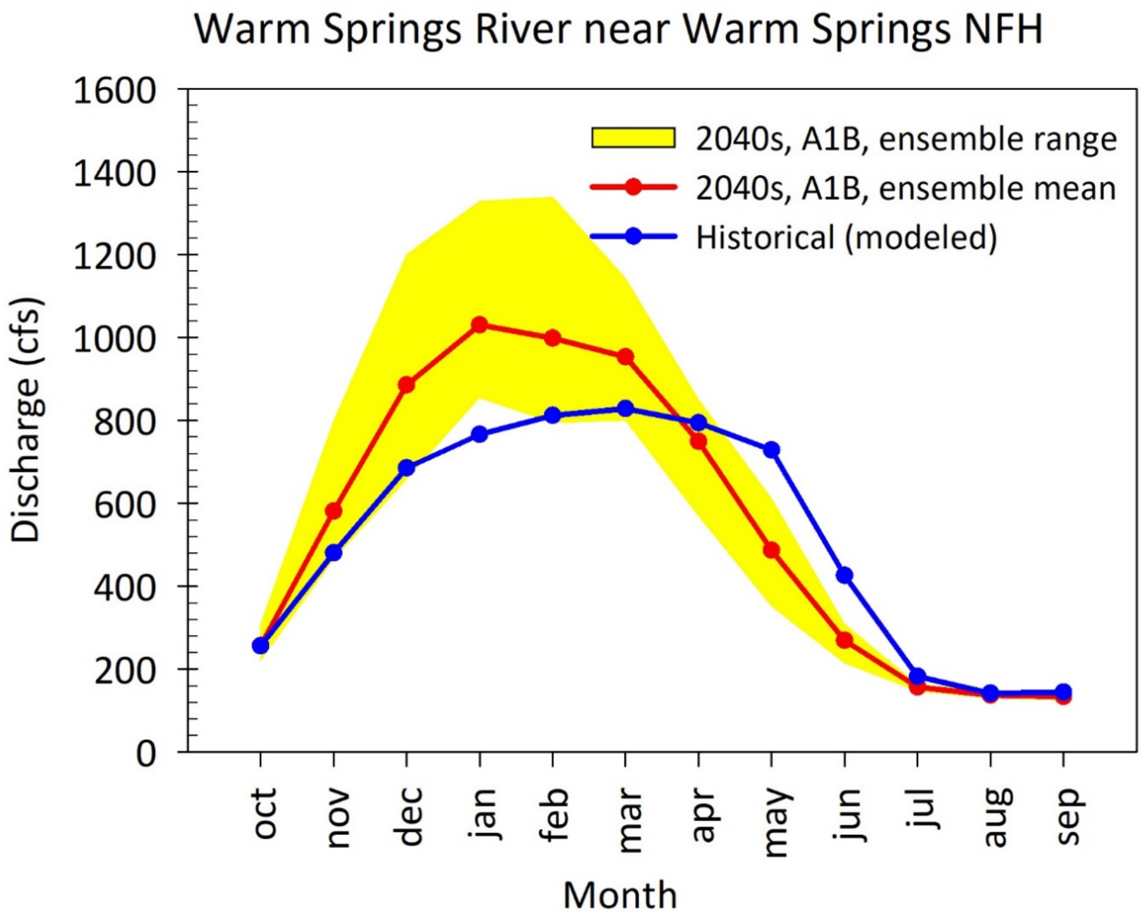

Figure B8. Modeled and observed mean monthly surface flow in Warm Springs River adjacent to Warm Springs NFH based on raw Variable Infiltration Capacity (VIC) simulations. Projected (2040s) surface flows are based on the VIC model forced by output from an ensemble of 10 general circulation models (GCMs) under the A1B greenhouse gas emissions scenario. Modeled flow data are routed to the location of the hatchery. The modeled historical period is based on the 1915 – 2006 meteorological record, and the 2040s represents a 30-year period (2030 – 2059) centered on the decade of the 2040s.

