Appendix B: Modeling the potential effects of changed water availability, water temperature, and sea level rise on Pacific salmon culture programs at Leavenworth National Fish Hatchery

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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 Leavenworth 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 Icicle Creek basin in Washington State – 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. We evaluated fish growth under future environmental conditions based on direct modeling of water flow and temperature of Icicle Creek under four scenarios with different assumptions about future temperature changes of groundwater and alpine lake (Upper Snow Lake) water resources. By the 2040s, surface water sources for Leavenworth NFH are expected to be warmer in all months with Chinook Salmon in the facility experiencing temperatures of 0.1 – 2.1 °C greater than the historical average. As a result, under the most conservative scenario we considered with respect to future increases in water temperature, juvenile Chinook Salmon reared at Leavenworth NFH are projected, on average, to be approximately 25% heavier and 7.5% longer at release because of faster growth rates. Concurrent with higher temperatures, the annual hydrograph in Icicle Creek will differ from historic average 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 2040s are projected to increase future FI values that will exceed fish health guidelines (FI < 0.6) for yearlings from August until April when fish are released. Similarly, increased fish growth may result in DI values that exceed threshold guidelines (DI < 0.2) by April (at release) if supplemental water from Upper Snow Lake warms at a similar rate to what is projected for Icicle Creek. Under these future conditions, physiological stress, disease risks, and mortality of Chinook Salmon reared at Leavenworth NFH will likely increase if current culture practices and infrastructure remain unchanged. Projections for reduced surface water flows during late summer in Icicle Creek by the 2040s, combined with existing surface water diversions that occur upstream from the hatchery for irrigation, suggest that complete dewatering of Icicle Creek is probable during August and September if additional water resources within the watershed are not available and current water use practices remain unchanged. As a result, managers could face a trade-off between diverting water released from Snow Lake for the hatchery vs. leaving it in Icicle Creek to meet instream flow requirements. The efficacy of current practices that mitigate for reduced water availability from Icicle Creek (e.g., timing and use of Snow Lake water rights) and high flow indices (e.g., serial reuse of water) during the summer may require additional

evaluation because both approaches may be constrained hydrologically under future climatic conditions.

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 due to 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 marine food webs 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 cultured 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 USFWS Fish and Aquatic Conservation program can design and implement climate mitigation and adaptation strategies.

Given these premises, our overall objective 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 impacts detected in (a) and (b). To achieve these objectives, we collated – from the scientific literature – 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 Leavenworth NFH, located on Icicle Creek – a tributary to the Wenatchee River – in north-central Washington State (Figure B1). We first describe hydrologic changes projected for the Icicle Creek basin upstream from the hatchery in the 2040s based on a moderate, future greenhouse gas emission scenario (A1B scenario; IPCC 2007). We then use empirical data on recent fish rearing conditions within the hatchery to predict 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. Our analyses include four scenarios that assume different changes in temperature of the groundwater and supplemental water supplies for the hatchery.

METHODS

Salmon thermal tolerances

In August 2011, a review of the peer-reviewed scientific literature of thermal tolerances of five focal species of Pacific salmon and anadromous 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 was performed 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 Leavenworth 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 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.

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

Water sources for Leavenworth NFH

Water management at Leavenworth NFH is complex because the facility uses a combination of surface water from two sources (Icicle Creek and Snow Creek) and groundwater from seven sources (four shallow wells and three deep wells) to rear salmon (Figures B2 and B3; see also Table 1 in main report). Surface water is diverted from Icicle Creek to the hatchery via an intake pipe approximately 0.6 miles (1 km) upstream of the hatchery property. Groundwater is used only at specific times in the rearing cycle to supplement surface water. In addition, an Icicle Creek bypass channel adjacent to the hatchery (referred to as the "hatchery channel") is re-watered as needed to recharge, via percolation, the shallow wells to supplement the water supply to the hatchery (Figures B2, B3). Additionally, the hatchery owns a water storage right (16,000 acre-feet per year) to Upper Snow Lake (total capacity = 12,400 acre-feet) in the Alpine Lake Wilderness Area (Anchor QEA 2010). Water is released from Upper Snow Lake via a control valve and bored tunnel into Nada Lake, which outflows naturally into Snow Creek, a tributary to Icicle Creek (river mile [RM] 5.5 [rkm 8.9]) approximately one mile upstream from the water intake for the hatchery (see Figure 3 in main report).[4] Water released from Upper Snow Lake supplements stream flows and reduces water temperatures of Icicle Creek during the critical summer months when up to 120 cfs of water can be diverted from Icicle Creek for irrigation and municipal use via a primacy water right (Fraser 2015; Potter et al. 2017).[5]

The U.S. Fish and Wildlife Service (USFWS) monitors water temperature at the hatchery and at several locations in the Icicle Creek drainage upstream and downstream of the hatchery (e.g., Fraser 2015), and reasonably complete temperature data are available for the past decade (Table B3; Figure B3).[6] To represent water conditions experienced by fish in the hatchery and to project future conditions, we needed to account for all the constituent water sources and their potential mixing. We were thus interested in temperatures and discharge (or water use) from (a) the deep and shallow wells, (b) Icicle Creek upstream from the confluence with Snow Creek (thermograph site IC1), (c) Snow Creek upstream from the confluence with Icicle Creek (RM 0.2 of Snow Creek, thermograph site IC2), and (d) Icicle Creek at the hatchery intake (RM 5.5 of Icicle Creek, approximately 100 meters upstream of the confluence of Snow Creek, thermograph site IC5; Table B3 and Figure B3). At approximately RM 5.8 (rkm 9.3), and 0.3 miles (0.5 km) upstream from the IC1 thermograph site (Table B3), the Icicle-Peshastin Irrigation District (IPID) diverts Icicle Creek water for both irrigation and municipal uses (Table B4).

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[4] In 1939, the U.S. Bureau of Reclamation constructed a bored tunnel with a valve into the bottom of Upper Snow Lake that allows water to be released at a controlled rate into Nada Lake that drains naturally into Snow Creek.

[5] The Icicle-Peshastin Irrigation District (IPID) and the City of Leavenworth have *primacy* water rights April – September of 117 cfs and 3 cfs, respectively, at RM 5.8, approximately 0.3 miles upstream of the confluence of Snow Creek and 1.3 miles upstream from the water intake for the hatchery.

[6] Data are missing for some years and months due to loss or malfunction of thermographs.

Surface water temperatures upstream from Leavenworth NFH

When salmon are being reared with surface water only, the water temperatures at IC5 (at the hatchery intake) are assumed to be representative of the thermal conditions within the hatchery rearing units. During August and September, temperatures at IC5 are influenced by release of water from Upper Snow Lake. Following standard operations, up to 60 cfs of water is drained from Upper Snow Lake into Snow Creek starting in late July to supplement Icicle Creek during low summer flows. In low flow situations, water originating from Upper Snow Lake ultimately represents a majority of the surface water in Icicle Creek that reaches the facility.

We were interested in isolating the thermal effect of supplemental flows from Snow Creek so that we could account for that effect under the thermal and hydrologic regimes projected for the 2040s. To do this, we needed to predict temperatures at IC5 (hatchery intake) as a function of discharge and temperature at IC2 (Snow Creek) and IC1 (Icicle Creek upstream of the confluence with Snow Creek). We started by establishing a regression relationship between monthly water temperatures at IC1 and IC5 using data from 2005 – 2006, 2008 – 2009, and 2011 – 2015, but excluding August and September which are months when temperatures at IC5 would be influenced by the water releases from Snow Lake[7]. The regression model was statistically significant (P-value <0.0001 with 1 and 8 d.f.), and explained over 99% of the variation in monthly temperatures at IC5. The predictive equation was:

$$IC5\ temperature\ (°C) = 0.0621 + 1.00953 \bullet IC1\ temperature\ (°C).$$

Second, we established a regression relationship between air temperature and water temperature at IC1 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 at IC1, which, in turn, served as inputs to predict water temperatures at IC5 for the months when water is not being released from Snow Lake. The non-linear regression model of Mohseni et al. (1998) is intended for use with weekly time-series data and takes the form,

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

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 Icicle Creek watershed was estimated from historic air temperatures downscaled from global climate models[8] by aggregating the daily mean air

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[7] Snow Creek naturally discharges into Icicle Creek, but the managed water releases from Upper Snow Lake represents additional discharge to Snow Creek.

[8] Flux files from: http://warm.atmos.washington.edu/2860 .

temperatures within the area of overlap between the 1/16° grid cells (scale of the downscaled historic climate data) and the Icicle Creek watershed boundary upstream from the Leavenworth NFH, as delineated by a Geographic Information System (GIS; see Figure B4). Consequently, we refer to the historic air temperatures as *area-weighted values*.

The modeled historical air temperature data covers the period of 1915 – 2006, but we only had water temperature data at IC1 that spanned the 11-year period of 2005 – 2015. We explored three approaches to fitting the model given the data in hand: (a) mean historical air temperature over 1915 – 2006 and mean IC1 water temperature over 2005 – 2015 (model fit 'a'), (b) a 78-week period of overlap between the two datasets in 2005 – 2006 (model fit 'b'), and (c) mean historical air temperatures for the most recent 11-year period 1996 – 2006 and mean IC1 water temperature over 2005 – 2015 (model fit 'c'). 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'. We were concerned that the short temporal overlap for model fit 'b' could result in parameter estimates strongly influenced by environmental conditions in a single year. Moreover, model fit 'b' had the lowest Nash-Sutcliff efficiency (0.896), whereas model fits 'a' and 'c' had nearly identical Nash-Sutcliff values (0.945 and 0.941, respectively). Predictions for fits 'a' and 'c' were similar for air temperatures below about 13 °C, but at higher air temperatures, model fit 'a' yielded higher water temperatures than model fit 'c'. For example, predicted water temperature under model fit 'a' was 1.3 °C warmer than under model fit 'c' when air temperature was 18 °C. For the purpose of assessing future risks due to climate change, we believed that managers would be better informed to address adaptation and mitigation strategies based on slightly higher water temperatures than temperatures that might underestimate actual future temperatures. This latter perspective was further supported by the results of our retrospective analyses. Actual mean historic annual water temperature at IC1 based on weekly empirical data was 6.42 °C, whereas model fits 'a' and 'c' predicted 6.49 °C (+0.07 °C) and 6.29 °C (-0.11 °C), respectively. We further inspected plots of the predicted future water temperature values for these two model fits at both weekly and monthly time steps – relative to historic empirical water temperatures at IC1 – and found that model fits 'a' and 'c' both predicted future peak temperatures that were earlier (in July) than what was generally observed in the historic empirical data (most often in August). Model fit 'a' also appeared to better represent the *magnitude* of the peak summer temperatures in the empirical data. Based on these comparisons and evaluations, we concluded that the goodness-of-fit between the air temperature and water temperature data was slightly better for model fit 'a' than model fit 'c'. Model fit 'a' thus yielded the following equation to predict water temperatures (T_{sw}) at IC1:

$$T_{sw} = 0 + \frac{20.93+0}{1+e^{0.18(9.25-T_{air})}} \ .$$

Predicted weekly historic surface water temperatures at IC1 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[9] 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).[10]

Weekly historic and 2040s surface water temperatures at IC1 were then aggregated by month to generate estimates of monthly surface water estimates at IC5 using the linear regression model. These estimates assume a natural hydrograph in Snow Creek and depict a situation where water is not being released from Upper Snow Lake. To account for the effect of water releases from Upper Snow Lake on water temperatures at IC5 during late summer, we applied a standard mixing equation to temperature and discharge values at IC1 (Icicle Creek), temperatures at IC2 (Snow Creek), and the estimated releases from Upper Snow Lake such that:

$$IC5\ temperature(°C)\ during\ Snow\ Lake\ releases =$$

$$\frac{(IC1\ temp\ [°C]) \bullet (IC1\ dicharge\ [cfs]) + (IC2\ temp.[°C]) \bullet (Snow\ Lake\ releases\ [cfs])}{(IC1\ discharge\ [cfs]) + (Snow\ Lake\ releases\ [cfs])}$$

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

[10] 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). A1B is one of a family of scenarios used in fourth global climate assessment (AR4) that describe greenhouse gas emissions under alternative developmental pathways assuming different future expectations for demographic, economic, and technological outcomes with 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 greenhouse gas emissions and other atmospheric elements that affect the radiative forcing of the earth's climate through time and 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; 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 Leavenworth NFH to maintain quantitative consistency with our previous and other ongoing vulnerability assessments of NFHs in the Pacific Northwest.

This latter equation was applied only during August and September when water is released continuously from Upper Snow Lake (e.g., Fraser 2015). These water releases typically begin the last week in July or the first week in August, and we used mean monthly release rates from Upper Snow Lake and water temperatures at IC2 in Snow Creek during 2005 – 2015 to estimate water temperatures at IC5. These calculations also considered whether water was being diverted at the IPID diversion (see Table B4)

Our purpose in decomposing the effect of Snow Lake on water temperatures at IC5 during August and September – by either applying the mixing equation to account for releases or simply using the linear regression for no releases – was so that we could more accurately represent its effect in the 2040s for evaluating the sensitivity of fish growth to water management of Upper Snow Lake. Additionally, we explored two potential future scenarios concerning Upper Snow Lake releases that encompass what we assume are best and worst cases. For the best-case scenario, we assumed the temperature of Snow Lake water releases in August and September during the 2040s would be the same as the recent average. Our reasoning here is that Upper Snow Lake is at high elevation and supplied by melting snow, so water temperatures would remain generally very cold, and the release valve drains water from the bottom of the lake which should be below any thermocline that has formed in August and September. For the worst-case scenario, we assumed that water from Snow Lake released in August and September would be 2 °C warmer than the recent average. Our reasoning here is there might be some warming that occurs: (a) in Snow Lake that could be exacerbated if the lake was drawn down significantly, (b) when the released water mixes with natural surface flow during its conveyance through Snow Creek where temperature are also projected to rise (e.g., see NMFS 2017), and (c) between where the water is discharged into Icicle Creek and before it reaches the hatchery's water intake. In aggregate, the 2 °C warming of the Snow Lake water would be similar in magnitude to what is projected for Icicle Creek.

Groundwater temperatures at Leavenworth NFH

The supply wells used by Leavenworth NFH are drilled into unconsolidated alluvial and glacial deposits and are hydraulically connected to Icicle Creek and the hatchery channel (McMillen Jacob Associates and DJ Warren Associates 2016). The shallow wells (#1, 2, 3, and 7) appear to be connected to a shallow, unconfined aquifer at the southern portion of the hatchery's footprint adjacent to the hatchery channel (Figure B2). The deep wells (#4, 5, and 6) are located further north (Figure B2) and appear to tap a localized and confined aquifer that underlies a layer of silt and clay. Water from the deep and shallow wells are blended in separate mixing chambers before entering the rearing units occupied by salmon, The shallow wells are approximately two degrees colder, on average (7.14 ± 0.97 °C, mean ± SD), than the deep wells (9.11 ± 0.23 °C) based on measurements at the mixing chamber.

We performed exploratory linear regression analyses to determine if monthly well temperatures were correlated statistically with surface water temperatures recorded at the Leavenworth NFH intake (IC5). Our objective was to determine if we needed to account for monthly variation in either set of wells and, thus, provide a basis for translating projected changes in surface water temperatures in Icicle Creek to potential future changes in well temperatures. We found that the blended shallow well temperatures were not correlated statistically with mean monthly surface water temperatures at IC5 under three separate assumptions: no time lag, a one-month lag, or a two-month lag ($P = 0.235 – 0.571$, with 1 and 10 d.f.). Similarly, water temperatures associated with test wells drilled into the aquifer next to the shallow wells did not appear to vary with surface water temperatures (Mary Lindenberg, USFWS R1 Water Resources, personal communication, Feb. 2, 2018). We subsequently determined that the regression equation for the blended deep-well temperatures may not be statistically valid (i.e., violation of underlying assumptions) because observed increases in blended well-water temperatures during the summer months in some years appeared to result from turning off or on individual wells that differed in temperature. Specifically, Well 4A is colder than Wells 5 and 6, and turning off Well 4A in the summer months could lead to a spurious conclusion that warmer surface water temperatures were responsible for the increase in well water temperature. Because we could not establish a statistical relationship between well and surface water temperatures, we analyzed two feasible scenarios for future well temperatures in the 2040s: (1) same constant temperature as the historical average for each well category (i.e., shallow-well mean = 7.1 °C, deep-well mean = 9.1 °C), and (2) an increase of 0.25 °C in all months when compared to historical averages.

Summary of modeled scenarios for water temperatures in the 2040s

Future water temperatures in Icicle Creek were modeled directly, as described above, with four potential scenarios for future water temperatures of Upper Snow Lake and well water that we could not model directly:

- ***Scenario A:*** no warming of Upper Snow Lake or well water (i.e., no change in temperatures from the historic average);
- ***Scenario B*****:** no warming of Upper Snow Lake but a 0.25 °C increase of well water temperatures;
- ***Scenario C:*** 2 °C increase in Upper Snow Lake but no warming of well water;
- **Scenario *D:*** 2 °C increase in Upper Snow Lake and a 0.25 °C increase of well water temperatures.

Projected water availability at Leavenworth NFH during the 2040s

To generate estimates for water availability at Leavenworth 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 Icicle Creek routed to the location of Leavenworth NFH (A. Hamlet, Climate Impacts Group, University of Washington, unpublished data). We assumed 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. The 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 the period of 2007 – 2010. 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). Additionally, we assumed the facility could not utilize additional water above the mean historical use for months where an increase in mean flow is projected.

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 Leavenworth 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:

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

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:

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

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

We applied the growth model to estimate monthly mean fish sizes of Spring Chinook Salmon after "ponding" (transfer) to outside raceways. 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 (a) recent historical conditions and (b) the four scenarios (A, B, C, D) projected for the 2040s. We then compared cumulative differences in mean size of Chinook Salmon between historical and projected thermal regimes.

