Appendix D. Modeling the potential effects of changed water availability and temperature on Pacific salmon culture programs at Winthrop National Fish Hatchery

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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 US (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 temperature and 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 production during that phase is 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 Fisheries Resources Program has 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 stocks, (b) identify the magnitude and timing of sub-lethal effects that may affect production, such as changes to growth, and the incidence of disease; and (c) suggest general mitigation strategies given the sensitivities detected in (a) and (b). To do this, we synthesized physiological tolerance data for Pacific salmon stocks of interest, 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; Wedenmeyer 2001) which integrate the effects of changing temperature and water availability within the Winthrop National Fish Hatchery (NFH). We briefly summarize the important hydrologic changes anticipated for the Methow River basin upstream from the hatchery. Using empirical data on recent rearing conditions within the hatchery, we then predict the future production of each of four salmon stocks by implementing the growth model and modeling flow and density indices based on in-hatchery environmental conditions predicted for the 2040s under one greenhouse gas scenario (A1B) and based on 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 (NFH's) 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 and ultimate lethal incipient temperature. 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 survival

4. *upper smoltification temperature limit*: the minimum temperature at which the smoltification process is inhibited
5. *CTM or UILT (upper ILT)*: 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 ± S.D. or range in mm), fish weight (mean ± S.D. or range, in g). The following supplemental meta-data from published values of CTM or ILT tests was also recorded, when provided, to facilitate proper interpretation of results: acclimation temperature (°C), maximum temperature from CTM or ILT tests (°C), and test endpoint criterion. Thermal tolerance data were categorized by the following life-history stages are relevant to hatchery production: 1) egg/fry (eggs, sac fry, and fry [fish length less than 70 mm] in early rearing containers) 2) juvenile (sexually immature fish in large rearing containers prior to release), and 3) adult broodstock (sexually mature fish that have returned to facility during the spawning migration). Data were averaged by life-history stage to determine representative thermal tolerances for each species at each life-history stage (Table A.1).

Pathogen Thermal Tolerances

In August, 2011, a review of the peer reviewed literature of thermal tolerances of common pathogens that infect salmon at aquaculture facilities in the Pacific Northwest was performed 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 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 A.2).

Winthrop NFH Rearing Conditions - Water Temperatures

Baseline thermal rearing conditions at Winthrop NFH were calculated based on water temperatures measured at the facility's surface and ground-water intake locations. Daily mean, maximum, and minimum temperatures of surface water flows collected from the Methow River were measured in the screen chamber of the water intake at the facility from 2001 – 2011. These values were used to calculate mean monthly values for mean, maximum, and minimum water temperatures for each year in the time series. Finally, a baseline 10-year average monthly water temperature was calculated for the surface flow data set. Similarly, shallow groundwater temperatures (3-5 m in depth) were measured weekly in on-site infiltration galleries at Winthrop NFH for the time period of 2001 – 2011. These infiltration galleries are perforated pipes buried adjacent to the river. The groundwater temperature data (daily mean, maximum, and minimum temperatures) were used to calculate the baseline 10 year average monthly groundwater temperatures following the process described above. The baseline water temperature information was used to calculate the thermal rearing conditions experienced by fish of each species across their rearing schedule (Table 1) within Winthrop NFH as determined by the source of water (or blend of surface and groundwater) supplied to rearing containers during each month.

Table 1: Mean water temperatures of sources that supply Winthrop NFH. Historical values are empirical data from 10 year historical baseline (2000 – 2009). Predictions for the 2040s based statistically downscaled air temperatures from 10 global circulation models under the A1B emissions scenario, and regression relationships between air, surface water, and ground water (see text for additional details).

Month	Surface Water (^{o}C ± 2 S.D)		Ground Water (^{o}C ± 2 S.D)	
	10 year historical baseline	2040s A1B predicted	10 year historical baseline	2040s A1B predicted
January	3.1 ± 1.4	3.3 ± 0.2	8.2 ± 0.4	8.0
February	4.1 ± 1.4	4.2 ± 0.4	7.9 ± 0.3	7.9
March	5.9 ± 1.3	5.9 ± 0.7	8.0 ± 0.4	8.2
April	7.6 ± 1.0	8.3 ± 0.7	8.2 ± 0.5	8.6
May	8.5 ± 1.4	10.4 ± 0.8	8.6 ± 0.6	9.3
June	10.3 ± 1.6	12.5 ± 0.5	9.0 ± 0.6	9.9
July	13.8 ± 1.5	14.5 ± 0.5	10.3 ± 0.7	10.4
August	14.1 ± 1.1	14.2 ± 0.6	10.8 ± 0.5	11.0
September	11.5 ± 1.3	11.8 ± 0.8	10.8 ± 0.6	10.9
October	8.2 ± 1.4	8.3 ± 1.3	10.3 ± 0.6	10.2
November	5.1 ± 1.4	5.1 ± 0.7	9.4 ± 0.5	9.3
December	3.3 ±1.3	3.7 ± 0.3	8.6 ± 0.4	8.4

Historical and Future Stream Temperatures near Winthrop NFH

Air temperature data from the statistically downscaled global circulation model simulations for the A1B emissions scenario were used to estimate surface water temperatures temperature in the Methow River near the Winthrop NFH. Historical and future (2040s) air temperatures were based on an ensemble of 10 global circulation models: ccsm3, cgcm3.1_t47, cnrm_cm3, echam5, echo_g, hadcm, hadgem1, ipsl_cm4, miroc_3.2, and pcm1 (Hamlet et al.

2010). A variety of greenhouse gas emissions scenarios have been utilized in climate modeling (IPCC 2007). The A1B scenario is often referred as a 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. 2011b). Over the time period being modeled, three commonly cited emissions scenarios (A2, B1, and A1B) used in the Intergovernmental Panel on Climate Change's fourth assessment report (AR4) yield similar air temperature increases at the global scale (IPCC 2007). Whether recent emission levels are exceeding those used in fourth assessment report is a subject of some debate (e.g., Le Quéré et al. 2007; Ganguly et al. 2009; Manning et al. 2010). The next climate assessment report (to be completely in 2014) will use a different methodology – representative concentration pathways (RCP) – to define emissions scenarios (Moss et al 2010). In the interim, the A1B scenario (and its cohorts from the AR4) provide a reasonable 'common currency' on which to base this modeling exercise, as the AR4 scenarios are still widely used.

Briefly, the regression model of Mohseni et al (1998) was fit to weekly modeled historical air temperature data for the 1/16th degree latitude × longitude grid cell (48.46875^{o}, -120.15625^{o}) containing the hatchery and surface water temperatures recorded at the water intake to the hatchery 2001-2010 (data in Table 1) following the approach of Mantua et al (2010). The relationship between air and water temperature is approximated by the logistic-type function:

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

where Ts_W is the estimated weekly average stream temperature, μ is the estimated minimum stream temperature (set to ≥ 0), α is the estimated maximum stream temperature, γ is a measure of the steepest slope of the function, β indicates the air temperature at the inflection point, and T_a is the average weekly air temperature. The model parameters were estimating using the method of least squares minimizing the sum of the squared errors (ε) between the observed (T_{obs}) and fitted values (T_w) for water temperatures:

$$Sum\ of\ squared\ errors\ (SSE) = \sum_{i=1}^{n} \varepsilon_i^2 = \sum_{i=1}^{n} \left(T_{obs_i} - \mu - \frac{\alpha - \mu}{1 + e^{\gamma(\beta - Ta_i)}} \right)^2.$$

Model fit was estimated by the Nash-Sutcliffe coefficient (NSC) (Nash and Sutcliffe 1970) as:

$$NSC = 1 - \left[\frac{\sum_{i=1}^{n} (T_W - T_{obs})^2}{\sum_{i=1}^{n} \left(\bar{T}_{obs} - T_{obs_i} \right)^2} \right].$$

We assume a stationary relationship between weekly average air and surface water temperature.

The regression model for the Methow River basin provided an adequate fit, with an NSC = 0.89. Surface water temperature (T_{SW}) predictions for the 2040s were generated by applying the statistically downscaled air temperature prediction (Table 1).

To determine monthly mean groundwater temperatures under the future climate change scenario (i.e., the 30-year period centered on the 2040s), the relationship of groundwater temperature to surface water temperature was calculated by regressing monthly groundwater temperatures against monthly surface water temperatures for each year in the 2000 – 2009 historical baseline then lagged by a month to account for the delay as water infiltrated into the shallow local aquifer (Mayer and Stratchan 2012). The following regression equation (R^2 = 0.83, F = 583, d.f. = 117, P < 0.001) was used to predict groundwater temperatures for the 10-model ensemble under the A1B emissions scenario:

$$T_{GW} = 0.2732\ (T_{SW}) + 7.0013$$

where T_{GW} represents groundwater temperature (°C) and T_{SW} represents surface water temperature (°C). The modeled 2040s A1B water temperature information (both ground- and surface water) was used to calculate the thermal rearing conditions experienced by fish of each species across their rearing schedule (Table 2) as determined by the source of water (or blend of surface and groundwater) supplied to rearing containers during each month.

Table 2: Mean monthly water temperatures and water sources experienced by juvenile spring Chinook salmon reared at Winthrop NFH based on the 10 year historical baseline (2000 – 2009) and projected values for the 2040's. Water sources are separated into either groundwater (GW) or surface water (SW).

			Rearing Temperature	
Month	Life-History Stage	Water Source	10 year historical baseline (°C)	2040 predicted (°C)
May	broodstock	100% GW	8.6	9.3
June	broodstock	100% GW	9.0	9.9
July	broodstock	100% GW	10.3	10.4
August	broodstock	100% GW	10.8	11.0
September	broodstock	100% GW	10.8	10.9
August (1)	egg/fry	100% GW	10.8	11.0
September (1)	egg/fry	100% GW	10.8	10.9
October (1)	egg/fry	100% GW	10.3	10.2
November (1)	egg/fry	100% GW	9.4	9.3
December (1)	egg/fry	100% GW	8.6	8.4
January (1)	egg/fry	100% GW	8.2	8.0
February (1)	egg/fry	100% GW	7.9	7.9
March (1)	egg/fry	100% GW	8.0	8.2
April (1)	egg/fry	100% GW	8.2	8.6
May (1)	juvenile	100% GW	8.6	9.3
June (1)	juvenile	100% GW	9.0	9.9
July (1)	juvenile	100% GW	10.3	10.4
August (2)	juvenile	100% GW	10.8	11.0
September (2)	juvenile	100% GW	10.8	10.9
October (2)	juvenile	50% GW, 50% SW	9.3	9.3
November (2)	juvenile	50% GW, 50% SW	7.3	7.2
December (2)	juvenile	50% GW, 50% SW	5.9	6.0
January (2)	juvenile	40% GW, 60% SW	5.1	5.2
February (2)	juvenile	30% GW, 70% SW	5.2	5.3
March (2)	juvenile	30% GW, 70% SW	6.6	6.6
April (2)	smolt	30% GW, 70% SW	7.8	8.4

Growth Model Simulation

To assess biologically-important changes in hatchery rearing density that may result from changes in water temperature, we used a simple model of salmon growth to calculate monthly changes in fork length (mm) and weight (g). This simple model reflects only the influence of temperature on growth as it assumes that fish have access to sufficient food to grow.

The salmon growth model was based upon the previous work of Iwama and Tautz (1981) and used the following equation to determine final fish weight based on initial weigh and the duration of rearing at a particular temperature:

$$W_t^{0.33} = W_0^{0.33} + \left(\frac{T}{1000}\right) t$$

where W_t represents the final weight in grams, W_0 represents the initial weight in grams, T represents the average temperature during the growth period (°C), and t represents the duration of the growth period in days. Final fish weights were converted to fork length (FL) by using an equation to determine condition factor (Anderson and Gutreuter 1983):

$$K = \left(\frac{W}{FL^3}\right) \times 100{,}000$$

where K represents condition factor, W_t represents the final weight of the fish (g), and FL represents the fork length of the fish (mm). The condition factor equation was re-arranged to solve for final fork length as:

$$FL = \left(\frac{W_t}{\left[{}^{K}/_{100{,}000}\right]}\right)^{0.33}$$

where K was held constant at 1 to represent fish in a healthy condition. To determine monthly differences in fish size, the average fish weight at ponding was used as the initial size for the first month time step of the model. Subsequent time steps used the predicted final weight of the fish from the preceding time step as the initial fish weight. As such, this simple model reflects only the influence of temperature on growth and relates cumulative differences in size between thermal regimes.