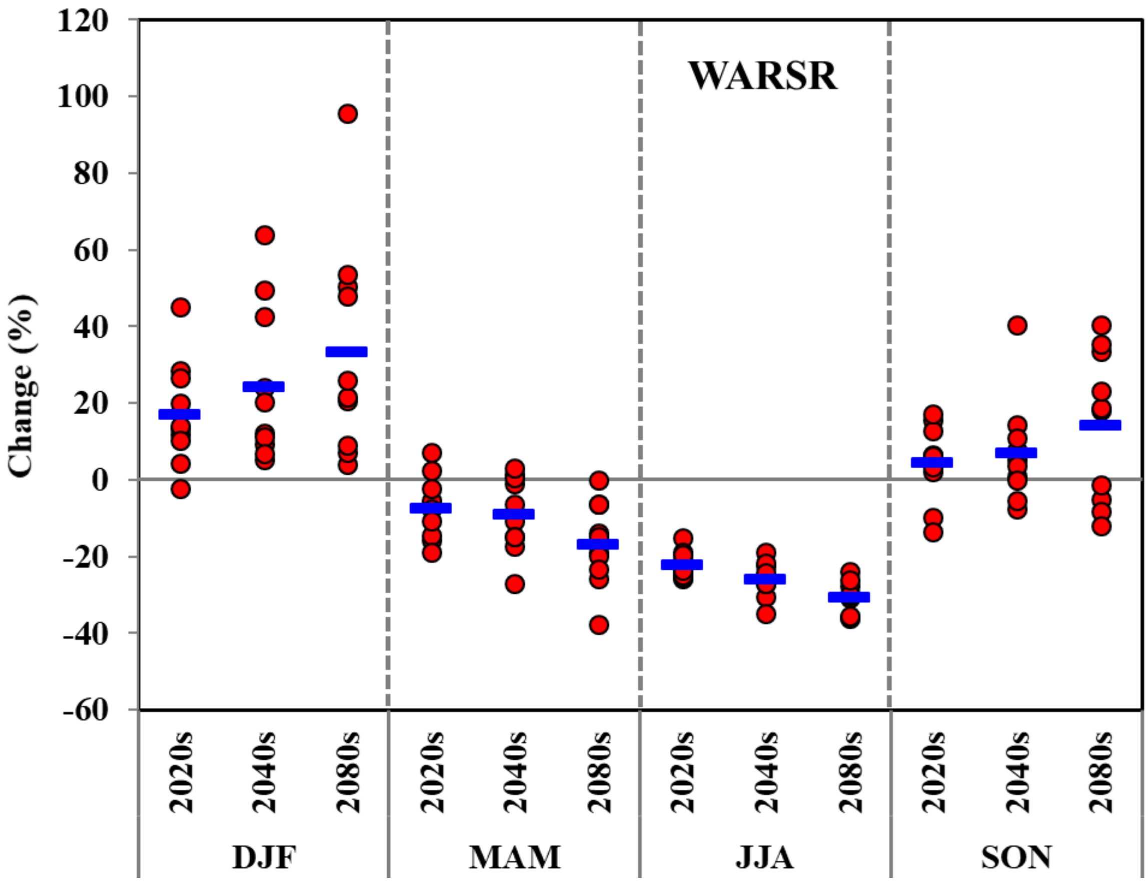

Figure B9. Projected percent change in mean seasonal flow in Warm Springs River (WARSR) adjacent to the Warm Springs NFH based on raw Variable Infiltration Capacity (VIC) simulations for the 30-year periods centered on the 2020s, 2040s, and 2080s. Flows projections are based on the VIC model forced by output from an ensemble of 10 general circulation models (GCMs) under the A1B greenhouse gas emissions scenario. Seasons depicted are winter (December, January, February – DJF), spring (MAM), summer (JJA), and fall (SON), where the letters denote the first initial of each month in the season. Red dots are the projections for the individual GCMs with hybrid-delta downscaling, and the blue horizontal dash (-) is the ensemble average. Differences (% change) are relative to the 1915 – 2006 historical period.