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) or (b) total rearing volume or capacity (density index):

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

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

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 (lbs), L_i is mean fish length (in), GPM_i is water use rate by the hatchery (gallons per minute), 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), thereby linking 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 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 Leavenworth 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 Leavenworth 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:

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

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

Thus, the future bias-corrected index values were:

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

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

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

RESULTS

Projected future climate in the Icicle Creek basin and at Leavenworth NFH under the A1B emissions scenario

Under the A1B emissions scenario by the 2040s, the Icicle Creek basin is projected to experience, (a) warmer air and stream temperatures, (b) reduced snowpack and earlier snowmelt runoff, (c) lower base flows and more extreme low-flow events in summer, and (d) higher flows in winter and larger magnitude 100-year peak flows (Table B5; Figures B5 – B15). Mean air temperature over the entire watershed is expected to increase in every month (mean increase = 2.0 °C, SD = 0.54 °C) with the largest absolute increases projected for July – September (range 2.6 – 3.0 °C; Table B5 and Figure B5). Total annual precipitation is projected to show little change, within 6% of the historical baseline (historical: 142 mm, 2040s: 150 mm). Seasonal differences may be possible, but the monthly historical precipitation generally falls within the range of predictions from the 10 GCMs (Table B5; Figure B6). Icicle Creek currently has a snowmelt-driven hydrology, and the 10 GCMs averaged a projected 28% reduction in peak snow water equivalent (SWE) in April (mean historical peak = 784 mm, 2040s mean = 562 mm) and a 35% reduction in mean monthly snowpack (mean historical monthly = 341 mm, 2040s mean = 223 mm; Table B5; Figure B7) for the 2040s. Consequently, with little projected change in total precipitation, more precipitation is expected to fall as rain and less precipitation as snow.

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[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).

Based on the VIC modeling, mean *annual* flows projected for Icicle Creek in the 2040s will be quite similar or slightly higher than modeled historical values (historical = 600 cfs, 2040s ensemble mean = 635 cfs) and within the range of projections from each of the 10 GCMs (Table B6). The same pattern is apparent when the flow data are plotted by stream segment across the contributing basin (Figure B8). The historical monthly hydrograph simulated by the VIC model was similar in shape to the hydrograph derived from empirical observations at the USGS gage for 1936 – 2017, although the modeled hydrograph appeared to underestimate flows in May and June and overestimate flows in July (Figure B9).

The shape of the modeled hydrograph for the 2040s was projected to be quite different from the historic average, with higher flows in late fall and winter, lower peak runoff (in June), and consistently lower flows in summer (Figures B9 – B15). Mean flows of Icicle Creek in the late fall and winter (November – March) in the 2040s at Leavenworth NFH were projected to increase by an average of 76.9% (ensemble range 62 – 108%) but decrease by an average of 42.5% (ensemble range -18.9% to -67.8%) in summer (June – September) (Figures B9 and B10). The date at which half the annual discharge occurs on a particular calendar day is projected to be more than two and a half weeks earlier in the 2040s for most of the stream segments in the Icicle Creek basin (Figure B11) with summer low flow events (7Q10) predicted to be more severe across much of the basin (Figures B12 and B13). In winter, the number of *W95* days – defined as the number of days in a calendar year when surface flows are among the top 5% (18 – 19 days) of annual daily flows – is projected to increase by at least one day across much of the basin and more than 2.55 days in Icicle Creek at the hatchery (Figure B14). The magnitude of very large flows or "100-year floods" (Q100) in the vicinity of Leavenworth NFH is also projected to increase by over 50%, from a historical average of approximately 9,500 cfs to approximately 15,000 cfs (12,000 – 21,000) in the 2040s (Figure B15 and B16).

Water temperature in Icicle Creek upstream of its confluence with Snow Creek (IC1) and at the surface water intake to Leavenworth NFH (IC5) are projected to be warmer in every month in the 2040s compared to the historical period (Table B7; Figures B17 and B18). At IC1, mean annual water temperature is projected to increase by 1.3 °C with increases of more than 2 °C predicted during July, August, and September. Virtually identical differences are projected at IC5 if the effect of cold water releases from Snow Lake are discounted (Table B7; Figure B18). If water releases from Snow Lake in August and September are applied, the mean annual temperature at IC5 increases by only about 1.5 °C and 1.1 °C in those two months, respectively (i.e., cooling of about 0.7 °C and 1.2 °C from the Snow Lake releases; Table B8) assuming that no water is diverted at the IPID diversion upstream from IC5 (Figure B18a).

Spring Chinook Salmon program

Adult Chinook Salmon returning to Leavenworth NFH are typically captured for broodstock from mid-May to early July and retained in holding ponds prior to spawning in early September (Cooper 2006). These ponds are supplied with a mix of groundwater and surface water from Icicle Creek until spawning. By the 2040s, water temperatures in the holding ponds from May through September are predicted to increase by 0.0 – 1.1 °C with the highest mean monthly water temperature during the broodstock holding time period – assuming no change in well water and Snow Lake temperatures (Scenario A) – predicted to be 11.1 °C (Table B9; Figure B19). When accounting for changes in well water temperatures (Scenarios B and D), an increase of 0.25 °C in the deep wells resulted in slightly higher water temperatures during the broodstock holding period with a maximum of 11.2 °C in June (Table B9; Figure B19). The projected increase in temperatures by the 2040s do not exceed the optimal spawning temperatures for Chinook Salmon (5.7 – 11.7 °C) based on literature values (Table B1), and it is unlikely that adult Chinook will experience physiological stress during holding and spawning due solely to temperature.

Juvenile Chinook Salmon reared in Leavenworth NFH will be exposed to warmer rearing conditions by the 2040s, with mean monthly water temperatures projected to increase by 0.1 to 2.1 °C across the rearing periods (August year 1 to April year 2; Table B9, Figure B18). Increases of more than 1.0 °C are projected for May (+1.3 °C), June (+1.8 °C), July (+2.1 °C), and October (+1.4 °C) of the first rearing year and at the time of release during the subsequent April (+1.1 °C).

For August and September, we modeled two separate scenarios for Snow Lake water temperatures (Figure B20). If conditions in Snow Lake in the 2040s remain the same as the historical baseline (Scenarios A and B), juvenile Chinook Salmon would experience decreases in rearing temperatures in August (-1.1 °C) and September (-0.2 °C). Under these latter scenarios, water temperatures at the hatchery intake are paradoxically cooler in the 2040s scenario despite warmer air temperatures because of complete dewatering of Icicle Creek at the IPID diversion and a complete reliance of the hatchery on cool water from Snow Creek assuming future water withdrawals by the IPID are equal to historic averages; Table B4). If Snow Lake water temperatures increase by 2 °C (Scenarios C and D), then juvenile salmon will experience increases in rearing temperatures in August (0.9 °C) and September (1.5 °C). Higher water temperatures in the wells (Scenarios B and D) would magnify the above-mentioned effects in months where groundwater is supplied to rearing containers (e.g., the first August – April of rearing, Table B9; Figure B20).

By the 2040s, water temperatures are projected to remain below the upper threshold for optimal temperature for eggs/fry and juveniles during rearing at Leavenworth NFH (Table B1; Figure B20). At the time of release, the future water temperature within the facility in April (5.7 °C) is also projected to remain well below the upper limit for proper smoltification (14.0 °C; Table B9). Water temperatures greater than 11 °C are predicted to occur during two to four months during the juvenile stage (Figure B20). Although these latter temperatures are below the optimal growth temperatures for common salmon pathogens (Table B2), higher water temperatures generally increase disease risks for certain pathogens.

While the predicted 2040s temperatures in the hatchery will not generally exceed physiological tolerances of Chinook Salmon, warmer water temperatures will increase the growth rates of juvenile Chinook Salmon throughout the rearing period under the four scenarios that we modeled (Table B10). The largest increases in mean weight and length of Chinook Salmon juveniles are predicted to occur in the warmest months relative to current/historical conditions (July of the first rearing year) and the four months prior to release (January through April of the second rearing year). Under Scenario A (no increases in well water and Upper Snow Lake temperatures), Chinook Salmon smolts from Leavenworth NFH are predicted to be, on average, 24.8% heavier and 7.8% longer at release compared to historical sizes assuming there are no culture modifications or compensatory biological responses (e.g., precocious sexual maturation that reduces growth). Under Scenario D (2 ℃ warming of Upper Snow Lake and 0.25 ℃ warming of well water), Chinook Salmon smolts from Leavenworth NFH are predicted to be, on average, 35.9% heavier and 10.6% longer at release compared to historical sizes.

Flow index values for Spring Chinook Salmon have historically been close to the threshold guideline value of 0.6 during the last eight months (September – April) of the rearing cycle (Table B11A; Figure B21). Assuming recent average rearing densities and water availability, the increased fish growth resulting from warmer water temperatures in the 2040s are predicted to result in flow index values that consistently exceed the threshold value of 0.6 during those last eight months of the rearing cycle (Table B11B; Figure B21a). Assuming recent average rearing densities and rearing unit capacity continue into the future, the density index is also predicted to increase (relative to the recent average) by the 2040s and approach the threshold guideline value of 0.2 by April, immediately prior to release of smolts (Table B11B; Figure B21b). Otherwise, density index values are predicted to remain below the 0.2 threshold value throughout the rearing cycle (Table B11B; Figure B21b).

DISCUSSION

The results of our analyses suggest that projected warming and hydrologic changes are likely to produce a different set of environmental conditions in the Icicle Creek basin by the 2040s. Warmer air and surface water temperatures are projected for every month. Ignoring the effect of irrigation diversions, mean annual flow in Icicle Creek during the 2040s is predicted to be similar to the historic baseline, but the shape of the annual hydrograph may be quite different with higher flows in winter, greater-magnitude peak flows (i.e., 100-year floods), and lower baseflows with more frequent and intense droughts expected during summer.

Water availability: future trade-offs in a hydrologically altered system

Although hydrologic changes projected for Icicle Creek in the 2040s are significant, total water availability projected for the Icicle Creek basin in the 2040s does not theoretically preclude rearing Spring Chinook Salmon at Leavenworth NFH. However, the Icicle Creek Work Group[12] has proposed a minimum instream flow of 60 cfs in Icicle Creek adjacent to the hatchery as a long-term management goal or strategy. Maintaining that minimum flow during the late summer coupled with surface water diversions upstream from the hatchery (71 – 101 cfs, April – September; Table B4) could present a seemingly fundamental challenge for rearing Spring Chinook Salmon through the summer months at Leavenworth NFH in the 2040s.

The modeled hydrography for the 2040s suggests that, on average, substantially less water will reach the Leavenworth NFH water intake during June – September compared to the historical time period (1915 – 2006) based on current water withdrawals and supplies. If no water is diverted from Icicle Creek upstream of the hatchery in the 2040s, then Leavenworth NFH would be able to divert its full surface water right of 42 cfs from Icicle Creek for fish culture during the low-flow months of August and September when the GCMs project mean flows of 95 cfs and 91 cfs, respectively (Table C4). However, if the current rates of surface water diversion at the IPID diversion structure continue into the 2040s (historic mean flows = 100 and 81cfs in August and September, respectively; Table C4) without additional inflow and/or storage during the spring, then Icicle Creek immediately downstream from the IPID diversion would be totally dewatered, or nearly so, in August and September. In this latter situation, the hatchery would need to depend almost entirely on inflows from Snow Creek to exercise it 42 cfs water right for maintaining Spring Chinook Salmon at the hatchery. However, projected flows from Snow Creek would be barely sufficient for meeting that 42 cfs demand assuming no future increase in water availability from Upper Snow Lake in the 2040s. For example, during the period 2008 – 2017, mean flows of Snow Creek – measured approximately 700 feet upstream from Icicle Creek – averaged 49.0 cfs and 56.5 cfs in August and September, respectively (USFWS R1 Water Resources Branch, unpublished data). During those same two months in 2005 – 2015, water released from Upper Snow Lake averaged 43.3 cfs and 56.2 cfs, respectively, indicating that water flow from Snow Creek into Icicle Creek in August and September depends almost entirely on the controlled releases from Upper Snow Lake. The ESA Biological Opinion for hatchery operations at Leavenworth NFH also notes the possibility of stream dewatering in the 2040s if additional water resources are not secured (NMFS 2017). Moreover, under existing long-term planning strategies, Leavenworth NFH would most likely not be able to maintain any fish on station during August and September because water released from Upper Snow Lake during August and September would need to remain in Icicle Creek to meet the proposed 60 cfs instream flow goal. Other, less draconian trade-offs between water use for the hatchery and instream flows are certainly possible (e.g., additional water storage in the Icicle Creek basin,

[12] https://www.co.chelan.wa.us/natural-resources/pages/icicle-work-group; https://storymaps.arcgis.com/stories/66bedf5374304a5296fdbbeae7075bb2; https://ecology.wa.gov/Water-Shorelines/Water-supply/Water-supply-projects-EW/Icicle-Creek-strategy .

relocation of the irrigation diversion), but the “low-water” scenario outlined above provides a foundation for evaluating future mitigation options and potential management trade-offs.

The magnitude of 100-year peak flows (aka 100-year floods) in the Icicle Creek basin in the 2040s is likely to increase by approximately 50% over historic baseline values, although our model outputs do not allow us to pinpoint the specific month(s) when those higher peak flows will most likely occur. Nevertheless, we can infer when those peak flows are most likely based on a collective examination of our precipitation and hydrology projections. The outputs of our models show a substantial reduction in snow pack during winter and spring. They also show the highest monthly precipitation occurring in November through February, both historically and in the future, with little change in projected values from historic baseline values. Collectively, those results and other model outputs (e.g., W95 projections, Figure B14) suggest that the highest magnitude flows and greatest flood risks (Q100 statistics; Figure B15) will most likely occur November – February when total precipitation is greatest (Fig. B6), but a substantially greater proportion of that precipitation is projected to fall as rain and less as snow compared to historic averages. In a general sense, those projections reflect a transition of the Icicle Creek watershed from a historically snowmelt-driven hydrology to a mixed rain-and-snowmelt driven hydrology in the future. That transition raises the future likelihood of “rain on snow events” in the Icicle Creek watershed compared to historic patterns, further increasing flood risks. Indeed, rain-on-snow events have historically created the greatest flood risks in western Washington where watersheds on the west slope of the Cascade Mountains have historically been mixed rain-and-snow-driven. The extent to which those projected higher peak flows of Icicle Creek pose significant flood risks to Leavenworth NFH cannot be ascertained at this time without additional hydrological and typological modelling of the Icicle Creek channel and ground elevations around the hatchery.

Water temperatures: future challenges of warmer water and faster fish growth

Spring Chinook Salmon reared at Leavenworth NFH are projected to experience higher water temperatures in the 2040s, especially during months when the primary water source for rearing fish is surface water from Icicle Creek (e.g., May – July). For the majority of months, water temperatures are not projected to exceed the physiological thresholds for Chinook Salmon (Table B1), but the magnitude of this warming suggests that fish may experience greater physiological stress and a consequential increase in disease risks in the spring and early summer when water temperatures approach 15 – 16 °C. While mortality from thermal stress would be unlikely, potential decreases in immune function would increase susceptibility to pathogens and disease. For example, at warmer temperatures, juvenile Chinook Salmon at Leavenworth NFH have previously experienced outbreaks of Ich (*Ichthyophthirius multifiliis*) that led to mortality. Additionally, projected water temperatures June – September in the 2040s are near the optimal temperatures for several common pathogens (Table B2) suggesting that the frequency of disease outbreaks may increase.

Under current culture protocols, the total biomass of Spring Chinook Salmon at Leavenworth NFH would likely exceed the ecological capacity of the hatchery prior to their April release in the 2040s because of warmer water temperatures and faster growth. At the end of hatchery rearing, mean length and mean weight of Chinook Salmon smolts at release were predicted to be 8 – 10% and 25 – 36% greater, respectively, in the 2040s across the four scenarios we considered. Under all scenarios, our modeling predicts that flow index values will exceed – with greater magnitude – the guideline threshold value of 0.6 during the last eight months of the rearing cycle compared to only three to four months historically. In contrast, density index values are projected to exceed the guideline threshold value of 0.2 only in the last month of rearing when a 2 °C warming of Snow Lake is included in the model (Scenarios C and D).

Index formulas 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 from 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. Consequently, the predicted increases in flow index values in the 2040s for Chinook Salmon at Leavenworth NFH imply an increased probability of competition and physiological stress, decreased condition factors and immune function, and higher risk of disease. Larger size at release can also lead to (a) precocious sexual maturation, particularly among male salmon (aka, "jacks") within a population (Vøllestad et al. 2004; Koseki and Fleming 2007) and (b) increased ecological risks to naturally-spawning populations through direct predation (Hawkins and Tipping 1999; Namen and Sharpe 2012) or competition for resources (Weber and Fausch 2003; Simpson et al. 2009).

Paradoxically, a significantly greater cooling effect from Snow Lake water was predicted for Icicle Creek at the Leavenworth NFH intake in August and September under Scenarios A and B. This prediction followed from the assumption that water releases from Snow Lake would continue at historic rates but that reduced streamflow in Icicle Creek (i.e., upstream from Snow Creek), coupled with continued water diversions by the IPID, would increase the relative contribution of the colder Snow Creek to downstream flows of Icicle Creek at the water intake for the hatchery. If either of those scenarios is realized in the future, growth rates of fish would decrease in those two months (Table B10) and the risk of thermal stress would likewise decrease when compared to historic conditions. However, this temporary cooling did not counteract the aggregate effect of a warmer environment over the entire rearing cycle and simulations still predicted exceedance of flow index thresholds during rearing and larger fish at release. Moreover, the potential outcome summarized above does not consider instream flow requirements in Icicle Creek during the summer months downstream of the water intake for the hatchery.

Assumptions and uncertainties

We caution that our predictions for higher flow index values in the 2040s may be conservative with respect to water availability and quality. In the case of Leavenworth NFH, we did not directly evaluate how incremental reductions in water availability would influence the flow index. Instead, we assumed that the hatchery would be able to fully utilize its existing surface water right from Icicle Creek, and under that assumption, even the "best-case" scenario for future water temperatures (Scenario A) indicated a high potential for chronic stress. If surface water diversions are not reduced or compensated by other means, then the flow index values would simply increase as predicted unless fish density and/or fish growth are reduced.