Integrating the Effect of Water Temperature and Water Availability on Hatchery Operations

Hatcheries can be considered a special type of habitat where the carrying capacity for the population or stock is largely influenced by the natural resources (e.g., water) legally available to facility, constrained by its infrastructure. Hatchery managers often use surrogate measurements or indices, such as flow index or density index, to represent this capacity during the production cycle (Piper et al. 1982; Wedenmeyer 2001). The Flow Index pertains to the relationship between fish mass and size and rate that water enters the rearing habitat (Piper et al. 1982), and is a surrogate for carrying capacity based largely on the amount of dissolved oxygen and the ability to remove metabolic waste (Wedenmeyer 2001). Similarly, the Density Index also considers fish mass and size but is calculated relative to the volume of the rearing capacity (Piper et al. 1982), and is a surrogate for behavioral and physiological effects that may occur with increasing fish density. The equations for these two indices are:

$$Flow\ Index = \frac{total\ mass\ (lb)}{FL\ (in) \times flow\ (GPM)} = \frac{N \times W_t\ (lb)}{FL\ (in) \times flow\ (GPM)}$$

and

$$Density\ Index = \frac{total\ mass\ (lb)}{FL\ (in) \times capacity\ (ft^3)} = \frac{N \times W_t\ (lb)}{FL\ (in) \times capacity\ (ft^3)};$$

where *Total mass* represents the combined weight of all fish (lb) (or, equivalently the total fish abundance N × the mean weight per fish, W_t (lb)), *FL* is the mean fork length (in), *flow* is the amount of water entering the rearing habitat (in gallons per minute, GPM), and *capacity* is the total habitat volume or rearing capacity (in cubic feet, ft^3).

Hatcheries typically operate to achieve a production target while remaining below index values identified as thresholds based on empirical observations of fish disease, mortality or poor growth; or general rules of thumb based on oxygen saturation for different water temperatures and elevation (e.g., Piper et al. 1982). We utilized these indices to integrate the effect of changing stream temperatures and water availability and estimate the carrying capacity for each stock in the Winthrop hatchery under current and future environmental conditions climate-model based and sensitivity approach. For the climate model approach, we calculated flow and density indices for each stock in each month (after initial ponding) for current and future conditions based the average monthly stock density and capacity, fish mass and size calculated using the above growth model, estimated mean monthly water temperature (see above), and water availability expected under the A1B emissions scenario. Sensitivity (or synthetic scenario) analyses explored how the flow and density indices changed based on incremental changes in temperature and water availability and explored which factor appears to most strongly influence changes in the index value. For flow index, we plotted monthly index values based on combinations of water temperature (100 increments covering historical mean temperature $T \pm 4^{o}C$) and *flow* (50 increments covering historical water use ± 2×, or a halving or doubling) to generate a monthly response surface of 5,000 points. We did the same for density index but utilized values for *capacity* (50 increments covering current capacity values ± 2×) rather than *flow*. For brevity and in the interest of focusing on periods when environmental conditions may pose acute challenges to hatchery managers, we restricted the analyses and results for each species to months where large (>20%) relative changes in index values were predicted. For the Winthrop NFH, this generally restricted sensitivity analyses to the flow index for the summer months (June-September) for each salmon stock.

The climate-model based scenario utilized the A1B emission scenario described above and statistically downscaled air temperature for the 30 year period centered on the 2040s (i.e., 2040s A1B) based on an ensemble of 10 global climate models. Statistically downscaled climate data (precipitation and temperature) was used to force a macroscale hydrologic model (variable infiltration capacity or VIC) to estimate streamflows. Under the climate model-based scenario, current water availability was based on the average monthly use during the period 2003-2009 and future water availability at the hatchery was based on proportional changes in surface water flow projected for the Methow River at Winthrop, WA (CIG site 6042, USGS Id: 12448500). This location is downstream from the hatchery and below the confluence with the Chuwach River (http://www.hydro.washington.edu/2860/products/sites/?site=6042), but was the closest location for which routed stream flows from VIC were available. Together, the two approaches permit a general examination of how carrying capacity will change in response to environmental condition, and a specific but internally-consistent estimate of the magnitude of changes anticipated in the 2040s.

Results

Future Climate at Winthrop NFH under the A1B Emissions Scenario

Climate and hydrologic modeling under the A1B emissions scenario predict the Methow River Basin will experience warmer air temperatures, reduced snowpack, earlier snowmelt runoff, and lower summer baseflows in by the 2040's (Figures 1-5). Mean monthly air temperature is expected to increase, average 2.07^{o}C (S.D. = 0.54) from the present to the 2040s (Figure 1). Increases are projected for each month, with the largest absolute increases predicted in summer the summer months (June-September). The climate models do not predict large changes in total precipitation, but the amount that falls as snow and remains in the snowpack is expected to decline (Figure 1). Changes in runoff, average flow, winter floods, and summer drought severity are also anticipated for the Methow River basin upstream from the Winthrop NFH (Figures 4-5, data from Wenger et al. 2011b, http://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml).

Hydrologic projections based on a different hydrologic modeling framework (Precipitation Runoff Modular System (PRMS)) produced qualitatively similar results (Voss and Mastin 2012, as cited by Mayer and Strachan 2012). Based on the VIC modeling, spring snowmelt runoff occurs earlier (Figure 2), the severity of summer drought increases (Figure 3), mean daily flows increase (Figure 4), and the frequency of winter floods and potential for bed scour increases (Figure 5). Snow levels are predicted to rise as air temperatures increase, and the basin may shift from a snowmelt to a so-called transitional or rain-driven system in the future (Mantua et al. 2010).

Water temperature in the 2040's based upon the A1B scenario and statistical downscaling of GCMs show impacts of varying degrees to surface and groundwater temperatures at Winthrop NFH (Table 1, Figure 6A & 6B). In most months, modeling predicts that Methow River surface water temperatures will increase, albeit by less than 1°C when compared to ten year historical averages (Table 1). In a single month, March, surface water temperatures are predicted to slightly decline from the historical average (Table 1). The most significant changes in surface water temperatures are predicted to occur in May (+1.9°C) and June (+2.2°C) (Table 1, Figure 6A). As groundwater at this facility is collected from shallow infiltration galleries, increases in groundwater temperatures track those of the surface waters of the Methow River with the largest increases predicted for May (+0.7°C) and June (+0.9°C) (Table 1, Figure 6B). Given the predicted alterations to surface and groundwater temperatures at Winthrop NFH, the water temperatures across the production cycle for each program will change. However, these changes will be program-specific due to the variation in the water source (or blend thereof) used for each species across the production cycle.

Concurrent with changes in water temperature, the monthly surface flows in the Methow River are also predicted to change by the 2040's. The Methow River is predicted to have increased flows from October to May annually when compared to the 10 year baseline (Table 3, Figure 1). The greatest increases in river flow (>50%) are predicted to occur between December and March (Table 3, Figure 1). Conversely, Methow River flows are predicted to decline in June (-22.5%), July (-47.0%), August (-32.6%), and September (-17.2%) from the 10 year baseline (Table 3, Figure 1).

Table 3: Comparison of the predicted mean monthly flow for the Methow River near Winthrop, WA (CIG site 6042, USGS Id: 12448500). Values are the simulated historical flows and simulated flows in the 2040s from the VIC hydrologic model forced by statistically downscaled climate projections from 10 global circulation models under the A1B emissions scenario.

	Mean flow (cfs)		
Month	Historical	2040s predicted	Percent change from historical
January	549	975	77.6%
February	571	1032	80.7%
March	717	1143	59.4%
April	1554	2157	38.8%
May	3254	3668	12.7%
June	3847	2981	-22.5%
July	1801	954	-47.0%
August	611	412	-32.6%
September	449	372	-17.1%
October	556	559	0.5%
November	742	990	33.4%
December	634	997	57.3%

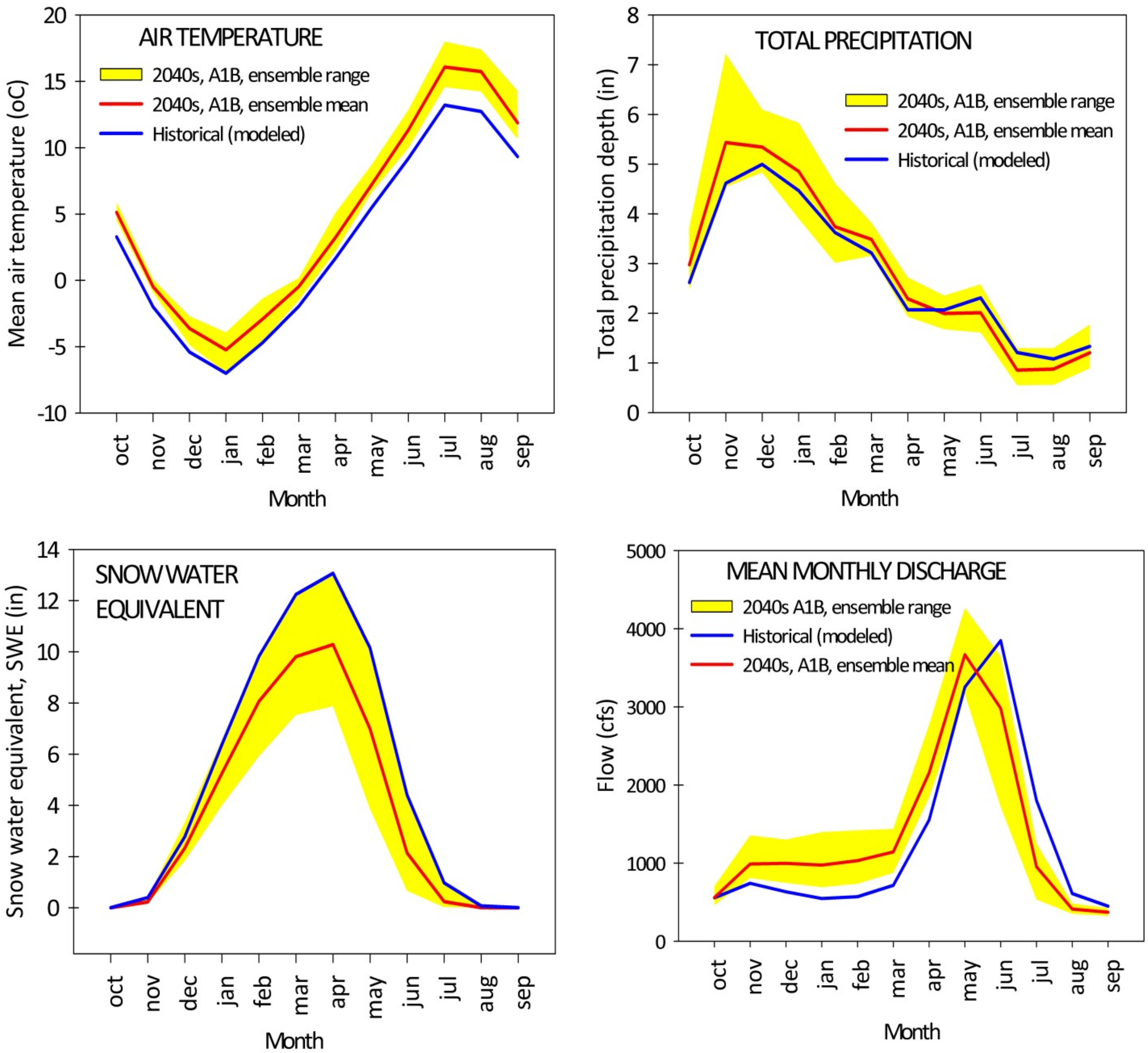


Figure 1. *Simulated historical and future monthly average air temperature, precipitation, total precipitation, snow water equivalent, and mean monthly discharge for the Methow River. The 2040s values are the ensemble average based on ten forcing general circulation models for the hybrid delta projections, and represent a 30-year time period centered on the 2040s (e.g., 2030-2059) (data from CIG: http://www.hydro.washington.edu/2860/products/sites/?site=6042). Temperature, precipitation, and snow water equivalents are basin-wide values, whereas the discharge estimates from the hydrologic model (VIC) are routed to CIG site 6042.*

