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

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ABSTRACT

Future climate conditions may make it difficult for salmon hatchery programs in the Pacific Northwest to operate under existing paradigms where those programs adhere to rigid rearing schedules and production targets. Here, we evaluate the vulnerability of the coho salmon (*Oncorhynchus kisutch*) program at Quilcene National Fish Hatchery (NFH) to climatic changes expected by the 2040s under a suite of 10 general circulation models (GCMs) forced by the 'middle-of-the-road' A1B greenhouse gas emissions scenario (IPCC 2007). We summarize projected environmental conditions in the Big Quilcene River basin in western Washington State and used those data to implement a temperature-driven growth model for hatchery-reared coho salmon that allowed us to evaluate temporal changes in mean fish size, water *flow index*, and fish *density index*. By the 2040s, the surface water sources for Quilcene NFH are expected to be warmer in all months with coho salmon in the facility experiencing temperatures 0.4 – 2.6 °C greater than the historical average. As a result, juvenile coho salmon reared in the facility are projected, on average, to be 30 – 40% heavier and 9 – 12% longer in most months because of earlier hatch dates and faster growth rates. Concurrent with increased temperatures, the annual hydrograph in Big Quilcene River will be different from present with mean river flows projected to be substantially higher in winter and somewhat lower in summer with a higher risk for more extreme winter floods. The combined effect of higher temperatures and lower summer flows will result in an increase in density index, such that the facility more frequently exceeds its threshold guideline value of DI = 0.2. Under these projected conditions, risks of physiological stress, disease incidence, and mortality of coho salmon reared at Quilcene NFH will likely increase if current culture practices remain unchanged. The efficacy of current practices that mitigate for reduced water availability, fish crowding and high density indexes (e.g., serial reuse of water and moving fish from the hatchery to saltwater net pens) may require additional evaluation because both approaches may be constrained under future climatic conditions.

INTRODUCTION

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

The viability of wild (naturally spawning) and propagated (hatchery-reared) populations of Pacific salmon could be affected by some or all of these factors, but a comprehensive analysis is beyond the scope this effort. Rather, our intent is to focus in significant detail on one portion of the life cycle of propagated salmon – that which takes place in the hatchery – and understand specifically how growth rates, mean size, and total biomass of the fish during that phase are affected by changes in water availability and temperature anticipated under climate change. 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 results 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 the hatchery. The hatchery represents an environment, albeit artificial, over which the USFWS Fish and Aquatic Conservation program has the scope to directly design and implement climate mitigation strategies.

Given these premises, our overall objective is to understand whether hatchery programs can operate in a 'business as usual' paradigm following existing rearing schedules and production targets under future climatic conditions, focusing specifically on changes in water temperature and water availability in the hatchery. Specific objectives are to: (a) determine if future environmental conditions are likely to altogether preclude rearing of certain species or populations, (b) identify the magnitude and timing of sub-lethal effects that may affect growth and survival, including the incidence of disease, and (c) suggest general mitigation strategies given the sensitivities detected in (a) and (b). To achieve these objectives, we synthesized 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 (Piper et al. 1982; Wedemeyer 2001) which integrate the effects of changing water temperatures and availability at Quilcene NFH. We briefly summarize the important hydrologic changes anticipated for the Big Quilcene River basin upstream from the hatchery. Using empirical data on recent rearing conditions within the hatchery, we then predict the future growth and total mean weights (biomass) of coho salmon reared at Quilcene NFH by implementing the growth model and modeling flow and density indices based on (a) in-hatchery environmental conditions projected for the 2040s under a moderate, future greenhouse gas scenario (A1B scenario; IPCC 2007) and (b) incremental changes in temperature and water availability.

METHODS

Salmon thermal tolerances

In August, 2011, a review of the peer reviewed literature of thermal tolerances of five focal salmon and trout species (Chinook, coho, chum, sockeye and steelhead trout) reared at National Fish Hatcheries (NFHs) was performed to determine the thermal tolerances for multiple life-history stages. This information was acquired though two general approaches. First, to identify relevant primary literature ISI's Web of Science (1945-present) 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 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 : (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 facility during the spawning migration and represent the pool of potential parents for the offspring generation). Data were averaged by each of the three life-history stages to determine representative thermal tolerances for each species at each life-history stage and, for the analysis presented here, for coho salmon at Quilcene 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

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

cause disease in salmon. The literature review followed the same protocols as described above, but with the common name or Latin binomial of pathogens 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. A total of four citations provided detailed information on the following two variables:

1. *optimal temperatures*: the pathogen-specific temperature range for optimal transmission between fish and moderate mortality in a population; and
2. *optimal outbreak temperatures*: the temperature range corresponding to optimal pathogen growth and virulence coinciding with major mortality in infected populations (Table B2).

Quilcene NFH rearing conditions - water temperatures

Baseline thermal rearing conditions at Quilcene NFH were calculated from water temperatures measured for the facility’s surface water sources: the Big Quilcene River and Penny Creek. Daily mean, maximum, and minimum temperatures of surface water flows from the Big Quilcene River, recorded at the Washington State Department of Ecology gaging station (gage 17A060, located at 47° 49' 06" N and 122° 52' 56" W) for the years 2003 - 2012 inclusively, were used to calculate monthly water temperatures (mean, maximum, and minimum) for each year in the time series. A baseline 10-year average monthly water temperature was calculated for the surface flow data set. Similarly, daily average surface water temperatures were measured at the hatchery water intake from Penny Creek in 2001 - 2002 and 2006 - 2008. The Penny Creek temperature data (daily mean, maximum, and minimum temperatures) were used to calculate baseline average monthly water temperatures following the process described above. The baseline water temperature information was used to estimate the thermal rearing conditions experienced by fish across their rearing schedule within Quilcene NFH as determined by the source(s) of water supplied to rearing containers during each month.

Projected thermal conditions in Quilcene NFH during the 2040s

To predict future surface water temperatures in the Big Quilcene River near Quilcene NFH, we established a regression relationship between recent air and water temperatures. We then used air temperatures predicted for the 2040s under the A1B greenhouse gas emissions scenario (IPCC 2007) to generate water temperature predictions for the 2040s based on the aforementioned regression model. We used the non-linear regression model of Mohseni et al. (1998),

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

and the approach of Mantua et al. (2010) to establish a site-specific relationship between weekly air and water temperatures. Weekly air temperature readings from sites within the 1/16th degree latitude × longitude grid cell (47.78125^{o} N latitude, 122.90625^{o} W longitude) adjacent to Quilcene NFH were fit to mean weekly water temperatures recorded during 2003-2012 Big Quilcene River flow gage (#17A060). Model fit was estimated by the Nash-Sutcliffe Coefficient (NSC; Nash and Sutcliffe 1970), and we assumed a stable relationship between weekly average air and surface water temperature. We fit the model with the non-linear regression package ‘nls’ in R version 3.0.1 (R Core Team 2013). The regression model for the Big Quilcene River provided an adequate fit with a NSC = 0.867, yielding the following parameterized equation:

$$T_{sw} = 2.55 + \frac{17.65 + 2.55}{1 + e^{0.16(13.25 - T_{air})}} .$$

Surface water temperature (T_{SW}) predictions for the 2040s were generated by applying the statistically downscaled air temperature predictions from on an ensemble of 10 general circulation 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 to as "middle-of-the-road" in terms of projected 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 also 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).

Thermal rearing conditions projected for Quilcene NFH during the 2040s were based on mean monthly temperatures estimated for Penny Creek – the hatchery's primary water source between spawning and ponding – and Big Quilcene River – the hatchery's water source after the fish have been placed into raceways (ponded). To determine mean monthly water temperatures for Penny Creek under the future climate change scenario (i.e., the 30-year period centered on the 2040s), the relationship of Penny Creek water temperature to Big Quilcene River water temperature was calculated by regressing monthly water temperatures for Penny Creek against monthly water temperatures for the Big Quilcene River water for each year in the 2000 – 2009 historical baseline. The following regression equation ($R^2 = 0.83$, $F = 583$, d.f. = 117, $P < 0.001$) was used to predict Penny Creek water temperatures for the 10 GCM ensemble under the A1B emissions scenario:

$$T_{PC} = 0.726\left(T_{BQ}\right) + 2.844$$

where T_{PC} represents surface water temperature in Penny Creek (°C), and T_{BQ} represents surface water temperature in the Big Quilcene River (°C). The modeled 2040s A1B water temperature information was used to calculate the thermal rearing conditions experienced by fish across their rearing schedule (Table B3) as determined by the source(s) of water supplied to rearing containers during each month.

Growth Model Simulation

We used the fish growth model of Iwama and Tautz (1981) to estimate how the growth of hatchery-reared coho salmon might change in response to climate warming. 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 fish size as a function of water temperature assuming unlimited 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:

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

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 fish sizes of coho salmon after ponding. The initial weight at ponding (when fish are transferred to outdoor raceways for rearing) 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) those projected for the 2040s. We then compared cumulative differences in size between those two thermal regimes.

Projected water availability at Quilcene NFH during the 2040s

To generate estimates for water availability at Quilcene 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). Flow data were summarized as mean monthly surface water discharge in the Big Quilcene River routed to the location of Quilcene 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 2007 - 2010. For example, if the coho salmon program uses 15 cubic-feet-per-second (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 cannot utilize additional water (above the mean historical use) for months where an increase in mean flow is projected.

Flow index and density index: critical 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 the mean fish length by water use (flow index) or by rearing capacity (density index):

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

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

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

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

We used flow index and density index as response variables to integrate and evaluate the combined effects of changing water temperatures, water availability, and physical rearing capacity at Quilcene NFH (and more generally as surrogates for carrying capacity under historical and future conditions) using two approaches to represent variation in climate and rearing conditions. First, 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 coho salmon at Quilcene NFH in each monthly time-step after initial ponding. This produced two 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 these 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:

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

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

Thus, the future bias-corrected index values were:

$$FI_i \text{ future corrected} = rFI_i \bullet FI_i \text{ modeled future}, \text{ and}$$

$$DI_i \text{ future corrected} = rDI_i \bullet DI_i \text{ modeled future}.$$

A complete description of the model formulation and underlying equations are presented in Hanson and Peterson (2014).[2]

Second, we conducted a sensitivity analysis to examine how the flow and density indices changed based on incremental changes in temperature and water availability. For the flow index, we plotted monthly index values based on combinations of water temperature (100 increments covering historical mean temperature ± 4°C) and water use (50 increments ranging from 40% to 150% of historical mean water utilization in cfs) to generate a monthly response surface of 5,000 points. We did the same for the density index but used incremental changes in capacity (50 increments ranging from 50% to 200% of the historical mean). The generating equations for the sensitivity analyses are those for FI_i and DI_i presented above, with the appropriate substitutions for temperature and fish size.

RESULTS

Projected future climate at Quilcene NFH under the A1B emissions scenario

Under the A1B emissions scenario, the Big Quilcene River basin is projected to experience warmer air temperatures, higher stream temperatures, lower summer baseflows, and more extreme winter floods by the 2040s (Tables B3, B4; Figures B1 - B7). Mean air temperature near the hatchery is expected to increase in every month (mean = 1.8 °C, SD = 0.46 °C) with the largest absolute increases predicted for July-September (range 2.3 - 2.5 °C; Table B4). Total annual precipitation is projected to be similar (historical: 124 mm vs. 2040s: 129 mm), but seasonally precipitation is projected to decline in summer (May - September) and

[2] 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 case (i.e., N_iW_i/L_i differs between modeled historical and empirical cases but not between DI_i and FI_i for each case), and (b) the values for GPM_i and C_i, respectively, at each time step were the same in both cases (i.e., the modeled historical case used the same values of GPM_i and C_i, respectively, as those measured empirically).

increase slightly in other months (Table B4). Based on the VIC modeling, mean annual flows projected for the Big Quilcene River in the 2040s (mean 388 cfs, range 331-429 for 10 GCM) will be similar to the modeled historical values (358 cfs; Table B5). Projected flows in Penny Creek follow a similar pattern (2040s mean 15 cfs; historical mean 14 cfs). The magnitude of seasonal flows, in contrast, is projected to be quite different in the future, especially in the Big Quilcene River, where mean flows by the 2040s are projected to increase 20 - 30% in the late fall and winter (November - March) and decrease by 25 - 42% in the summer (May - August) (Figures B1a and B7). By the 2040s, moderate increases in monthly flows during winter are projected for Penny Creek (Figure B1b). The shape of the hydrographs are generally similar for both time periods (Figure B1), but in the future the timing of the center of flow mass is earlier in the year (Figure B3), perhaps because of the increase in winter flows. Minor increases in the severity of summer drought (Figure B4) and large increases in the magnitude of large winter floods (Figure B5) are also predicted at the watershed scale.

Water temperature in the 2040s based upon the A1B scenario and statistical downscaling of GCMs are expected to increase in both the Big Quilcene River and Penny Creek (Table B3). In all months, modeling predicts that Big Quilcene River surface water temperatures will increase by between 0.4 °C (November) and 2.6 °C (June) when compared to historical averages. The most significant changes in surface water temperatures are predicted to occur in May (+2.1 °C), June (+2.6 °C), and July (+1.8 °C). The water temperatures in Penny Creek follow a similar pattern with predicted warming in all months. The most significant changes in Penny Creek water temperatures are predicted to occur in May (+1.5 °C), June (+1.9 °C), and July (+1.3 °C). Given the predicted alterations to surface water temperatures at Quilcene NFH, the water temperatures across the production cycle will change.

Coho Salmon Program

Adult coho salmon returning to Quilcene NFH are typically captured between August and November and retained in holding ponds supplied with water from the Big Quilcene River until spawning. By the 2040s, water temperatures between August and November are predicted to increase by between 0.4 °C and 0.8 °C, and the predicted highest mean monthly water temperature in the hatchery during the broodstock holding time period is 13.7 °C (Table B6; Figure B8). In August and September, the historical temperatures meet or exceed the optimal spawning temperatures for coho salmon (5.7 – 11.7 °C) based on literature values (Table B1), so the projected increase in temperatures by the 2040s makes it more likely that adult coho will experience physiological stress during holding and spawning, especially for fish captured and spawned earlier in the run.

Juvenile coho salmon reared in Quilcene NFH will be exposed to warmer rearing conditions by the 2040s, with projected increases ranging between 0.3 °C and 2.6 °C across the broodstock holding and rearing periods (Table B6, Figure B9). Increases of more than 1.0 °C are projected for April (+1.4 °C), May (+2.1 °C), June (+2.6 °C), July (+1.8 °C) of the first rearing year as well as February (+1.0 °C) of the second rearing year and at release in the subsequent April (+1.4 °C) (Table B6, Figure B9). By the 2040s, water temperatures are predicted to approach the upper physiological threshold for optimal temperature for eggs and fry during October in the first rearing year at Quilcene NFH (cf. Table B1 and Figure B9). At the time of release, the predicted future water temperature within the facility in April (8.2 °C) remains well below the upper limit for proper smoltification (14.3 °C; Table B1). Water temperatures greater than 11 °C are predicted to occur during two months for both the broodstock and the egg/fry stages and four months during the juvenile stage (Figure B9). Although these latter temperatures are below the optimal growth temperatures for common salmon pathogens (Table B2), higher water temperatures increase the risk of outbreak for certain pathogens (Table B2).

While the predicted future (2040s) temperatures in the hatchery may not consistently exceed physiological tolerances of coho salmon, warmer water temperatures will likely increase the growth rates of juvenile coho salmon from January through June immediately after hatching then stabilize thereafter (Table B7, Figure B10). The largest increases in mean weight and length of coho salmon juveniles are predicted to occur in June – August (warmest months) when fish weight is predicted to increase by 37.6 – 41.5%, and fish length is predicted to increase by 11.1 – 12.1% relative to current/historical conditions (Table B7, Figure B10). Due to the warmer thermal environment during the entire rearing period, coho salmon smolts from Quilcene NFH are predicted to be, on average, 34.7% heavier and 10.3% longer at release compared to historical sizes assuming there are no culture modifications or compensatory biological responses (e.g. precocious sexual maturation).