In addition, we did not directly consider how water re-use would affect water quality in the hatchery rearing units, and our calculations for flow index assume optimum water quality for fish culture (i.e., single-pass water). During February through April (year 1 of the salmon life cycle), Leavenworth NFH typically uses a serial water reuse strategy in a gravity-feed, tiered raceway structure where juvenile Chinook Salmon in "downstream" raceways receive 50% of their water as effluent from upstream raceways with the remainder a blend of fresh well (45%) and surface (5%) water (Table B9). During December through April of their second year (until release), fish are again subjected to serial reuse after they are moved to adult ponds (see Figure B21) such that 28% of their water supply is "second pass" reuse water and 72% is fresh surface water. In general, water quality decreases because of reduced dissolved oxygen and the accumulation of metabolic waste as it passes through a raceway occupied by fish. This reduced water quality essentially increases the *effective* density and flow indices for fish in raceways subject to serial reuse. However, no accepted way exists currently to quantify those effects mathematically relative to fish-health guidelines. Therefore, the modeled density and flow index values we present here for the 2040s may be conservative from a fish health perspective under current fish-culture protocols and probably underestimate disease risks during months of serial water reuse.

We should emphasize also that our analysis of climate vulnerability for the Chinook Salmon program at Leavenworth NFH focused primarily on the quality (temperature) and quantity (availability) of surface water within the Icicle Creek basin. Hatchery managers have long recognized that year-round hatchery operations at Leavenworth NFH would probably not be possible without both surface- and groundwater sources (USFWS 2014). For example, current protocols require diverting a portion of Icicle Creek through the hatchery channel to recharge the adjacent, shallow wells via percolation. This interdependency (and variability) between surface and groundwater at Leavenworth NFH creates additional uncertainties regarding future conditions for salmon culture.

Consequently, we caution that our assumptions and the uncertainties associated with the modeling approach and available data limit our ability to make more accurate predictions about the future vulnerabilities of the Chinook Salmon program and hatchery to climate change. First, we did not model the dynamics of the groundwater source available to Leavenworth NFH or explore whether availability or temperature of the well water would fluctuate in relation to surface water under future climate conditions. All of the wells at the hatchery are drilled into unconsolidated alluvial and glacial deposits and are hydraulically connected to Icicle Creek and the hatchery channel. The shallow wells connected to a shallow, unconfined aquifer that is available when the hatchery channel is watered and the deep wells tap into a localized, confined aquifer that underlies a layer of silt and clay (McMillen Jacob Associates and DJ Warren Associates 2016). Unfortunately, we were unable to analytically detect, and thus model, a temperature relationship between well and surface waters. As a result, we were unable to predict future groundwater temperatures for either the shallow or the deep wells based on downscaled climate and hydrology projections for the Icicle Creek basin. As such, caution should be taken in the interpretation of data points affected by the use of well water because future conditions may be more or less extreme than the four scenarios we investigated. Future decreases in availability or increases in temperature of groundwater could greatly affect broodstock holding and early rearing of Chinook Salmon and would most likely require modification of operations for the program to continue.

Mitigating the effects of climate change at Leavenworth NFH

In the 2040s, Leavenworth NFH will likely contend with significant shortages of surface water during late summer if current diversions upstream from the hatchery continue without additional water resources. Competing water demands in the Icicle Creek basin present many challenges related to water rights and use. Predicted lower flows during the summer months, coupled with the ability of senior water users upstream to divert a large proportion (possibly all) of the flow from Icicle Creek for irrigation, will likely impede the ability of the hatchery to continue rearing 1.2 M Chinook Salmon in the 2040s unless a mitigation strategy can be implemented that would ensure an adequate and consistent supply of cold water to the hatchery. The possible option of increasing the use of colder groundwater would slow fish growth and, thus, reduce impacts to flow and density indexes resulting from warmer temperatures. However, we do not know whether this latter strategy is practical or feasible currently. Existing well water rights (6,700 gpm) are not sufficient to fully replace the surface water flow rate (42 cfs or 18,851 gpm) that is typically used to rear 1.2 M Spring Chinook Salmon to approximately 18 months of age at Leavenworth NFH. Whether other aquifers could be tapped to supply additional groundwater is unknown. As mentioned previously, the mechanics of the groundwater sources near Leavenworth NFH are poorly understood, although they have been the subject of targeted study (e.g., USFWS Columbia-Pacific Northwest Region Water Resources Program; see also McMillen Jacob Associates and DJ Warren Associates 2016). Opportunities for additional water resources in the Icicle Creek watershed upstream of the IPID diversion could be explored.

If additional water cannot be secured for the hatchery in the future, alternative measures to mitigate for reduced water availability might include (a) development of a recirculating-water aquaculture system (RAS), (b) raising fewer numbers of Spring Chinook Salmon, or (c) raising a different species or stock with lower water demands (e.g., Summer Chinook Salmon[13]). At least one mitigation measure will likely be necessary in the future to avoid exceeding the ecological capacity of the hatchery (i.e., flow and density indices) under projected environmental conditions and lower water quantities during the summer months.

Warmer water temperatures in the future are expected to also present challenges at Leavenworth NFH. Not only will those temperatures result in faster fish growth as noted above, higher temperatures would also increase disease risks, particularly during the summer months. Potential approaches to reduce water temperatures at the hatchery include an increased reliance on (colder) groundwater sources, expanding the period of diverting water from Upper Snow Lake, or mechanical chilling of surface water.

Water from Upper Snow Lake has been long recognized as a fundamental resource necessary for Leavenworth NFH to rear Spring Chinook Salmon (USFWS 2014). Currently, cold water is routinely diverted from Upper Snow Lake in August and September. If cooler water is needed in July or October, release of water from Upper Snow Lake could theoretically be extended into those months. However, we do not know whether snow/water resources under future climate conditions will be sufficient to allow expanding the period of those releases without depleting the water resources of Upper Snow Lake too early or preventing sufficient refilling between years. The current protocol releases approximately 7,000 acre-ft. of storage water annually with an estimated 60% probability that inflows to Upper Snow Lake will meet or exceed the total release volume (Wurster 2006; USFWS 2014). Releasing more water annually would reduce that probability, but the magnitude of that reduction is unknown without additional analyses.

Electro-mechanical chilling of surface water is theoretically possible also as a mitigation strategy to reduce growth rates, although cooling by 1 to 2 °C the large volume of water needed for rearing 1.2 M Spring Chinook Salmon (40+ cfs) for multiple months would be energy intensive and expensive. To decrease energy costs, chilled water could be used early in the rearing cycle during the first spring and summer to slow fish growth and reduce flow and density indexes and potential crowding prior to release. However, we do not know whether this approach would offset increased compensatory growth later in the rearing cycle. Coupling mechanical chilling to a RAS would reduce the cost of chilling but would incur additional expenses related to pumping and filtering. Growth modulation through reduced rations is another mitigation option, although ration levels would need to be maintained at a level sufficient to ensure adequate physiological condition and health at warmer than desired temperatures. In the absence of additional coldwater resources for the hatchery, some combination of chilling and increased use of reuse water (e.g., RAS) may be necessary if the current Spring Chinook Salmon program of 1.2 M smolts is to be maintained into the 2040s.

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[13] Summer Chinook Salmon in the Mid-Columbia River typically exhibit an "ocean-type" life history and outmigrate to mainstem rivers and the Columbia River estuary in the spring of their first year as age 0+ fish.

Overall, several mitigation strategies are theoretically possible for addressing climate-related impacts. However, each conceivable strategy has obvious drawbacks and trade-offs, all of which will require further study to determine their potential efficacy and feasibility.

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Table B1. Thermal tolerances (°C) of Pacific salmon species (*Oncorhynchus* sp.) reared at Leavenworth 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. Location of important physical features, human-made structures, and water temperature monitoring sites on Icicle Creek near the location of Leavenworth NFH (see Figure B3). Locations are river km (rkm) and river miles (RM) upstream from confluence of Icicle Creek with the Wenatchee River (adapted from Fraser 2015).

Location river km (rkm)	Location river mile (RM)	Description
9.4	5.9	USGS gage #12458000 Icicle Creek[a]
9.3	5.8	Icicle-Peshastin Irrigation District (IPID) diversion[b]
8.9	5.6	IC1 thermograph[c]
8.8	5.5	Snow Creek[d]
8.7	5.4	IC3 thermograph[e]
7.2	4.5	IC5 thermograph[f]
7.2	4.5	Leavenworth NFH water intake
4.1 – 6.2	2.6 – 3.9	Leavenworth NFH property boundaries

[a] IC19 thermograph is located at the USGS gage reported to be at rkm 9.3, but this gage is upstream from the IPID diversion.

[b] Diversion is downstream from USGS gage #12458000.

[c] IC1 thermograph is located 100 m upstream of confluence of Snow Creek, on opposite bank.

[d] IC2 thermograph is located at RM 0.2 (rkm 0.3) of Snow Creek.

[e] The IC3 thermograph is no longer deployed (Gregory Fraser, Mid-Columbia Fish and Wildlife Conservation Office, U.S. Fish and Wildlife Service, Leavenworth, Washington, personal communication, August 24, 2018).

[f] The IC5 thermograph is located at the water intake for the hatchery.

Table B4. Historical monthly diversions and allocations at the Icicle-Peshastin Irrigation District (IPID) diversion on Icicle Creek, at rkm 9.3 (RM 5.8). Table modified from USFWS (2014) and NMFS (2017); the years over which these mean values were estimated was not reported. The table reports the mean monthly amount of water, measured in cubic feet per second, diverted from Icicle Creek by the Icicle-Peshastin Irrigation District and the City of Leavenworth.

Month	Icicle-Peshastin Irrigation District (IPID)[a]	City of Leavenworth[b]	Total
January	0	2	2
February	0	2	2
March	0	2	2
April	69	2	71
May	88	2	90
June	96	2	98
July	99	2	101
August	98	2	100
September	79	2	81
October	0	2	2
November	0	2	2
December	0	2	2

[a] IPID water right during their period of use (April – September) is 117.7 cfs.

[b] City of Leavenworth's water right during their period of use is 3 cfs.

Table B5. Modeled historical and future monthly average air temperatures (T_{ave}), precipitation, and snow water equivalent (SWE) for the drainage area of Icicle Creek upstream from Leavenworth 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_{ave} (°C) Projected 2040s (± S.D.)	T_{ave} (°C) Diff.	PPT (mm) Historical	PPT (mm) Projected 2040s (± S.D.)	PPT (mm) Diff.	SWE (mm) Historical	SWE (mm) Projected 2040s (± S.D.)	SWE (mm) Diff.
January	-5.7	-3.9 ± 1.0	1.8	280	299 ± 38	19	369	272 ± 41	-97
February	-3.7	-2.2 ± 1.0	1.5	212	219 ± 30	7	584	436 ± 65	-148
March	-1.3	0.2 ± 0.8	1.5	171	186 ± 10	15	724	534 ± 83	-190
April	1.8	3.4 ± 1.1	1.7	95	104 ± 13	9	784	562 ± 99	-222
May	5.6	7.1 ± 0.6	1.6	63	58 ± 4	-4	686	445 ± 108	-241
June	9.2	11.3 ± 0.7	2.1	50	42 ± 9	-8	451	242 ± 75	-209
July	13.4	16.3 ± 1.2	2.9	24	17 ± 5	-8	207	69 ± 29	-138
August	12.9	15.9 ± 1.0	3.0	30	24 ± 7	-5	53	4 ± 3	-49
September	10.0	12.5 ± 1.0	2.6	70	60 ± 13	-10	23	0 ± 0	-23
October	4.1	6.0 ± 0.4	1.9	152	168 ± 19	16	20	0 ± 0	-20
November	-1.6	-0.1 ± 0.3	1.5	245	286 ± 41	41	39	9 ± 2	-29
December	-4.3	-2.6 ± 0.6	1.7	310	331 ± 27	21	158	108 ± 19	-50

Table B6. Projected mean annual flows (cfs) of Icicle Creek near the hatchery 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 is based on the 1915 – 2006 period. Values do not account for irrigation withdrawals or any hydrologic alterations upstream from the water intake of Leavenworth NFH.

GCM	Mean annual flow in 2040s (cfs)
ccsm3	610
cgcm3	693
cnrm_cm3	649
echam5	634
echo_g	598
hadcm	641
hadgem1	544
ipsl_cm4	700
miroc_3.2	711
pcm1	568
2040s AVERAGE	635
Historical AVERAGE	600

Table B7. Mean water temperatures of the surface water sources that supply Leavenworth NFH. Historical values for Icicle Creek above (at IC1) and below (at IC5) the confluence with Snow Creek are empirical data (°C ± S.D.) from 2005 – 2006, 2008 – 2009, and 2011 – 2015. 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).[a]

Month	IC1 Historical empirical mean temperature °C ± SD	IC1 Historical modeled temperature °C	IC1 2040s A1B ensemble mean temperature °C (Min. –Max.)	IC5 Historical empirical mean temperature °C ± SD)	IC5 Historical modeled temperature °C	IC5 2040s A1B ensemble mean temperature °C (Min. – Max.)
January	0.9 ± 1.0	1.6	2.2 (1.8 – 2.5)	1.0 ± 1.0	1.7	2.3 (1.8 – 2.6)
February	1.4 ± 0.9	2.1	2.7 (2.2 – 3.2)	1.7 ± 1.1	2.2	2.8 (2.3 – 3.3)
March	3.0 ± 1.3	3	3.8 (3.2 – 4.3)	3.3 ± 1.3	3.1	3.9 (3.3 – 4.4)
April	4.9 ± 0.9	4.5	5.6 (4.8 – 7.7)	5.1 ± 1.0	4.6	5.7 (4.9 – 7.8)
May	6.2 ± 1.4	7.3	8.7 (8.1 – 9.7)	6.3 ± 1.4	7.5	8.8 (8.2 – 9.8)
June	8.7 ± 2.6	10.6	12.5 (11.3 – 13.3)	8.9 ± 2.7	10.8	12.6 (11.5 – 13.5)
July	13.9 ± 2.4	14.1	16.1 (15.3 – 17.5)	14.0 ± 2.2	14.3	16.3 (15.5 – 17.7)
August	15.3 ± 1.4	13.7	15.9 (14.9 – 17.1)	14.4 ± 1.3[a]	13.9, 13.5[a]	16.1 (15.1 – 17.3), 12.4 (12.4 – 12.4)[a]
September	12.0 ± 1.9	11	13.2 (12.3 – 14.7)	11.0 ± 1.6[a]	11.1, 10.4[a]	13.4 (12.5 – 14.9), 10.2 (10.1 – 10.5)[a]
October	7.1 ± 2.1	6	7.4 (6.9 – 8.0)	7.4 ± 2.1	6.1	7.5 (7.0 – 8.1)
November	2.8 ± 1.7	2.7	3.3 (3.1 – 3.6)	2.9 ± 1.8	2.7	3.4 (3.2 – 3.7)
December	0.8 ± 1.0	1.9	2.4 (2.0 – 2.7)	1.0 ± 1.2	1.9	2.5 (2.1 – 2.8)

[a] Values assume release of water from Upper Snow Lake enters Icicle Creek upstream from the IC5 thermograph site. Values also assume that the IPID diversion takes its historical diversion amount during August and September in the 2040s. Under this latter assumption, projected flow conditions in the 2040s would dewater Icicle Creek at IC5 in August and very nearly dewater it in September if water is not released from Upper Snow Lake.

Table B8. Data used to estimate water temperatures in Icicle Creek at the Leavenworth NFH intake (IC5) when water is released from Upper Snow Lake. Snow Lake releases and IC2 temperatures are empirical means from 2005 – 2015, and values for IC1 were generated by models. Only data from August and September were used to project the effect of water released from Upper Snow Lake because, from the historical record, there was only one year (2015) when water was released before August 1.

Month	Mean release Snow Lake observed historical[a] cfs (SD)	Mean flow Icicle Creek (IC1), modeled historical[b] cfs (SD)	Mean flow Icicle Creek (IC1), 2040s ensemble[c] cfs (SD)	Mean temp. Snow Creek (IC2), observed historical[a] °C (SD)	Mean temp. Icicle Creek (IC1), modeled historical[d] °C (SD)	Mean temp. Icicle Creek (IC1), 2040s ensemble[d] °C (SD)
August	43.3 (12.8)	296.8, 196.8	95.4 (22.8)	12.4 (1.6)	13.7 (1.9)	15.9 (0.6)
September	56.2 (4.0)	140.4, 59.4	91.0 (16.8)	9.7 (1.3)	11.0 (2.4)	13.2 (0.8)

[a] Estimates and standard deviations are based on empirical data, 2005 – 2015. Snow Lake release data are from Fraser (2005), and IC2 stream temperature data were provided by Leavenworth NFH.

[b] Modeled historical flows were generated from the hydrologic model routed to the approximate location of Leavenworth NFH (values provided by the Climate Impacts Group, University of Washington). The first number is the modeled mean flow (SDs not available), and the second number is the modeled net flow downstream from the IPID diversion (= the modeled historical flow at IC1 [first number] minus the average monthly diversion at the IPID [Table B4]).

[c] Projected mean flows for the 2040s generated from the hydrologic model routed to the approximate location of Leavenworth NFH. Standard deviations for the 2040s are based on the 10-model ensemble.

[d] Modeled historical and projected 2040s temperature data were generated by the non-linear regression model. Standard deviations for the modeled historical values are based on variation among the 91 years of simulation. Standard deviations for the 2040s are based on the 10-model ensemble.

Table B9. Mean monthly water temperatures and water sources experienced by juvenile Chinook Salmon reared at Leavenworth NFH based on the historical baseline and projected values for the 2040s under four future temperature scenarios. **Scenario A:** no change in future temperature of Upper Snow Lake and groundwater (well water). **Scenario B:** no change in future temperature of Upper Snow Lake but a 0.25 °C increase in groundwater temperature. **Scenario C:** 2 °C increase in future temperature of Upper Snow Lake but no change in groundwater temperature. **Scenario D:** 2 °C increase in future temperature of Upper Snow Lake and 0.25 °C increase in groundwater temperature.