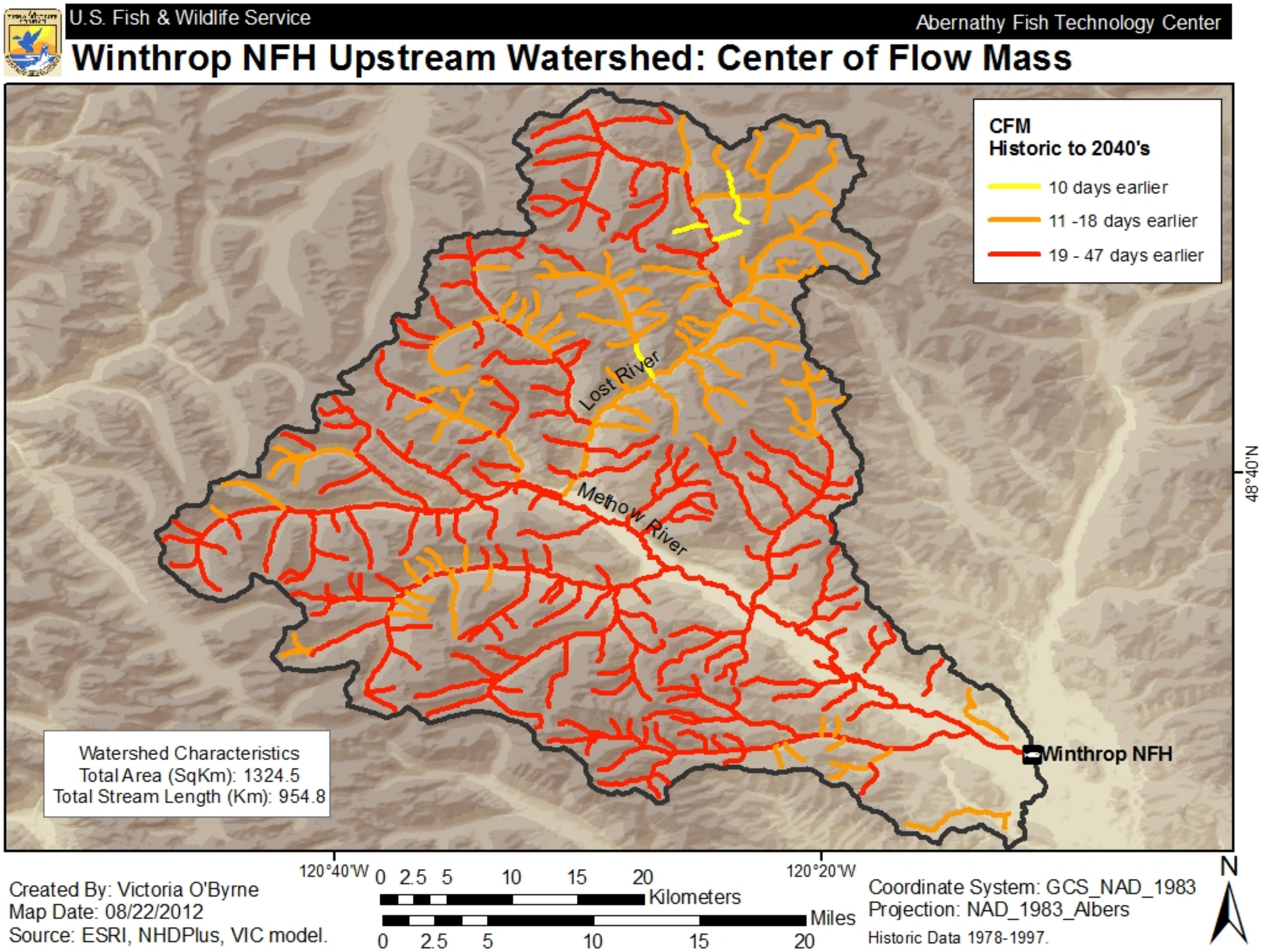


Figure 2. *Projected change in the timing of snowmelt runoff (date of center of flow mass, CFM) for the Methow River basin upstream from Winthrop NFH between historical and 2040s time periods. Data are from VIC hydrologic model (Wenger et al. 2011b) and the historical reference period is 1978-1997.*

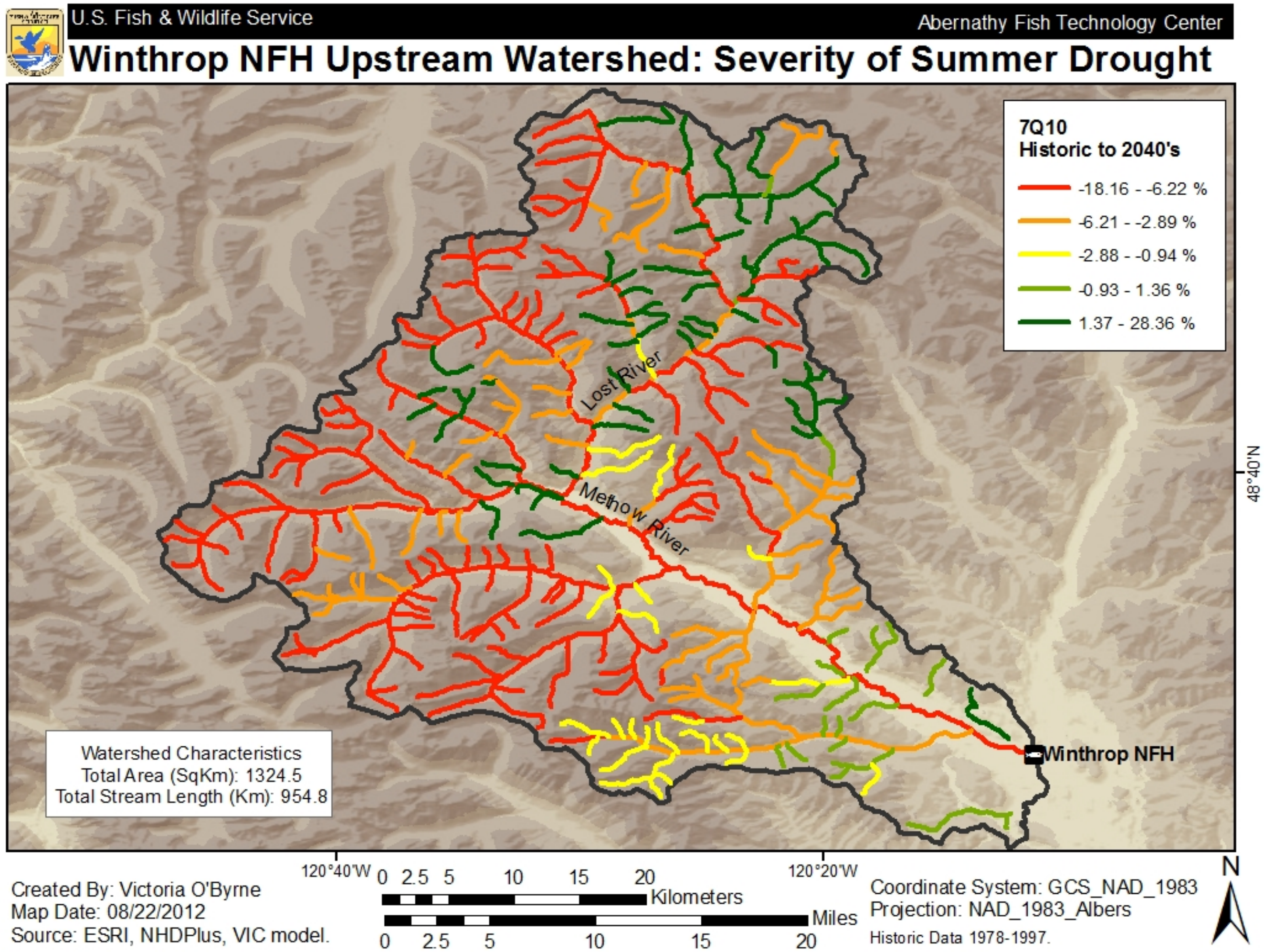


Figure 3. *Projected change in the severity of summer drought (7-day low flow 10-yr return interval, 7Q10) for the Methow River basin upstream from Winthrop NFH between historical and 2040s time periods. Data are from VIC hydrologic model (Wenger et al. 2011b) and the historical reference period is 1978-1997.*

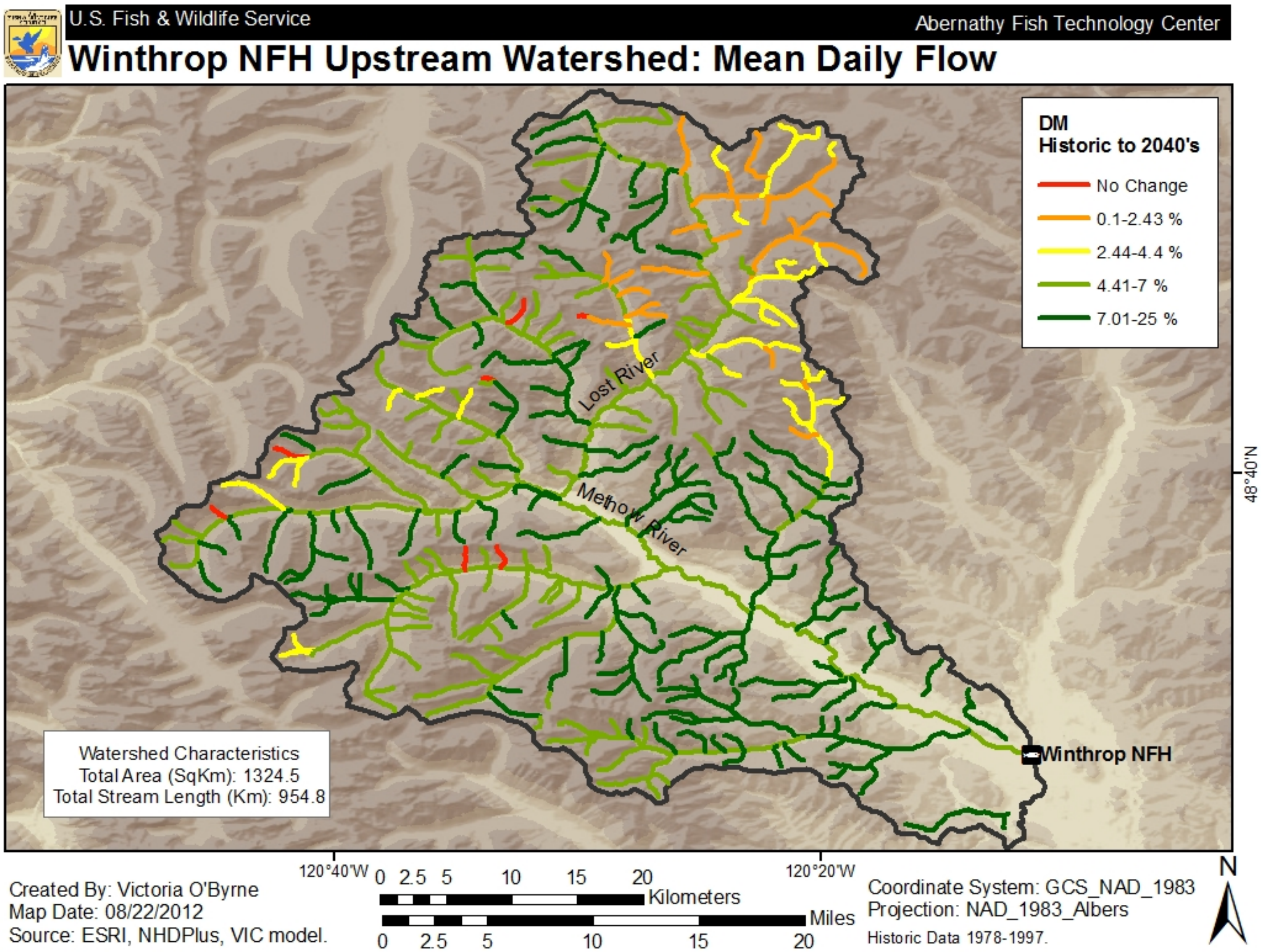


Figure 4. *Projected change mean daily flow (DM, in %) for the Methow River basin upstream from Winthrop NFH between historical and 2040s time periods. Data are from VIC hydrologic model (Wenger et al. 2011b) and the historical reference period is 1978-1997.*