The model-based climate scenarios suggest Quilcene NFH may experience small-to-modest increases in the flow index for coho salmon throughout the entire rearing period (Table B8, Figure B11a). These increases are driven by higher water temperatures and faster fish growth, but overall the flow index is projected to remain well below the threshold guideline of 1.0. The density index is also predicted to increase throughout the rearing period, but it will likely exceed the threshold guideline for coho salmon during March and April immediately prior to release of smolts (Table B8, Figure B11b). The current practice is to move 200,000 pre-smolt coho salmon juveniles of each brood year from Quilcene NFH to saltwater net pens in Quilcene Bay, Puget Sound (operated by the Skokomish Tribe), for the final two months of rearing. A current concern for this latter program is harmful algal blooms (HABs) at the net pen location that cause salmon mortality (Moore et al. 2011). Those blooms may be an even greater concern in the future as warming coastal waters are thought to result in more frequent HABs (Huppert et al. 2009). If HABs preclude moving juvenile fish from the hatchery to saltwater net pens for the final two months of rearing, then modest increases in flow and density index values are predicted at the hatchery if raceway *Bank C* remains in operation with fish that would have been transferred to the net pens under current protocols (Table B9; Figure B12). Under this latter approach, the density index would likely exceed the upper guideline value of 0.2 in both March and April (Figure B12b).

Results of the sensitivity analyses are presented as contour plots in Figures B13 - B14. The contour plots are most easily interpreted by examining the range of potential index values that could occur and the relative position of the historical value. Flow and density indices are color coded from low values (green) to high values that meet or exceed threshold guidelines (red) for coho salmon at Quilcene NFH. High flow or density index values are in the top left portion of each month's plot and represent combinations of reduced water and increased temperature (flow index) or reduced capacity and increased temperature (density index). Relatively large declines in water availability or increases in temperature would be required to shift the flow index above threshold values in most months. Sensitivity analyses indicate the density index is more sensitive to a relative decrease in capacity than an increase in temperature (Figure B14). Although total fish rearing capacity is usually a constant constrained by the physical infrastructure of a facility, density indexes are expected to increase in response to climate change because of increasing temperatures and consequential monthly increases in total biomass (quantified via the ratio Wi/Li) if the total number of fish reared and physical rearing capacity remain unchanged. In other words, any temperature increase is expected to result in faster fish growth which increases the density index value for a fixed rearing capacity. We should note also that the density index at Quilcene NFH is already approaching the threshold guideline value of 0.2 in some months.

DISCUSSION

The future will be warmer and more variable: fundamental challenges

Climate warming and hydrologic changes are projected to produce a different set of environmental conditions in the Big Quilcene River basin by the 2040s. Warmer air and water temperatures are projected for every month, and though the mean annual flow will be similar, the timing and variability of that discharge will change considerably. Higher flows and larger floods are projected for winter, and lower baseflows and more frequent and intense droughts are expected during summer. For hydrologic changes, we generally limited our analyses to how decreases in water availability could affect the ability of Quilcene NFH to rear coho salmon to the smolt stage in freshwater (approximately 18 months, including egg incubation). Clearly, the projections for larger floods – as soon as the 2020s – suggest an increased risk of damage to hatchery facilities and water intake structures.

Projected hydrologic changes, current instream flow requirements in the Big Quilcene River, and established water rights of the hatchery interact to present a seemingly fundamental constraint on fish culture (Table B10). Modeling indicates that in certain months, Quilcene NFH will have no more than 15 cfs available from the Big Quilcene River to devote to coho salmon culture because the first or *primacy* (earliest) water right for the facility allows diversion of 15 cfs from the Big Quilcene River regardless of river flows. The hatchery's second water right from the Big Quilcene River (25 cfs; priority date 1998) is linked to an instream flow requirement to maintain a minimum flow of 50 or 83 cfs (depending on month) before this latter right can be used. Currently, Quilcene NFH withdraws only 12 - 15 cfs during low flow conditions in August and September and relies on serial reuse to supply sufficient water to the occupied raceways (D. Magnuson, Quilcene NFH, personal communication, August 1, 2014). By the 2040s, the projected decreases in discharge for the Big Quilcene River for August and September, when combined with the instream flow requirement for the second water right, will dictate serial reuse for those months (Table B10). The most pessimistic hydrologic projections suggest that serial reuse may have to begin earlier in July. These are average projections – so not all years will be as optimistic or pessimistic as presented here – but the results indicate the serial reuse will have to be the norm in late summer.

Moreover, the hydrologic projections for the Big Quilcene River presented in Table B10 may overestimate the actual discharge near the hatchery. The City of Port Townsend, WA, and the Port Townsend Paper Corporation operate a water diversion on the Big Quilcene River several miles upstream from the hatchery and typically divert water during base flows or when water clarity is high. The City of Port Townsend and Port Townsend Paper Corporation have imposed a 27 cfs minimum instream flow at their diversion structure, but substantially less than 27 cfs may reach the water intake for Quilcene NFH during the summer (D. Magnuson and R. Wong, Quilcene NFH, personal communication, October 2, 2014) which is less than the modeled flows for those months (Table B10).

Warmer water and lower summer flows: future chronic challenges

Quilcene NFH is projected to experience higher water temperatures throughout the year coupled with lower water availability in the summer months. Alone or in concert, these changes should result in a higher probability that coho salmon reared under current practices may face increased physiological stress and a higher probability of disease or mortality.

By the 2040s, coho salmon in Quilcene NFH will be exposed to higher water temperatures in nearly all months of the culture cycle, from capture of broodstock through release of smolts. Adult broodstock, captured and held in August and September, already experience water temperatures near their physiological tolerance (based on literature values), and warming should only increase the probability of mortality. Chronic thermal stress caused by exposure to high water temperatures would be expected to decrease immune function, and increase the potential for disease outbreaks in the captive population. Coho eggs and fry developing during August and September will likely experience water temperatures that meet or exceed their physiological tolerances (based on literature values), thus developmental abnormalities and mortality seems increasingly probable. Fortunately at this life-history stage, coho are supplied with virtually pathogen-free water from Penny Creek; thus, the probability of disease outbreaks may continue to be minimal assuming no contamination of the rearing containers or the water source (Penny Creek). However, juvenile coho salmon transferred to raceways - supplied with water from the Big Quilcene River which is not pathogen free - will be exposed to increased water temperatures during every month of rearing which will, most likely, increase disease risks and growth rates. Juvenile coho at Quilcene NFH have previously experienced outbreaks of bacterial coldwater disease (*Flavobacterium psychrophilum*), bacterial kidney disease (*Renibacterium salmoninarum*), and pathogenic fungi (*Saprolegnia* spp.). Additionally, *Aeromonas salmonicida*, the causative agent of Furunculosis, and infectious hematopoietic necrosis virus (IHNV [*Novirhabdovirus* spp.]) have been documented within fish in the Big Quilcene River. Especially during May - October, water temperatures in the hatchery are well within or near the optimal temperatures for those pathogens (Table B2), suggesting that the frequency of disease outbreaks may increase. Standard hatchery practices stressful to fish (e.g., handling, mass marking, moving fish between rearing containers) that occur during the summer months are expected to exacerbate the effects of thermal stress and further increase the probability of disease. For example, mass marking currently occurs in June, the month that is predicted by the model to have the largest absolute increase in water temperature.

Projected increased water temperatures should result in larger coho salmon grown in Quilcene NFH, all other things being equal. Coho are projected to be 30 - 40% heavier and 9-12% longer in most months. Such increases in fish size may cause the facility to exceed its threshold guidelines for density index unless the hatchery's capacity is increased or fish abundance is reduced. Additionally, increased frequency and duration of HABs in Puget Sound may prevent moving fish to net pens for the final month of rearing. If these fish were kept on station, major increases to flow and density indices would occur during the final month of rearing. In general, flow and density indices integrate growth and water use – or physical capacity – and roughly approximate carrying capacity based on dissolved oxygen levels, removal of metabolic waste, and the ecological and physiological consequences of crowding (Wedemeyer 2001). Biological correlates of index values that exceed a facility's threshold guideline value for a particular species or population could include reduced growth and condition, chronic stress, decreased immune function and higher risk of disease.

During the summer months of increased density index, Quilcene NFH often operates on serial water reuse where fish in downstream raceway banks may receive second- or third-pass water. As this water passes through each raceway, water quality is reduced by oxygen use and metabolic waste accumulation. This reduced water quality would effectively increase the density and flow indices for fish in raceways subject to serial reuse, but there is currently no accepted way to model this phenomenon. Therefore, the modeled density and flow index values we present here probably underestimate the true values related to fish health risks, and index values could be substantially greater in raceways where fish receive second- or third-pass water.

Additionally, increased fish growth could compromise the ability of hatchery managers to meet legislated size-at-release targets. Large body size of individual fish at seawater entry has been correlated to an increased proportion of precociously-mature male salmon (aka, "jacks") within a population (Vøllestad et al. 2004; Koseki and Fleming 2007)[3]. When larger juvenile salmon from a hatchery are released into an environment that contains smaller, naturally-spawned salmon, they can also pose an ecological threat to wild populations through direct predation (Hawkins and Tipping 1999; Namen and Sharpe 2012) and competition for resources (Weber and Fausch 2003; Simpson et al. 2009).

Our analysis of climate vulnerability for the coho program at Quilcene NFH focused primarily on the quality (temperature) and quantity of surface water within the Big Quilcene River basin. We caution that there are assumptions and uncertainties with the modeling approach and available data that limit our ability to make more precise predictions about the future vulnerability of the coho salmon program and facility to climate change. First, we did not model the dynamics of the groundwater source available to Quilcene NFH or explore whether it could be used to mitigate for expected reductions in surface water availability. The facility has a well that supplies 320 gallons per minute (gpm) to an isolation/quarantine building; the well water is not used for propagation of coho salmon. If climate change affects Big Quilcene River and Penny Creek discharge, it is unclear how this may affect the well. Consequently, it is difficult to evaluate whether well water would be able to compensate for reductions in surface water flows (e.g., groundwater availability may decrease in concert with surface flows). Second, we did not

[3] Coho salmon in Washington State typically mature at three years of age. Males maturing at two years of age are commonly called "jacks" because of their much smaller size relative to three-year old males and females.

directly model climate change impacts to the near shore environment in Quilcene Bay, such as HABs, ocean acidification, and sea level rise, as these events are clearly beyond the hatchery manager's control. Modeling suggests that the frequency and duration of HABs in Puget Sound will increase under the A1B emissions scenario (e.g., Moore et al. 2011). HABs are known to cause extensive mortality in juvenile salmon, and up to 50% mortality was recorded in exposed coho salmon from Quilcene NFH. Consequently, the current monitoring program for HABs in Quilcene Bay will need to be continued, and an emphasis placed on identifying the climate drivers that influence these events. Modeling has also predicted varying levels of ocean acidification and sea level rise for Puget Sound (Huppert et al. 2009). These factors may impact the near shore environment and food webs that juvenile salmon depend on after emigration from the Big Quilcene River.

Mitigating the effects of climate change on the coho salmon program at Quilcene NFH

In the future, Quilcene NFH will likely have to contend with year-round increases in water temperature of its source water, decreased water availability during the summer months, and instream flow requirements in the Big Quilcene River. Mitigation of climate-related effects is possible, but many of the logical approaches have obvious drawbacks and might require further study to determine their efficacy. Two straightforward ways to reduce water temperatures in the facility are using (colder) groundwater sources or chilling surface water. While colder groundwater could conceivably be used to slow fish growth at Quilcene NFH, this has not yet been attempted in practice. Additionally, the volume of well water currently available to the facility (~320 gpm) is not sufficient to fully replace the surface water required for the full production of coho salmon at Quilcene NFH, where each of up to 24 raceways has a target inflow of 600 gpm. Mechanical cooling of surface water by using chillers is theoretically possible, though cooling the large volume of water needed for rearing (~12 - 15 cfs) by 1 to 2° C for multiple months would be energy intensive and likely quite expensive. To decrease energy costs, chilled water could be used early in rearing to slow fish growth, though it is unknown if a sufficient decrease in fish size could be attained by this method. If water temperatures could not be decreased, growth modulation through reduced rations could be used, though ration levels would need to be maintained at a level sufficient to ensure fish condition and health. To mitigate for reduced water availability, the hatchery could pursue administrative actions such as seeking additional water rights or attempting to re-negotiate the instream flow requirements for the Big Quilcene River, though competing water demands in the basin may present a challenge. Operationally, the hatchery could attempt further serial reuse during periods of lower water availability. The current reuse system is fairly complex, and it is uncertain whether additional modifications would affect fish health. Finally, managers could avoid exceeding density index thresholds by rearing fewer fish, especially towards the end of the rearing schedule. Given that HABs in Puget Sound are expected to become more frequent, Quilcene NFH may also need to explore alternatives to the current practice of moving fish to net pens.

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REFERENCES

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

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

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

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

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

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

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

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

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

Good, C., J. Davidson, C. Welsh, B. Brazil, K. Snekvik, and S. Summerfelt. 2009. The impact of water exchange rate on the health and performance of rainbow trout *Oncorhynchus mykiss* in water recirculation aquaculture systems. Aquaculture 294(1–2):80-85.

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

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

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

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

Huppert, D. D., A. Moore, and K. Dyson. 2009. Impacts of climate change on the coasts of Washington State. Pages 285-309 in J. S. Littell, M. McGuire Elsner, L. C. Whitely Binder, and A.K. Snover, editors. The Washington Climate Change Impacts Assessment: Evaluating Washington's Future in a Changing Climate. Climate Impacts Group, University of Washington, Seattle.

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

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

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

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

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

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

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

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

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

Moore, S.K., N.J. Mantua, and E.P. Salathe Jr, E. P. 2011. Past trends and future scenarios for environmental conditions favoring the accumulation of paralytic shellfish toxins in Puget Sound shellfish. Harmful Algae 10(5): 521–529.

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

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

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

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

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

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

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

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

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

Vøllestad, L. A., J. Peterson, and T. P. Quinn. 2004. Effects of freshwater and marine growth rates on early maturity in male coho and Chinook salmon. Transactions of the American Fisheries Society 133:495-503.

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

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

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

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

Table B1. Thermal tolerances (°C) of species reared at Quilcene NFH

Species	Latin Binomial	Life- History Stage	Optimal Range	Optimal Growth Range	Spawn Range	Smoltification Threshold
Coho salmon	*O. kisutch*	adult			5.7 – 11.7 °C	
		egg/fry	1.7 – 9.9 °C			
		juvenile	7.4 – 15.6 °C	17 – 17 °C		14.3 °C

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

Common Name	Latin Binomial	Optimal Growth	Outbreak
Bacteria			
Furunculosis	*Aeromonas salmoncida*	20 – 22 °C	12 °C
Motile aeromonad disease	*A. hydrophila, A. punctata*	20 – 22 °C	12 – 14 °C
Vibriosis	*Listonella anguillarum*	18 – 20 °C	14 °C
Pseudomonad septicemia	*Pseudomonas fluourescens*	20 – 25 °C	
Enteric redmouth disease	*Yersinia ruckeri*	22 °C	11 – 18 °C
Columnaris disease	*Flavobacterium columnaris*	28 – 30 °C	15 °C
Coldwater disease (fin rot)	*Flavobacterium psychrophilum*	4 – 10 °C	4 – 10 °C
Mycobacteriosis	*Mycobacterium marinum, M. fortuitum*	25 – 35 °C	
Nocardiosis	*Nocardia asteroides*		37 °C
Streptococcus septicemia	*Streptococcus* spp.		37 °C
Bacterial kidney disease	*Renibacterium salmoninarum*		15 °C
Fungus			
Saprolegniasis	*Saprolegnia parasitica, Achyla hoferi, Dictyuchus* spp.	15 – 30 °C	
Parasitic ichtyobodiasis (costiasis)	*Ichthyobodo necatrix, I pyrifornis*	10 – 25 °C	
Ichthyophthirius (ich)	*Ichthyophthirius multifiliis*	24 – 26 °C	12 – 15 °C
Parasite			
Proliferative kidney disease	*Tetracapsuloides bryosalmonae*	16 °C	
Virus			
Infectious pancreatic necrosis virus (IPNV)	unknown virus	20 – 23 °C	

Infectious hematopoietic necrosis (IHN)	*IHNV*	13 – 18 °C	15 °C

Table B3. Mean water temperatures of the two sources that supply Quilcene NFH. Historical values for Big Quilcene River are empirical data (ºC ± S.D.) from 9-year historical baseline (2004 – 2012). Penny Creek data (ºC ± S.D.) are from 2001-2002 and 2006-2008. 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).