Month	Life-History Stage	Percent Surface water	Percent Well water	Percent Reuse water	Rearing Temp. Historical baseline (°C)	Rearing Temp. Scenario A (°C)	Rearing Temp. Scenario B (°C)	Rearing Temp. Scenario C (°C)	Rearing Temp. Scenario D (°C)
May	Broodstock	57%	43%		7.8	8.6	8.7	8.6	8.7
June	Broodstock	57%	43%		10.1	11.1	11.2	11.1	11.2
July	Broodstock		100%		9.1	9.1	9.4	9.1	9.4
August	Broodstock		100%		9.1	9.1	9.4	9.1	9.4
September	Broodstock		100%		9.1	9.1	9.4	9.1	9.4
August	egg/fry		100%		9.1	9.1	9.4	9.1	9.4
September	egg/fry		100%		9.1	9.1	9.4	9.1	9.4
October	egg/fry		100%		8.3	8.3	8.6	8.3	8.6
November	egg/fry		100%		8.3	8.3	8.6	8.3	8.6
December	egg/fry		100%		8.3	8.3	8.6	8.3	8.6
January	egg/fry		100%		8.3	8.3	8.6	8.3	8.6
February	egg/fry	10%	90%	50%	7.7	7.8	8.0	7.8	8.0
March	juvenile	10%	90%	50%	7.8	7.9	8.1	7.9	8.1
April	juvenile	60%	40%	50%	6.1	6.8	6.8	6.8	6.9
May	juvenile	100%			7.5	8.8	8.8	8.8	8.8
June	juvenile	100%			10.8	12.6	12.6	12.6	12.6

Month	Life-History Stage	Percent Surface water	Percent Well water	Percent Reuse water	Rearing Temp. Historical baseline (°C)	Rearing Temp. Scenario A (°C)	Rearing Temp. Scenario B (°C)	Rearing Temp. Scenario C (°C)	Rearing Temp. Scenario D (°C)
July	juvenile	100%			14.3	16.4	16.4	16.4	16.6
August	juvenile	100%			13.5	12.4	12.4	14.4	14.4
September	juvenile	100%			10.4	10.2	10.2	11.9	11.9
October	juvenile	100%			6.1	7.5	7.5	7.5	7.5
November	juvenile	100%			2.8	3.4	3.4	3.4	3.4
December	juvenile	100%		28%	1.9	2.5	2.5	2.5	2.5
January	juvenile	100%		28%	1.7	2.3	2.3	2.3	2.3
February	juvenile	100%		28%	2.2	2.8	2.8	2.8	2.8
March	juvenile	100%		28%	3.1	3.9	3.9	3.9	3.9
April	smolt	100%		28%	4.6	5.7	5.7	5.7	5.7

Table B10. Monthly percent size differences of juvenile Chinook Salmon reared at Leavenworth NFH in the 2040s under four future temperature scenarios relative to baseline historical water temperatures. **Scenario A:** no change in future temperature of Upper Snow Lake and groundwater (well water). **Scenario B:** no change in future temperature of Upper Snow Lake but a 0.25 °C increase in groundwater temperature. **Scenario C:** 2 °C increase in future temperature of Upper Snow Lake but no change in groundwater temperature. **Scenario D:** 2 °C increase in future temperature of Upper Snow Lake and 0.25 °C increase in groundwater temperature.

Month	**Life-History Stage**	**Scenario A Weight diff. (g)**	**Scenario A Length diff. (mm)**	**Scenario B Weight diff. (g)**	**Scenario B Length diff. (mm)**	**Scenario C Weight diff. (g)**	**Scenario C Length diff. (mm)**	**Scenario D Weight diff. (g)**	**Scenario D Length diff. (mm)**
January	egg/fry	0.0%	0.0%	2.3%	0.8%	0.0%	0.0%	2.3%	0.8%
February	egg/fry	0.4%	0.1%	3.8%	1.3%	0.4%	0.1%	3.8%	1.3%
March	Juvenile	0.8%	0.3%	5.1%	1.7%	0.8%	0.3%	5.1%	1.7%
April	Juvenile	4.5%	1.5%	9.0%	2.9%	4.5%	1.5%	9.0%	2.9%
May	Juvenile	11.0%	3.5%	15.0%	4.7%	11.0%	3.5%	15.0%	4.7%
June	Juvenile	17.6%	5.5%	21.1%	6.5%	17.6%	5.5%	21.1%	6.5%
July	Juvenile	22.6%	7.0%	25.6%	7.8%	22.6%	7.0%	25.6%	7.8%
August	Juvenile	15.3%	4.8%	17.8%	5.5%	22.3%	6.9%	24.8%	7.6%
September	Juvenile	13.3%	4.2%	15.4%	4.9%	24.8%	7.6%	27.0%	8.2%
October	Juvenile	16.6%	5.2%	18.6%	5.8%	27.5%	8.3%	29.6%	8.9%
November	Juvenile	18.0%	5.6%	19.9%	6.2%	28.5%	8.6%	30.6%	9.2%
December	Juvenile	19.1%	5.9%	21.0%	6.5%	29.5%	8.9%	31.5%	9.5%
January	Juvenile	20.3%	6.3%	22.2%	6.8%	30.5%	9.2%	32.5%	9.7%
February	Juvenile	21.4%	6.6%	23.2%	7.1%	31.3%	9.4%	33.2%	9.9%
March	Juvenile	22.7%	7.0%	24.5%	7.5%	32.3%	9.7%	34.2%	10.2%
April	Smolt	24.8%	7.6%	26.6%	8.1%	34.0%	10.2%	35.9%	10.6%

Table B11, Part A. Mean historical, empirical and modeled, flow and density index values and constituent variables for Spring Chinook Salmon at Leavenworth NFH. Flow and density index values are shown graphically in Figure B21. 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.

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	Jan	1,378,488	10,552	31	1.73	0.95	2765	0.16	0.60	1.80	1.07	0.17	0.65	0.93
2	Feb	1,377,914	17,193	28	2.07	1.64	3871	0.14	0.62	2.17	1.89	0.15	0.68	0.90
3	Mar	1,354,124	37,375	31	2.40	2.51	6,715	0.08	0.47	2.59	3.22	0.10	0.55	0.84
4	Apr	1,362,616	47,860	30	2.71	3.60	8,776	0.08	0.45	2.89	4.51	0.10	0.53	0.85
5	May	1,329,072	76,257	31	3.03	5.03	15,835	0.06	0.31	3.28	6.60	0.08	0.37	0.82
6	Jun	1,325,616	81,887	30	3.46	7.53	17,495	0.08	0.36	3.81	10.45	0.10	0.46	0.79
7	Jul	1,312,896	78,842	31	3.91	10.84	17,128	0.10	0.47	4.55	17.81	0.14	0.66	0.71
8	Aug	1,289,975	81,882	31	4.32	14.58	17,883	0.12	0.54	5.23	27.13	0.18	0.83	0.65
9	Sep	1,286,924	81,353	30	4.61	17.67	17,758	0.13	0.61	5.70	35.38	0.22	0.99	0.62
10	Oct	1,282,170	84,754	31	4.73	19.13	18,317	0.13	0.62	5.96	40.44	0.23	1.05	0.60
11	Nov	1,284,193	84,546	30	4.74	19.28	18,577	0.14	0.62	6.03	41.89	0.23	1.06	0.59
12	Dec	1,283,118	84,880	31	4.74	19.28	19,157	0.14	0.60	6.06	42.50	0.23	1.04	0.58
13	Jan	1,275,145	81,548	31	4.75	19.46	20,032	0.14	0.57	6.08	42.83	0.24	0.99	0.58
14	Feb	1,273,511	82,020	28	4.83	20.32	20,152	0.14	0.59	6.11	43.51	0.24	0.99	0.59
15	Mar	1,269,905	81,599	31	5.04	22.71	20,657	0.15	0.61	6.20	45.49	0.25	0.99	0.61
16	Apr	1,264,036	81,836	30	5.25	25.64	19,469	0.17	0.70	6.36	49.09	0.26	1.11	0.63

[a] Calendar month in rearing cycle.

[b] Numbers of post-hatch juvenile fish or abundance (N_i) based on hatchery averages during 2001 – 2014 brood years.

[c] Mean hatchery capacity (C_i) used during 2001 – 2014 brood years based on the number of raceways, their sizes, and water depth.

[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 2001 – 2014 brood years.

[f] Empirical mean fish weight (W_i) in grams, at the end of each monthly time-step i averaged over the 2001 – 2014 brood years.

[g] Empirical mean flow rates through the hatchery (GPM_i) in gallons per minute at each monthly time-step i averaged over the 2001 – 2014 brood years.

[h] Empirical density index (DI_i) at time-step i averaged over the 2001 – 2014 brood years.

[i] Empirical mean flow index (FI_i) at time-step i averaged over the 2001 – 2014 brood years.

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

[k] Modeled historical or projected future 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 14.

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

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

Table B11, Part B. Bias-adjusted future (2040s) modeled mean length, mean weight, and flow and density index values for Spring Chinook Salmon at Leavenworth NFH under four future temperature scenarios. **Scenario A:** no change in future temperature of Upper Snow Lake and groundwater (well water). **Scenario B:** no change in future temperature of Upper Snow Lake but a 0.25 °C increase in groundwater temperature. **Scenario C:** 2 °C increase in future temperature of Upper Snow Lake but no change in groundwater temperature. **Scenario D:** 2 °C increase in future temperature of Upper Snow Lake and 0.25 °C increase in groundwater temperature. Flow and density index values are shown graphically in Figure B21. Values under Scenario A are shown in columns 3 – 6. Values under Scenario B are shown in columns 7 – 10. Values under Scenario C are shown in columns 11 – 14. Values under Scenario D are shown in columns 15 – 18.

		Scenario A: cols. 3 – 6				**Scenario B: cols. 7 – 10**				**Scenario C: cols. 11 – 14**				**Scenario D: cols. 15 – 18**			
Time step (i)	**Month[a]**	L_i [b]	W_i [c]	DI_i [d]	FI_i [e]	L_i [b]	W_i [c]	DI_i [d]	FI_i [e]	L_i [b]	W_i [c]	DI_i [d]	FI_i [e]	L_i [b]	W_i [c]	DI_i [d]	FI_i [e]
1	Jan	1.80	1.07	0.16	0.60	1.81	1.09	0.16	0.61	1.80	1.07	0.16	0.60	1.81	1.09	0.16	0.61
2	Feb	2.17	1.90	0.14	0.62	2.20	1.97	0.14	0.64	2.17	1.90	0.14	0.62	2.20	1.97	0.14	0.64
3	Mar	2.59	3.24	0.08	0.47	2.63	3.38	0.09	0.48	2.59	3.24	0.08	0.47	2.63	3.38	0.09	0.48
4	Apr	2.93	4.71	0.09	0.47	2.97	4.92	0.09	0.48	2.93	4.71	0.09	0.47	2.97	4.92	0.09	0.48
5	May	3.39	7.32	0.07	0.33	3.43	7.59	0.07	0.34	3.39	7.32	0.07	0.33	3.43	7.59	0.07	0.34
6	Jun	4.02	12.29	0.09	0.40	4.06	12.66	0.09	0.41	4.02	12.29	0.09	0.40	4.06	12.66	0.09	0.41
7	Jul	4.87	21.85	0.12	0.54	4.90	22.38	0.12	0.55	4.87	21.85	0.12	0.54	4.90	22.38	0.12	0.55
8	Aug	5.48	31.30	0.13	0.59	5.52	31.95	0.13	0.60	5.59	33.18	0.13	0.61	5.62	33.86	0.14	0.62
9	Sep	5.94	40.08	0.15	0.67	5.98	40.84	0.15	0.67	6.14	44.14	0.16	0.71	6.17	44.94	0.16	0.72
10	Oct	6.27	47.15	0.15	0.69	6.31	47.97	0.15	0.70	6.46	51.56	0.16	0.73	6.50	52.43	0.16	0.74
11	Nov	6.37	49.41	0.15	0.69	6.40	50.24	0.15	0.70	6.55	53.85	0.16	0.73	6.59	54.72	0.16	0.74
12	Dec	6.42	50.62	0.15	0.67	6.46	51.45	0.15	0.68	6.60	55.02	0.16	0.71	6.63	55.89	0.16	0.72
13	Jan	6.46	51.53	0.16	0.65	6.49	52.35	0.16	0.66	6.63	55.88	0.17	0.69	6.67	56.74	0.17	0.69
14	Feb	6.51	52.80	0.16	0.67	6.54	53.61	0.17	0.67	6.68	57.12	0.17	0.70	6.71	57.97	0.17	0.71
15	Mar	6.63	55.83	0.18	0.70	6.66	56.65	0.18	0.71	6.80	60.20	0.19	0.74	6.83	61.06	0.19	0.74
16	Apr	6.84	61.27	0.19	0.81	6.87	62.13	0.19	0.82	7.00	65.81	0.20	0.85	7.03	66.70	0.20	0.86

[a] Calendar month in rearing cycle.

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

[c] Modeled projected future 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 (Table B11, Part A)

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

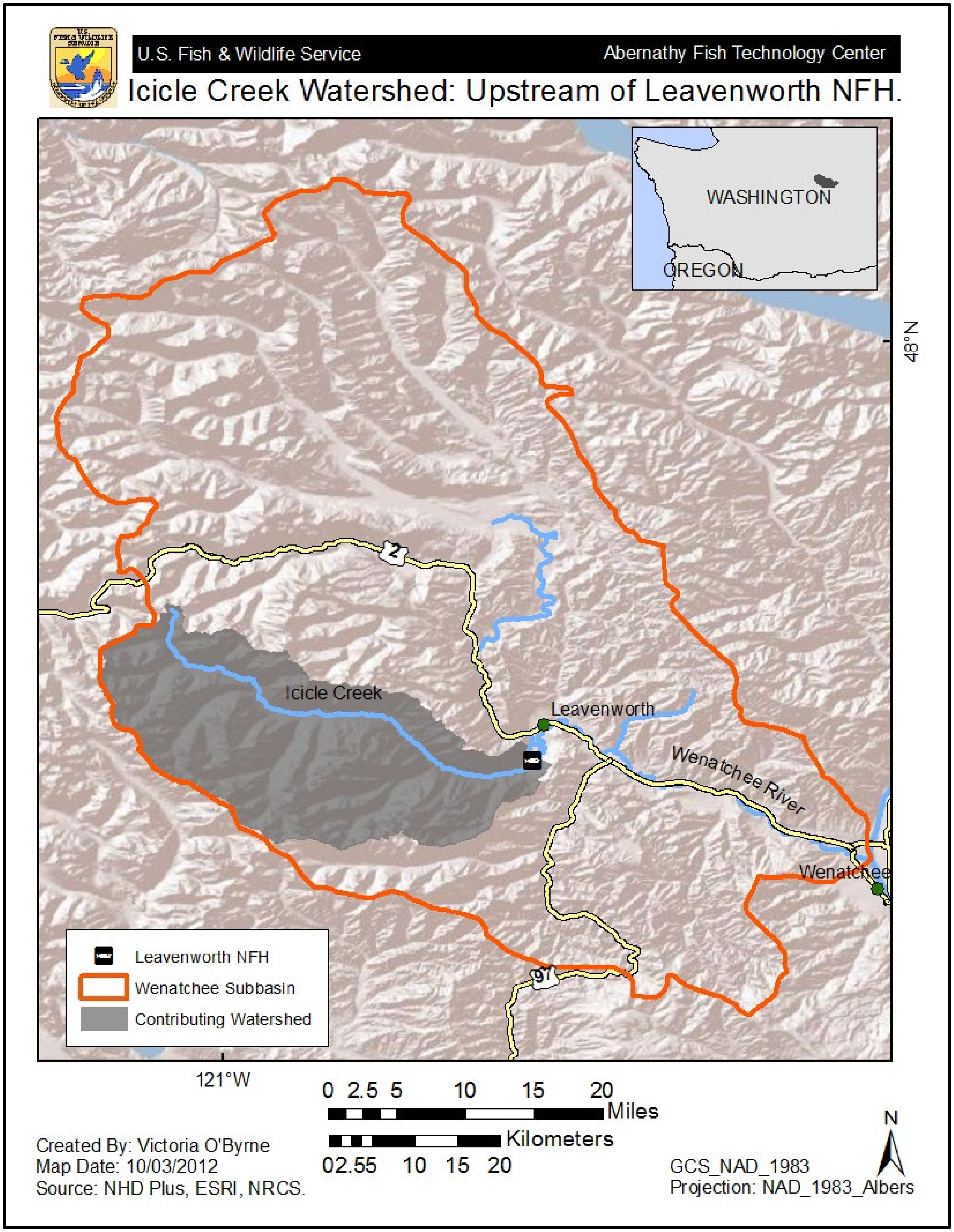

Figure B1. Icicle Creek contributing watershed (gray shaded area) and Leavenworth NFH in north-central Washington state.

Figure B2. Aerial view of Leavenworth NFH and Icicle Creek (blue line). Letters denote hatchery infrastructure. Shallow wells (#1, 2, 3, and 7) are denoted by: M (Well 1), N (Well 2 and 7), and O (Well 3). Deep wells are denoted by A (Well 5), F (Well 6), and K (Well 4). The hatchery channel is labeled P and is dewatered in this image. The figure is adapted from Potter et al. (2017).