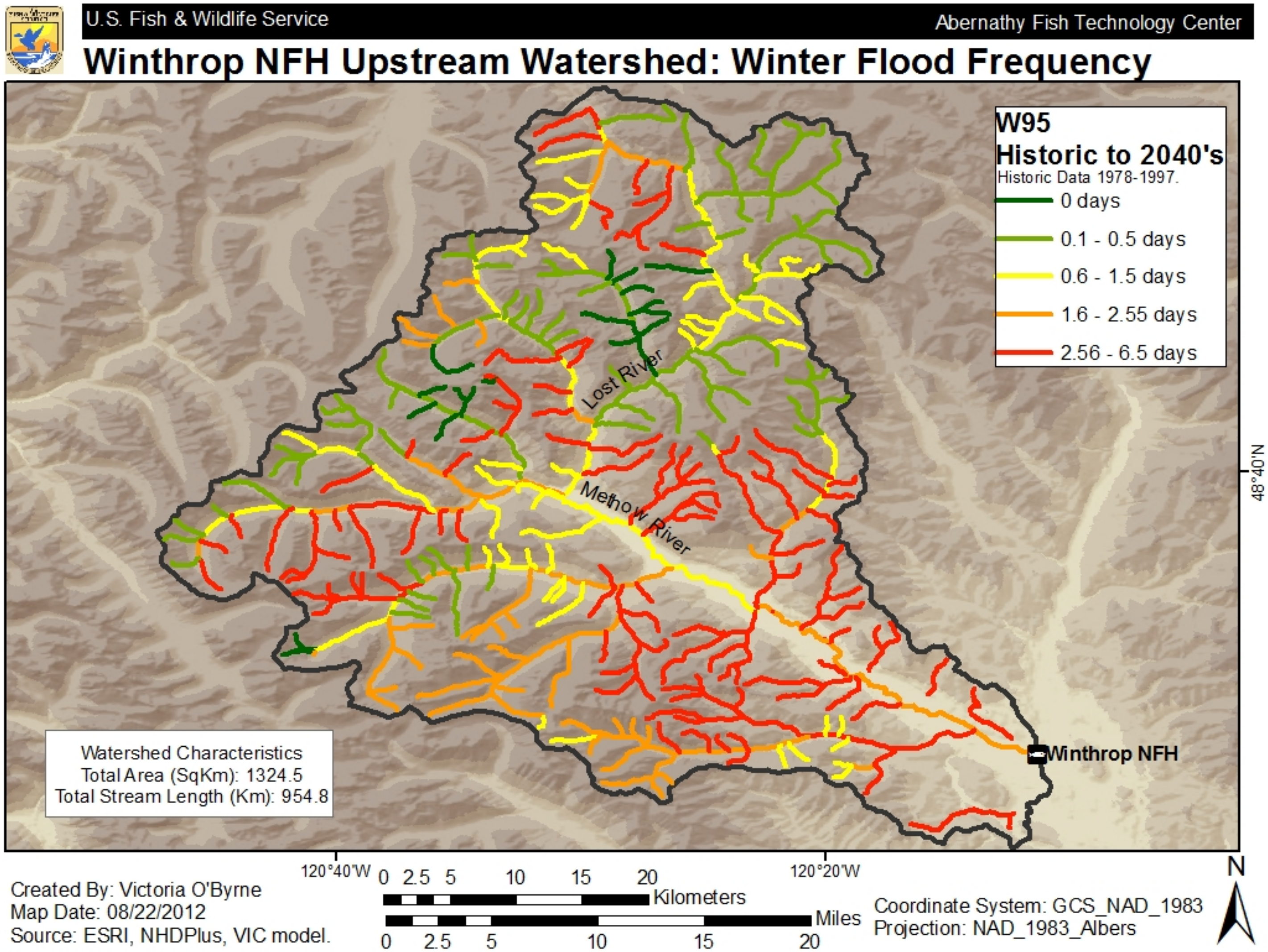


Figure 5. *Projected change winter flood frequency (w95 or number of days when the flows are in highest 5% for the year) for the Methow River basin upstream from Winthrop NFH between historical and 2040s time periods. Data are from VIC hydrologic model (Wenger et al. 2011b) and the historical reference period is 1978-1997.*

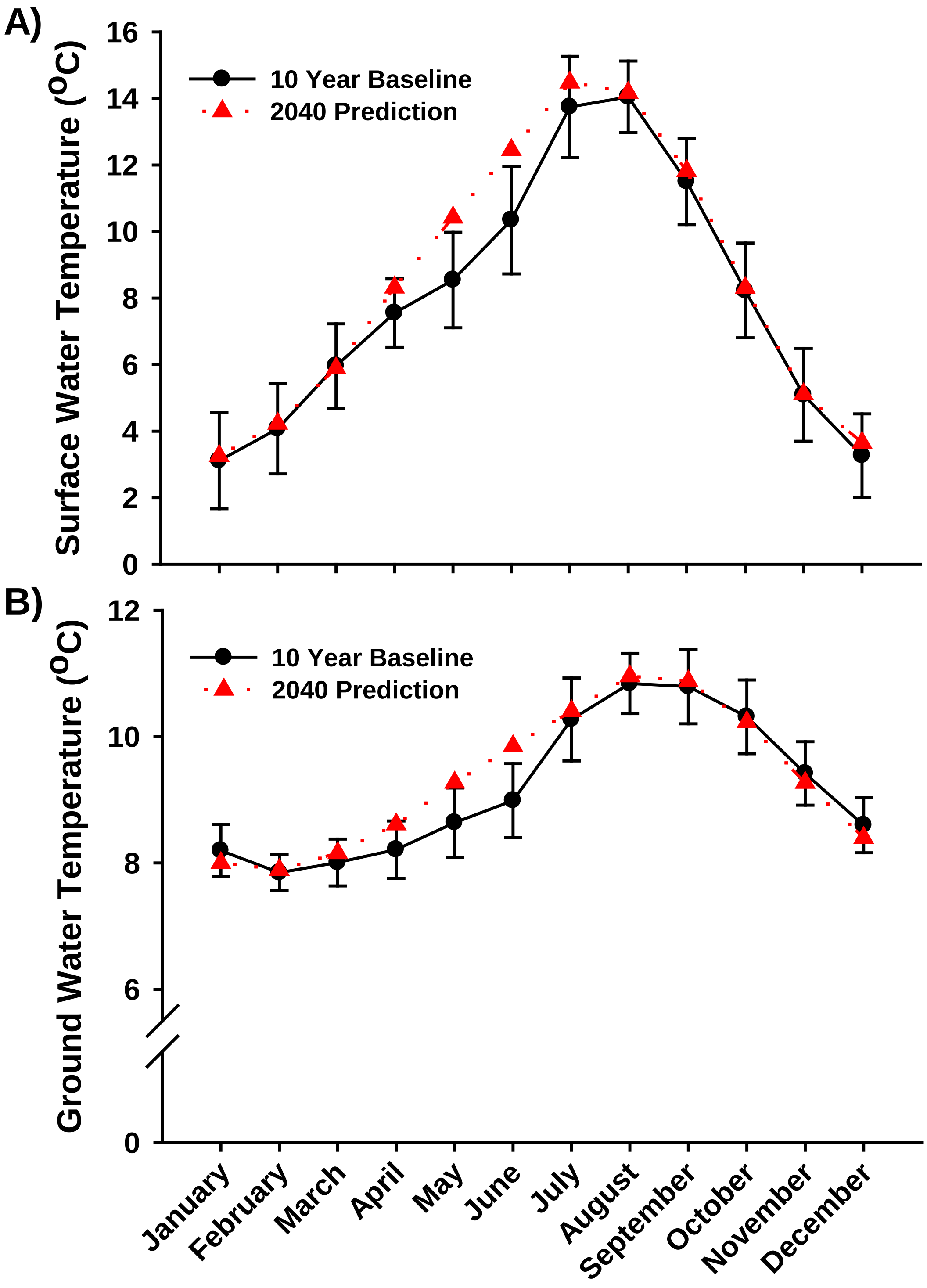


Figure 6*. Comparison of the mean (± 2 S.D.) water temperatures of water sources that supply Winthrop NFH from the 10 year historical baseline (2000 – 2009) and projected values for the 2040's.*

Spring Chinook Salmon Program

During a standard production cycle, adult Chinook salmon are captured between May and September and retained in holding ponds supplied with groundwater until spawning (Figure 7). Groundwater temperatures between May and September are predicted to increase by less than 0.25°C (Table 3). The maximum predicted groundwater temperature during the broodstock holding time period is 11.0°C (Figure 7), well within the range of optimal spawning temperatures (9 – 12.3°C) of Chinook as documented in the literature (Table A.1). As such, the predicted climatic conditions in 2040 should have a minimal impact on broodstock holding conditions.

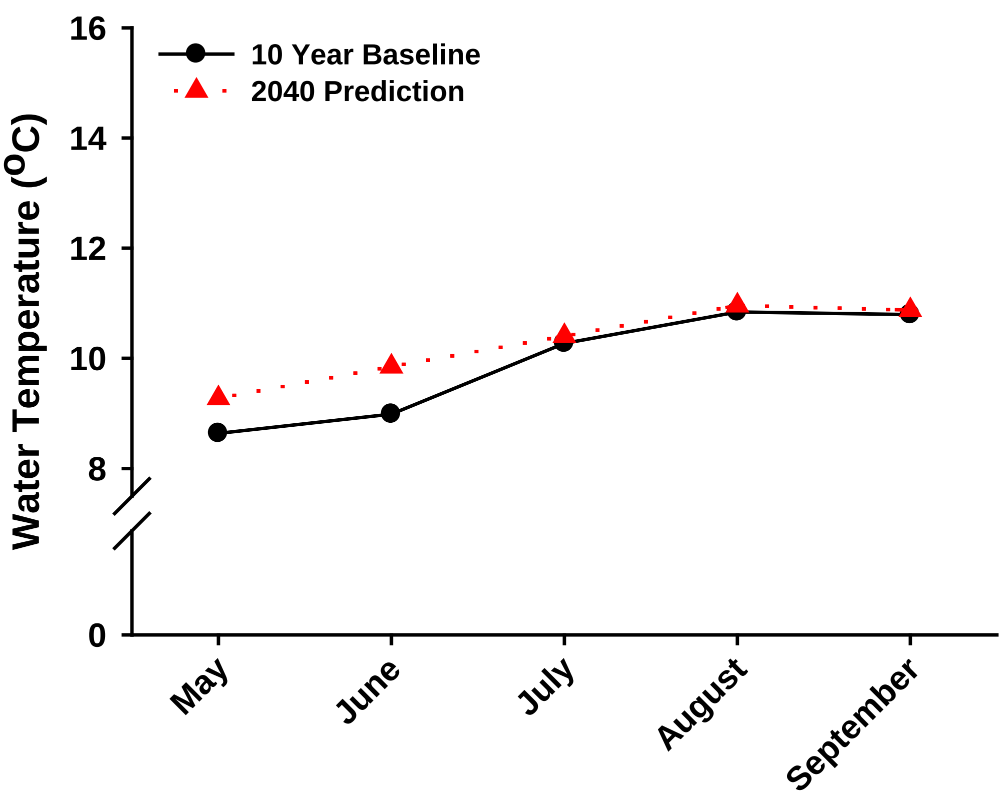


Figure 7: *Comparison of the mean water temperatures experienced by spring Chinook salmon broodstock held at Winthrop NFH based on the 10 year historical baseline (2000 – 2009) and projected values for the 2040s.*

Juvenile Chinook salmon will be exposed to altered rearing conditions during the production cycle as a result of the predicted changes in both surface and groundwater in 2040. In general, the thermal environment inhabited by juvenile Chinook in 2040 is predicted to be quite similar to current conditions at Winthrop NFH with minor increases or decreases of less than 0.25°C in most months (Table 2, Figure 8). The greatest deviations from historical baseline are predicted to occur in April (+0.4°C), May (+0.7°C), June (+0.9°C), and at release in the subsequent April (+0.6°C) (Table 2). Across the rearing cycle, water temperatures are not predicted to exceed any physiological thresholds in the 2040's at Winthrop NFH. During the