Month	**Big Quilcene River (ºC)**		**Penny Creek (ºC)**	
	9-year historical baseline ± S.D.	**2040s A1B Predicted (Min. – Max.)**	**5-year historical baseline ± S.D.**	**2040s A1B Predicted (Min. – Max.)**
January	4.9 ± 1.4	5.4 (4.9 – 5.7)	6.4 ± 0.6	6.7 (6.4 – 7.0)
February	4.9 ± 1.1	6 (5.5 – 6.4)	6.4 ± 0.3	7.2 (6.8 – 7.5)
March	5.7 ± 1.0	6.5 (6 – 6.9)	7.0 ± 0.5	7.6 (7.2 – 7.9)
April	6.7 ± 0.9	8.2 (7.6 – 9.2)	7.7 ± 0.7	8.8 (8.4 – 9.5)
May	8.0 ± 1.1	10.1 (9.7 – 10.9)	8.7 ± 0.4	10.2 (9.9 – 10.8)
June	9.4 ± 1.3	12 (11.3 – 12.6)	9.6 ± 0.6	11.6 (11.0 – 12.0)
July	11.8 ± 1.8	13.6 (13.1 – 14.6)	11.4 ± 1.1	12.7 (12.4 – 13.4)
August	12.9 ± 1.3	13.7 (13.2 – 14.2)	12.2 ± 0.4	12.8 (12.4 – 13.2)
September	11.9 ± 0.9	12.4 (11.9 – 13.1)	11.4 ± 0.3	11.8 (11.5 – 12.4)
October	9.1 ± 1.3	9.5 (9.2 – 9.9)	9.4 ± 0.4	9.8 (9.5 – 10.0)
November	6.3 ± 1.4	6.8 (6.5 – 7)	7.4 ± 0.7	7.8 (7.6 – 7.9)
December	5.0 ± 1.4	5.8 (5.4 – 6.2)	6.5 ± 0.9	7.1 (6.8 – 7.4)

Table B4. Modeled historical and future monthly average air temperatures (T_{ave}) and precipitation for the 1/16° grid cell (latitude: 47.78125, longitude -122.90625) that contains Quilcene NFH. Modeled projected future values are ensemble means based on 10 GCMs extracted from monthly flux files. S.D. values represent the variability in monthly estimates among the 10 GCMs. 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) Difference: Projected – Historical	Precipitation (mm) Historical	Precipitation (mm) Projected 2040s (± S.D.)	Precipitation (mm) Difference: Projected – Historical
January	1.9	3.3 ± 0.9	1.4	224	239 ± 26	15
February	3.8	5.1 ± 0.9	1.4	200	205 ± 26	5
March	5.1	6.5 ± 0.7	1.3	156	173 ± 11	17
April	8.4	9.9 ± 0.8	1.5	98	104 ± 14	7
May	11.6	13.1 ± 0.6	1.5	71	66 ± 6	-5
June	14.5	16.4 ± 0.6	1.9	50	42 ± 10	-9
July	17.2	19.7 ± 1.0	2.5	29	20 ± 6	-9
August	17.3	19.9 ± 0.7	2.6	32	25 ± 8	-7
September	15.1	17.4 ± 0.7	2.3	47	42 ± 10	-4
October	10.8	12.6 ± 0.3	1.8	112	127 ± 14	15
November	5.9	7.4 ± 0.3	1.5	191	216 ± 30	25
December	3.4	5.0 ± 0.6	1.6	274	292 ± 20	18

Table B5. Projected mean annual flows (cfs) in the 2040s in the Big Quilcene River and Penny Creek from VIC hydrologic model forced by output from 10 GCMs under the A1B emissions scenario.

GCM	Big Quilcene River Mean annual flow in 2040s (cfs)	Penny Creek Mean annual flow in 2040s (cfs)
ccsm3	349	14
cgcm3	415	17
cnrm_cm3	385	15
echam5	379	15
echo_g	363	14
Hadcm	379	15
hadgem1	331	13
ipsl_cm4	412	16
miroc_3.2	429	17
pcm1	349	14
2040s AVERAGE	379	15
Historical AVERAGE	359	14

Table B6. Mean monthly water temperatures and water sources experienced by juvenile coho salmon reared at Quilcene NFH based on the 9-year historical baseline (2004 – 2012) and projected values for the 2040s. Water sources are separated into either Big Quilcene River (BQ) or Penny Creek (PC).

Month	Life-History Stage	Water Source	Rearing Temperature (°C) Historical baseline	Rearing Temperature (°C) 2040s predicted
August	Broodstock	BQ	12.9	13.7
September	Broodstock	BQ	11.9	12.4
October	Broodstock	BQ	9.1	9.5
November	Broodstock	BQ	6.3	6.8
August	egg/fry	PC	12.2	12.8
September	egg/fry	PC	11.5	11.8
October	egg/fry	PC	9.4	9.8
November	egg/fry	PC	7.4	7.7
December	egg/fry	PC	6.5	7.1
January	egg/fry	PC	6.4	6.7
February	egg/fry	PC	6.4	7.2
March	juvenile	BQ	5.7	6.5
April	juvenile	BQ	6.7	8.2
May	juvenile	BQ	8.0	10.1
June	juvenile	BQ	9.4	12.0
July	juvenile	BQ	11.8	13.7
August	juvenile	BQ	12.9	13.7
September	juvenile	BQ	11.9	12.4
October	juvenile	BQ	9.1	9.5
November	juvenile	BQ	6.3	6.8
December	juvenile	BQ	5.0	5.8
January	juvenile	BQ	4.9	5.4
February	juvenile	BQ	4.9	6.0
March	juvenile	BQ	5.7	6.5
April	smolt	BQ	6.7	8.2

Table B7. Monthly size differences of juvenile coho salmon reared at Quilcene NFH exposed to projected water temperatures for the 2040s relative to fish reared at water temperatures from the historical baseline (2003 – 2012).

Month	Life-History Stage	Weight difference (g)	Length difference (mm)
January (1)	egg/fry	3.4%	1.1%
February (1)	egg/fry	8.7%	2.8%
March (1)	egg/fry	13.6%	4.3%
April (1)	egg/fry	21.1%	6.5%
May (1)	Juvenile	30.5%	9.2%
June (1)	Juvenile	39.9%	11.7%
July (1)	Juvenile	41.5%	12.1%
August (2)	Juvenile	37.6%	11.1%
September (2)	Juvenile	34.1%	10.2%
October (2)	Juvenile	32.2%	9.6%
November (2)	Juvenile	31.2%	9.4%
December (2)	Juvenile	31.9%	9.6%
January (2)	Juvenile	31.5%	9.5%
February (2)	Juvenile	32.7%	9.8%
March (2)	Juvenile	33.0%	9.9%
April (2)	Smolt	34.7%	10.3%

Table B8. Modeled flow and density index values and constituent variables for coho salmon in Quilcene NFH. Values and calculations assume that some fish are moved from the hatchery to near-shore marine net pens in March and April of the second year in the rearing cycle. Mean historical and bias-adjusted future (2040s) flow and density indexes are shown graphically in Figure B11.

Time		Rearing parameters			Modeled historical					Modeled 2040s					
step (i)	**Month**[a]	**N_i** [b]	**C_i (ft^3)** [c]	**d_i** [d]	**L_i** [e]	**W_i** [f]	**GPM_i** [g]	**DI_i** [h]	**FI_i** [i]	**L_i** [e]	**W_i** [f]	**GPM_i** [g]	**DI_i** [h]	**FI_i** [i]	**r_i** [j]
1	Jan (1)	253,998	4,352	31	1.66	0.84	2,175	0.065	0.130	1.68	0.87	2,175	0.067	0.133	0.62
2	Feb (1)	575,993	9,567	28	1.97	1.42	4,858	0.095	0.188	2.03	1.54	4,858	0.101	0.199	0.53
3	Mar (1)	610,826	10,146	31	2.28	2.19	5,269	0.128	0.246	2.38	2.49	5,269	0.139	0.268	0.59
4	Apr (1)	609,571	10,080	30	2.62	3.36	5,400	0.171	0.319	2.79	4.07	5,400	0.194	0.362	0.65
5	May (1)	607,399	10,080	31	3.04	5.27	5,400	0.230	0.429	3.32	6.88	4,028	0.275	0.688	0.63
6	Jun (1)	597,018	28,611	30	3.51	8.14	14,400	0.107	0.212	3.92	11.38	8,355	0.133	0.457	0.66
7	Jul (1)	594,889	28,611	31	4.12	13.21	14,400	0.147	0.292	4.62	18.69	8,276	0.185	0.641	0.63
8	Aug (1)	594,728	28,611	31	4.78	20.68	14,400	0.198	0.394	5.31	28.45	10,532	0.246	0.667	0.62
9	Sep (1)	584,253	28,611	30	5.35	29.07	14,400	0.245	0.486	5.89	38.98	11,720	0.298	0.727	0.56
10	Oct (1)	583,024	28,611	31	5.77	36.63	14,400	0.285	0.567	6.33	48.41	14,400	0.344	0.683	0.51
11	Nov (1)	581,469	28,611	30	6.03	41.83	14,400	0.311	0.618	6.59	54.89	14,400	0.373	0.741	0.50
12	Dec (1)	579,925	28,611	31	6.22	46.03	14,400	0.331	0.657	6.82	60.70	14,400	0.398	0.791	0.47
13	Jan (2)	578,075	30,240	31	6.41	50.26	14,400	0.331	0.694	7.01	66.09	14,400	0.397	0.834	0.46
14	Feb (2)	576,606	30,240	28	6.56	54.02	14,400	0.346	0.727	7.20	71.67	14,400	0.418	0.879	0.47
15	Mar (2)	388,821	21,297	31	6.78	59.66	10,200	0.354	0.740	7.45	79.36	10,200	0.429	0.895	0.48
16	Apr (2)	387,024	19,914	30	7.03	66.74	9,600	0.407	0.843	7.76	89.91	9,600	0.496	1.030	0.50

[a] Calendar month in rearing cycle. Numbers in parentheses indicate the year for that rearing cycle, e.g., "Jan (2)" indicates that this is the second January in the rearing cycle.
[b] Numbers of post-hatch juvenile fish or abundance (N_i) based on hatchery averages during 2007-2010 brood years.
[c] Mean hatchery capacity (C_i) used during 2007-2010 based on the number of raceways, their sizes, and water depth.
[d] Number of days (d_i) in the monthly time-step i.
[e] Modeled historical or projected future mean fish length (L_i) in inches, at each monthly time-step i.
[f] Modeled historical or projected future mean fish weight (W_i) in grams, at each monthly time-step i.
[g] Estimated historical or future flow rates through the hatchery (GPM_i) in gallons per minute at each monthly time-step i. Historical values are based on (a) the number of raceways used at each time-step, multiplied by (b) the average flow rate of 600 gpm. Future projected flow rates are

based on the expected changes in mean monthly discharge in Big Quilcene River, with the assumption that the hatchery will not utilize any more water than the historical amount at any given time-step; thus only reductions in water availability are depicted.
[h] Modeled historical or projected future density index (*DI_i*) at time-step *i*.
[i] Modeled historical or projected future flow index (*FI_i*) at time-step *i*.
[j] Bias correction factors are the ratio between empirical mean index values and simulated historical values (see also footnote at bottom of page 14):

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

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

Table B9. Modeled flow and density index values and constituent variables for coho salmon in Quilcene NFH during the last two months in the rearing cycle. Values and calculations assume that all fish remain in the hatchery throughout the rearing cycle, no fish are moved to net pens (i.e., no net pen split) in the last two months of the rearing cycle, and that raceway bank C remains in use. All table values for time steps 1 through 14 are identical to those in Table B8 so are not repeated here. See Table B8 footnotes for parameter definitions. See also Figure B12.

Time		Rearing parameters			Modeled historical					Modeled 2040s					
Step (i)	Month	N_i [a]	C_i (ft^3)	d_i	L_i	W_i	GPM_i	DI_i	FI_i	L_i	W_i	GPM_i	DI_i	FI_i	r_i
15	Mar (2)	573,601	30,240	31	6.78	59.66	14,400	0.368	0.773	7.45	79.36	14,400	0.446	0.936	0.48
16	Apr (2)	570,613	30,240	30	7.03	66.74	14,400	0.395	0.829	7.76	89.91	14,400	0.482	1.012	0.50

[a]Abundance (N_i) during time steps 15 and 16 were estimated by applying a monthly mortality rate of 0.5% – calculated from the average mortality during time steps 4-14 (Table B8) when the raceways were fully seeded – to the average abundance at time step 14 (Table B8).

Table B10. Modeled historical and future discharge in the Big Quilcene River, estimates of historical and future surface water from the Big Quilcene River available for use by the Quilcene NFH, and minimum instream requirement needed to activate the hatchery's second, newer water right (last column). Highlighted cells (in yellow) denote months when the projected water availability will be too low (<50 cfs) to invoke the second water right under the current requirement to maintain instream flows of either 50 or 83 cfs (depending on month); hence, the hatchery will most likely only be able to divert up to 15 cfs from the Big Quilcene River in August and September (in the 2040s) based on its first water right.

	Modeled discharge in Big Quilcene River (cfs) in 2040s [a]				Modeled discharge in Big Quilcene River (cfs) in 2040s after initial withdrawal of 15 cfs [b]				Minimum instream flow to activate second water right (cfs) [c]
Month	**Historical**	**Min**	**Mean**	**Max**	**Historical**	**Min**	**Mean**	**Max**	
Oct	144	122	156	210	129	107	141	195	50
Nov	348	320	429	622	333	305	414	607	50
Dec	623	651	765	999	608	636	750	984	50
Jan	601	663	778	955	586	648	763	940	50
Feb	647	608	786	977	632	593	771	962	50
Mar	526	578	630	695	511	563	615	680	83
Apr	456	418	472	509	441	403	457	494	83
May	393	224	293	352	378	209	278	337	83
Jun	299	111	174	223	284	96	159	208	83
Jul	138	63	80	90	123	48	65	75	50
Aug	64	38	46	58	49	23	31	43	50
Sep	62	40	51	60	47	25	36	45	50

[a] Projected discharge in the Big Quilcene River estimated from the VIC hydrologic model forced by the climate expected under the A1B greenhouse gas emissions scenario and 10 GCMs. Columns are the minimum (Min), average (Mean), and maximum (Max) estimated discharges for the 10 GCMs.
[b] Water available to hatchery is the difference between the modeled discharge of the Big Quilcene River and hatchery's oldest water right, e.g.,

estimated water availability = (Historical, Min, Mean, or Max discharge) – 15 cfs.
[c] Monthly instream flow requirement for the Big Quilcene River in the so-called bypass channel that is the section of river between the hatchery's water intake and outfall.