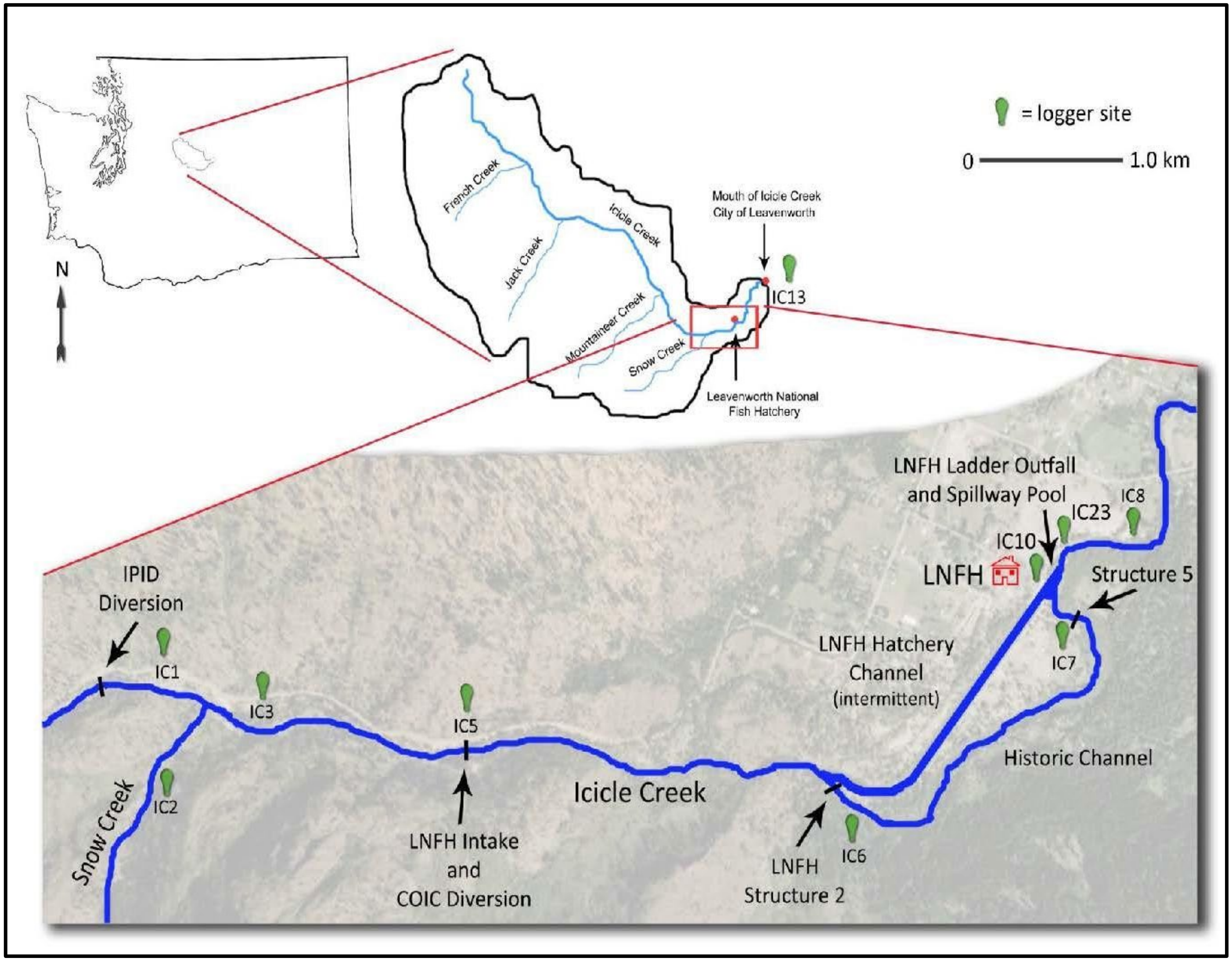

Figure B3. Map of Icicle Creek drainage showing the relative position of Leavenworth National Fish hatchery (LNFH) and selected features and thermograph sites (labeled with the prefix IC; see also Table B3). In the inset, Icicle Creek flows from left to right. Map is adapted from Fraser (2015).

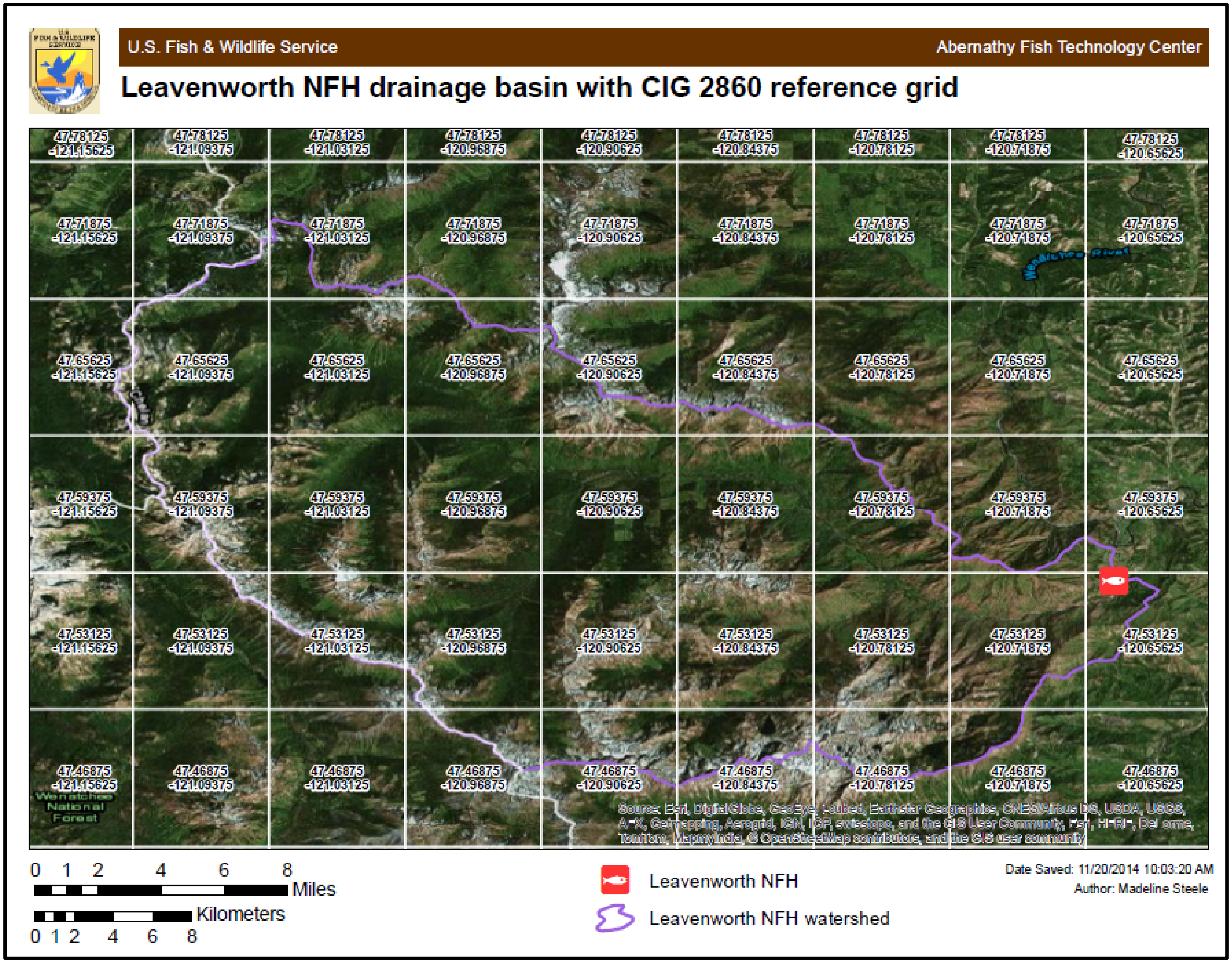

Figure B4. Icicle Creek watershed showing the intersection between the watershed delineation and the 1/16° grid cells to which the climate data were downscaled.

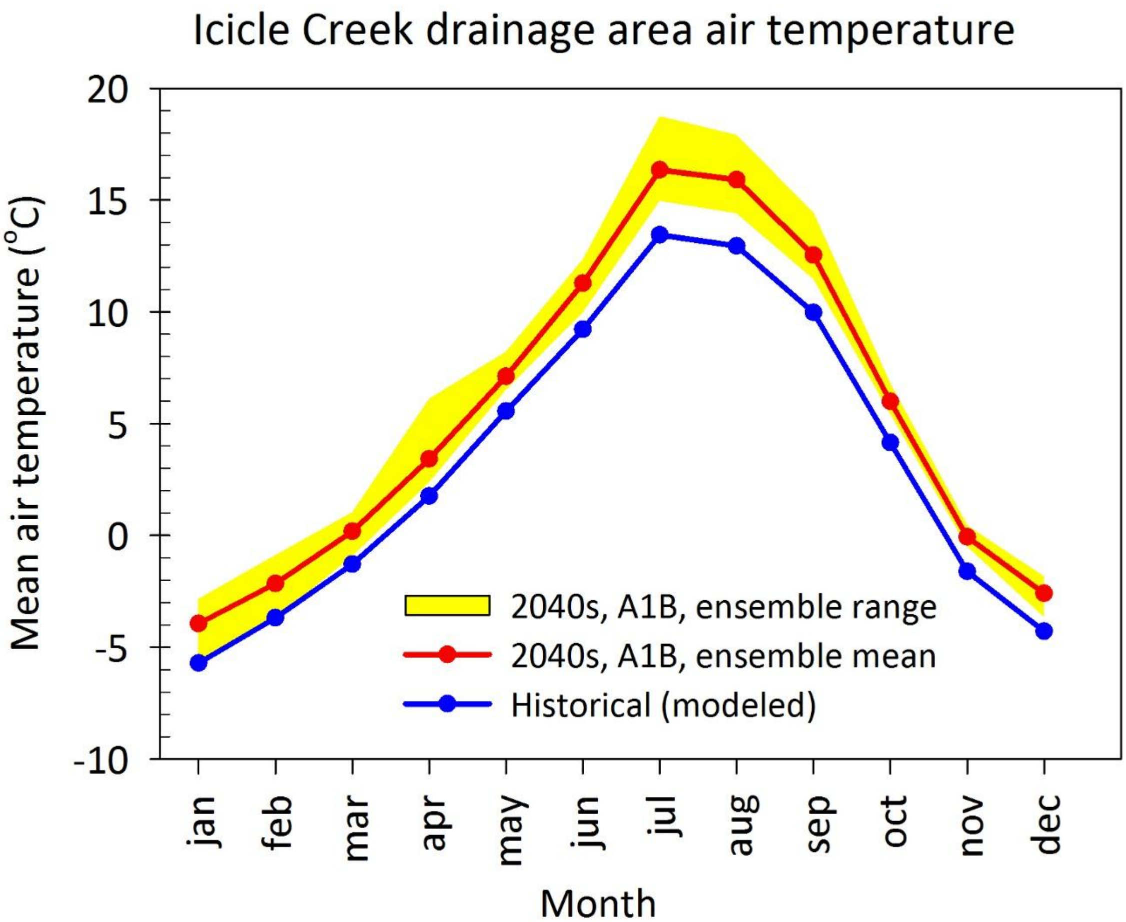

Figure B5. Modeled mean monthly air temperatures across the Icicle Creek watershed upstream from Leavenworth NFH based on an ensemble of 10 GCMs. Values are weighted by the intersection of the delineated watershed and the 1/16° grid cells underlying the flux files. The historical period is based on the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

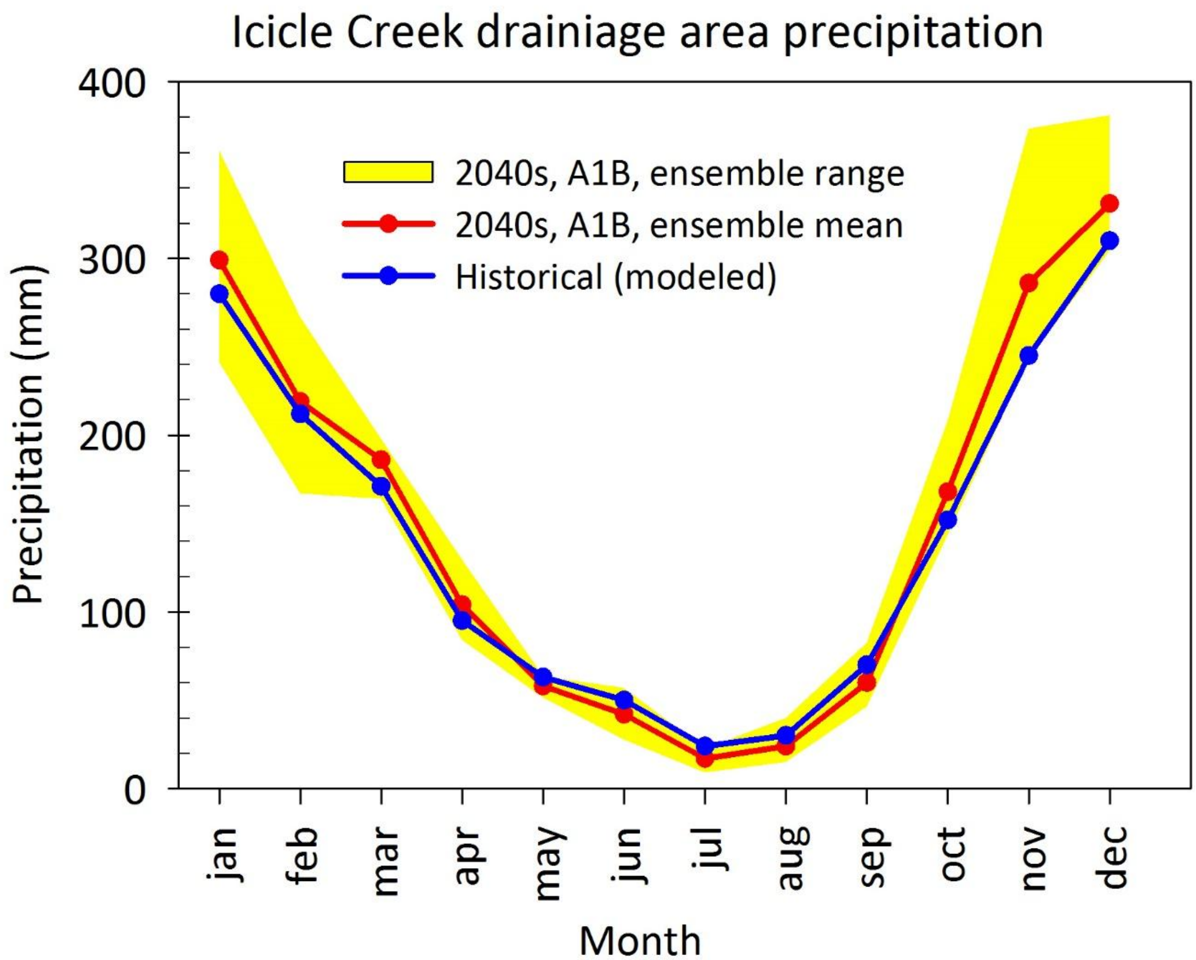

Figure B6. Modeled mean monthly precipitation across the Icicle Creek watershed upstream from Leavenworth NFH based on an ensemble of 10 GCMs. Values are weighted by the intersection of the delineated watershed and the 1/16° grid cells underlying the flux files. The historical period is based on the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

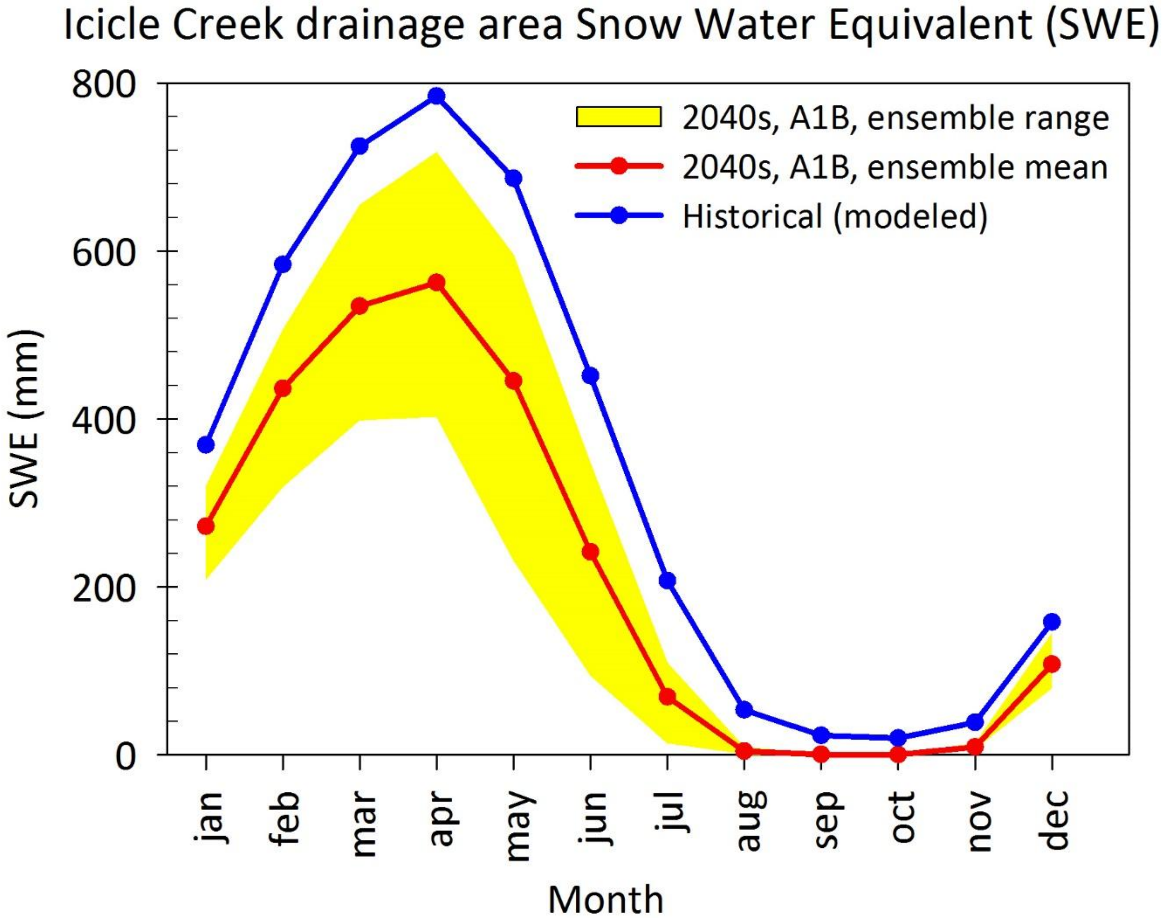

Figure B7. Modeled mean monthly snow water equivalent (SWE) across the Icicle Creek watershed upstream from Leavenworth NFH based on an ensemble of 10 GCMs. Values are weighted by the intersection of the delineated watershed and the 1/16° grid cells underlying the flux files. The historical period is based on the 1915 – 2006 meteorological record, and the 2040s represents a 30-year period (2030 – 2059) centered on the decade of the 2040s.