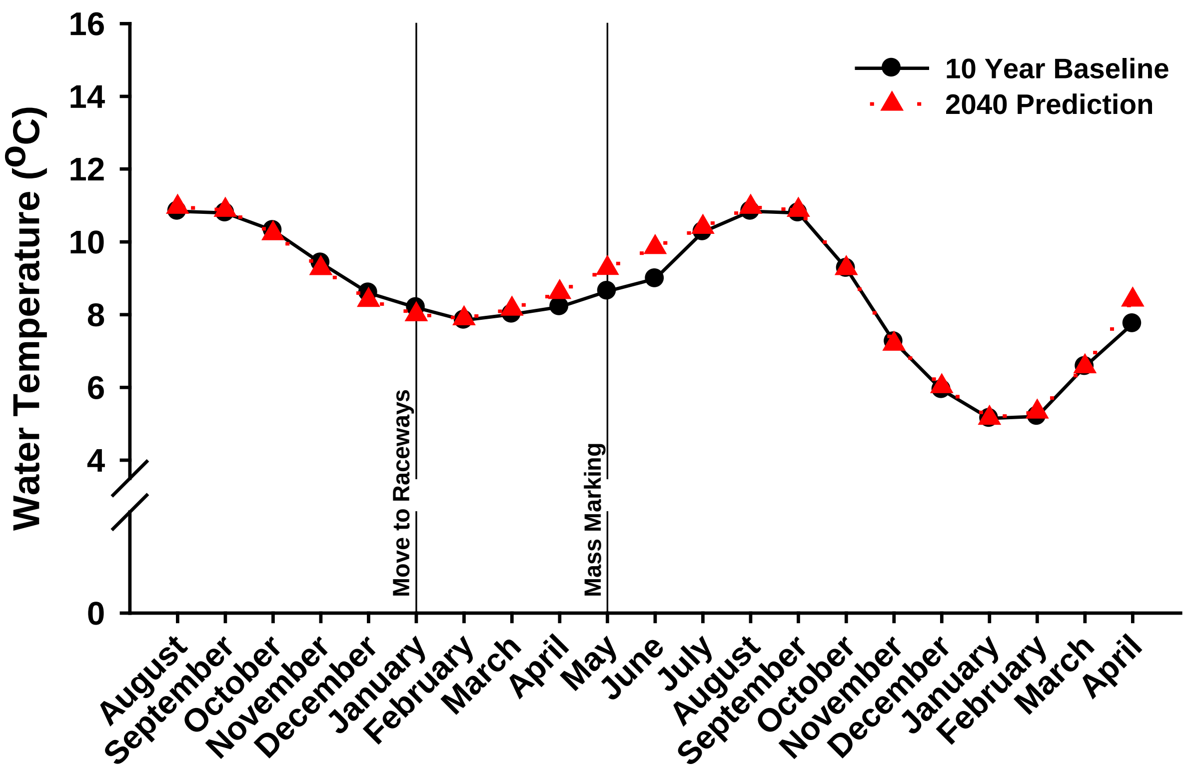


Figure 8: *Comparison of the mean water temperatures experienced by juvenile spring Chinook salmon reared at Winthrop NFH based on the 10 year historical baseline (2000 – 2009) and projected values for the 2040's. The approximate dates of important hatchery events are denoted by labeled vertical lines.*

months when Chinook salmon are developing as eggs or fry (August – April), water temperatures are predicted to be within or below the optimal temperature egg and fry development range for this species (Table A.1). The predicted temperatures that Chinook salmon will experience as juveniles between May and April are also within or below the optimal temperature range for this species (Table A.1). At the time of release, the predicted water temperature within the facility in April (8.4°C) is well below the upper limit for proper smoltification at 14°C (Table A.1). As the thermal environment within the hatchery in 2040 is predicted to be similar to the current conditions, water temperatures are not predicted to rise to within the optimal growth temperature for common salmon pathogens (Table A.2). However, increases in water temperatures approaching 1°C in May and June may increase the risk for disease outbreaks in these months compared to historical trends.

While the predicted temperature changes in the 2040's may not exceed physiological tolerances of Chinook salmon, growth of fish within Winthrop NFH will change as a result. During early rearing of juvenile Chinook salmon, cooler temperatures are likely to induce reduced growth in the 2040's when compared to historical baselines resulting in fish being of a smaller size relative to fish at historical temperatures (Table 4, Figure 9). However, fish growth will accelerate in warmer months with the largest differences in weight and length occurring in April – June (Table 4, Figure 9). Exposure to groundwater blended with cold surface water will decrease growth rates at the end of the rearing cycle, but not by enough to compensate for accelerated growth over the summer months (Table 4, Figure 9). Accordingly, due to the altered thermal environment, Chinook salmon smolts released from the facility are predicted to be 5.6% heavier and 1.8% longer than the historical size of fish at release (Table 4, Figure 9).

Table 4: Monthly size differences of juvenile spring Chinook salmon reared at Winthrop NFH exposed to projected water temperatures for the 2040s relative to fish reared at water temperatures from the 10 year historical baseline (2000 – 2009).

Month (Year)	Life-History Stage	Weight (g) difference	Length (mm) difference
January (1)	egg/fry	-1.7%	-0.6%
February (1)	egg/fry	-1.1%	-0.4%
March (1)	egg/fry	-0.1%	-0.1%
April (1)	egg/fry	2.1%	0.7%
May (1)	juvenile	4.8%	1.6%
June (1)	juvenile	7.8%	2.5%
July (1)	juvenile	7.2%	2.3%
August (2)	juvenile	6.7%	2.2%
September (2)	juvenile	6.1%	2.0%
October (2)	juvenile	5.6%	1.8%
November (2)	juvenile	5.0%	1.6%
December (2)	juvenile	4.9%	1.6%
January (2)	juvenile	4.7%	1.5%
February (2)	juvenile	4.8%	1.5%
March (2)	juvenile	4.5%	1.5%
April (2)	smolt	5.6%	1.8%

The model-based climate scenarios suggest Winthrop NFH may experience relative increases of 26-98% in the flow index during the summer months (June-September; Table 5, Figure 10A) driven by increased water temperatures (hence faster growth) and reduced water availability. Results are presented as relative differences because the index values are based on simulated growth, and are not calibrated to empirical values. Applying these relative increases to the mean flow index over 2003-09 implies that the flow indices will increase from 0.42 to 0.58, 0.50 to 0.98, 0.55 to 0.86 for June, July, and August, respectively, assuming no change in rearing practices. Thus, only in July would the flow index approach the threshold value of 1.0 for this stock at the Winthrop NFH. The density index is also predicted to increase and peak in summer, but overall the relative increases were relatively minor (≤5.1% relative increase) (Table 5, Figure 10B). Both density and flow index integrate fish growth (via temperature), but the larger relative changes predicted for the flow index suggests that decreases in water availability during the summer may be a more significant challenge to rearing spring Chinook salmon in the 2040s than increases in water temperature, per se   Sensitivity analyses confirm this (Figure 11, only summer months are shown).   The contour plots are most easily interpreted by examining the range of potential flow index values that could occur and the relative position of the historical and future (2040's) model-based environmental conditions. High flow index values are in the top left portion of each month's plot, as these represent combinations of reduced water and increased temperature. During June, July, August, and September the future conditions are shifted to the left of the historical values, or in other words they are much closer to the range of higher flow index values (red shading in Figure 11). A much greater relative shift occurs on the horizontal axis (water inflow) relative to the vertical axis (temperature), thus the projected changes in water availability appear to be driving the predicted changes in flow index. Sensitivity analyses and plots for density index were not presented because of the small relative changes predicted in the model-based analysis. In general, these results indicate the facility has physical rearing capacity adequate to accommodate the projected increase in water temperature.

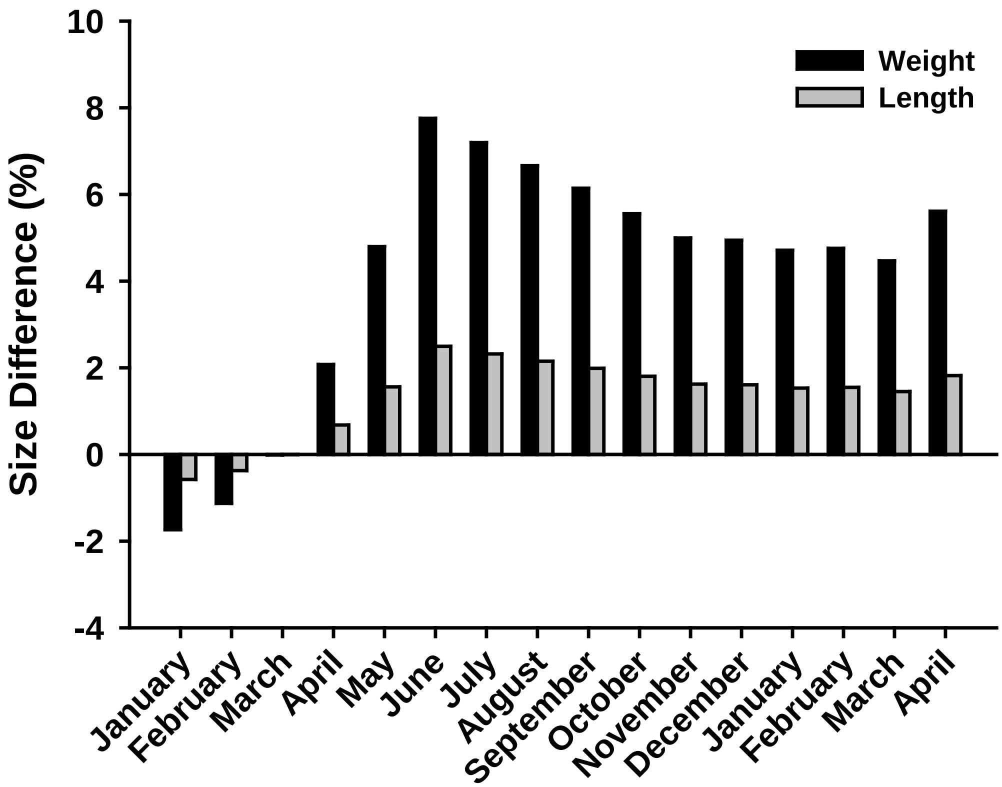


Figure 9: *Cumulative predicted monthly size differences of juvenile spring Chinook salmon reared at Winthrop NFH. Values are the simulated mean differences in weight and length of fish exposed to water temperatures predicted for the 2040s versus fish exposed the 10 year historical baseline (2000 – 2009*

Table 5. Mean input conditions, simulated flow indices (FI) and density indices (DI), and recently observed (empirical) flow and density index values for Chinook salmon at Winthrop NFH.

	Mean values used to initiate simulations						Empirical		Simulated FI [7]		Simulated DI [7]	
Month	Abundance (1000s) [1]	Capacity (1000s ft^3) [2]	Mass per fish (g) [3]	Days	Flow (cfs) [4]	2040s flow (cfs) [5]	Mean FI [6]	Mean DI [6]	Mean	2040s	Mean	2040s
December (1)	752.000	8.526	0.470	31	3.57	3.57	0.27	0.04	0.36	0.36	0.07	0.07
January (1)	741.472	8.526	1.104	31	5.02	5.02	0.33	0.04	0.44	0.44	0.12	0.12
February (1)	731.091	22	1.967	28	5.06	5.06	0.49	0.05	0.64	0.63	0.07	0.07
March (1)	720.856	22	3.363	31	5.06	5.06	0.65	0.07	0.90	0.90	0.09	0.09
April (1)	710.764	22	5.255	30	6.59	6.59	0.77	0.09	0.92	0.93	0.12	0.13
May (1)	700.813	22	7.961	31	12.10	12.10	0.46	0.05	0.65	0.67	0.16	0.17
June (1)	691.002	64.89	11.430	30	14.37	11.14	0.42	0.05	0.69	0.93	0.07	0.07
July (1)	681.328	64.89	16.636	31	14.48	7.67	0.50	0.05	0.86	1.71	0.09	0.09
August (2)	671.789	64.89	23.518	31	14.59	9.83	0.55	0.06	1.07	1.65	0.11	0.11
September (2)	662.384	64.89	31.520	30	24.62	20.38	0.37	0.07	0.76	0.95	0.13	0.13
October (2)	653.111	64.89	39.655	31	24.62	24.62	0.40	0.07	0.87	0.90	0.15	0.15
November (2)	643.967	64.89	46.120	30	23.89	23.89	0.41	0.08	0.98	1.01	0.16	0.17
December (2)	634.952	64.89	51.667	31	23.78	23.78	0.41	0.08	1.05	1.08	0.17	0.18
January (2)	626.063	64.89	56.416	31	23.78	23.78	0.42	0.08	1.10	1.13	0.18	0.19
February (2)	617.298	64.89	60.689	28	23.78	23.78	0.45	0.08	1.14	1.17	0.19	0.19
March (2)	608.656	64.89	67.922	31	23.78	23.78	0.50	0.09	1.21	1.24	0.20	0.20
April (2)	600.134	64.89	77.070	30	23.67	23.67	0.54	0.10	1.30	1.35	0.21	0.22

[1] Abundance based on production target of at least 600,000 smolts and assuming a monthly mortality rate of 1.4% estimated from hatchery data from 2003-2009.
[2] Mean capacity during 2003-2009.
[3] Initial or “seed” fish mass calculated by dividing total fish mass by number of fish in the facility annually from 2000 – 2009; subsequent monthly values are based on growth model and rearing conditions.
[4] Inflow to rearing containers based on monthly means during 2003-2009.

[5] Inflows to rearing containers in 2040s based on incremental adjustments of historical values determined by projected changes in streamflow at the Methow River gage (CIG site 6042; USGS Id: 12448500) Flows based on incremental adjustments under the A1B emissions scenario and an ensemble of GCMs. The calculations assume: (a) a direct correspondence between the gaged river flow and water availability at the hatchery for months where a reduction in flow is projected; and (b) the facility cannot utilize additional water (above the mean historical value) for months where an increase in mean flow is projected.