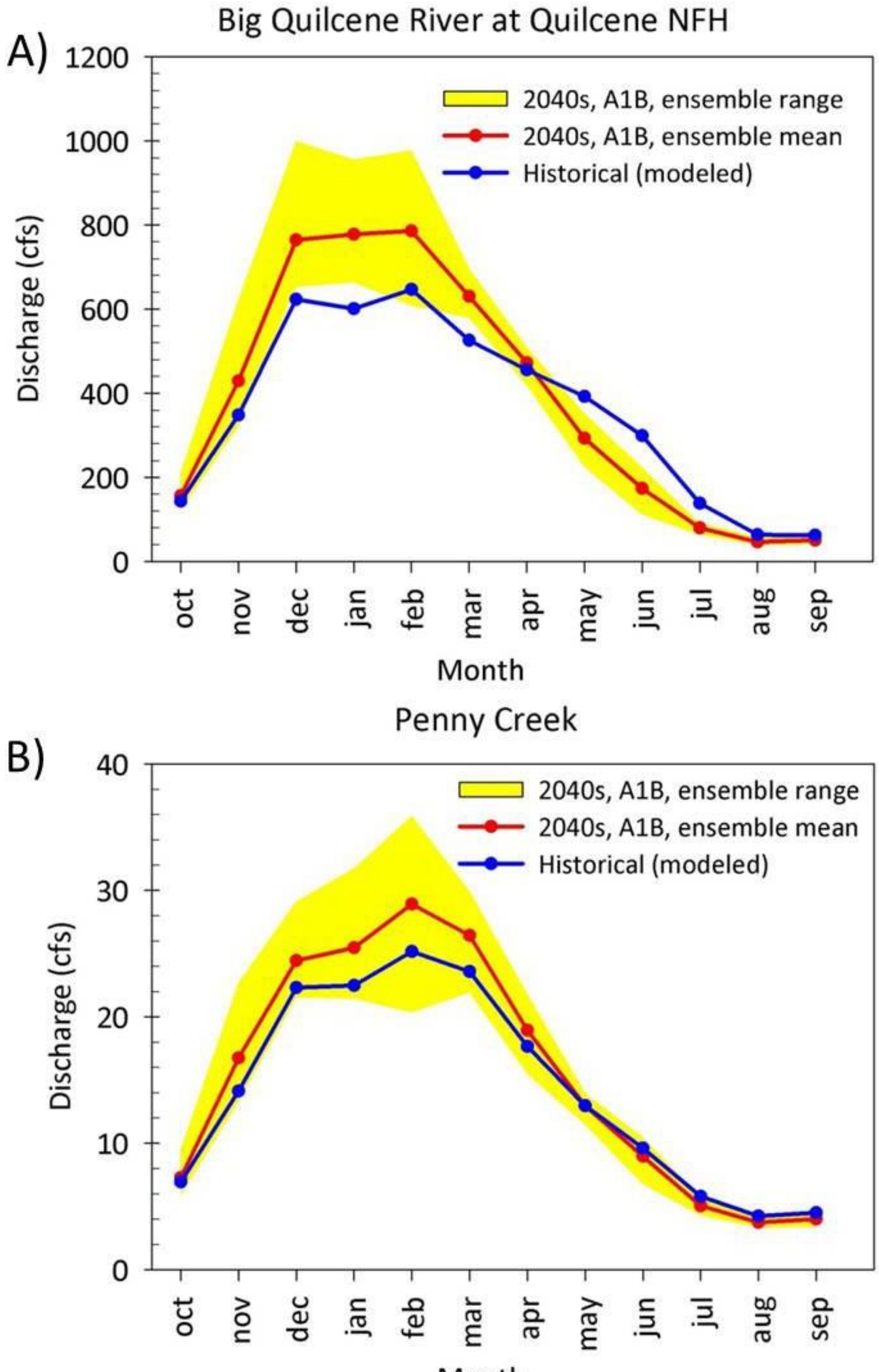

Figure B1. *Mean monthly surface flow in the A) Big Quilcene River and B) Penny Creek adjacent to the Quilcene National Fish Hatchery based on raw Variable Infiltration Capacity (VIC) simulations. Projected (2040s) surface flows are based on the VIC model forced by output from an ensemble of 10 general circulation models (GCMs) under the A1B greenhouse gas emissions scenario.*

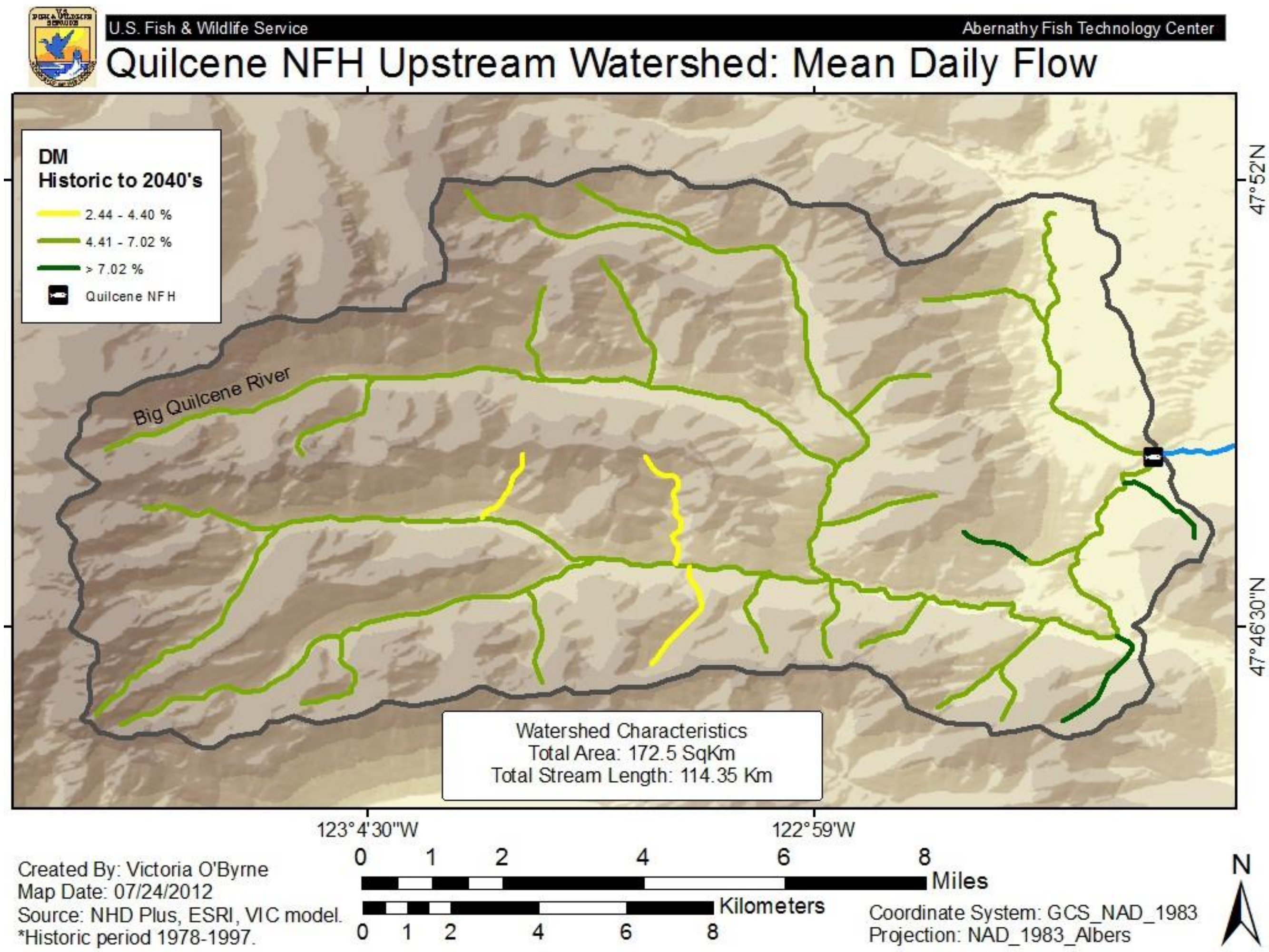

Figure B2. *Projected change mean daily flow (DM, in %) for the Big Quilcene River basin upstream from Quilcene NFH between historical and 2040s time periods. Data are from VIC hydrologic model (Wenger et al. 2011b) and the historical reference period is 1978 - 1997.*

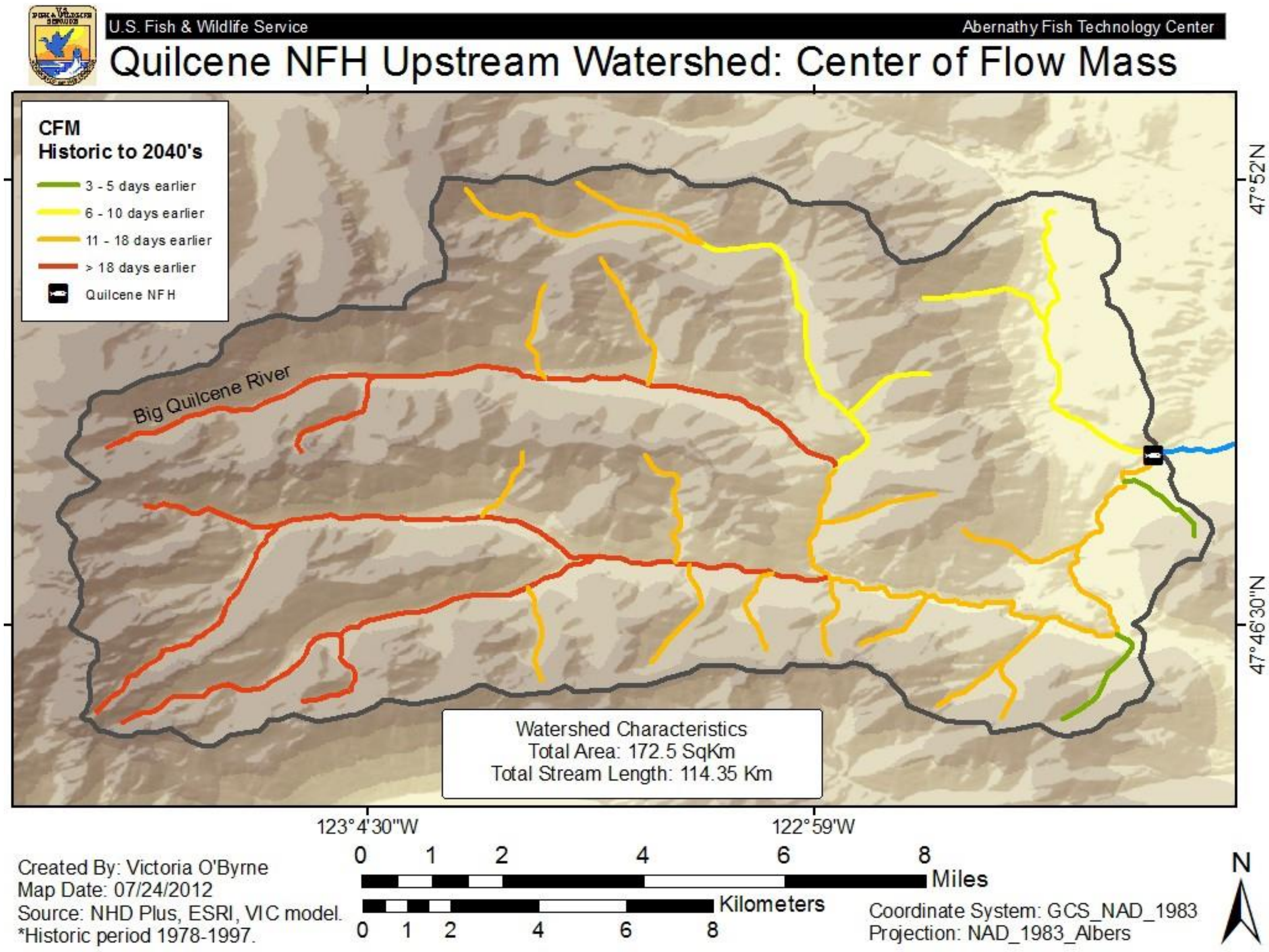

Figure B3. *Projected change in the timing of snowmelt runoff (date of center of flow mass, CFM) for the Big Quilcene River basin upstream from Quilcene NFH between historical and 2040s time periods. Data are from VIC hydrologic model (Wenger et al. 2011b) and the historical reference period is 1978 - 1997.*

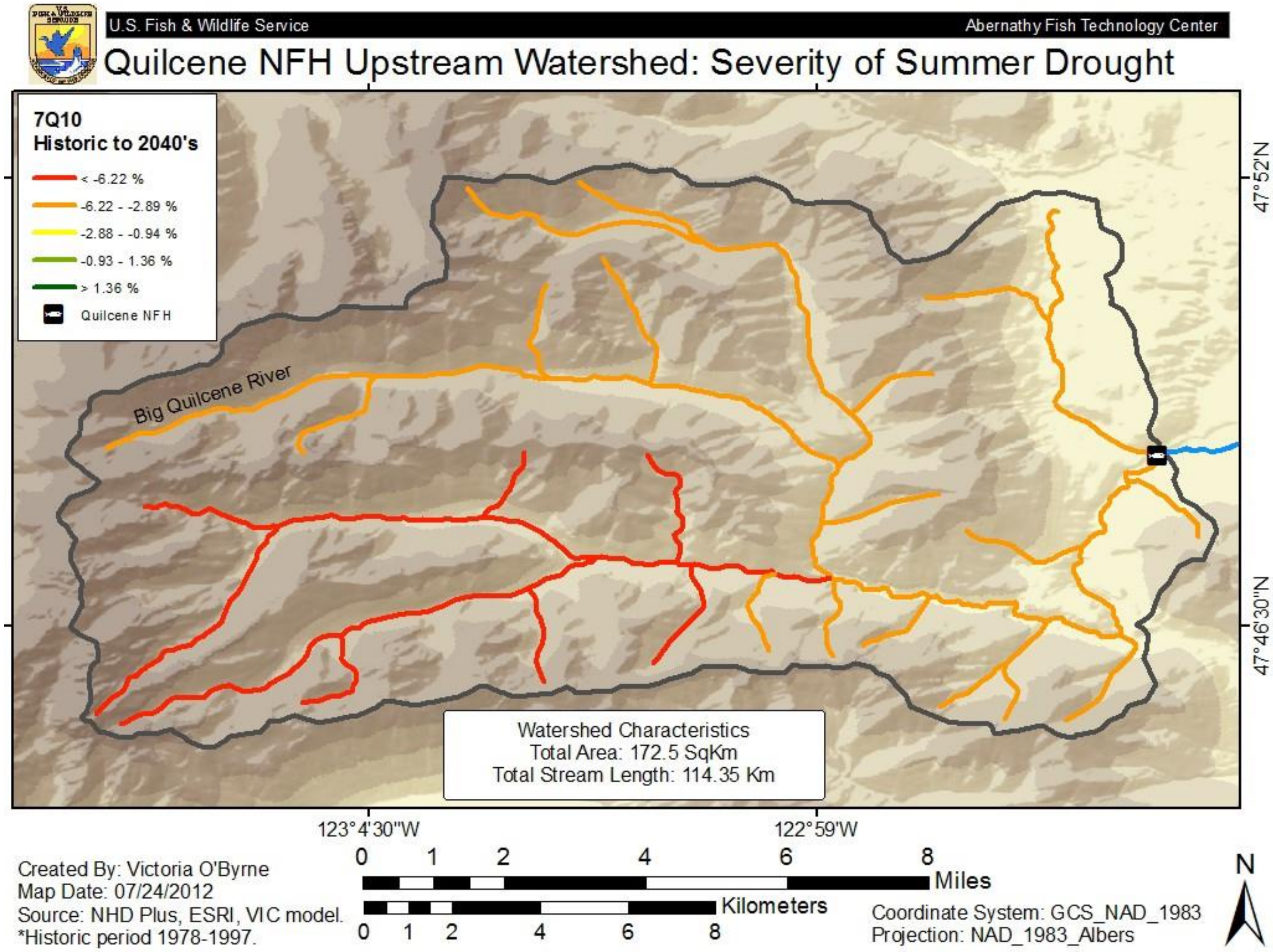

Figure B4. *Projected change in the severity of summer drought (7-day low flow 10-yr return interval, 7Q10) for the Big Quilcene River basin upstream from Quilcene NFH between historical and 2040s time periods. Data are from VIC hydrologic model (Wenger et al. 2011b) and the historical reference period is 1978 - 1997.*