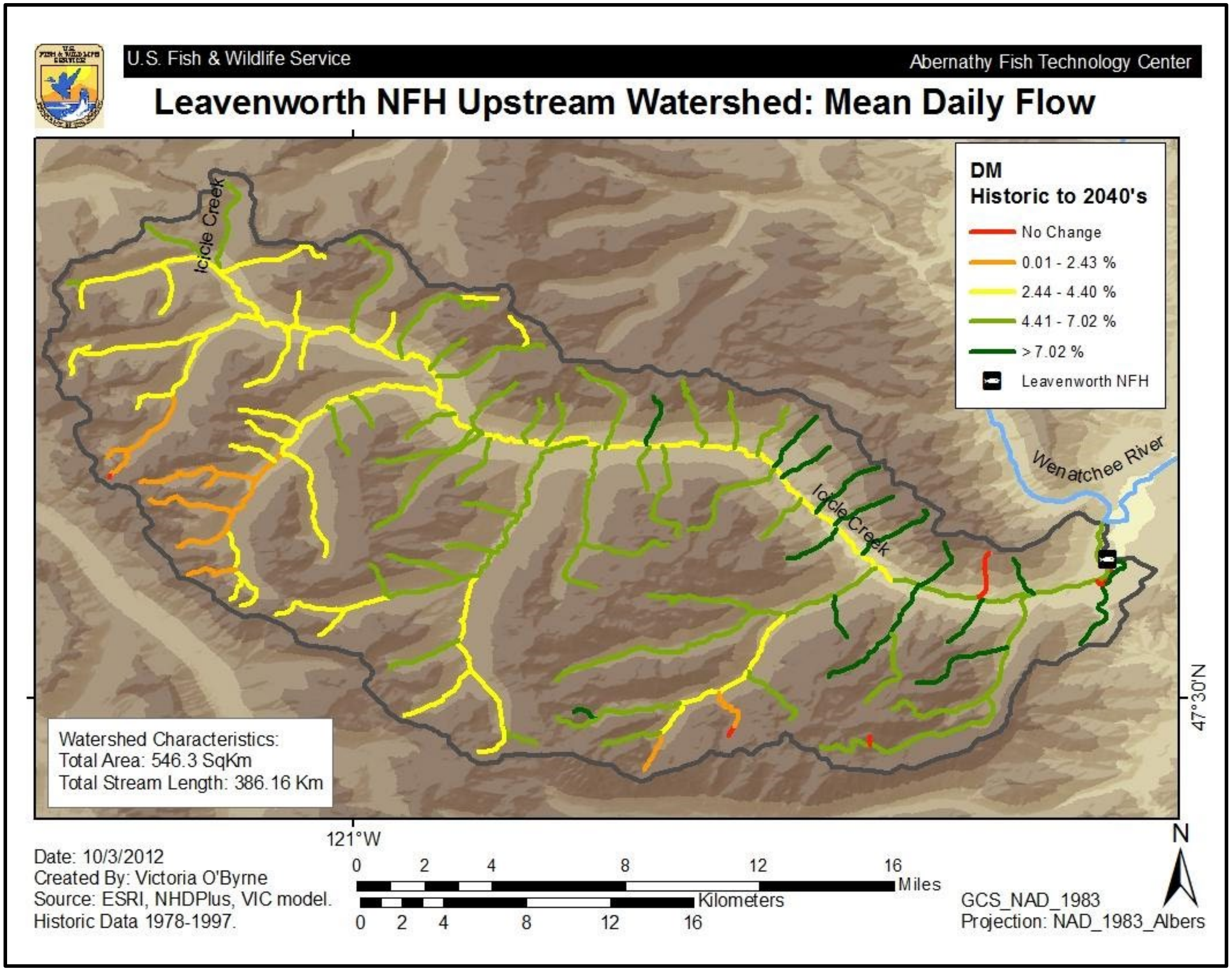

Figure B8. Projected change in mean daily flow (DM, in %) for the Icicle Creek basin upstream from Leavenworth NFH between the 1980s and 2040s time periods. Data are from VIC hydrologic model (Wenger et al. 2011), and the historical reference period is 1978 – 1997.

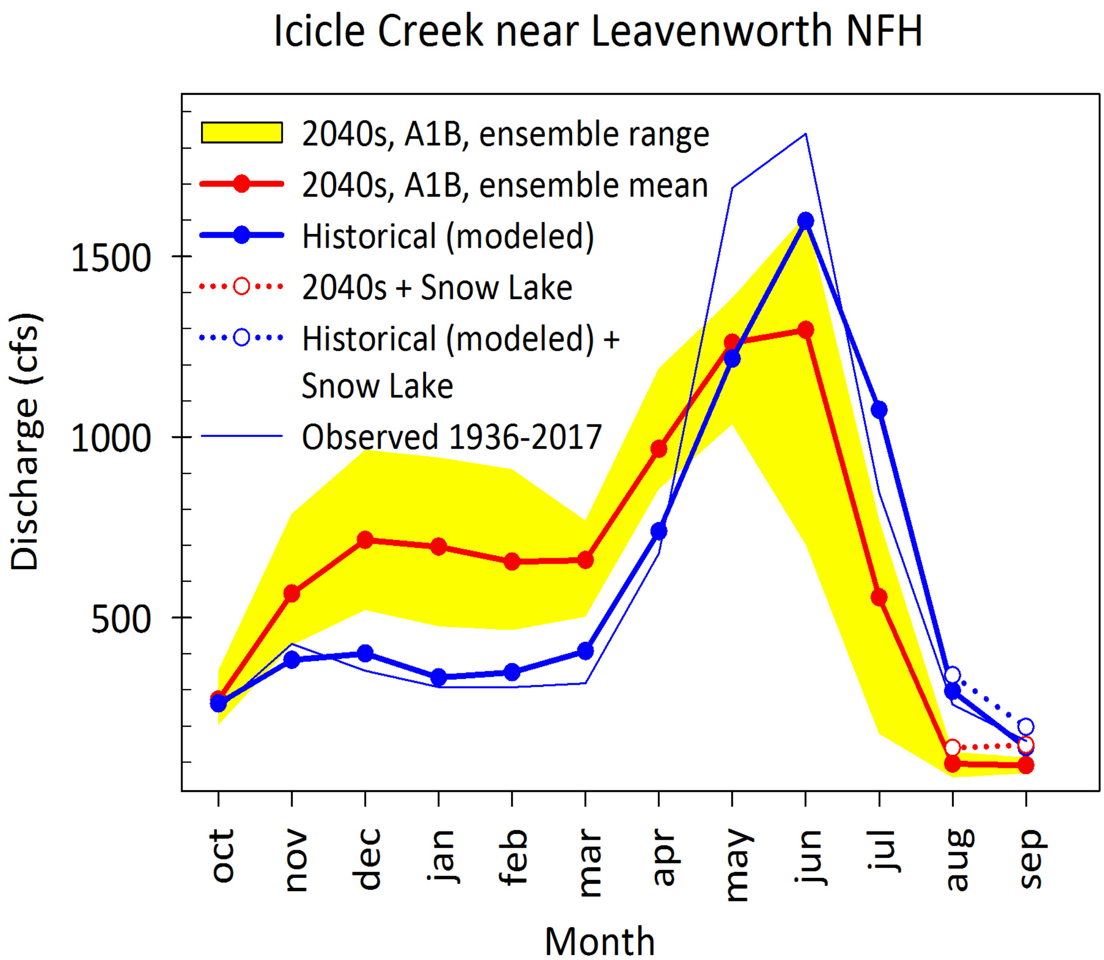

Figure B9. Modeled and observed mean monthly surface flow in Icicle Creek adjacent to Leavenworth National Fish Hatchery based on raw Variable Infiltration Capacity (VIC) simulations. Projected (2040s) surface flows are based on the VIC model forced by output from an ensemble of 10 general circulation 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. For comparison to the modeled hydrography, the observed flows were recorded at the USGS gage #12458000, at rkm 9.3, upstream from the confluence of Snow Creek. Dotted lines for August and September denote estimates that incorporate the average monthly releases from Upper Snow Lake recorded at the lake's release valve during 2005 – 2015. Values plotted do not account for irrigation withdrawals or any hydrologic alterations upstream from the water intake of Leavenworth NFH, other than to show the water releases from Upper Snow Lake.

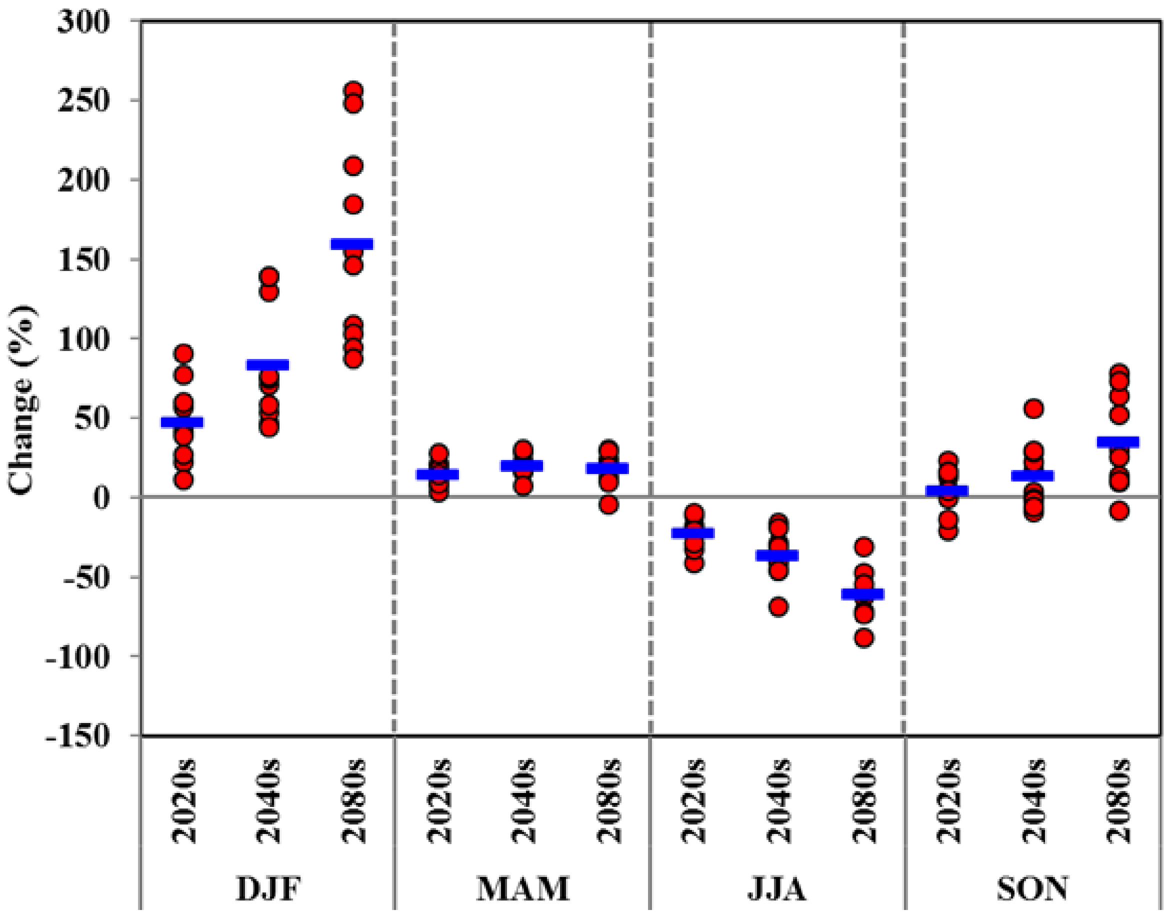

Figure B10. Projected percent change in mean seasonal flow in Icicle Creek adjacent to the Leavenworth National Fish Hatchery based on raw Variable Infiltration Capacity (VIC) simulations for the 30-year periods centered on the 2020s, 2040s, and 2080s. Flows projections are based on the VIC model forced by output from an ensemble of 10 general circulation models (GCMs) under the A1B greenhouse gas emissions scenario. Seasons depicted are winter (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.

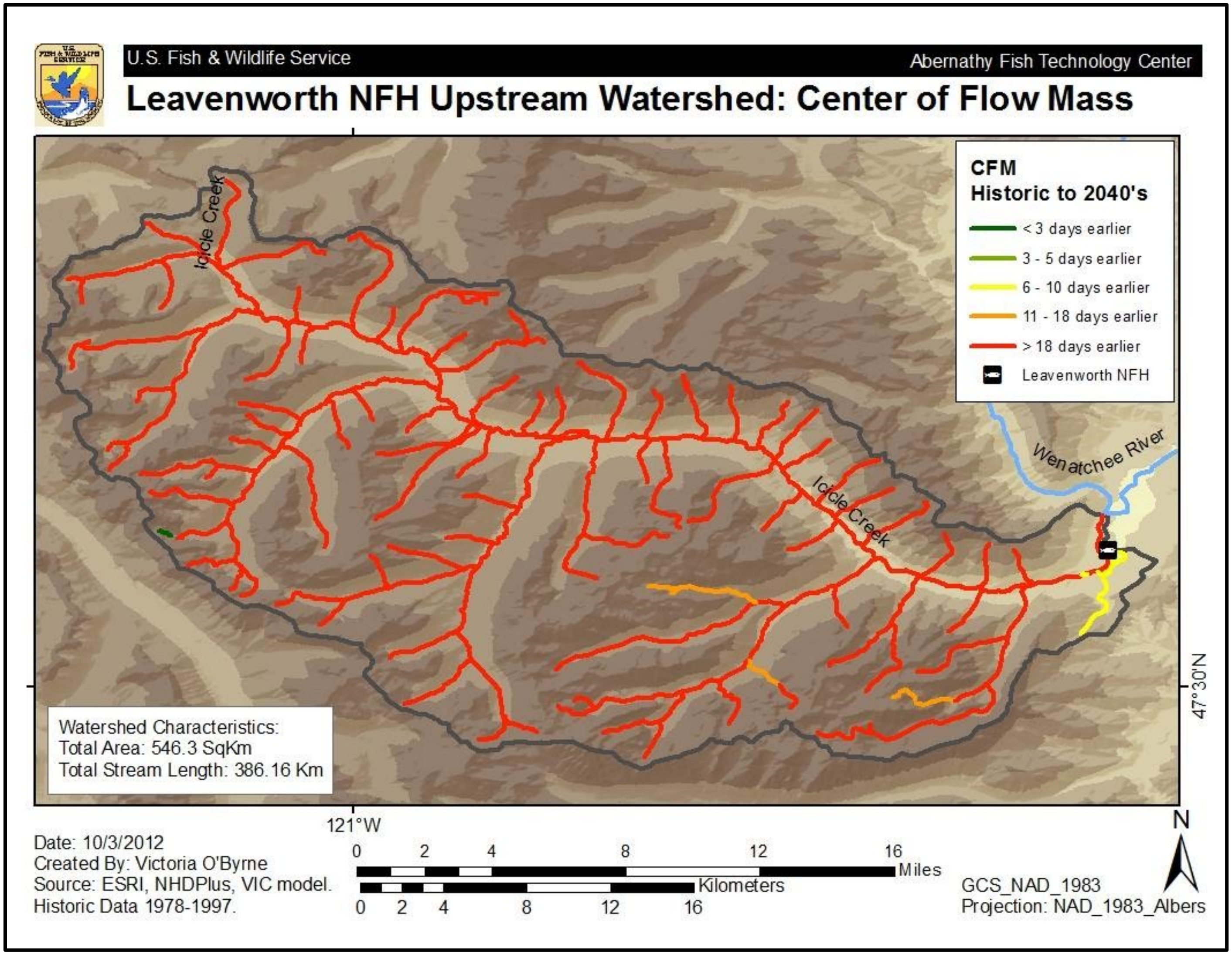

Figure B11. Projected change in the timing of snowmelt runoff (date of center of flow mass, CFM) for the Icicle Creek basin upstream from Leavenworth NFH between the 1980s and 2040s time periods. Data are from VIC hydrologic model (Wenger et al. 2011), and the historical reference period is 1978 – 1997.

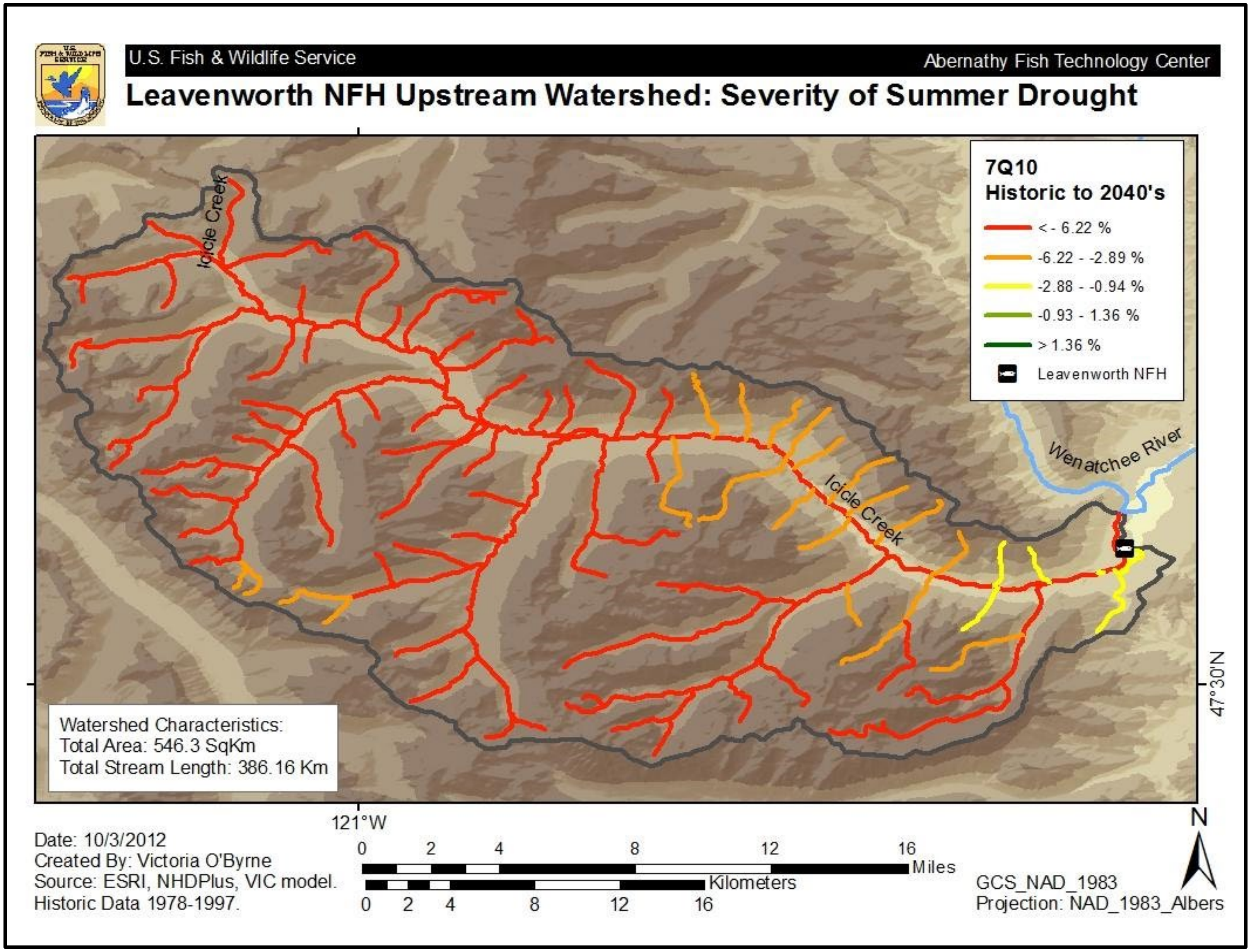

Figure B12. Projected change in the severity of summer drought (7-day low flow 10-yr return interval [7Q10]) for the Icicle Creek basin upstream from Leavenworth NFH between the 1980s and 2040s periods. Data are from VIC hydrologic model (Wenger et al. 2011), and the historical reference period is 1978 – 1997.