[6] Mean flow index (FI) and density index (DI) values recorded at the Winthrop NFH during 2003-09.

[7] Simulated mean (historical) and future (2040s) index values based on fish size and mass estimated under the temperature-driven growth model.

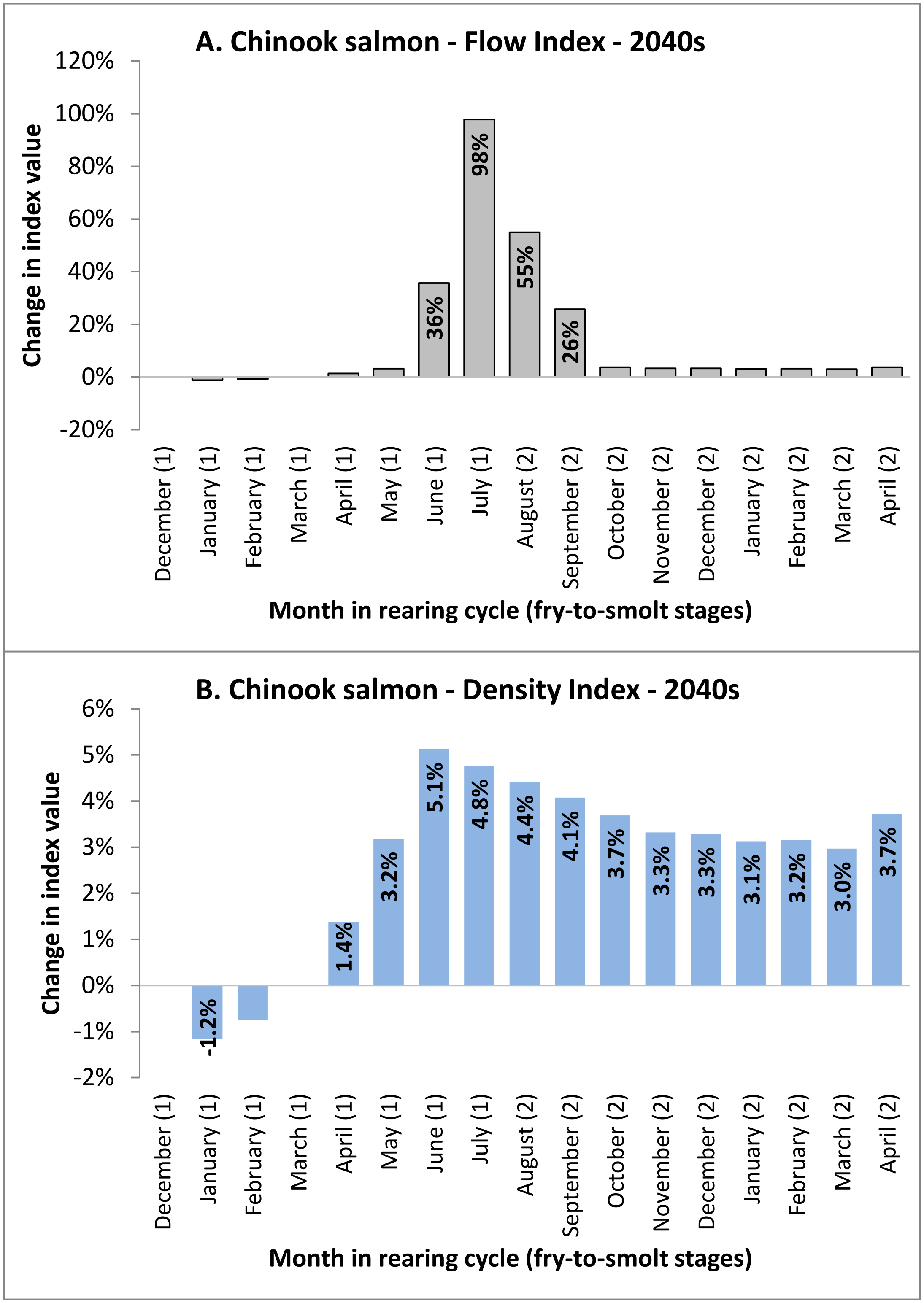


Figure 10. *Predicted changes in flow (A) and density (B) indices for spring Chinook salmon at Winthrop NFH in the 2040s based on statistically downscaled projections for water temperature and stream flow (A1B emissions scenario, environmental variables are ensemble means). Percent changes are relative to the modeled historical average (see Table 5).*

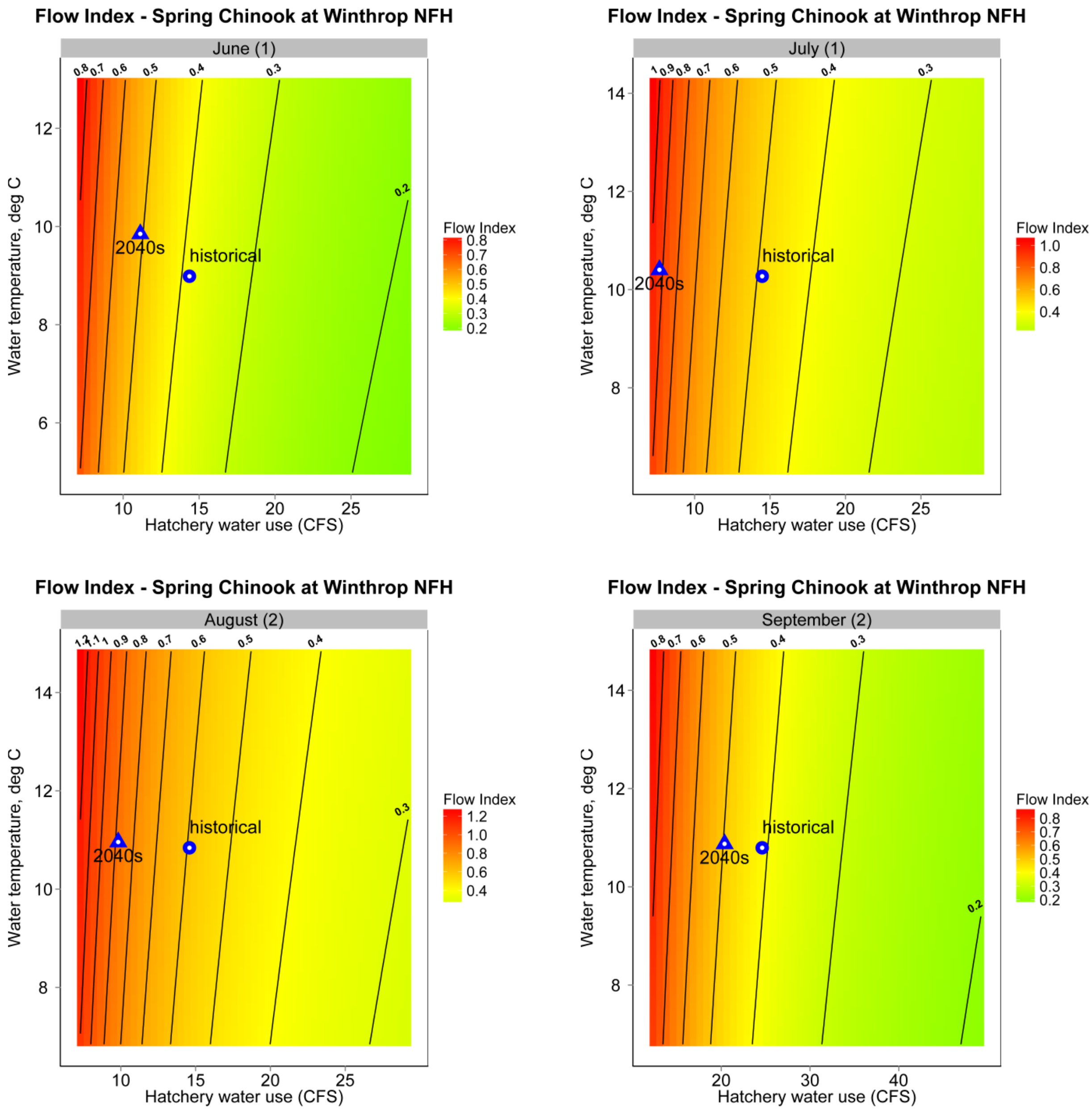


Figure 11. *Predicted flow index for spring Chinook salmon during June-September at Winthrop NFH based on incremental changes in water availability and temperature. Contour lines are 0.1 isopleths. Points represent historical average conditions (circle) and conditions projected for the 2040s (triangle).*

One Year Steelhead Trout Program

During a standard production cycle, adult steelhead are captured between February and May and retained in holding ponds supplied with groundwater until artificial spawning. During this time period, groundwater temperatures in the 2040's are predicted to increase by less than 0.75°C, with the largest increase occurring in May (Table 6, Figure 12). The maximum predicted groundwater temperature during the broodstock holding time period is 9.3°C, well within the range of optimal spawning temperatures (6.4 – 15.3°C) for steelhead as documented in the literature (Table A.1). As such, the predicted climate in 2040 should have a minimal impact on broodstock holding conditions.

Table 6: Mean monthly water temperatures and water sources experienced by juvenile steelhead trout reared for one year at Winthrop NFH based on the 10 year historical baseline (2000 – 2009) and projected values for the 2040s. Water sources are separated into either groundwater (GW) or surface water (SW).

			Rearing Temperature (^{o}C)	
Month	Life-History Stage	Water Source	10 year historical baseline	2040s predicted
February	broodstock	100% GW	7.9	7.9
March	broodstock	100% GW	8.0	8.2
April	broodstock	100% GW	8.2	8.6
May	broodstock	100% GW	8.6	9.3
February (1)	egg/fry	100% GW	7.9	7.9
March (1)	egg/fry	100% GW	8.0	8.2
April (1)	egg/fry	100% GW	8.2	8.6
May (1)	egg/fry	100% GW	8.6	9.3
June (1)	egg/fry	100% GW	9.0	9.9
July (1)	juvenile	100% GW	10.3	10.4
August (2)	juvenile	100% GW	10.8	11.0
September (2)	juvenile	100% GW	10.8	10.9
October (2)	juvenile	100% GW	10.3	10.2
November (2)	juvenile	100% GW	9.4	9.3
December (2)	juvenile	100% GW	8.6	8.4
January (2)	juvenile	100% GW	8.2	8.0
February (2)	juvenile	100% GW	7.9	7.9
March (2)	juvenile	30% GW, 70% SW	6.6	6.6
April (2)	smolt	30% GW, 70% SW	7.8	8.4

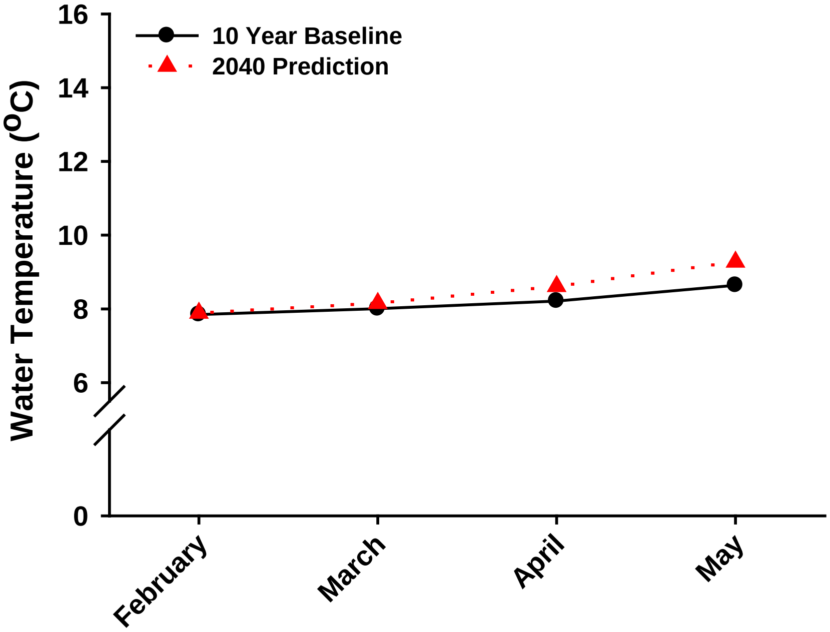


Figure 12: *Comparison of the mean water temperatures experienced by adult steelhead trout broodstock held at Winthrop NFH based on the 10 year historical baseline (2000 – 2009) and projected values for the 2040's.*