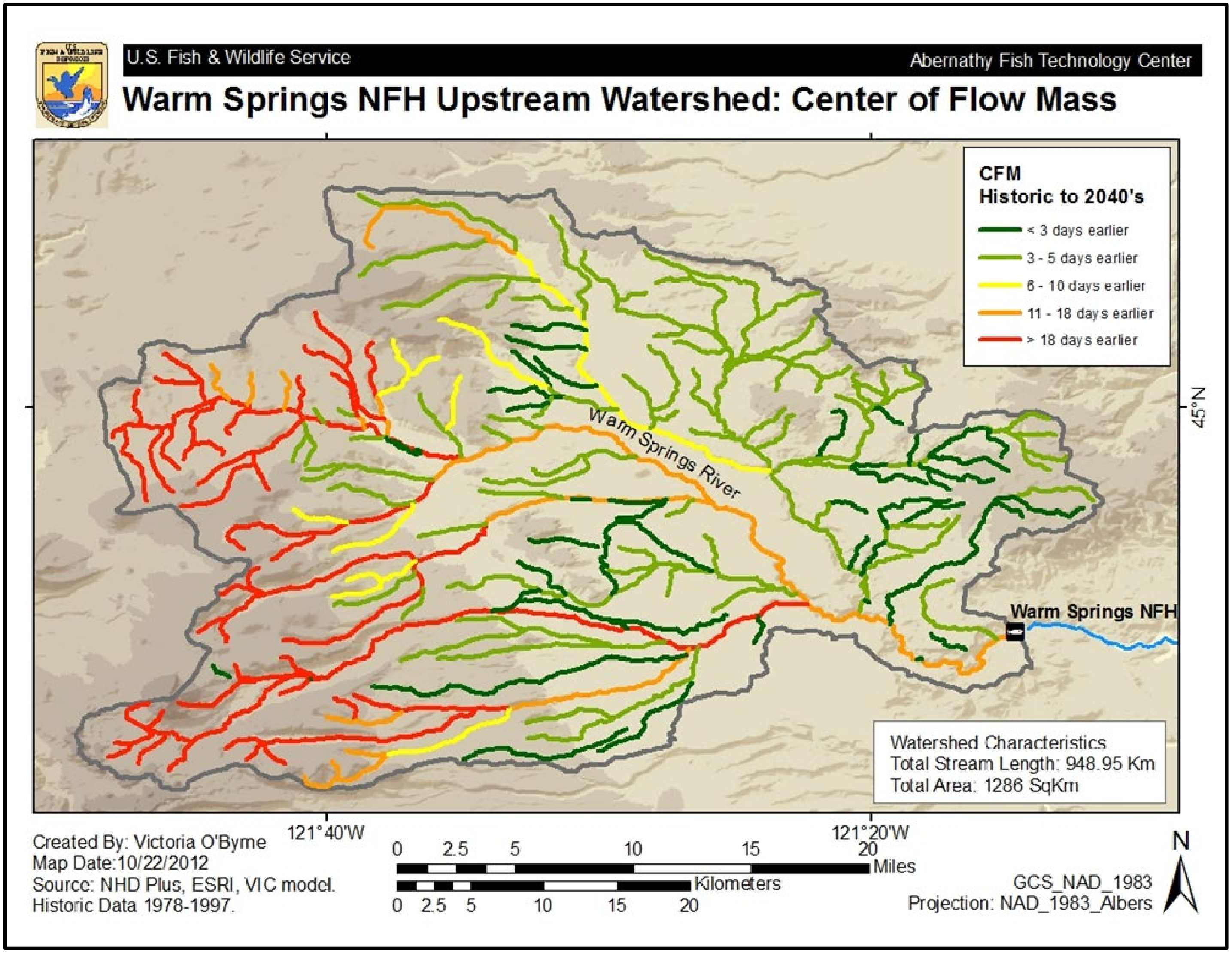

Figure B10. Projected change in the timing of snowmelt runoff (date of center of flow mass, CFM) for the Warm Springs River basin upstream from Warm Springs NFH between the 1980s and 2040s time periods. Data are from VIC hydrologic model (Wenger et al. 2011), and the historical reference period is 1978 – 1997.

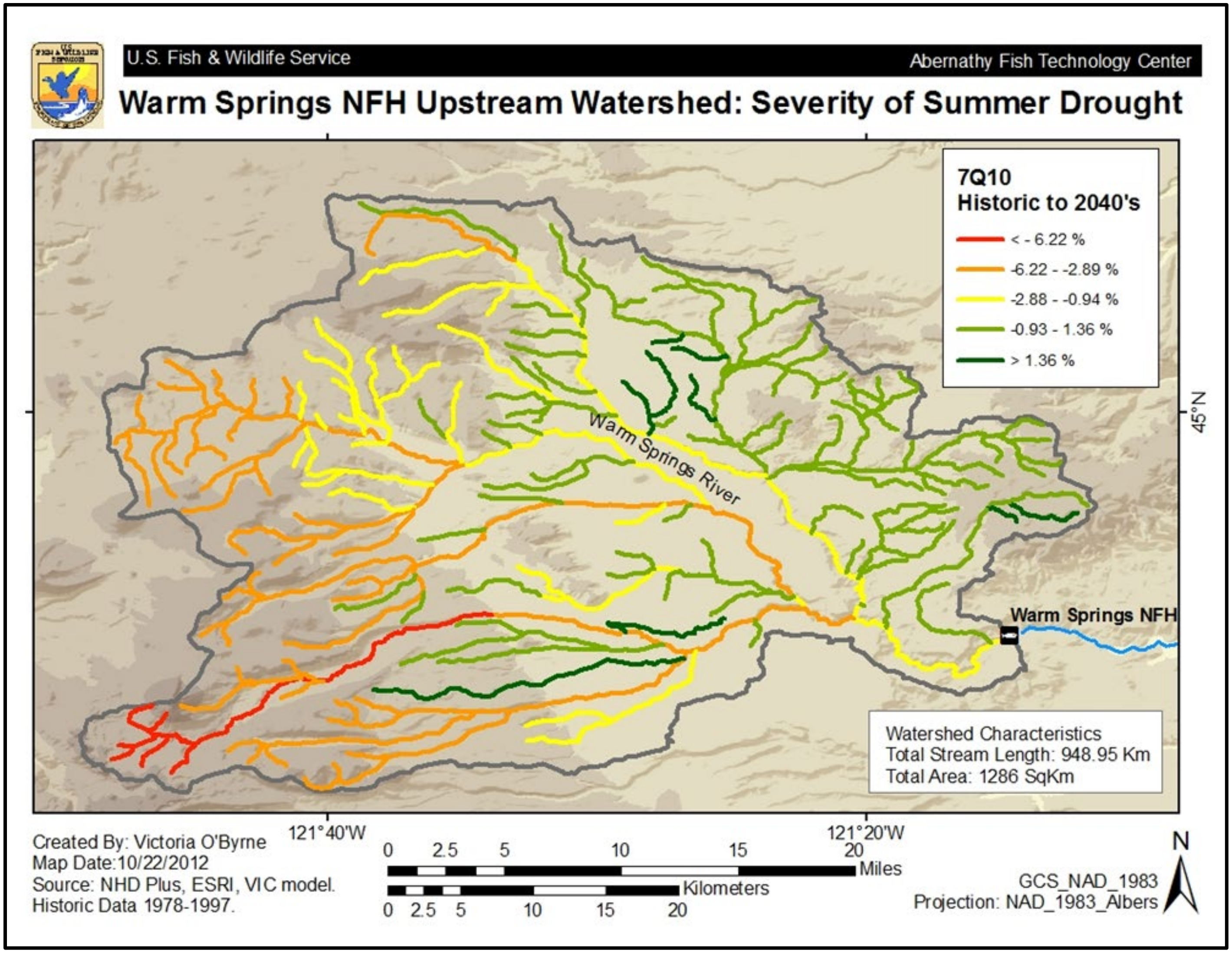

Figure B11. Projected change in the severity of summer drought (7-day low flow 10-yr return interval [7Q10]) for the Warm Springs River basin upstream from Warm Springs NFH between the 1980s and 2040s periods. Data are from VIC hydrologic model (Wenger et al. 2011), and the historical reference period is 1978 – 1997