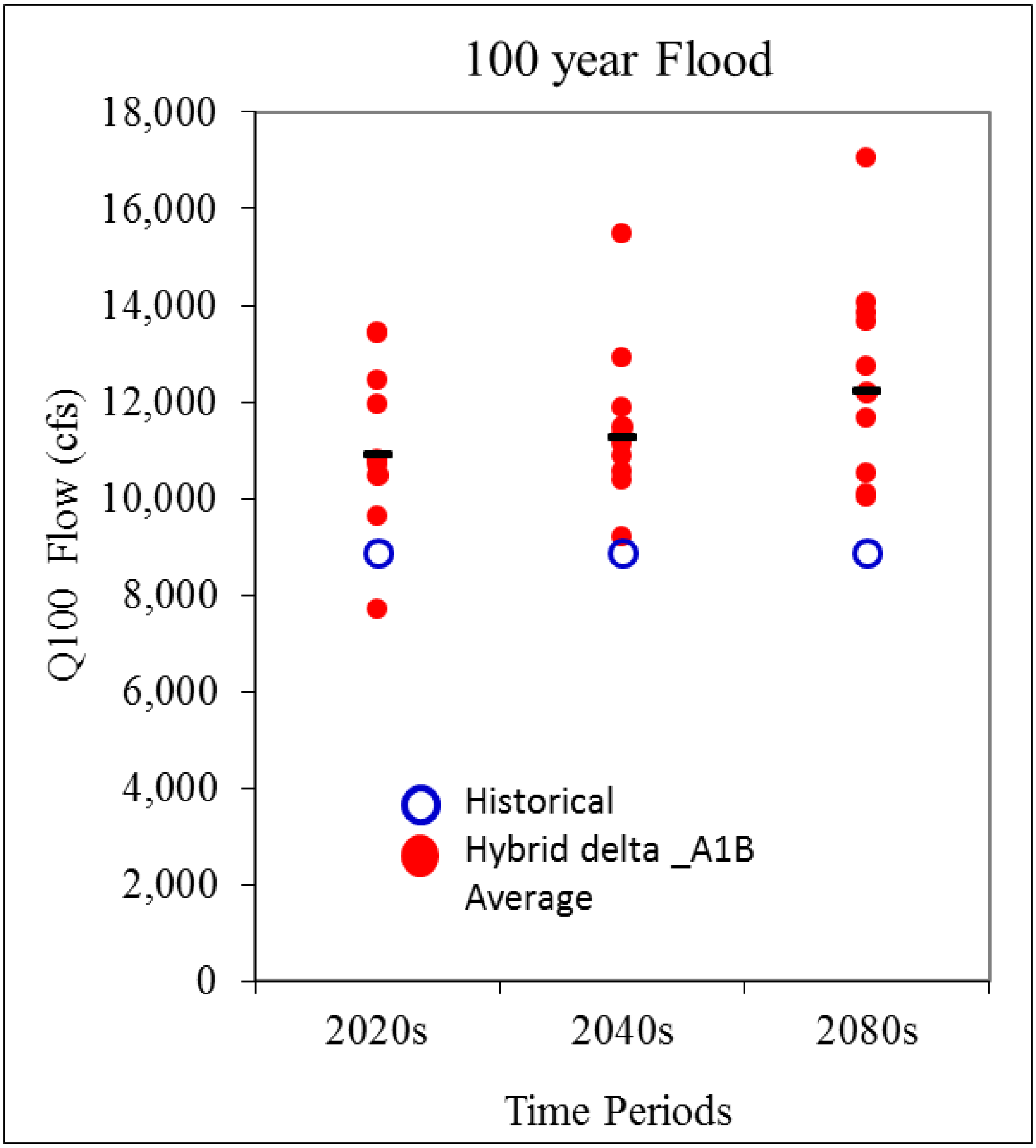

Figure B5. *Magnitude of large (100-year) floods for the Big Quilcene River adjacent to the Quilcene National Fish Hatchery based on raw Variable Infiltration Capacity (VIC) simulations for the 2020s, 2040s, and 2080s. Flows projections are based on the VIC model forced by output from an ensemble of 10 general circulation models (GCMs) under the A1B greenhouse gas emissions scenario. Red dots are the projections for the individual GCMs, the black horizontal dash (-) is the ensemble average, and the open circle is the historical frequency.*

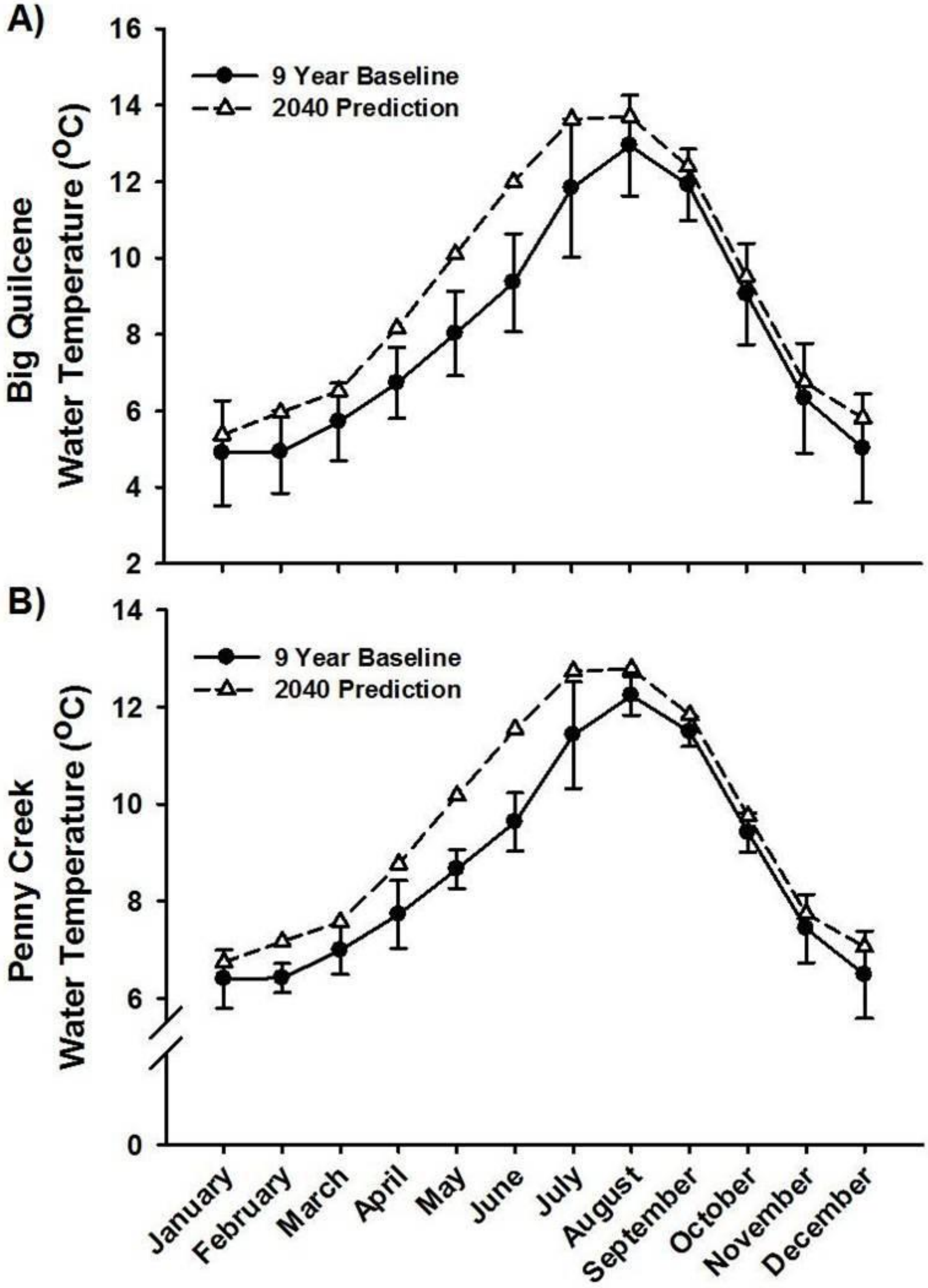

Figure B6. *Comparison of the mean (± S.D.) water temperatures of water sources that supply Quilcene NFH from the historical baseline (2004 – 2012) and projected values for the 2040s.*

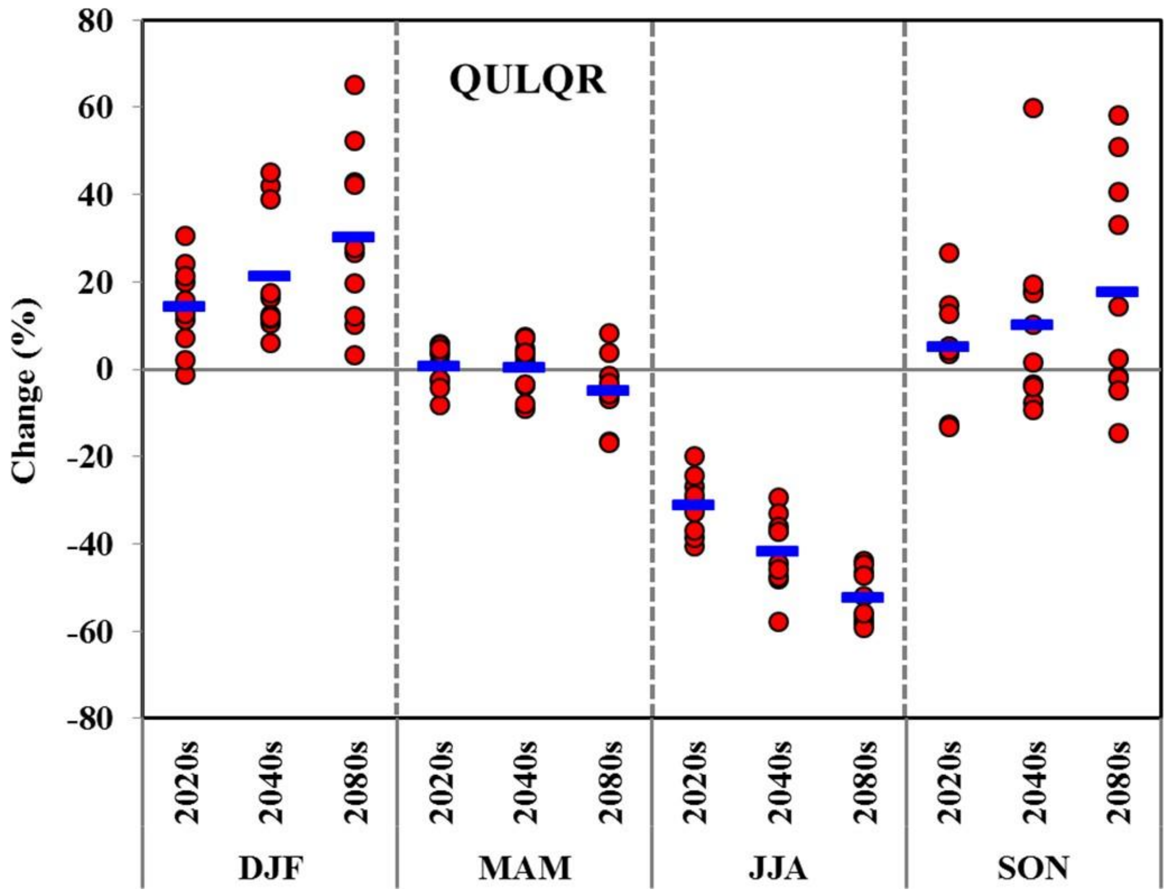

Figure B7. *Projected percent change in mean seasonal flow in the Big Quilcene River adjacent to the Quilcene National Fish Hatchery based on raw Variable Infiltration Capacity (VIC) simulations for the 2020s, 2040s, and 2080s. Flows projections are based on the VIC model forced by output from an ensemble of 10 general circulation models (GCMs) under the A1B greenhouse gas emissions scenario. 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.*

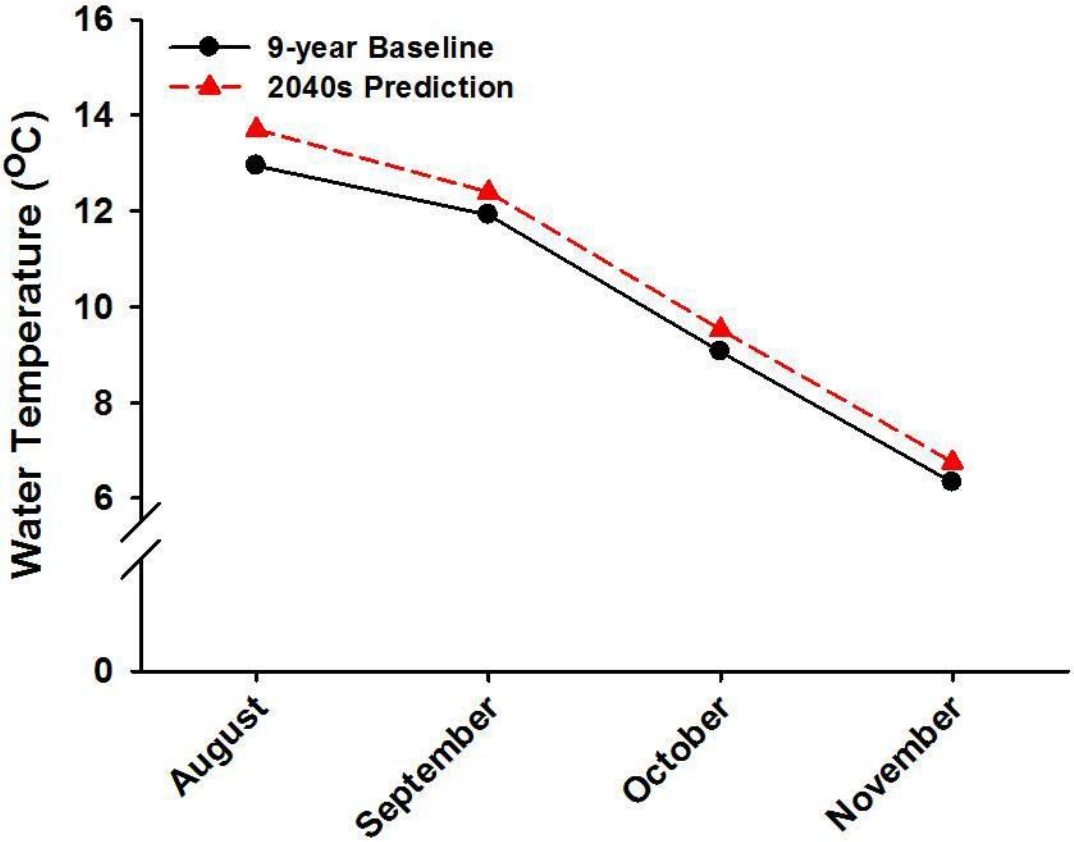

Figure B8. *Comparison of the mean water temperatures experienced by coho salmon broodstock held at Quilcene NFH based on the historical baseline (2004 – 2012) and projected values for the 2040s.*