Juvenile steelhead will be exposed to altered rearing conditions during the production cycle as a result of the predicted changes in both surface and groundwater in 2040. In general, the thermal environment inhabited by juvenile steelhead in 2040 is predicted to be quite similar to current conditions at the facility with minor increases or decreases of less than 0.25°C in most months (Table 6, Figure 13). The greatest deviations from historical baseline are predicted to occur April (+0.4°C), May (+0.7°C), June (+0.9°C), and at release in the subsequent April (+0.6°C) (Table 6). Across the rearing cycle, water temperatures are not predicted to exceed any physiological thresholds in the 2040's at Winthrop NFH. During the months when steelhead are developing as eggs or fry (February – June), water temperatures are predicted to be within or below the optimal temperature egg and fry development range for this species (Table A.1). The predicted temperatures that steelhead will experience as juveniles between July and April are also within or below the optimal temperature range for this species (Table A.1). At the time of release, the predicted water temperature within the facility in April (8.4°C) is well below the upper limit for proper smoltification at 14°C (Table A.1). As the thermal environment within the hatchery in 2040 is predicted to be similar to the current conditions, water temperatures are not

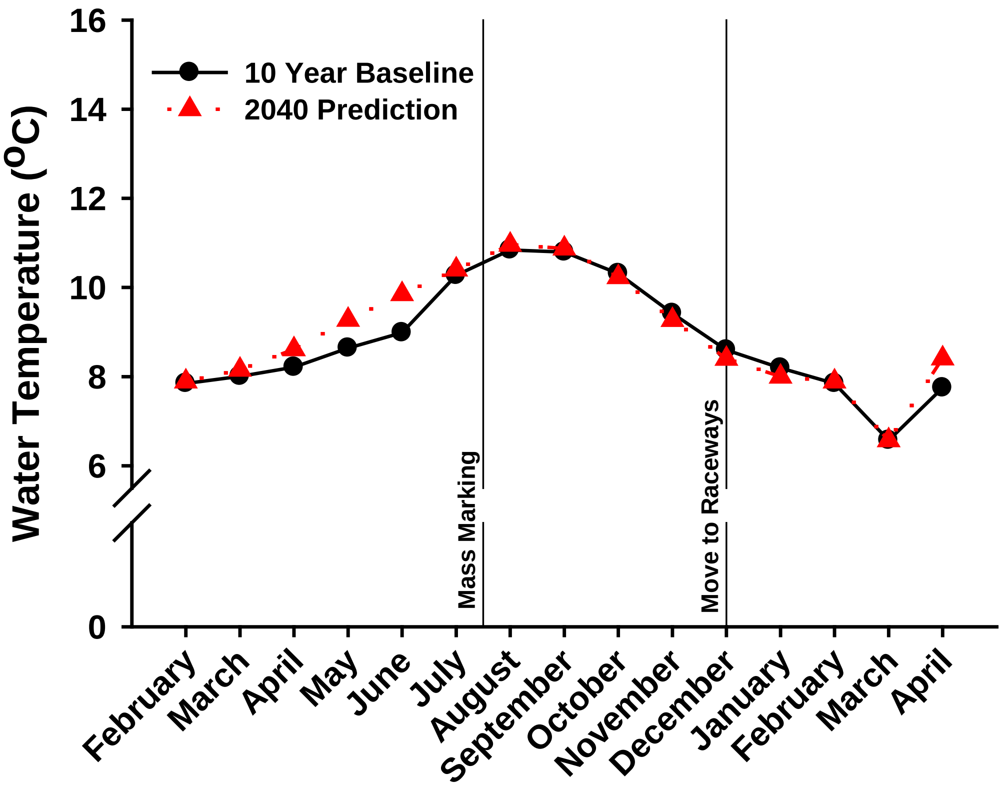


Figure 13: *Comparison of the mean water temperatures experienced by juvenile steelhead trout reared for one year at Winthrop NFH based on the 10 year historical baseline (2000 – 2009) and projected values for the 2040's. The approximate dates of important hatchery events are denoted by labeled vertical lines.*

predicted to rise to within the optimal growth temperature for common salmon pathogens (Table A.2). However, increases in water temperatures approaching 1°C in May and June may increase the risk for disease outbreaks in these months compared to historical trends.

While the predicted temperature changes in the 2040's may not exceed physiological tolerances of steelhead, growth of fish within the facility will change as a result. Juveniles are predicted to experience higher rearing temperatures during the summer months resulting in drastically increased fish sizes when compared to historical averages (Table 7, Figure 14).

Table 7: Monthly size differences of juvenile steelhead trout reared for one year at Winthrop NFH exposed to projected water temperatures for the 2040s relative to fish reared at water temperatures from the 10 year historical baseline (2000 – 2009).

Month	Life-History Stage	Weight (g) difference	Length (mm) difference
April (1)	egg/fry	3.7%	1.2%
May (1)	egg/fry	7.8%	2.5%
June (1)	egg/fry	11.7%	3.7%
July (1)	juvenile	10.2%	3.3%
August (2)	juvenile	9.0%	2.9%
September (2)	juvenile	8.1%	2.6%
October (2)	juvenile	6.7%	2.2%
November (2)	juvenile	5.6%	1.8%
December (2)	juvenile	4.5%	1.5%
January (2)	juvenile	3.6%	1.2%
February (2)	juvenile	3.4%	1.1%
March (2)	juvenile	4.7%	1.5%
April (2)	smolt	5.6%	1.8%

Relative differences in weight and length will be the greatest June and July (Table 7, Figure 14). Though 2040's rearing temperatures are predicted to be lower than historical temperatures from November to January, decreases in growth rates will not be sufficient to compensate for accelerated growth over the summer months (Table 7, Figure 14). Accordingly, due to the altered thermal environment, steelhead smolts released from the facility are predicted to be 5.6% heavier and 1.8% longer than the historical size of fish at release (Table 7, Figure 14).

The model-based climate scenarios suggest the flow index for the one-year steelhead program is predicted to experience a relative increase of 27-102% during the summer and early fall (June-September; Table 8, Figure 15A). Applying these relative increases to the observed

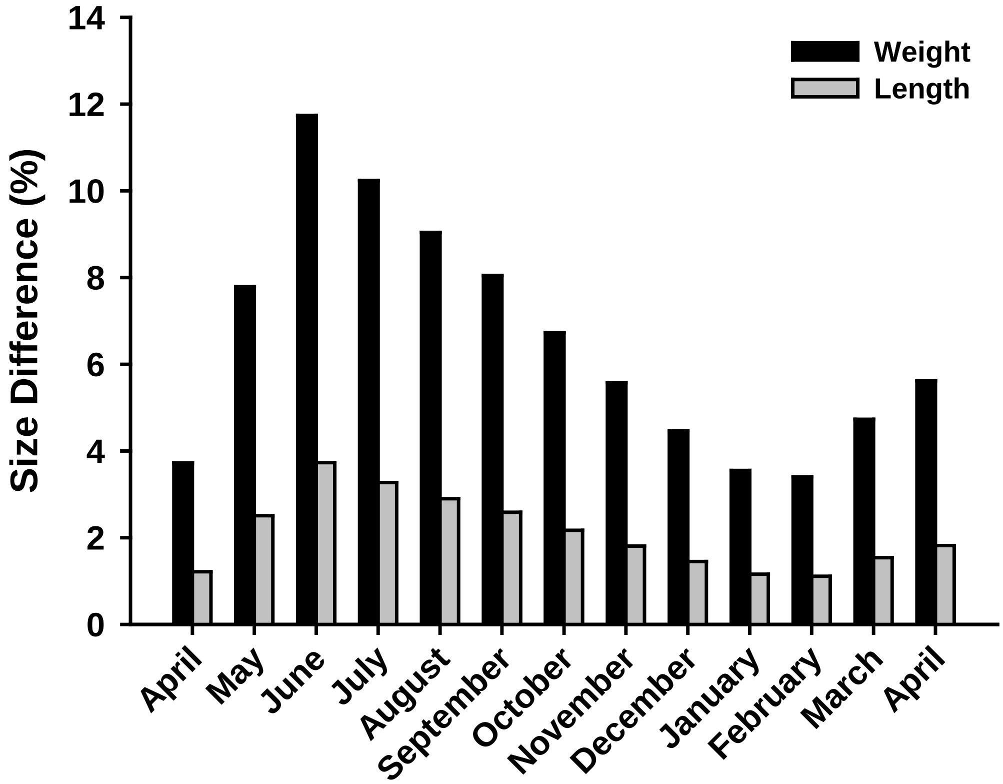


Figure 14: *Monthly size differences of juvenile steelhead trout reared for one year at Winthrop NFH. Values are the simulated mean differences in weight and length of fish exposed to water temperatures predicted for the 2040s versus fish exposed the 10 year historical baseline (2000 – 2009).*

mean flow index values during 2003-09 implies that the flow indices will increase from 0.7 to 0.97, 0.47 to 0.95, 0.54 to 0.85, and 0.63 to 0.80 for June-September, respectively, assuming no change in rearing practices. Small relative increases were predicted the subsequent December-April period (Figure 15A), but the flow index value observed in the hatchery has consistently exceeded the target of 1.0 during those months in the recent past (Table 8). The density index is also predicted to increase and peak in summer, but overall the relative increases were relatively minor (≤7.7% relative increase) (Table 8, Figure 15B). The density index observed in the hatchery has, at times, approached the threshold value of 0.2 near the end of the production cycle.

Sensitivity analysis of flow index values during summer indicates a strong effect of reduced water availability (Figure 16, note shift from right to left between historical and 2040s periods), but the flow index value should still not exceed the threshold value (1.0), on average. The results for the one-year steelhead program should be interpreted cautiously, especially with respect to the empirical observation of flow and index values meeting or exceeding threshold values at or near the end of the rearing cycle. We modeled rearing densities based on the target value of 50,000 smolts, which was less than the actual rearing densities (up to 100,000) present in the hatchery during recent years. Consequently, the modeled flow and density indices were substantially lower than the empirical values. Any changes in growth rate (affected by different rearing densities) could further confound modeled results.

Table 8. Mean input conditions, simulated flow indices (FI) and density indices (DI), and recently observed (empirical) flow and density index values for the one-year steelhead at Winthrop NFH.

	Mean values used to initiate simulations						Empirical		Simulated FI [7]		Simulated DI [7]	
Month	Abundance (1000s) [1]	Capacity (1000s ft^3) [2]	Mass per fish (g) [3]	Days	Flow (cfs) [4]	2040s flow (cfs) [5]	Mean FI [6]	Mean DI [6]	Mean	2040s	Mean	2040s
March (1)	52.500	0.356	0.390	31	0.18	0.18	0.68	0.15	0.44	0.44	0.10	0.10
April (1)	52.307	0.476	0.939	30	0.28	0.28	0.53	0.19	0.50	0.51	0.13	0.14
May (1)	52.115	0.725	1.940	31	0.36	0.36	0.68	0.15	0.63	0.66	0.14	0.15
June (1)	51.923	1.221	3.471	30	0.61	0.47	0.7	0.16	0.55	0.76	0.12	0.13
July (1)	51.733	4.426	6.091	31	1.31	0.69	0.47	0.08	0.37	0.75	0.05	0.05
August (2)	51.543	8.275	9.957	31	2.02	1.36	0.54	0.06	0.33	0.52	0.04	0.04
September (2)	51.353	9.847	14.864	30	2.40	1.99	0.63	0.07	0.36	0.46	0.04	0.04
October (2)	51.165	10.550	20.942	31	2.64	2.64	0.73	0.08	0.42	0.43	0.05	0.05
November (2)	50.977	10.536	27.301	30	2.66	2.66	0.93	0.1	0.49	0.51	0.06	0.06
December (2)	50.789	10.536	34.157	31	2.77	2.77	1.12	0.13	0.55	0.56	0.06	0.07
January (2)	50.603	10.236	41.445	31	2.99	2.99	1.08	0.14	0.57	0.59	0.08	0.08
February (2)	50.417	10.236	48.137	28	2.99	2.99	1.21	0.16	0.63	0.65	0.08	0.08
March (2)	50.232	10.221	53.838	31	3.01	3.01	1.39	0.18	0.67	0.70	0.09	0.09
April (2)	50.047	10.221	62.229	30	3.01	3.01	1.59	0.21	0.74	0.77	0.10	0.10

[1] Abundance based on production target of at least 50,000 smolts and assuming a monthly mortality rate of 0.4% estimated from hatchery data from 2003-2009.

[2] Mean capacity during 2003-2009.

[3] Initial or "seed" fish mass based on calculated by dividing total fish mass by number of fish in the facility annually from 2000 – 2009; subsequent monthly values are based on growth model and rearing conditions.