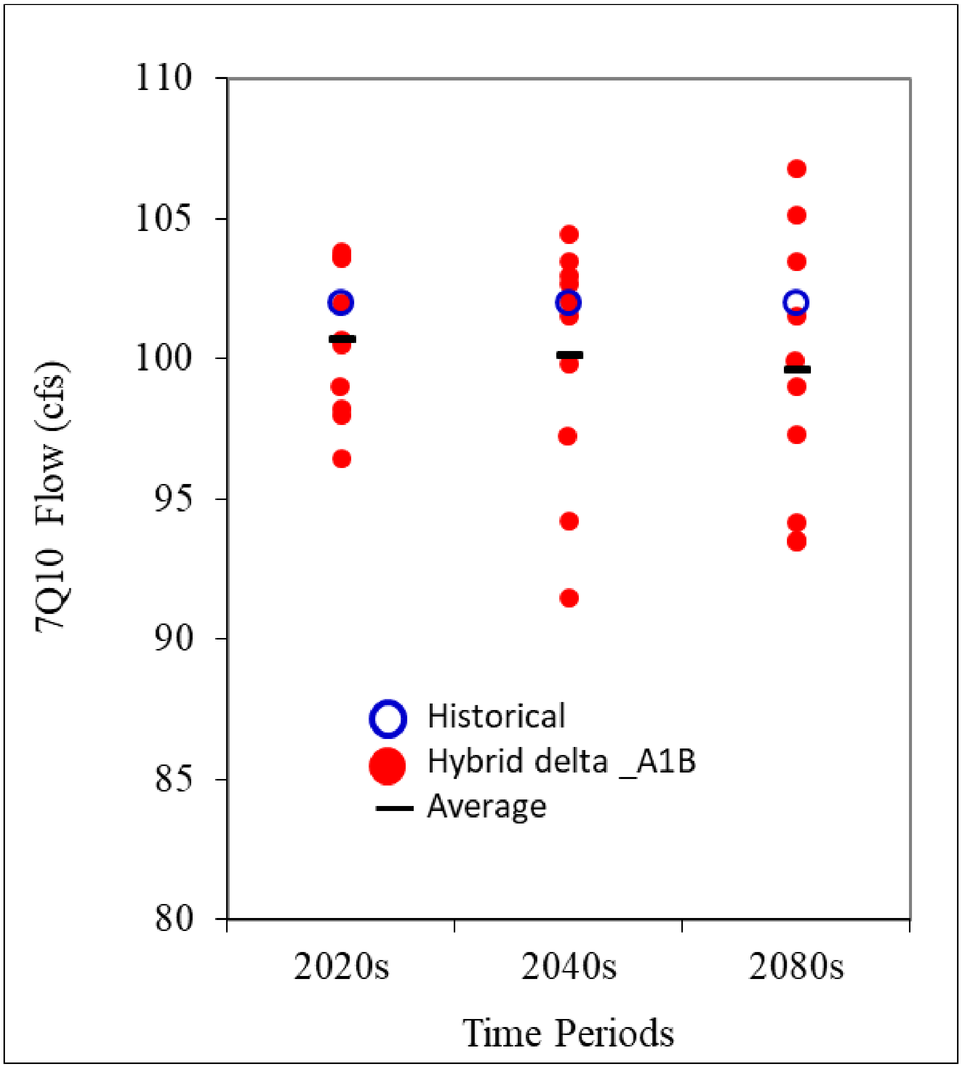

Figure B12. Projected flow rate for the 7-day low flow with a 10-yr return interval (7Q10) in Warm Springs River adjacent to the Warm Springs NFH based on raw Variable Infiltration Capacity (VIC) simulations for the 2020s, 2040s, and 2080s. Flows projections are based on the VIC model forced by output from an ensemble of 10 general circulation models (GCMs) under the A1B greenhouse gas emissions scenario. Red dots are the projections for the individual GCMs with hybrid-delta downscaling, the black horizontal dash (-) is the ensemble average, and the open blue circle is the historical mean value.