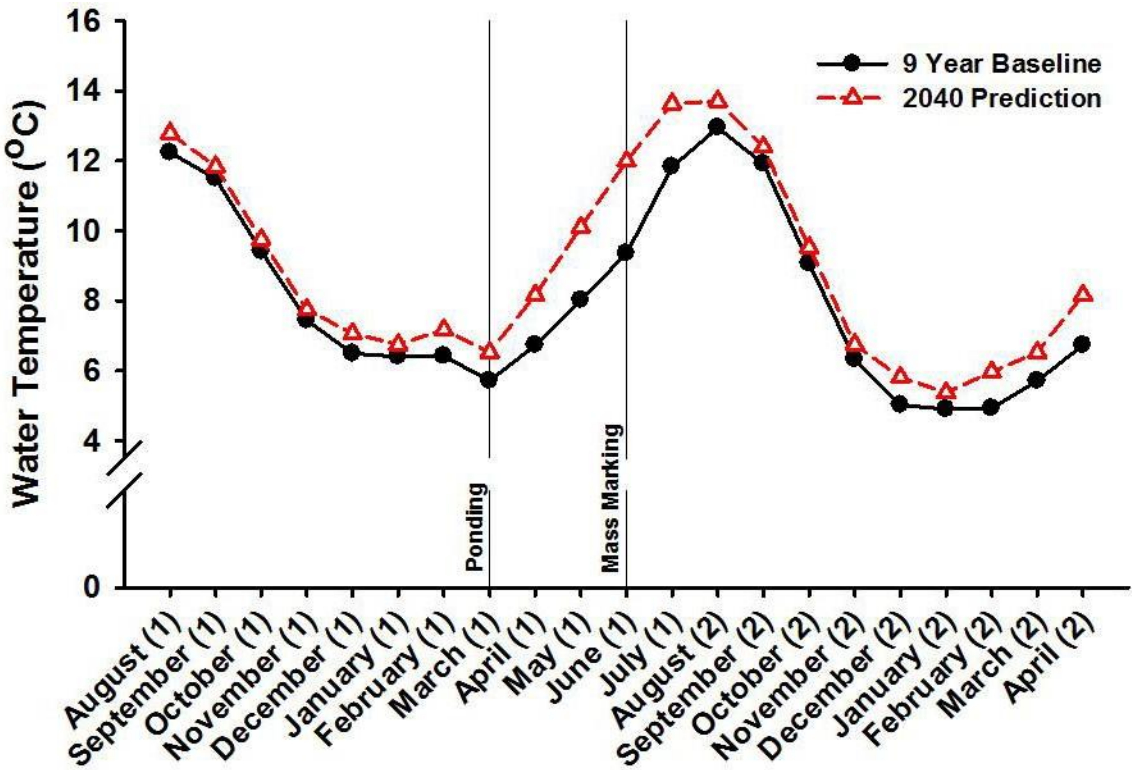

Figure B9. *Comparison of the mean water temperatures experienced by juvenile coho salmon reared at Quilcene NFH based on the historical baseline (2004 – 2012) and projected values for the 2040s. The approximate dates of important hatchery events are denoted by labeled vertical lines.*

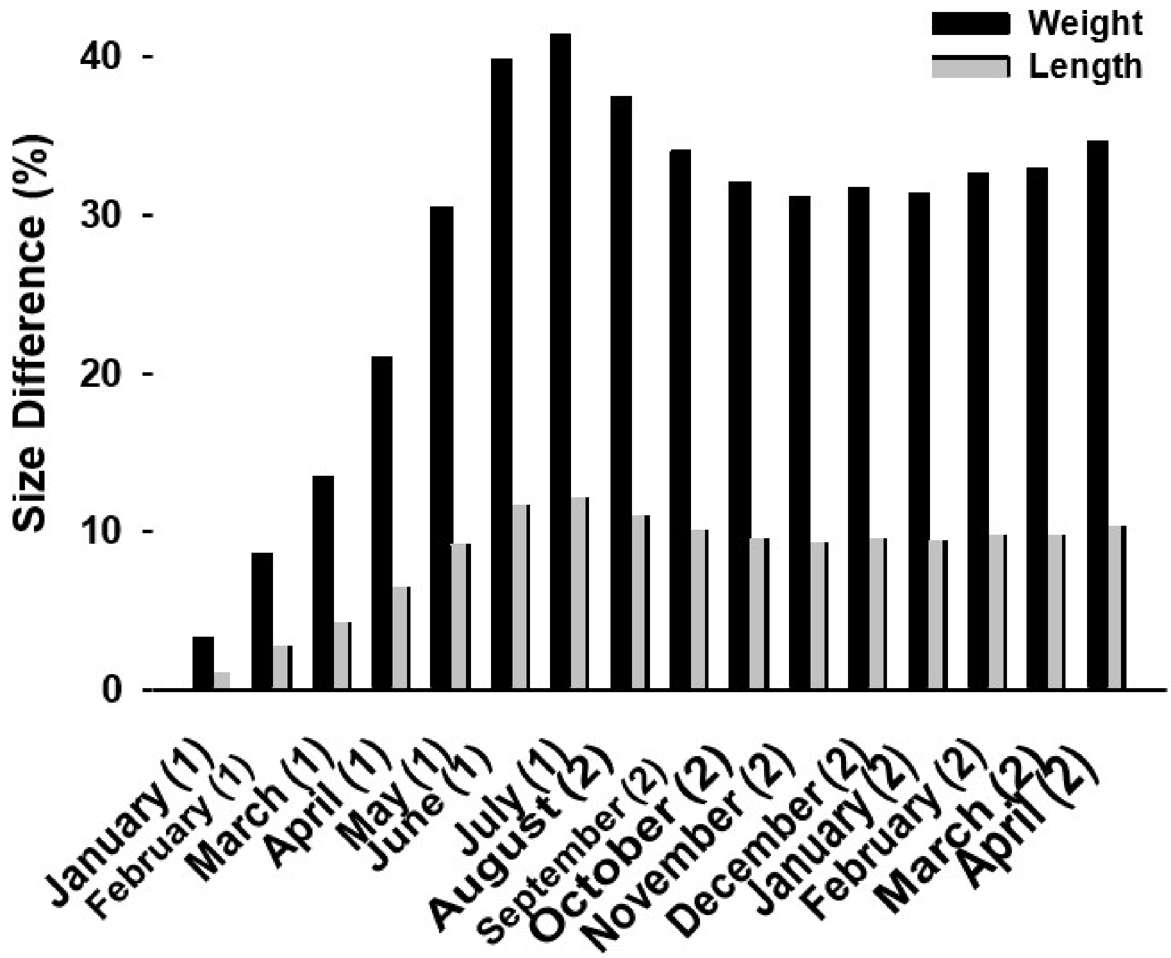

Figure B10. *Predicted monthly size differences of juvenile coho salmon reared at Quilcene NFH. Values are the simulated mean differences in weight and length of fish exposed to water temperatures predicted for the 2040s versus fish exposed the historical baseline (2004 – 2012).*

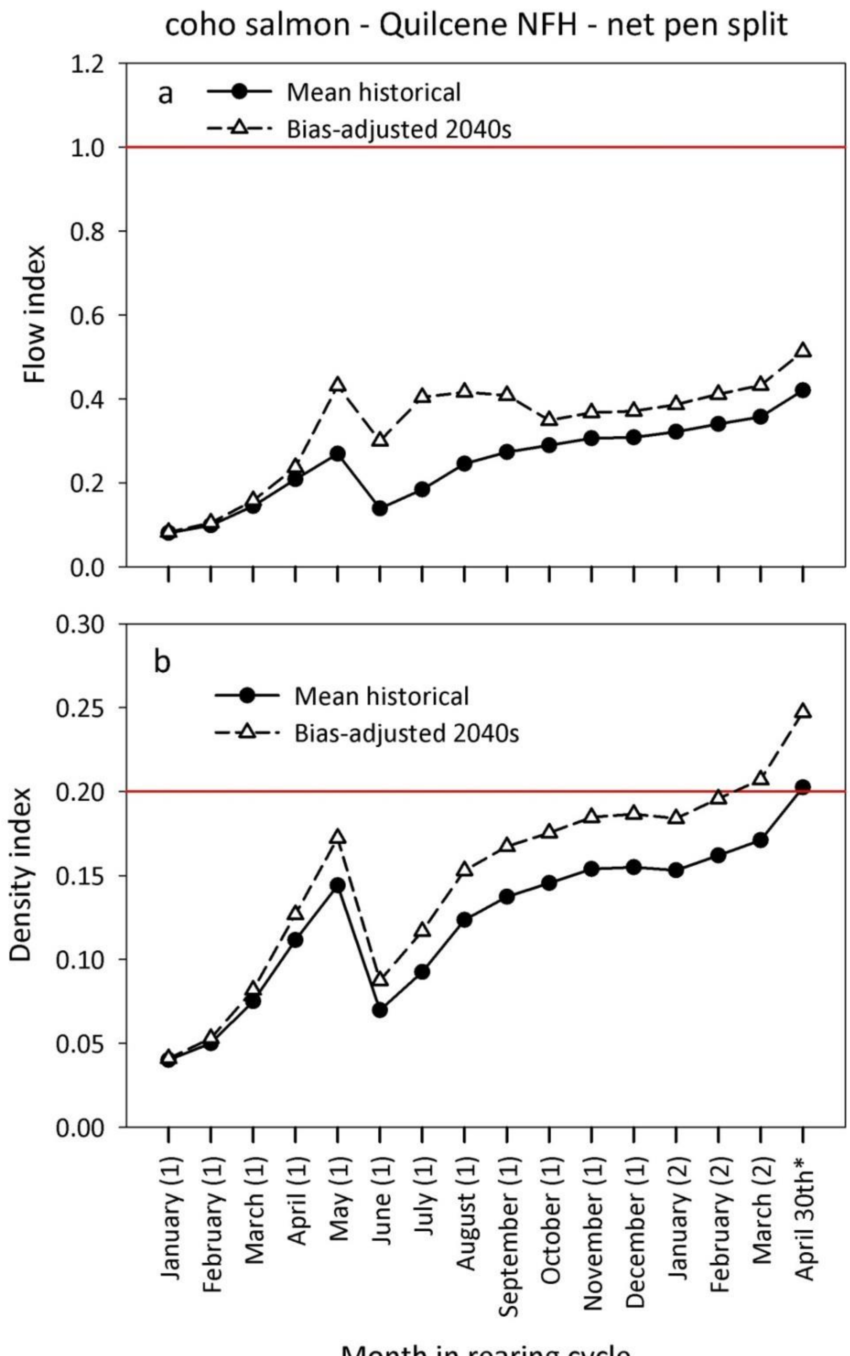

Figure B11. *Mean historical and bias-corrected future flow index (FI) and density index (DI) values (a and b, respectively) for coho salmon at Quilcene National Fish Hatchery based on average rearing conditions during 2007 - 2010, and assuming that 200,000 fish are moved to a net pen during the last two months of the rearing cycle. Values for the 2040s have been bias corrected by multiplying the uncorrected future values by the ratio: (observed mean historical value 2007 - 2010) / (modeled historical value). See Table B7 for bias correction values. The horizontal lines at FI = 1.0 and DI = 0.2 denote the upper threshold guideline values for each index.*

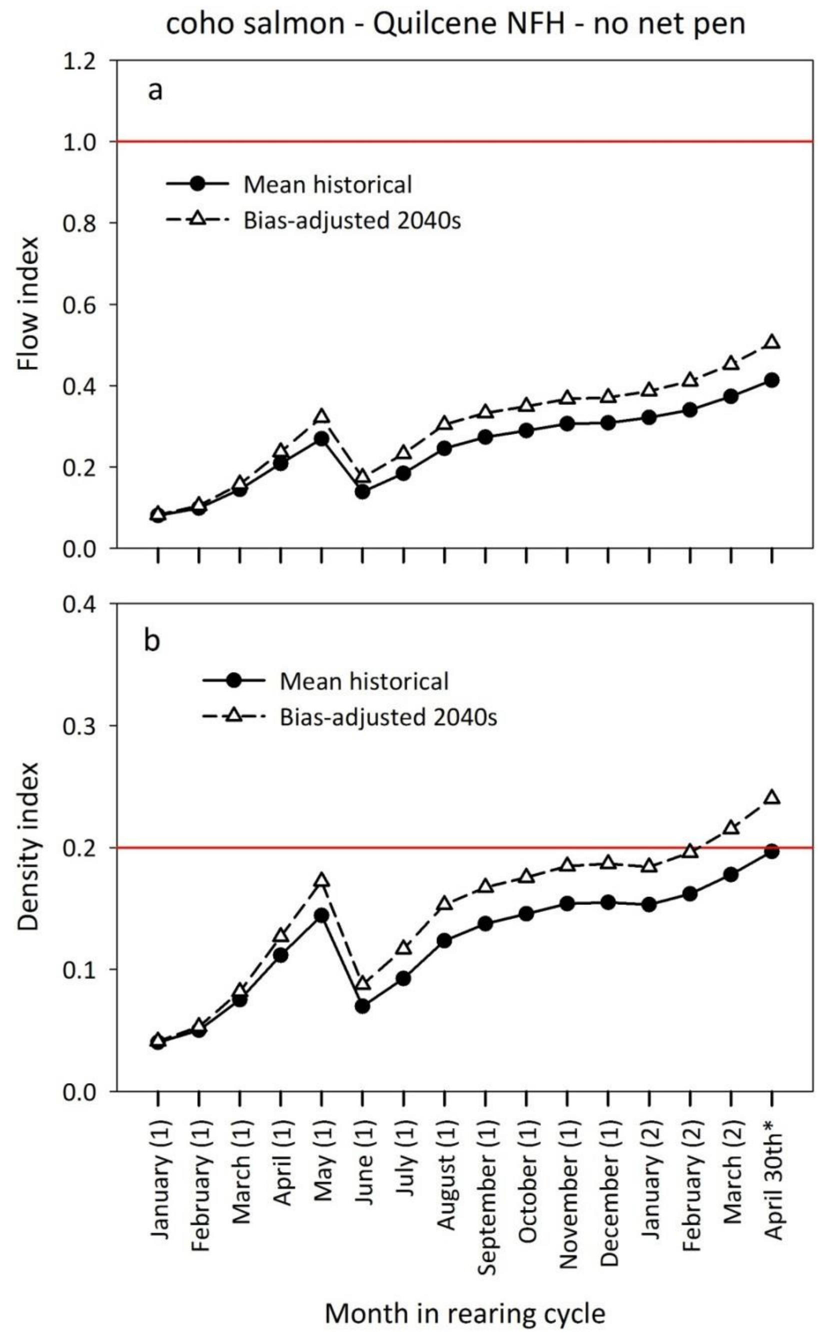

Figure B12. *Mean historical and bias-corrected future flow index (FI) and density index (DI) values (a and b, respectively) for coho salmon at Quilcene National Fish Hatchery based on average rearing conditions during 2007 - 2010, and assuming that all fish remain in the hatchery facility during the entire rearing cycle (i.e., no transfer to net pet) and that raceway bank C remains in operation. Values for the 2040s have been bias corrected by multiplying the uncorrected future values by the ratio: (mean historical value 2007 - 2010) / (modeled historical value). See Table B8 for bias-correction values. The horizontal lines at FI = 1.0 and DI = 0.2 denote the upper threshold guideline values for each index.*