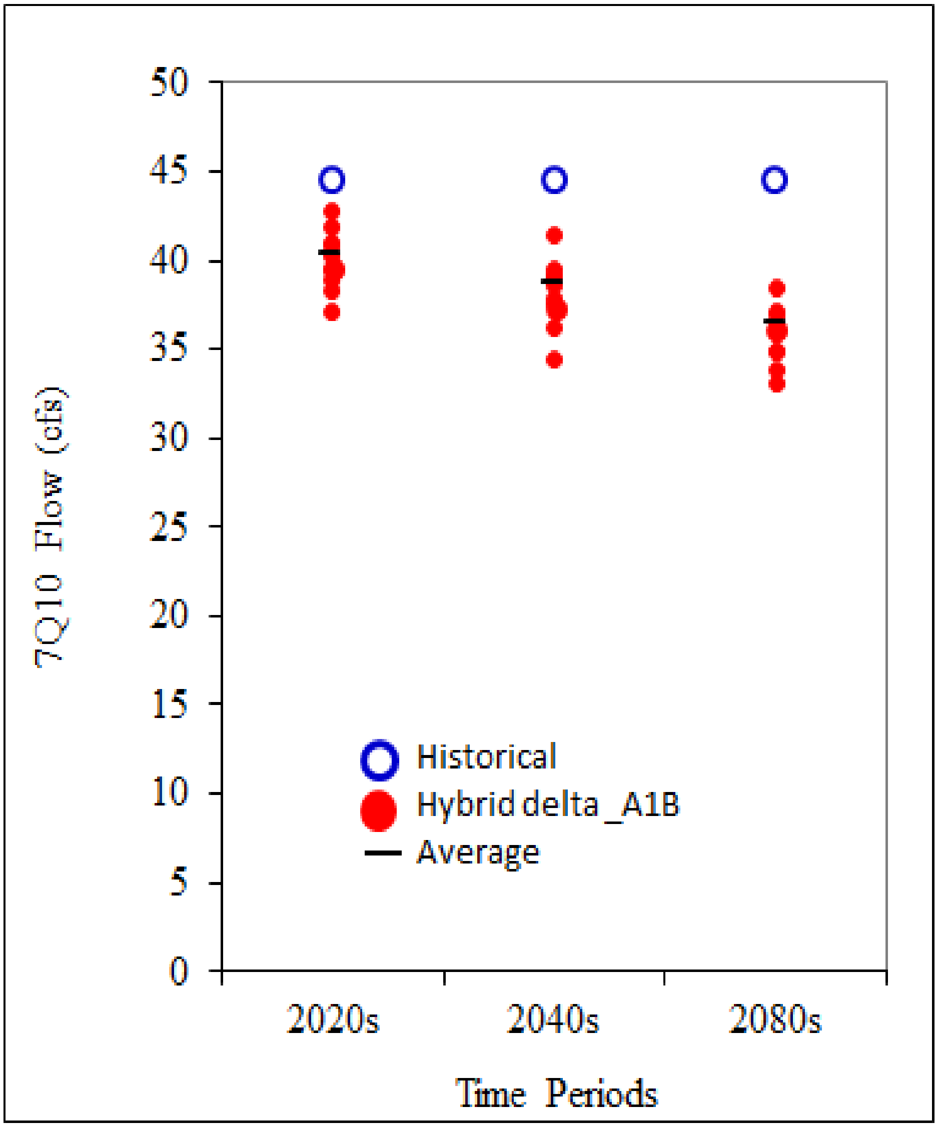

Figure B13. Projected flow rate for the 7-day low flow with a 10-yr return interval (7Q10) in Icicle Creek adjacent to the Leavenworth National Fish Hatchery based on raw Variable Infiltration Capacity (VIC) simulations for the 2020s, 2040s, and 2080s. Flows projections are based on the VIC model forced 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.

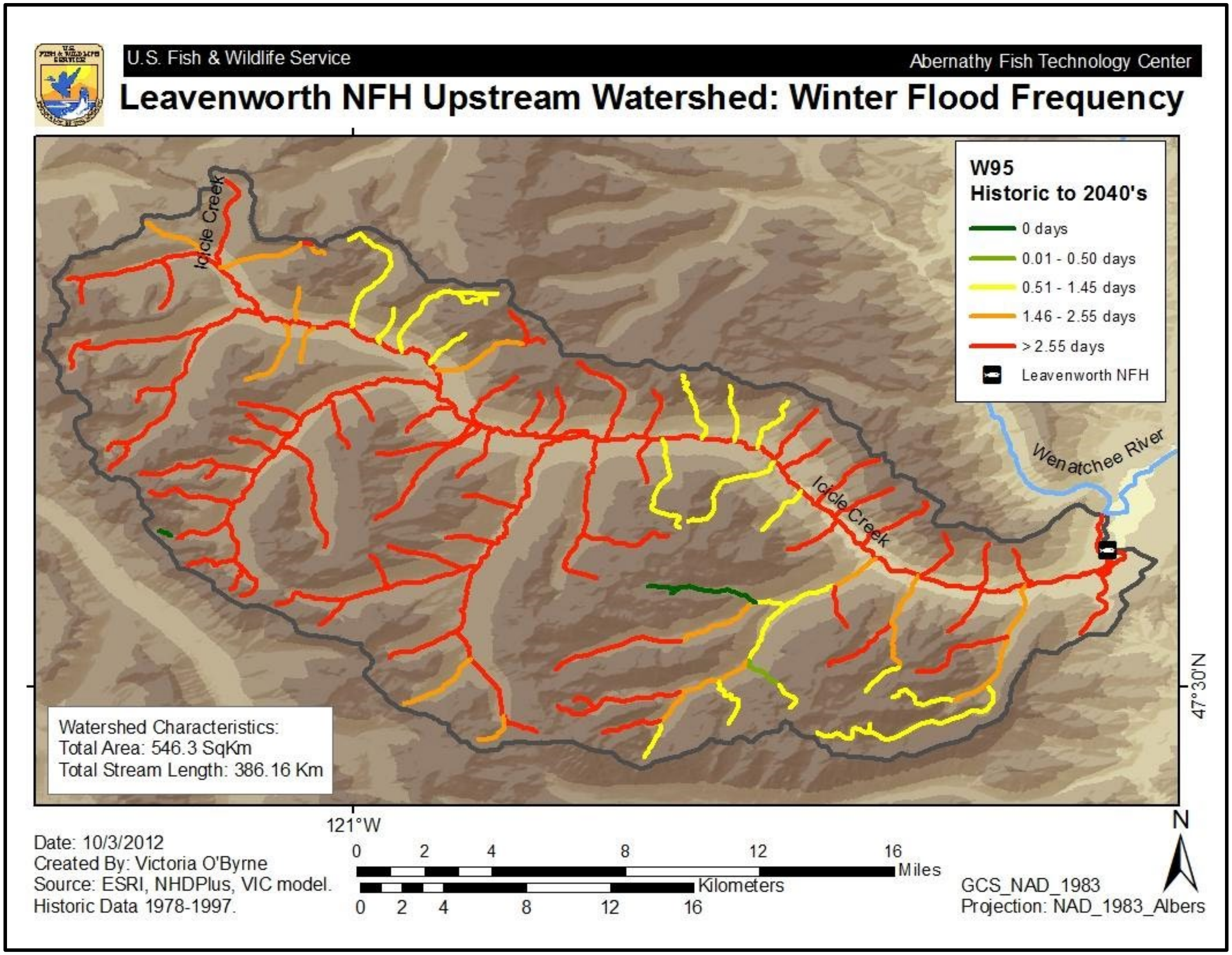

Figure B14. Projected change in the frequency of winter high flows (W95; i.e., number of days in winter that modeled flow was in the top 5% of annual flows) for the Icicle Creek basin upstream from Leavenworth NFH between the 1980s and 2040s periods. Data are from VIC hydrologic model (Wenger et al. 2011), and the historical reference period is 1978 – 1997.

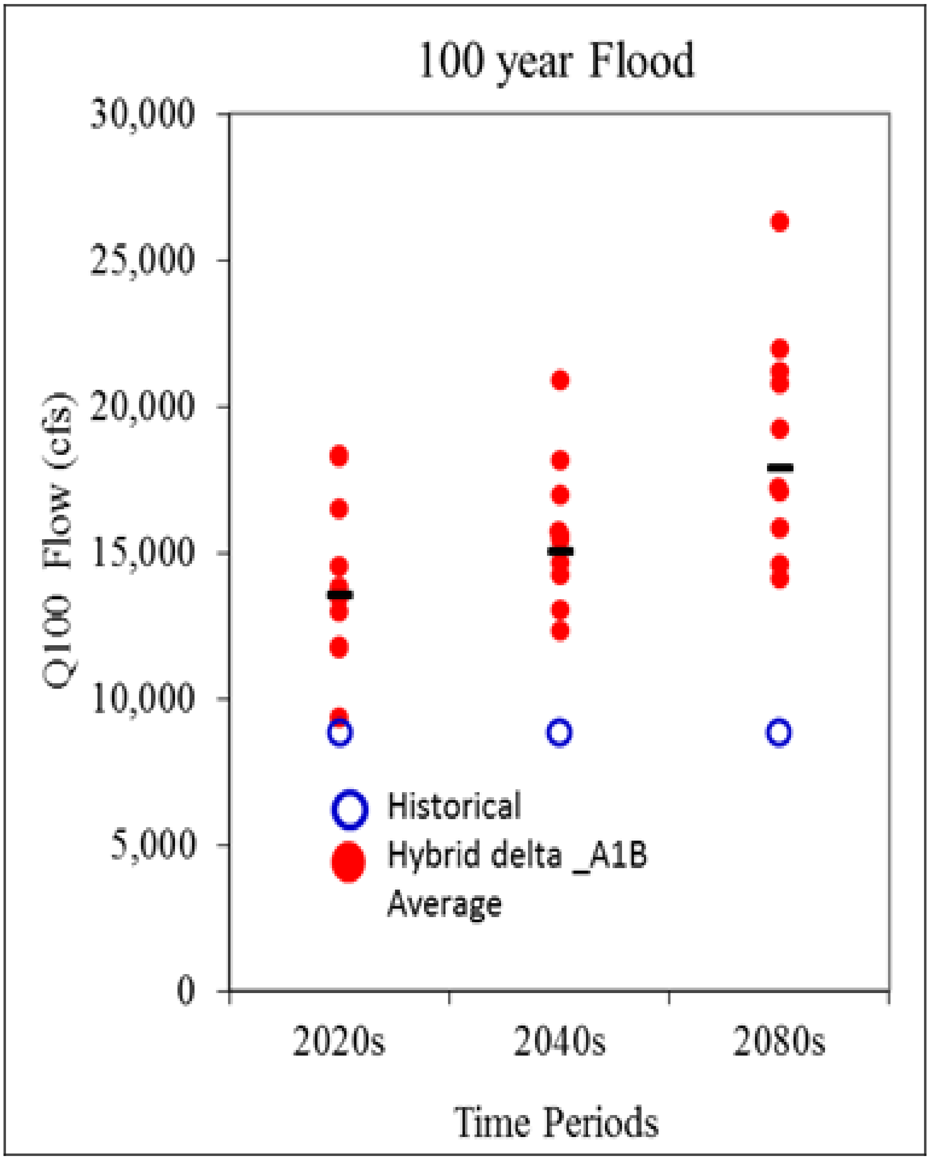

Figure B15. Magnitude of large (100-year) floods for Icicle Creek adjacent to the Leavenworth National Fish Hatchery based on raw Variable Infiltration Capacity (VIC) simulations for the 2020s, 2040s, and 2080s. Flows projections are based on the VIC model forced by output from an ensemble of 10 general 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.

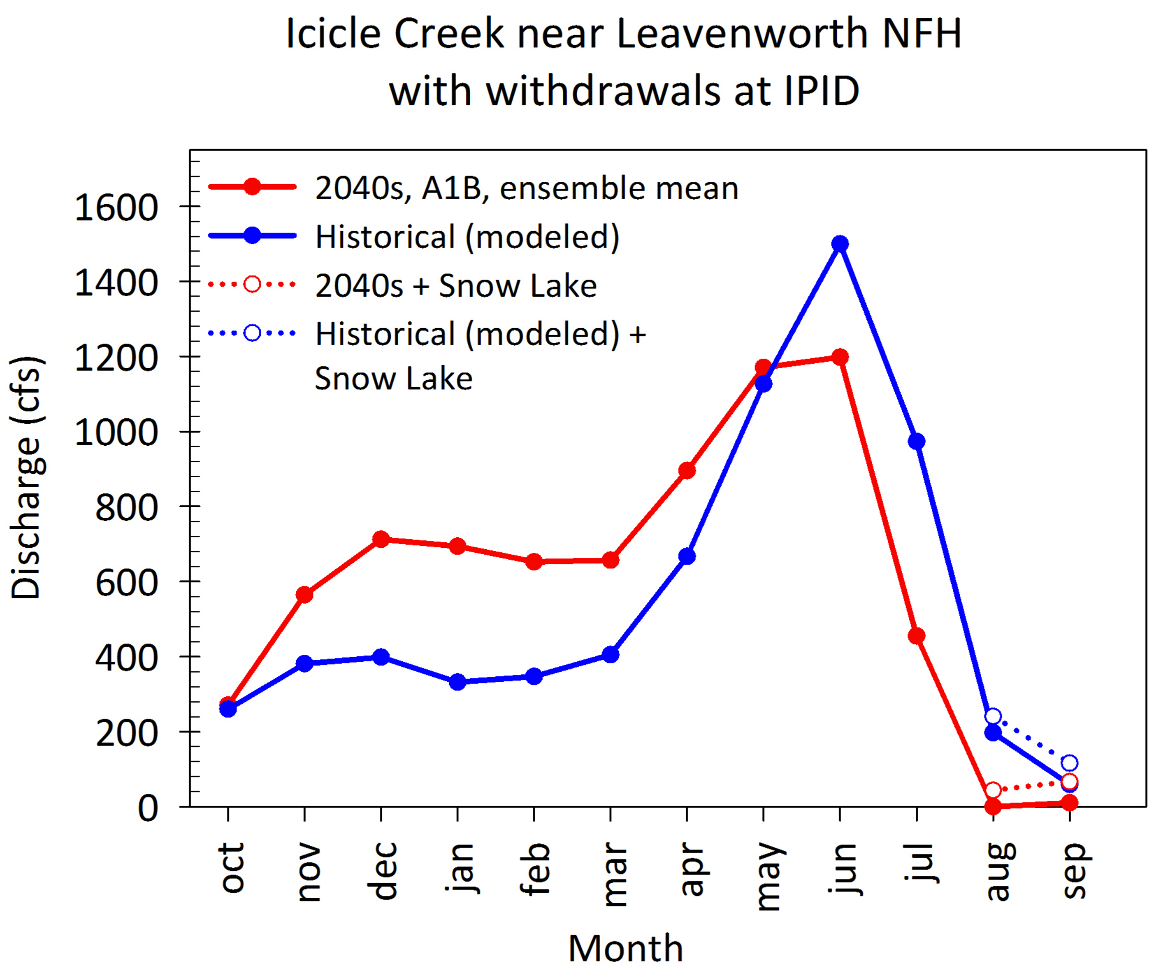

Figure B16. Modeled mean monthly surface flow in Icicle Creek adjacent to Leavenworth National Fish Hatchery based on raw Variable Infiltration Capacity (VIC) simulations and accounting for historical diversion amounts at the Icicle-Peshastin Irrigation District (IPID) diversion structure and Upper Snow Lake inputs. 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. Dotted lines for August and September denote estimates that incorporate the average monthly releases from Upper Snow Lake recorded at the lake's release valve during 2005 – 2015.