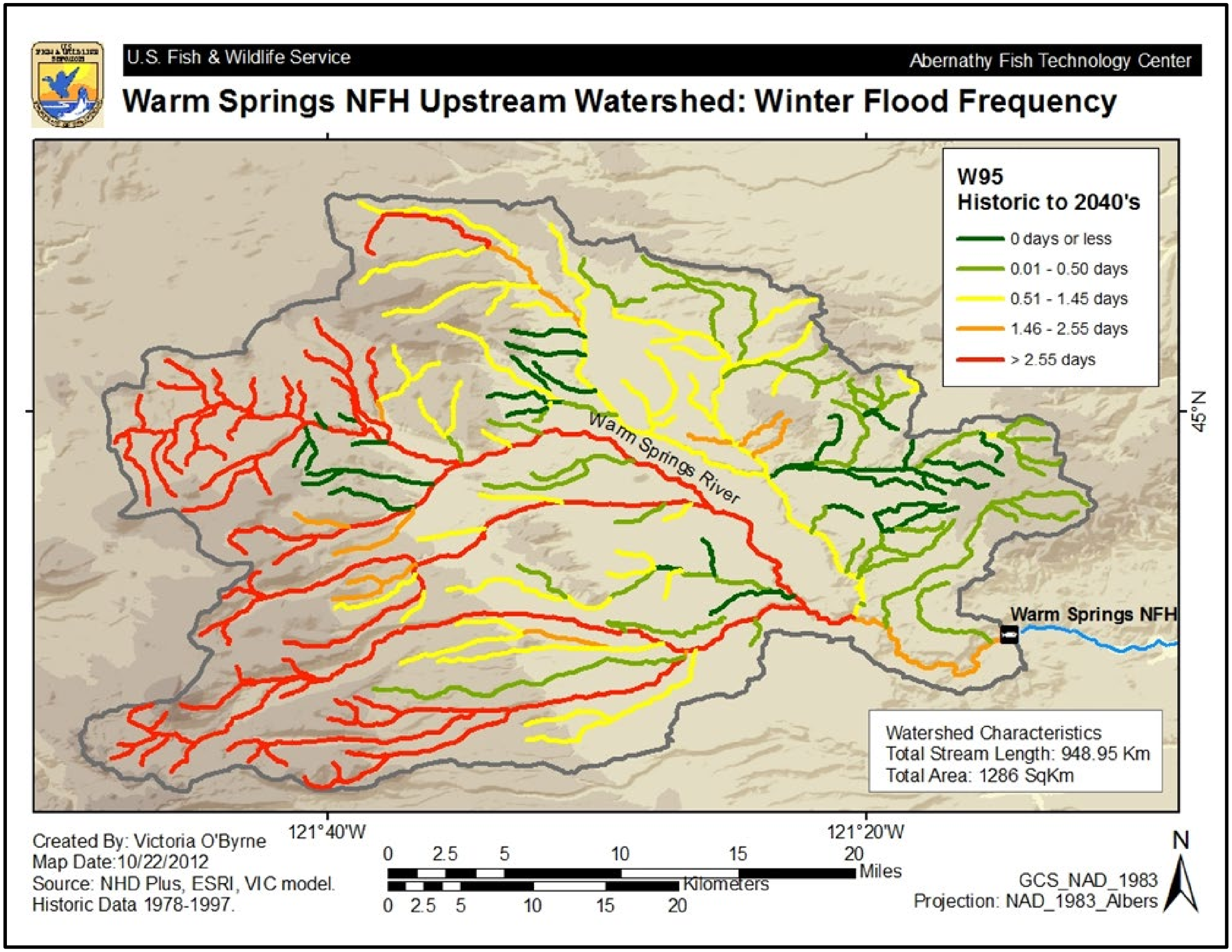

Figure B13. Projected change in the frequency of winter high flows (W95: number of days between December 20 and March 20 when modeled flows were in the top 5% of annual flows) between the 2040s and the historical reference period (1978 – 1997) for the Warm Springs River basin upstream from Warm Springs NFH. Data are from the VIC hydrologic model (Wenger et al. 2011).

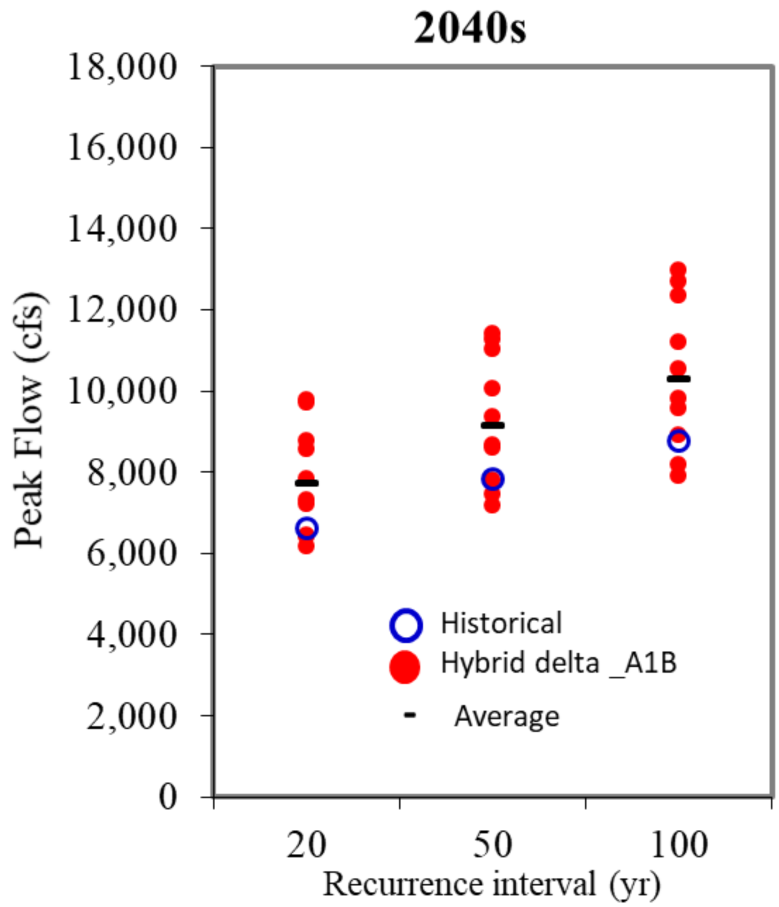

Figure B14. Magnitude of 20, 50, and 100-year recurrence interval floods for Warm Springs River adjacent to the Warm Springs National Fish Hatchery based on raw Variable Infiltration Capacity (VIC) simulations for the 2040s. Flows projections are based on the VIC model forced by output from an ensemble of 10 general circulation models (GCMs) under the A1B greenhouse gas emissions scenario. Red dots are the projections for the individual GCMs with hybrid-delta downscaling, the black horizontal dash (-) is the ensemble average, and the open blue circle is the historical mean.