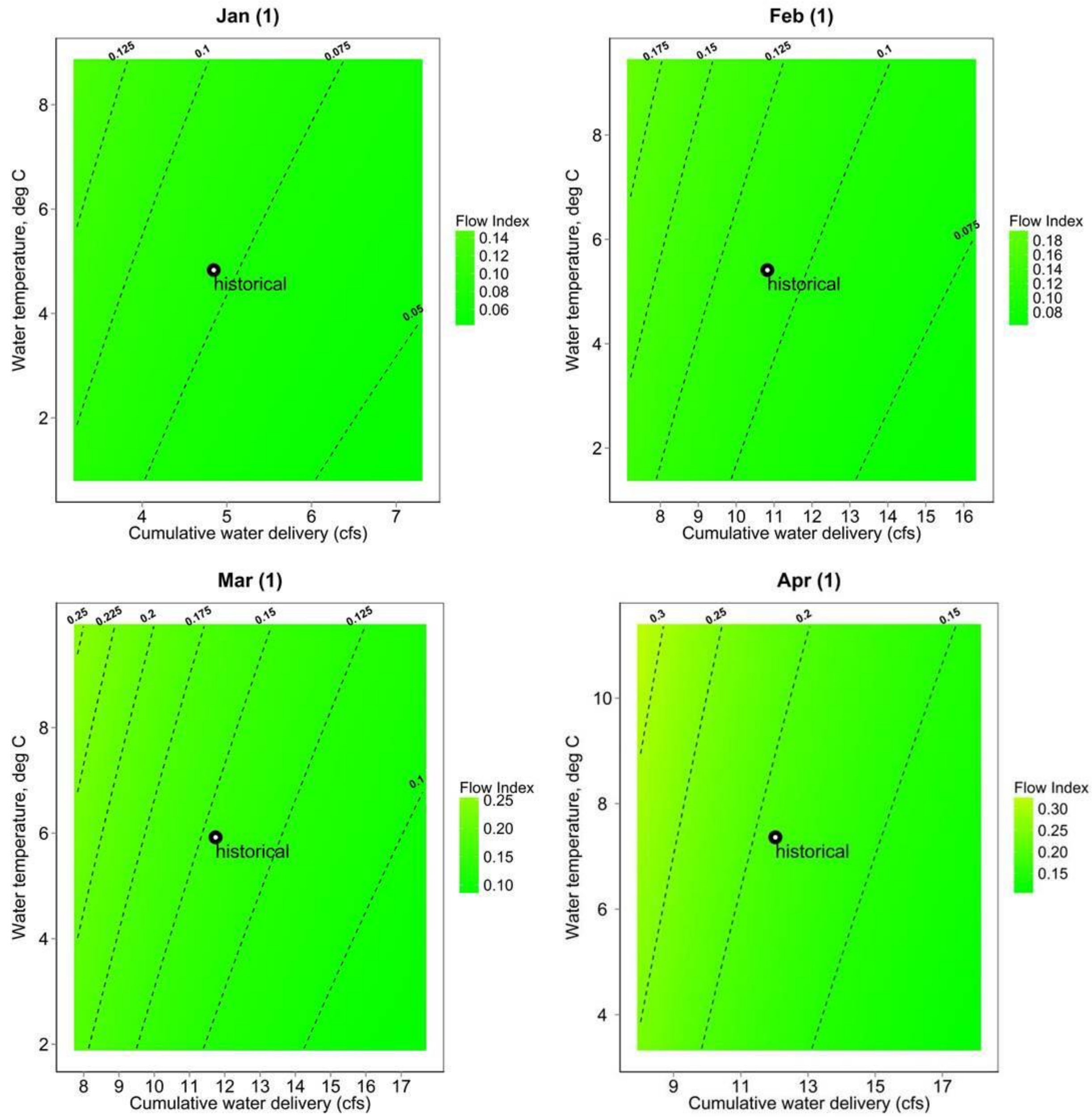

Figure B13. *Predicted flow index values for coho salmon during January - April for the first year in the rearing cycle at Quilcene NFH based on incremental differences in water availability and temperature. The point represents the average historical conditions.*

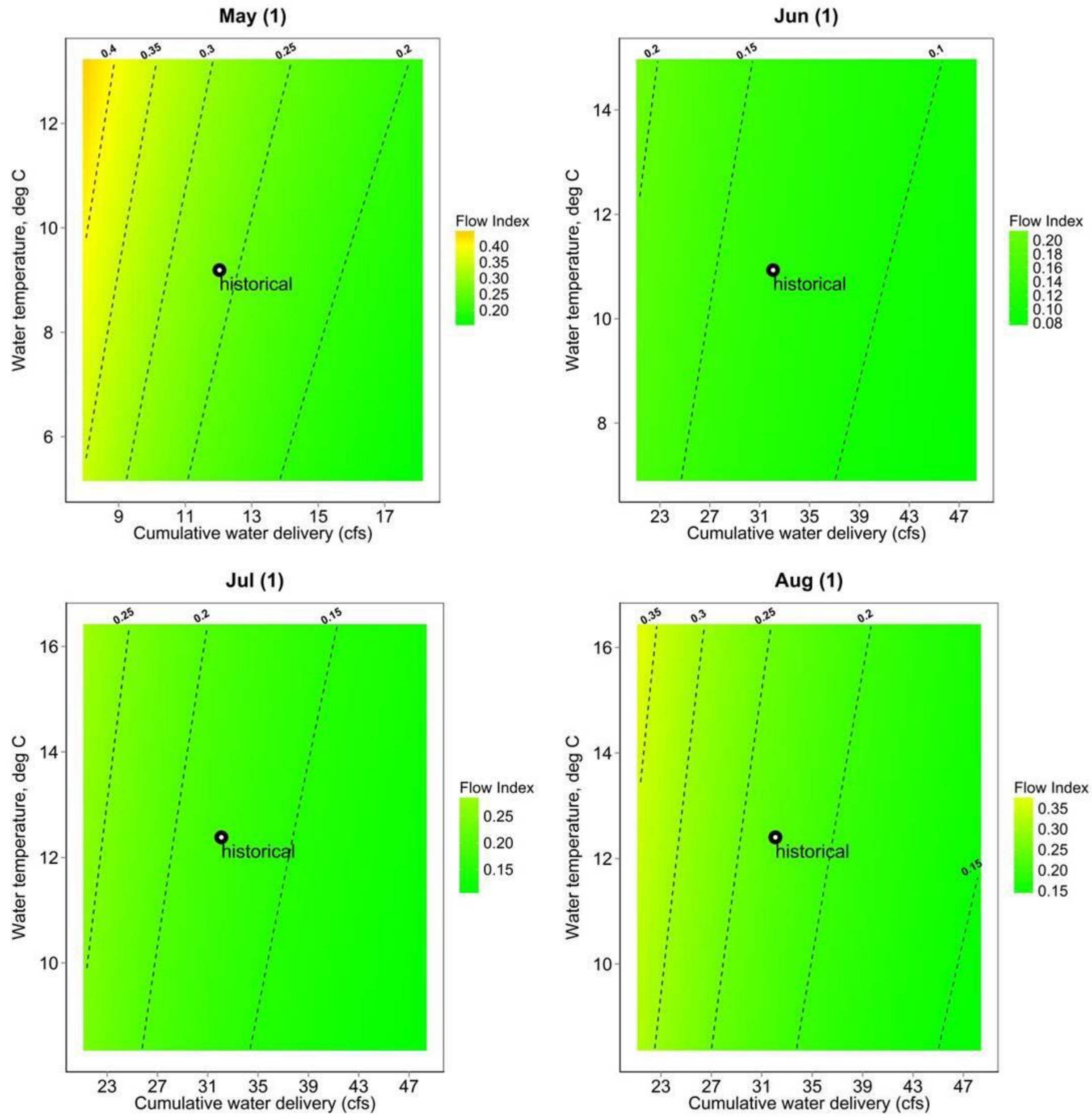

Figure B13 (continued). *Predicted flow index values for coho salmon during May - August for the first year in the rearing cycle at Quilcene NFH based on incremental differences in water availability and temperature. The point represents the average historical conditions.*

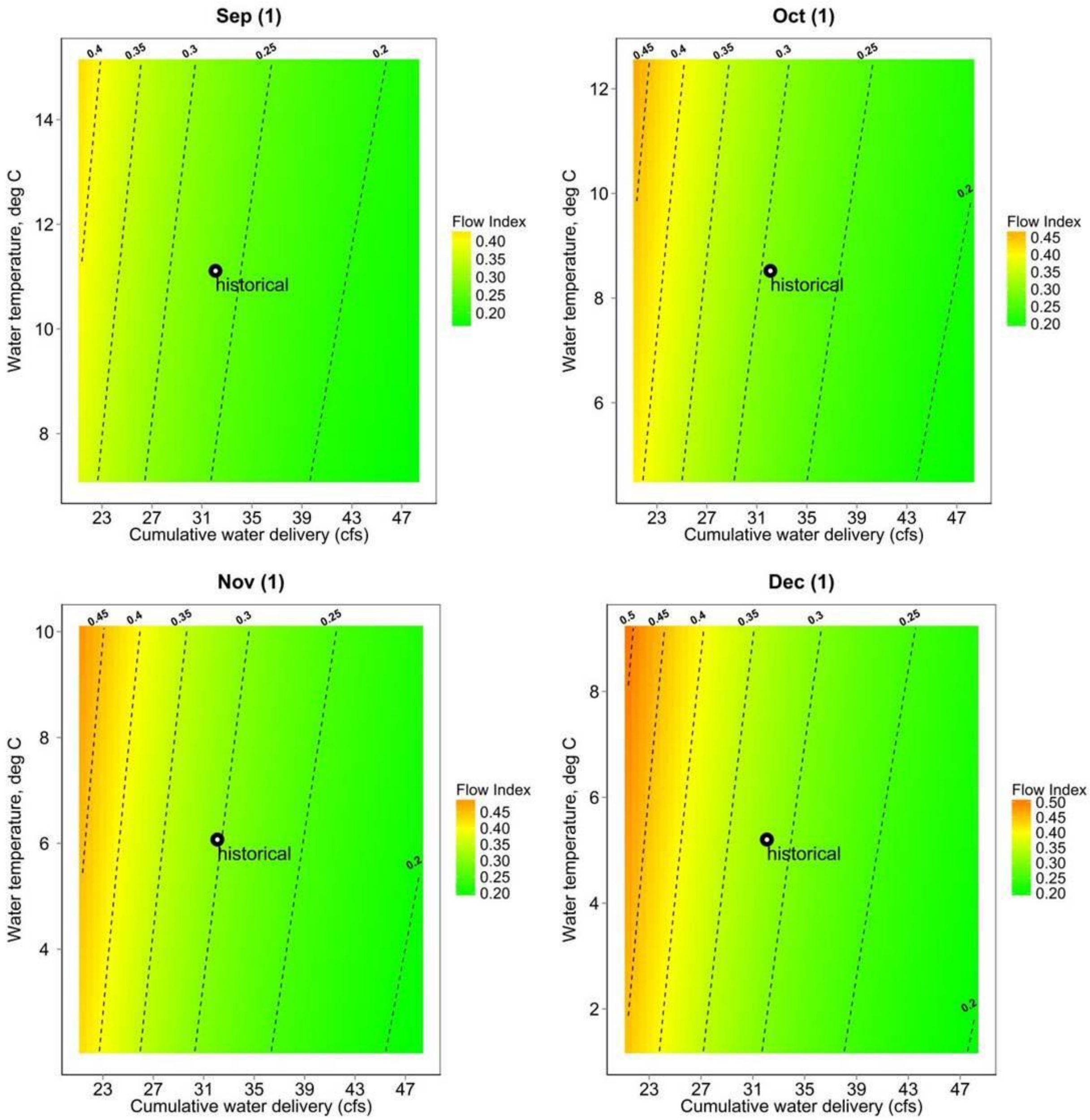

Figure B13 (continued). *Predicted flow index values for coho salmon during September - December for the first year in the rearing cycle at Quilcene NFH based on incremental differences in water availability and temperature. The point represents the average historical conditions.*

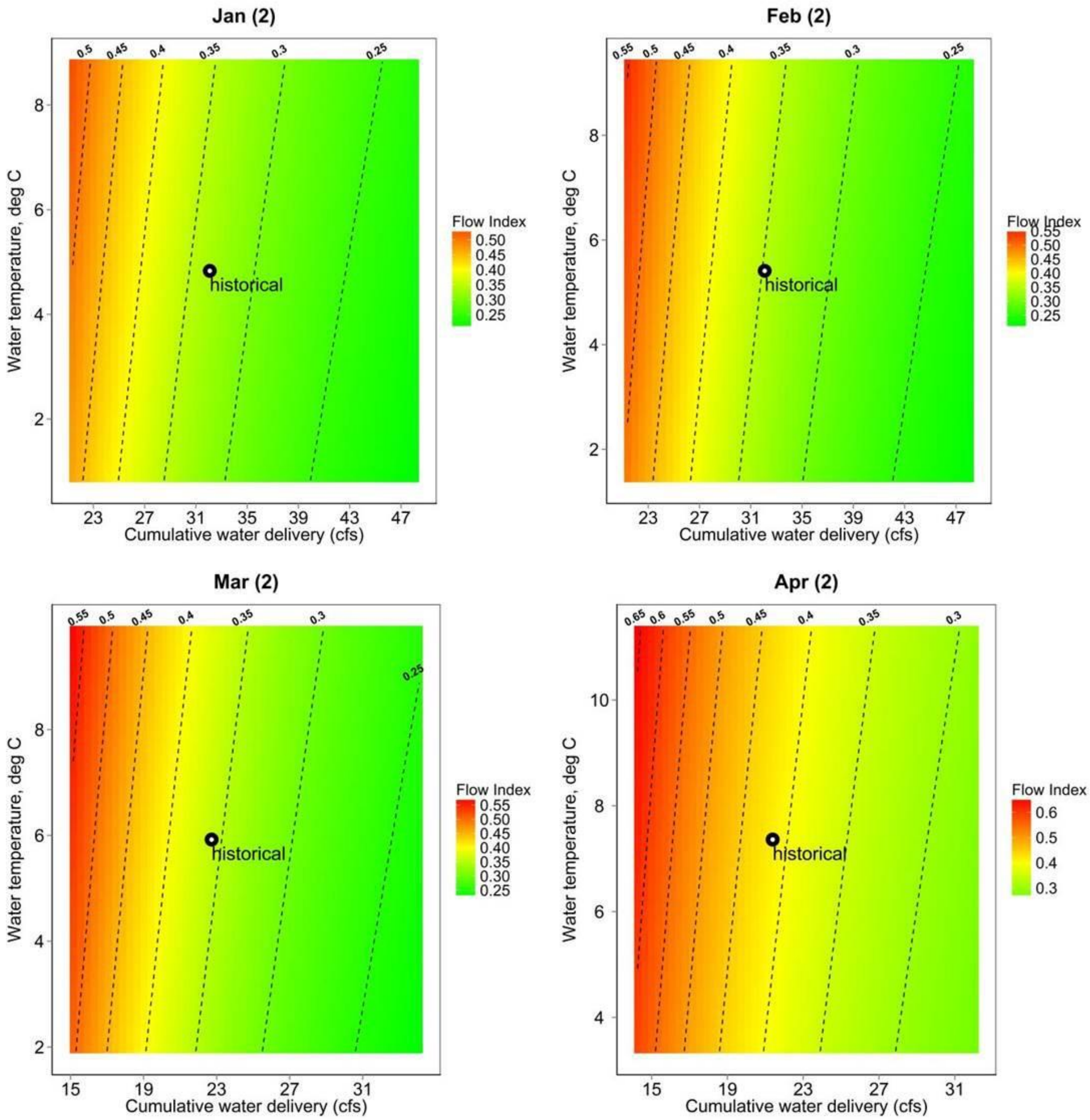

Figure B13 (concluded). *Predicted flow index values for coho salmon during January - April for the second year in the rearing cycle at Quilcene NFH based on incremental differences in water availability and temperature. The point represents the average historical conditions.*