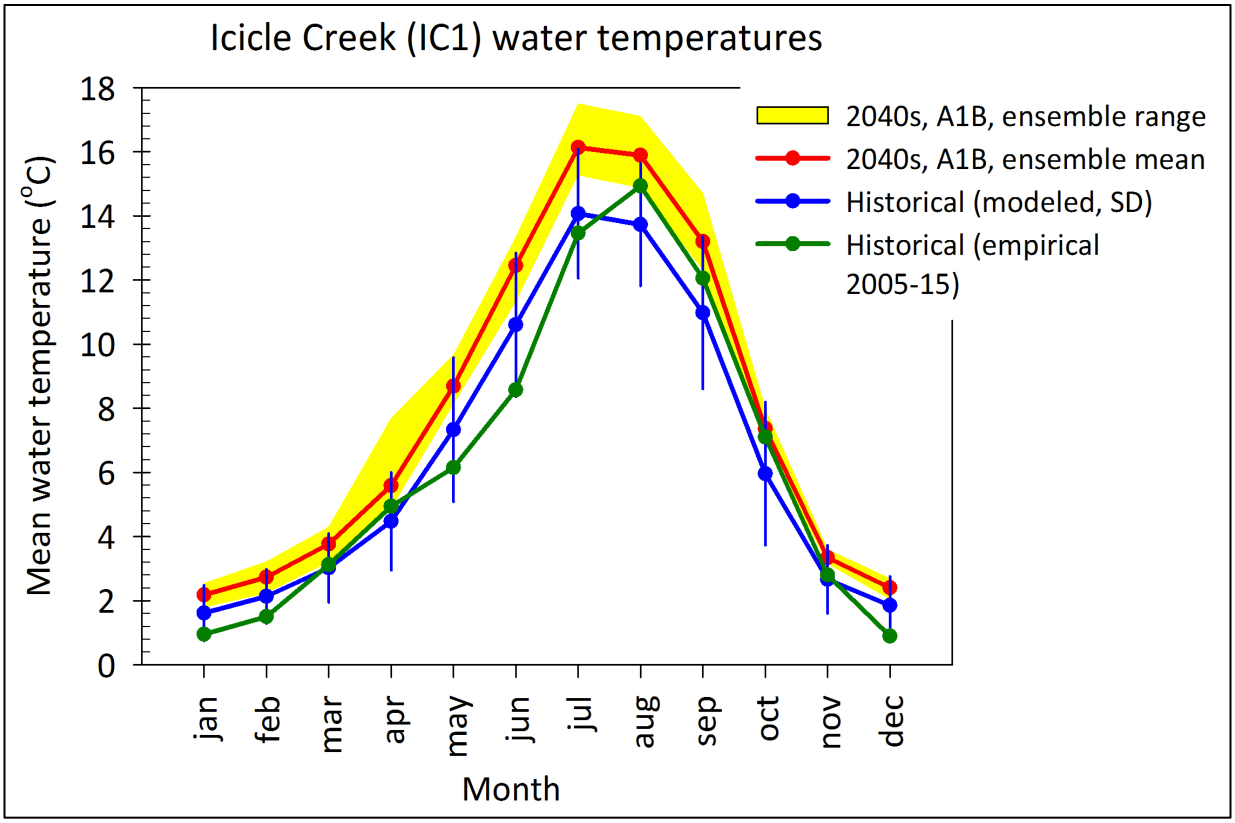

Figure B17. Modeled water temperatures in Icicle Creek (at IC1) upstream from the confluence with Snow Creek. Modeled estimates of projected (2040s) water temperatures were generated via the regression model and are forced by output from an ensemble of 10 GCMs under the A1B greenhouse gas emissions scenario. 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 at IC1 are shown for reference. The standard deviation of the simulated historical values are presented to show the variability across 1915 – 2006.

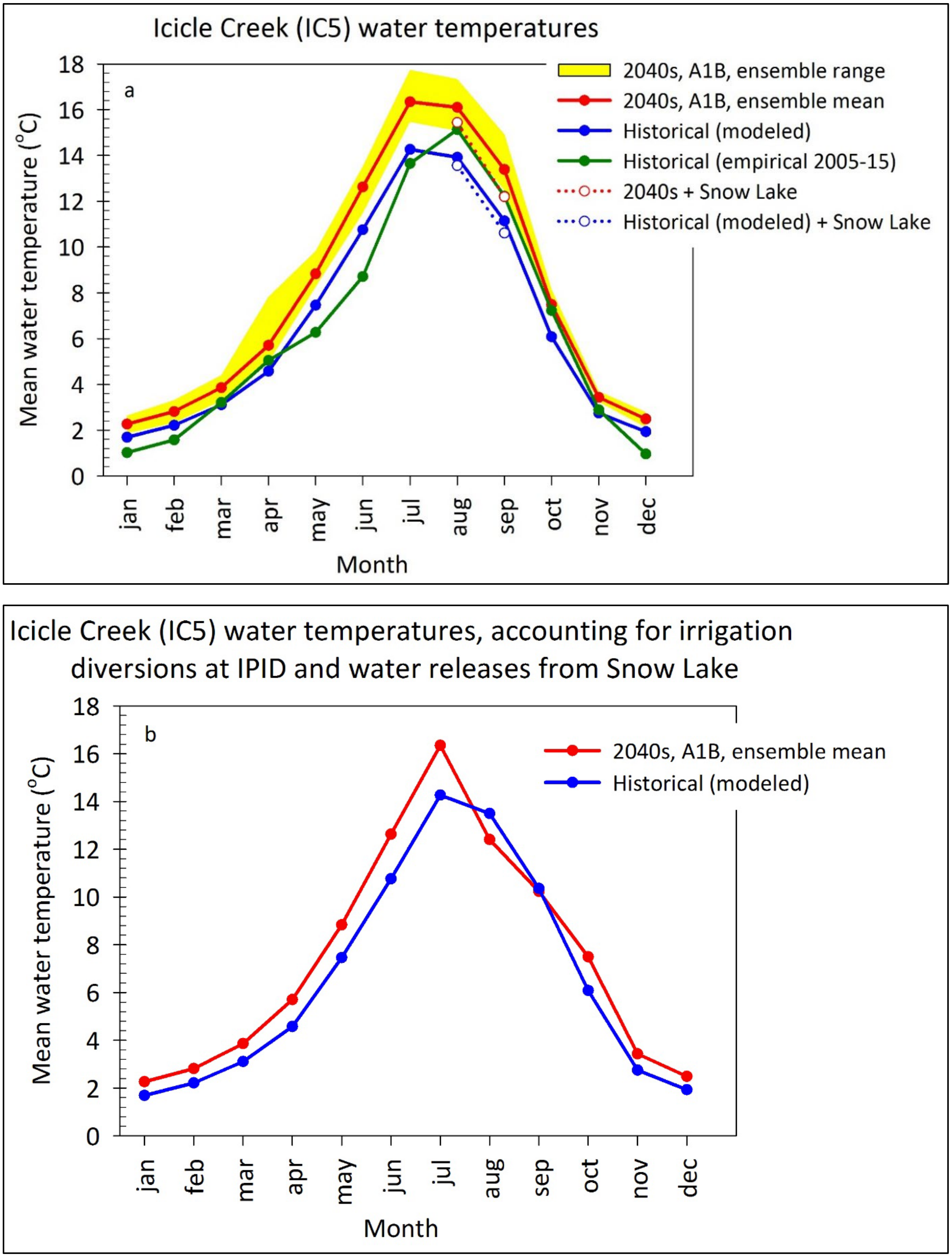

Figure B18. Modeled water temperatures in Icicle Creek at the water intake to Leavenworth National Fish Hatchery (thermograph site IC5). Modeled estimates of projected (2040s) water temperatures were generated via the regression model and are forced by output from an ensemble of 10 GCMs under the A1B 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 estimates based on thermograph data at IC5 are shown for reference. **Panel (a):** Dotted lines for August and September denote estimates that consider monthly releases from Upper Snow Lake recorded at the lake's release valve during 2005 – 2015, water temperatures in Snow Creek (IC2), and modeled surface flow and water temperatures at IC1. **Panel (b):** The plot of the 2040s GCM ensemble mean incorporates the effect of releases from Upper Snow Lake and the historical surface water diversions at the IPID diversion structure.

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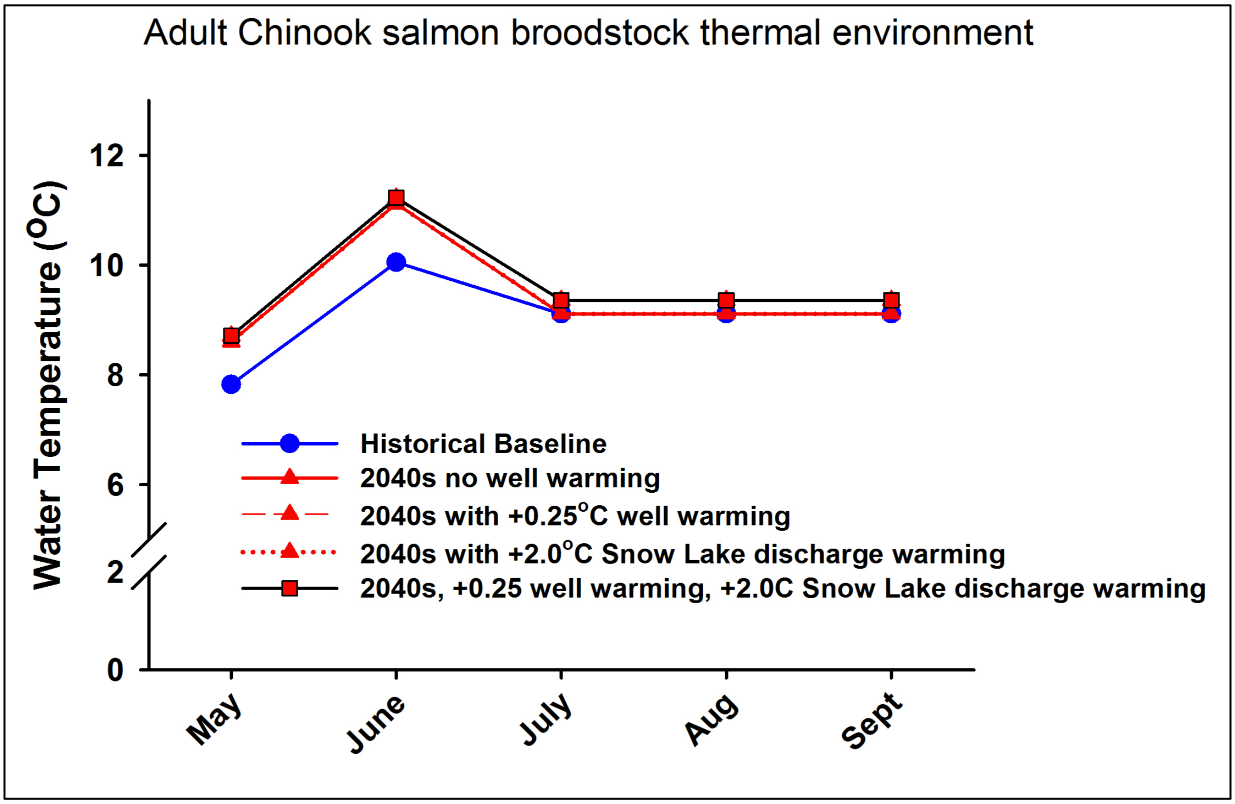

Figure B19. Comparison of the mean water temperatures experienced by adult Spring Chinook Salmon broodstock held at Leavenworth NFH based on the simulated historical baseline and projected values for the 2040s under the A1B emission scenario and four future temperature scenarios. **Scenario A:** no change in future temperature of Upper Snow Lake and groundwater (no well warming). **Scenario B:** no change in future temperature of Upper Snow Lake but a 0.25 °C increase in groundwater (well water) temperature. **Scenario C:** 2 °C increase in future temperature of Upper Snow Lake but no change in groundwater temperature. **Scenario D:** 2 °C increase in future temperature of Upper Snow Lake and 0.25 °C increase in groundwater temperature.

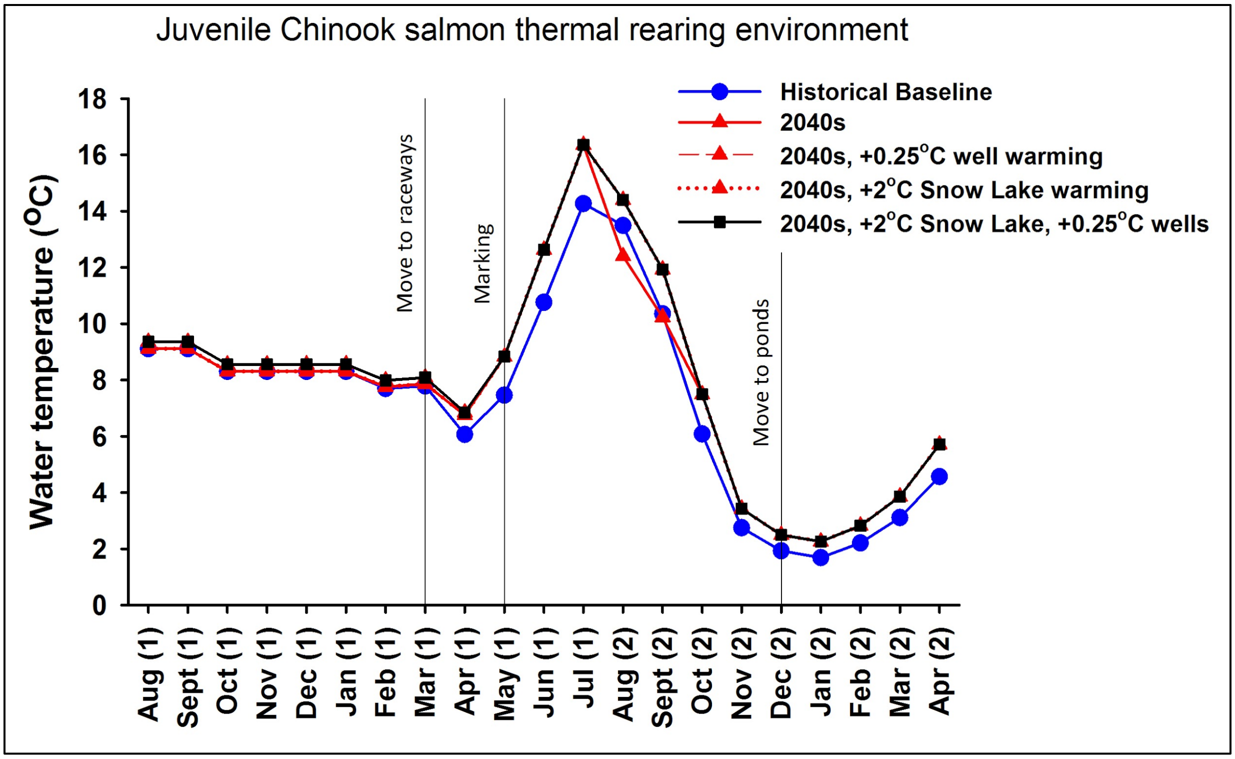

Figure B20. Comparison of the mean water temperatures experienced by juvenile Spring Chinook Salmon reared at Leavenworth NFH based on the simulated historical baseline and projected values for the 2040s under the A1B emission scenario and four future temperature scenarios. **Scenario A:** no change in future temperature of Upper Snow Lake and groundwater (no well warming). **Scenario B:** no change in future temperature of Upper Snow Lake but a 0.25 °C increase in groundwater (well water) temperature. **Scenario C:** 2 °C increase in future temperature of Upper Snow Lake but no change in groundwater temperature. **Scenario D:** 2 °C increase in future temperature of Upper Snow Lake and 0.25 °C increase in groundwater temperature.

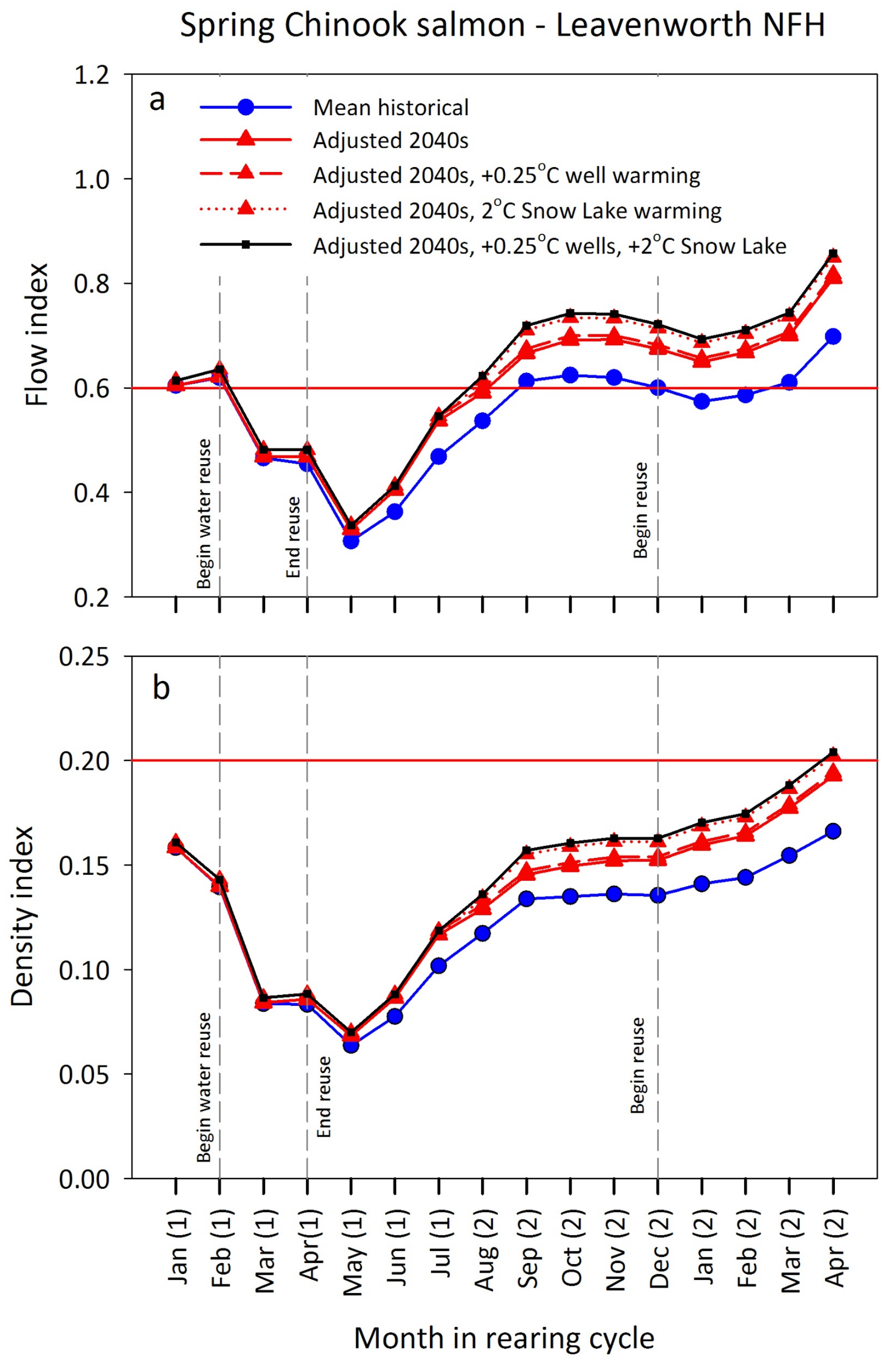

Figure B21. Mean historical and bias-corrected future flow index (a) and density index (b) values for Spring Chinook Salmon at Leavenworth National Fish Hatchery based on average rearing conditions during 2003 – 2014 brood years and four future temperature scenarios (see Figure B20). Values for the 2040s have been bias corrected by multiplying the uncorrected future values by the ratio: (observed mean historical value 2003 – 2014 brood years) / (modeled historical value). See Table B7 for bias correction values. The horizontal lines in each plot represents the upper-limit, fish health guideline for Spring Chinook Salmon.

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