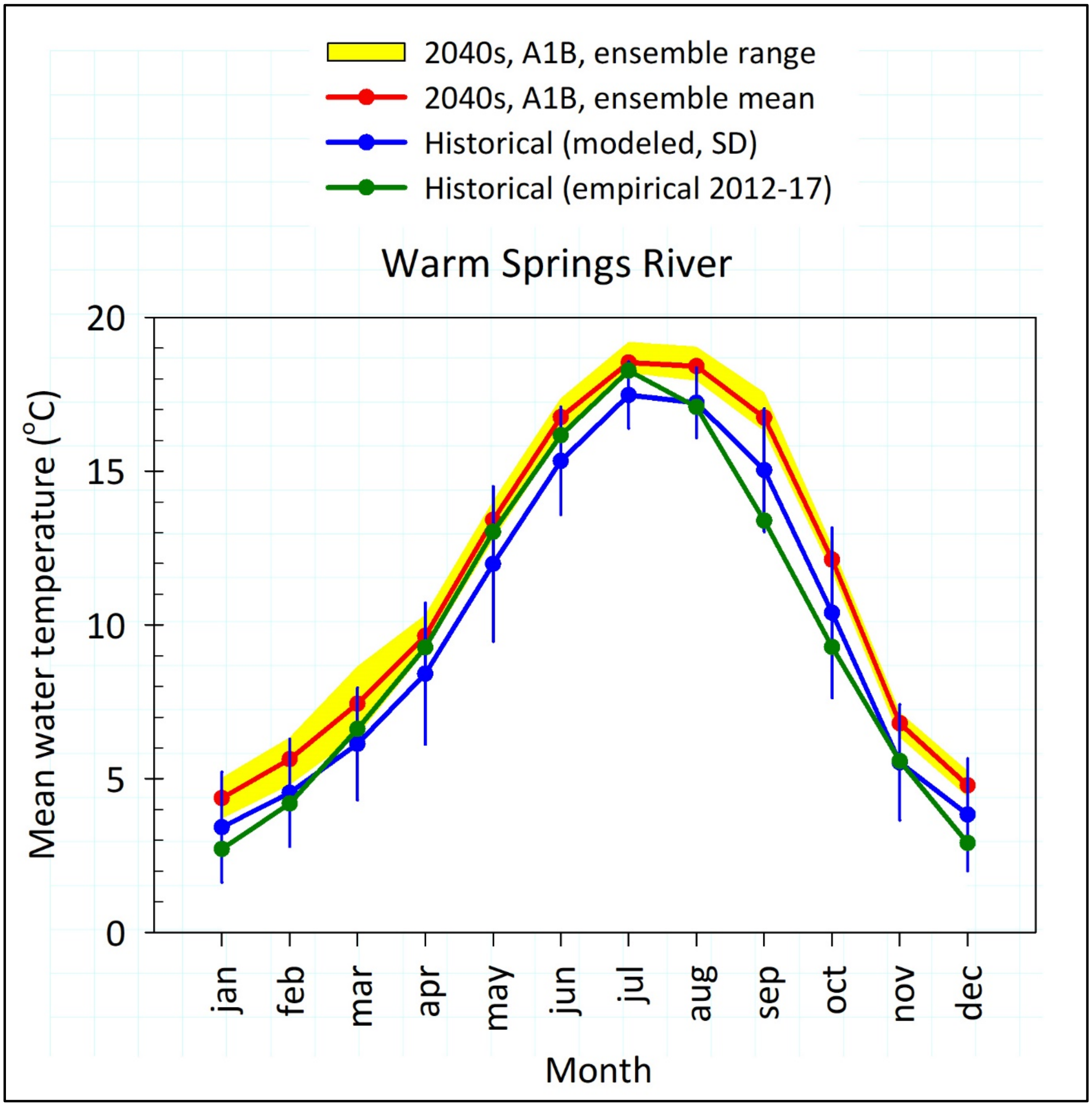

Figure B15. Measured and modeled water temperatures in Warm Springs River at the diversion structure for Warm Springs NFH. Modeled estimates of projected (2040s) water temperatures were generated via the regression model and are forced by output from an ensemble of 10 GCMs under the A1B greenhouse gas emissions scenario. The modeled historical period is based on the 1915 – 2006 meteorological record, and the 2040s represents a 30-year period (2030 – 2059) centered on the decade of the 2040s. Empirical point estimates based on thermograph data during 2012 – 2017 (green plot) are shown for reference, and error bars are SD. The simulated historical values is presented to show the variability across 1915 – 2006, and error bars are SD.