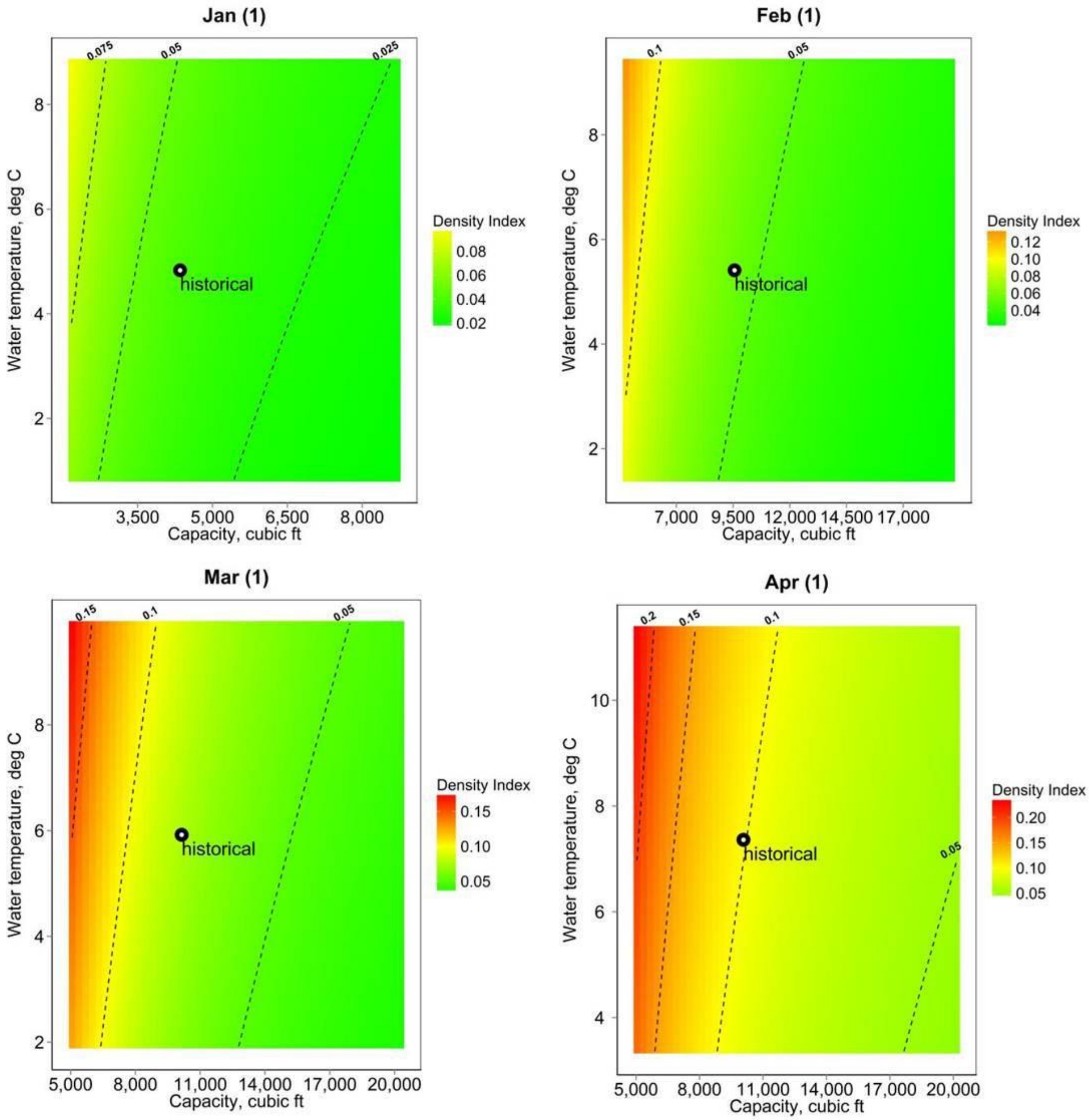

Figure B14. *Predicted density index values for coho salmon during January - April for the first year in the rearing cycle at Quilcene NFH based on incremental differences in hatchery capacity and temperature. The point represents the average historical conditions.*

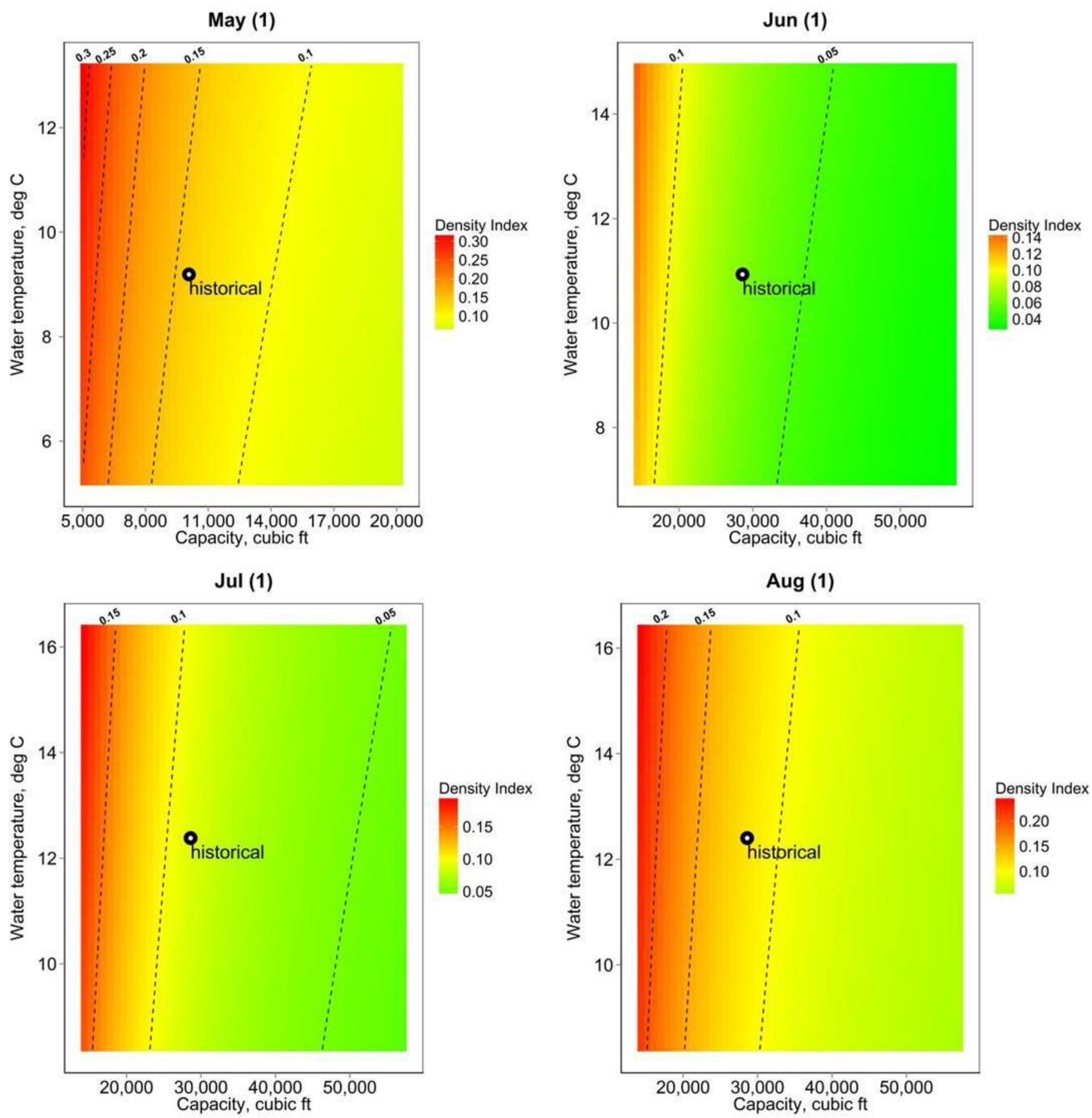

Figure B14 (continued). *Predicted density index values for coho salmon during May - August for the first year in the rearing cycle at Quilcene NFH based on incremental differences in hatchery capacity and temperature. The point represents the average historical conditions.*

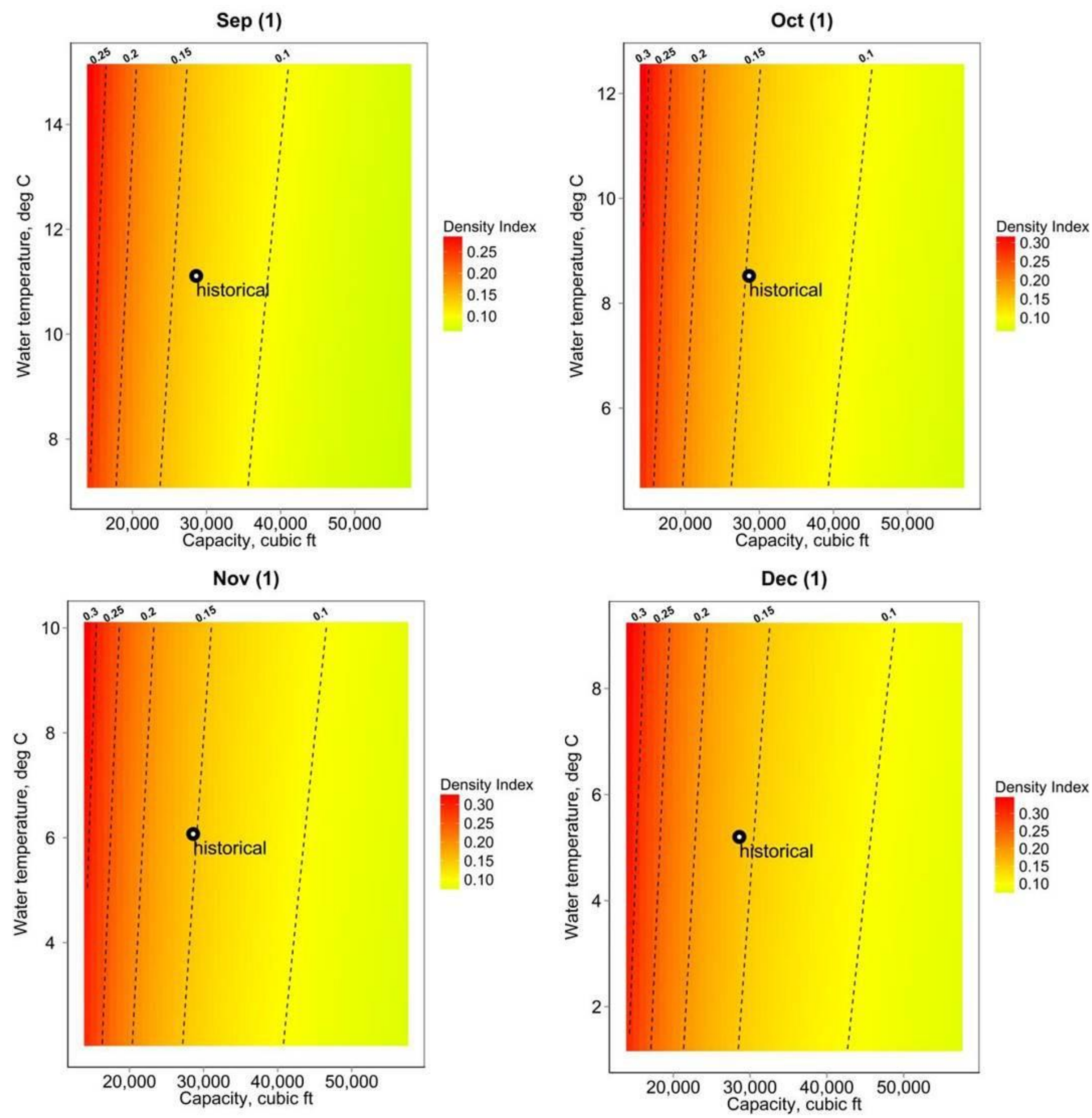

Figure B14 (continued). *Predicted density index values for coho salmon during September - December for the first year in the rearing cycle at Quilcene NFH based on incremental differences in hatchery capacity and temperature. The point represents the average historical conditions.*

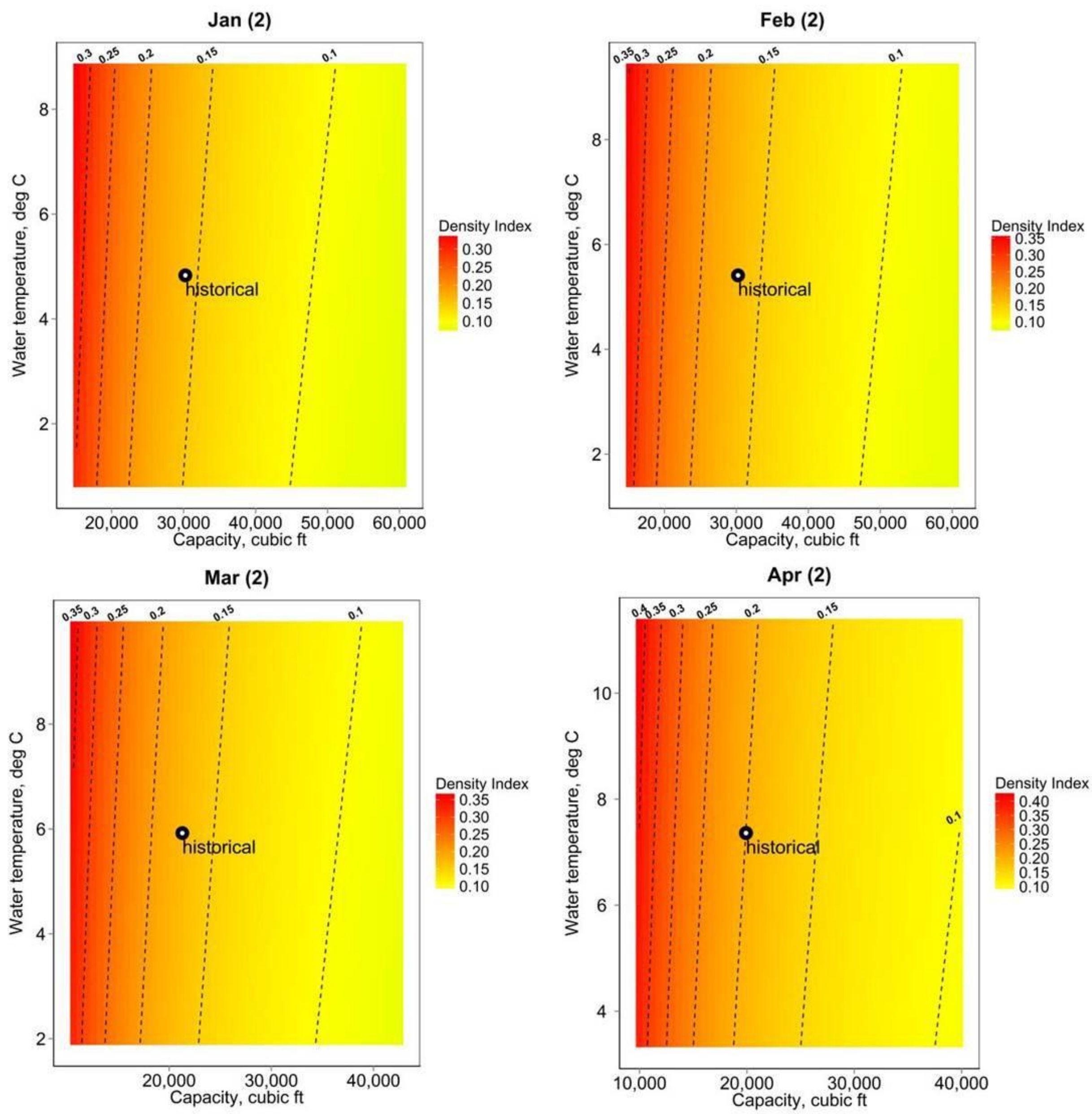

Figure B14 (concluded). *Predicted density index values for coho salmon during January - April for the second year in the rearing cycle at Quilcene NFH based on incremental differences in hatchery capacity and temperature. The point represents the average historical conditions, and assumes that some fish are moved to net pens in March and April.*