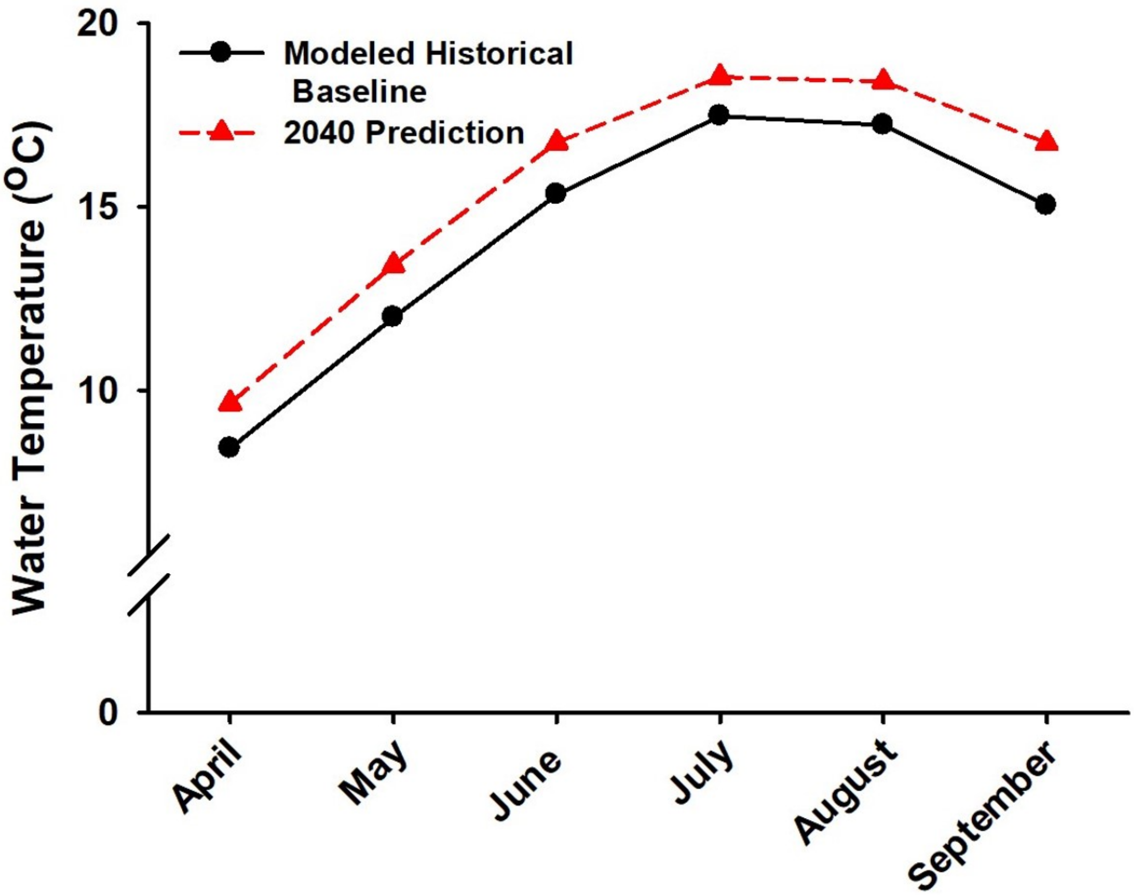

Figure B16. Comparison of the mean water temperatures experienced by adult Spring Chinook Salmon broodstock held at Warm Springs NFH based on the simulated historical baseline and projected values for the 2040s under the A1B emission scenario.

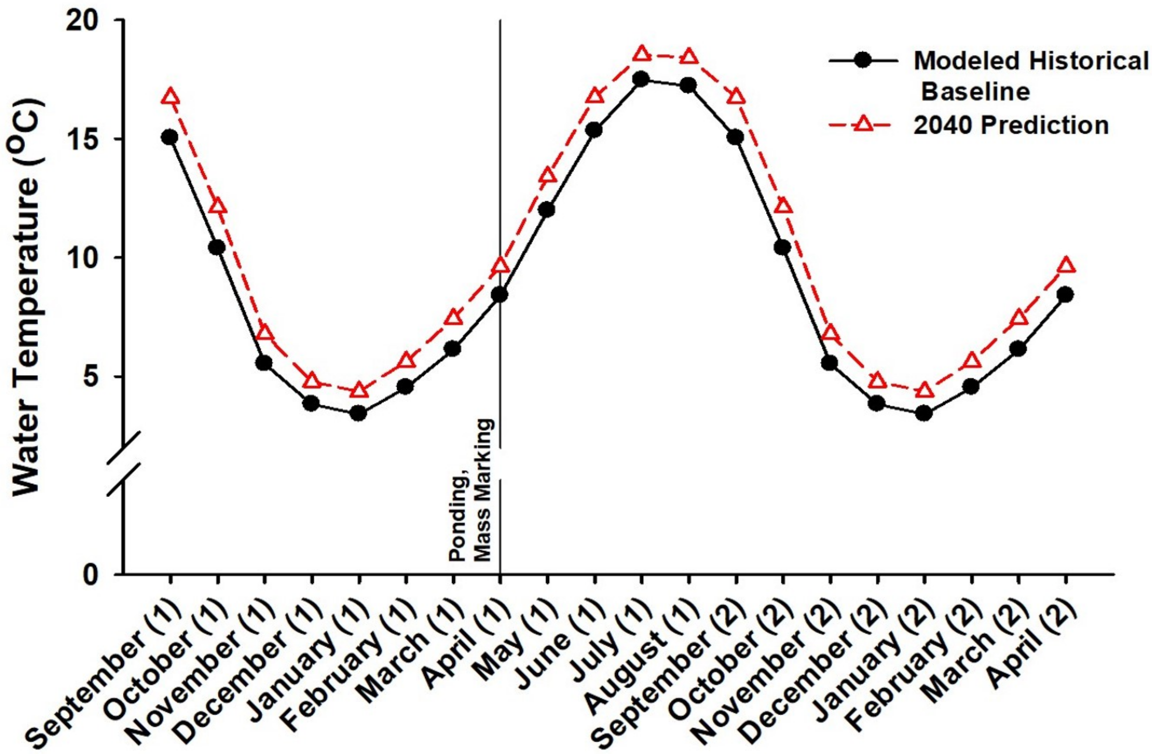

Figure B17. Comparison of the mean water temperatures experienced by juvenile Spring Chinook Salmon reared at Warm Springs NFH based on the simulated historical baseline and projected values for the 2040s under the A1B emission scenario.

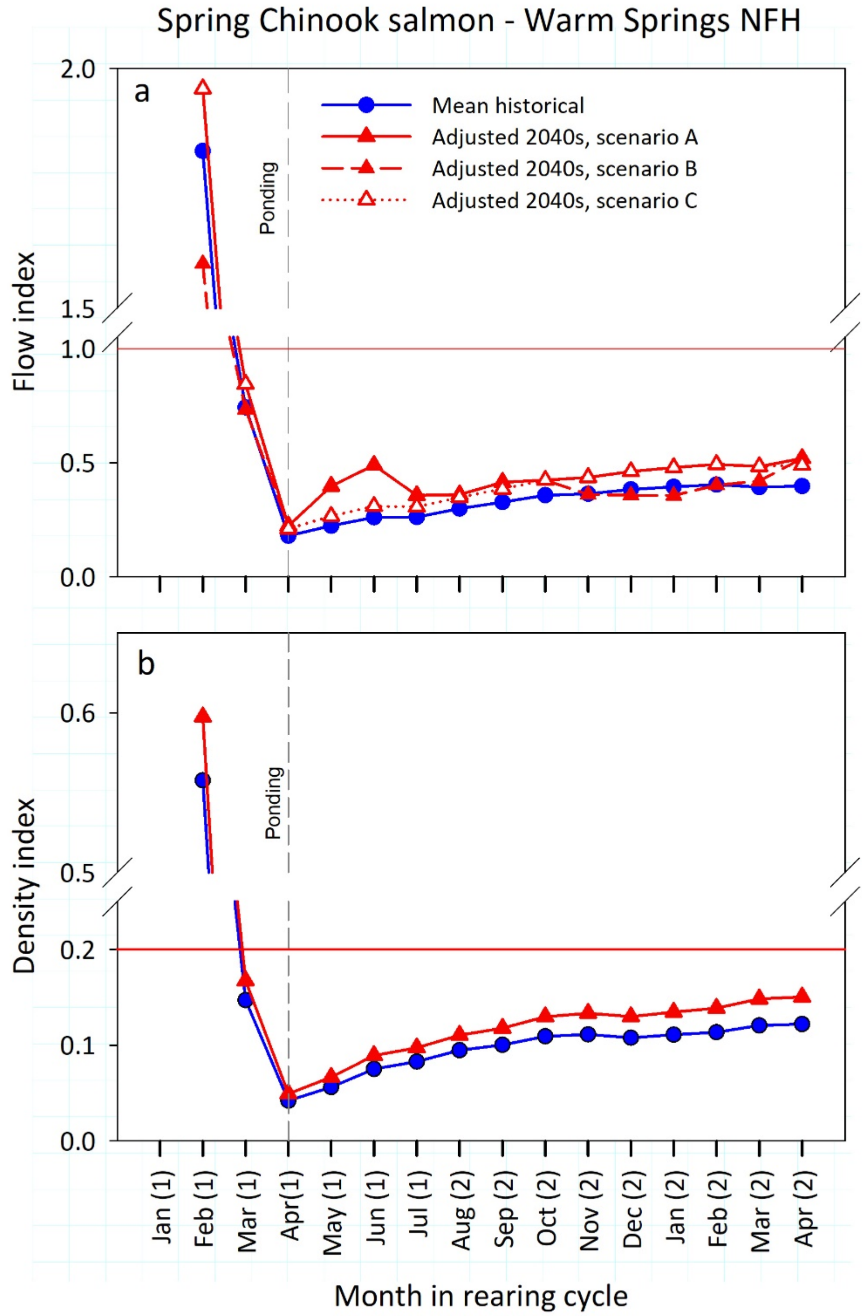

Figure B18. Mean historical and bias-corrected future flow index (a) and density index (b) values for Spring Chinook Salmon at Warm Springs National Fish Hatchery based on average rearing conditions during 2000 – 2004 and 2008 brood years, one future temperature scenario (see Figure B20), and a future for surface water flow in the Warm Springs River that affects rearing water availability in three different ways (see Table B11). Values for the 2040s have been bias corrected by multiplying the uncorrected future values by the ratio: (observed average historical value across 2000 – 2004 and 2008 brood years) / (modeled historical value). See Table B7 for bias correction values. The red horizontal lines represent the upper-limit, fish health guidelines for flow and density indices for Spring Chinook Salmon.

This page left blank purposefully.