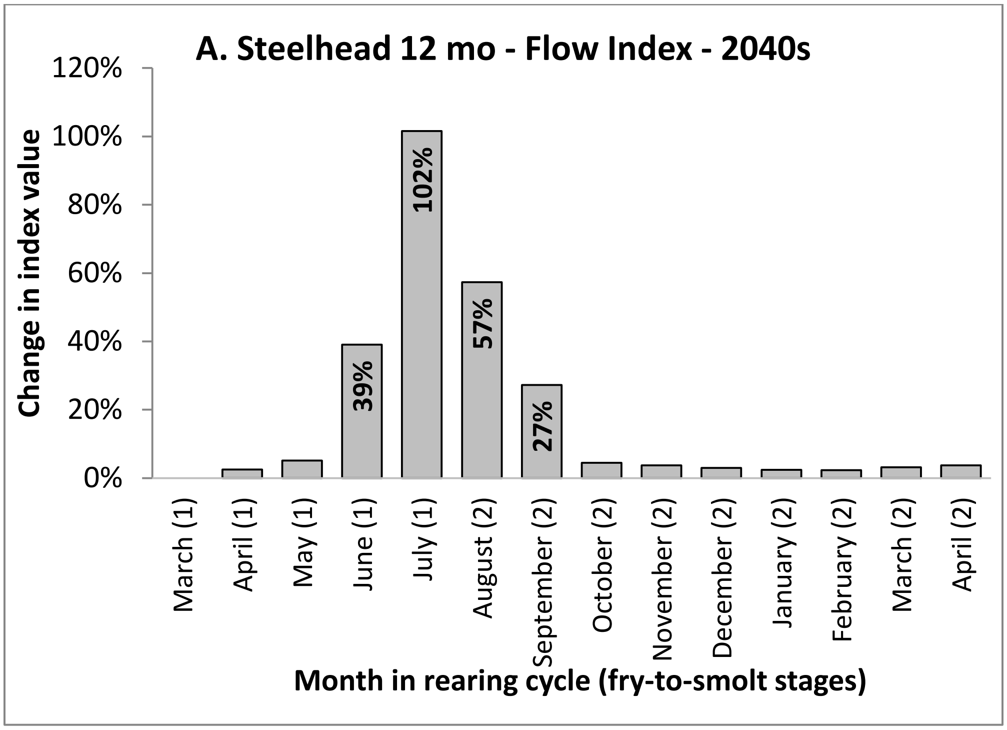
[4] Inflow to rearing containers based on monthly means during 2003-2009.

[5] Inflows to rearing containers in 2040s based on incremental adjustments of historical values determined by projected changes in streamflow at the Methow River gage (CIG site 6042; USGS Id: 12448500) Flows based on incremental adjustments under the A1B emissions scenario and an ensemble of GCMs. The calculations assume: (a) a direct correspondence between the gaged

river flow and water availability at the hatchery for months where a reduction in flow is projected; and (b) the facility cannot utilize additional water (above the mean historical value) for months where an increase in mean flow is projected.

[6] Mean flow index (FI) and density index (DI) values recorded at the Winthrop NFH during 2003-09.

[7] Simulated mean (historical) and future (2040s) index values based on fish size and mass estimated under the temperature-driven growth model.



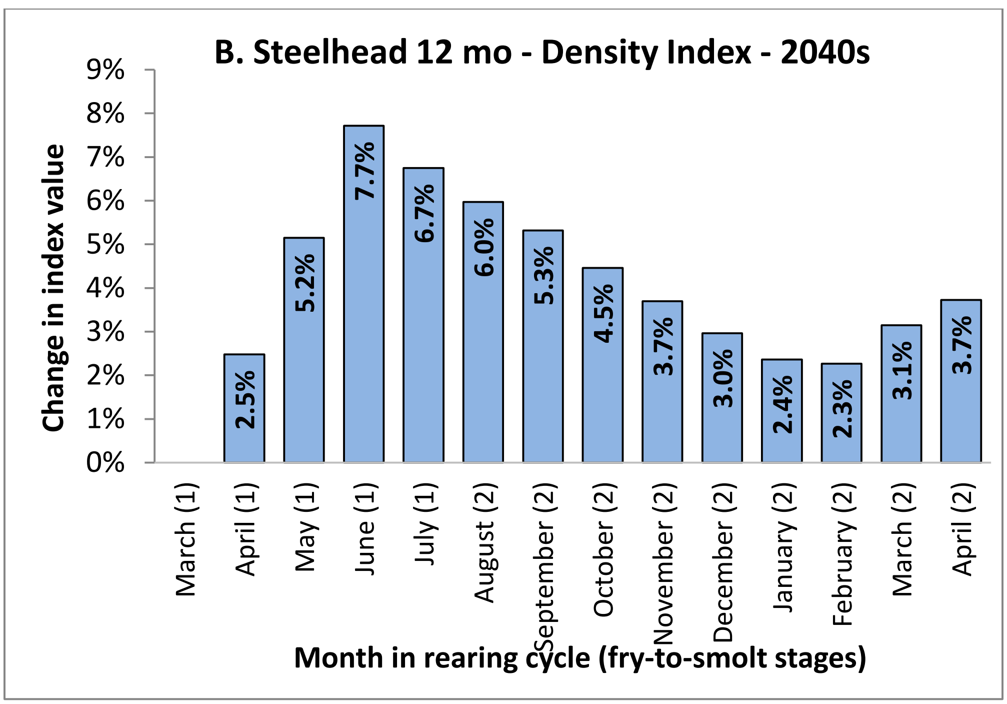


Figure 15. *Predicted changes in flow (A) and density (B) indices for one-year steelhead salmon at Winthrop NFH in the 2040s based on statistically downscaled projections for water temperature and stream flow (A1B emissions scenario, environmental variables are ensemble means). Percent changes are relative to the modeled historical average (see Table 8).*

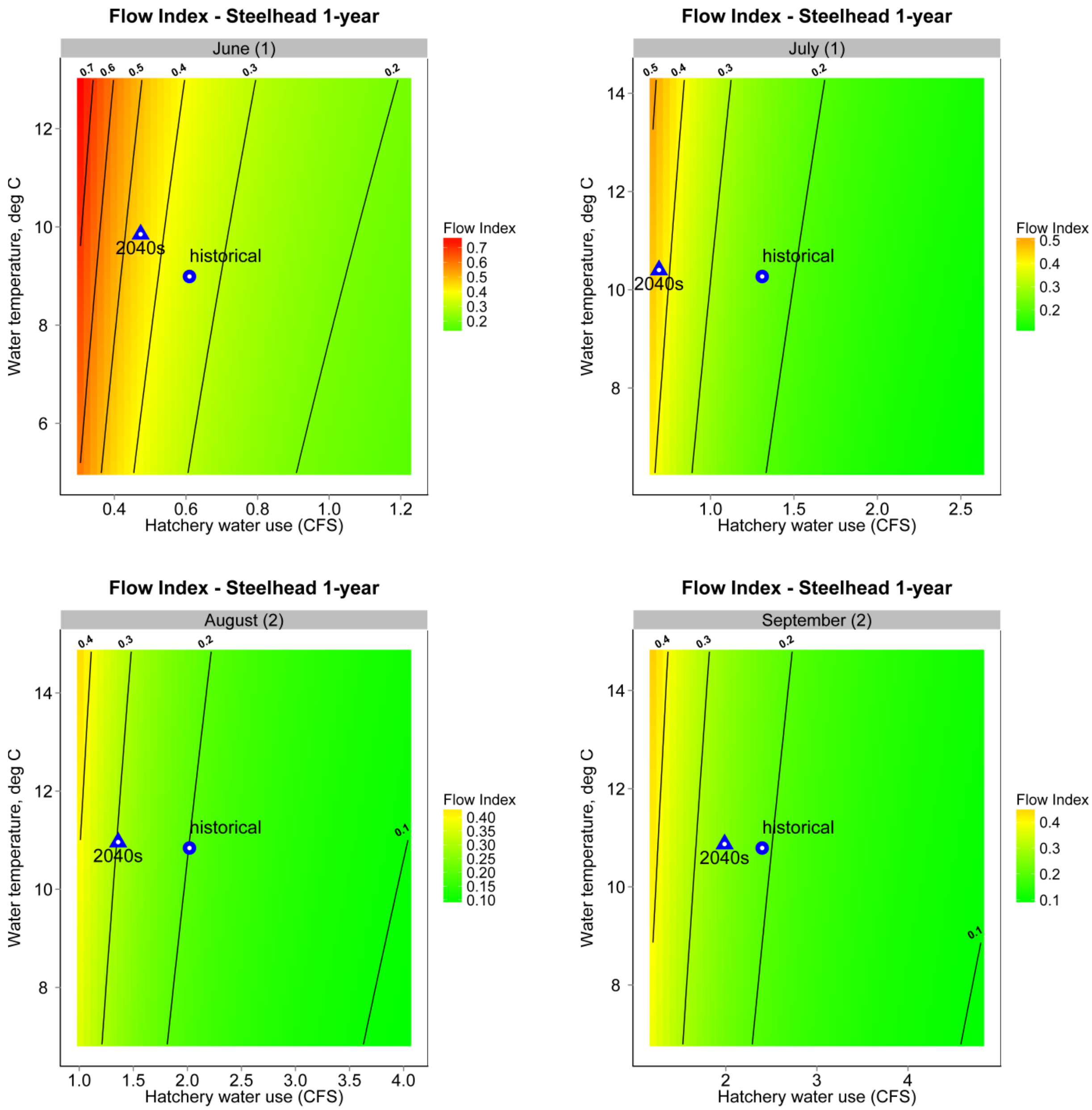


Figure 16. *Predicted flow index for one-year steelhead salmon during June-September at Winthrop NFH based on incremental changes in water availability and temperature. Contour lines are 0.1 isopleths. Points represent historical average conditions (circle) and conditions projected for the 2040s (triangle).*

Two Year Steelhead Trout Program

Broodstock collection for the two year steelhead program occurs as a portion of the broodstock collection for the one year steelhead program, and all of these fish are treated in the same manner.

Juvenile steelhead will be exposed to altered rearing conditions during the production

Table 9: Mean monthly water temperatures and water sources experienced by juvenile steelhead trout reared for two years at Winthrop NFH based on the 10 year historical baseline (2000 – 2009) and projected values for the 2040's. Water sources are separated into either groundwater (GW) or surface water (SW).

			Rearing Temperature (^{o}C)	
Month	Life-History Stage	Water Source	10 year historical baseline	2040s predicted
April	egg/fry	100% GW	8.2	8.6
May (1)	egg/fry	100% GW	8.6	9.3
June (1)	egg/fry	100% GW	9.0	9.9
July (1)	egg/fry	100% GW	10.3	10.4
August (1)	egg/fry	100% GW	10.8	11.0
September (1)	egg/fry	100% GW	10.8	10.9
October (1)	egg/fry	100% GW	10.3	10.2
November (1)	egg/fry	50% GW, 50% SW	7.3	7.2
December (1)	juvenile	50% GW, 50% SW	5.9	6.0
January (1)	juvenile	40% GW, 60% SW	5.1	5.2
February (1)	juvenile	30% GW, 70% SW	5.2	5.3
March (1)	juvenile	30% GW, 70% SW	6.6	6.6
April (1)	juvenile	30% GW, 70% SW	7.8	8.4
May (2)	juvenile	100% GW	8.6	9.3
June (2)	juvenile	100% GW	9.0	9.9
July (2)	juvenile	100% GW	10.3	10.4
August (2)	juvenile	100% GW	10.8	11.0
September (2)	juvenile	100% GW	10.8	10.9
October (2)	juvenile	60% GW, 40% SW	9.5	9.5
November (2)	juvenile	50% GW, 50% SW	7.3	7.2
December (2)	juvenile	50% GW, 50% SW	5.9	6.0
January (2)	juvenile	40% GW, 60% SW	5.1	5.2
February (2)	juvenile	30% GW, 70% SW	5.2	5.3
March (2)	juvenile	30% GW, 70% SW	6.6	6.6
April (2)	smolt	30% GW, 70% SW	7.8	8.4

cycle as a result of the predicted changes in both surface and groundwater in 2040. As steelhead produced in this program are retained within the facility for two years, these fish will experience the altered thermal regime multiple times during rearing. In general, the thermal environment inhabited by juvenile steelhead in 2040 is predicted to be quite similar to current conditions at the facility with minor increases or decreases of less than 0.25°C in most months (Table 9, Figure 17). The greatest deviations from historical baseline are predicted to occur April (+0.4°C), May (+0.7°C), and June (+0.9°C) during both years of the rearing period and at release in the final April (+0.6°C) (Table 9). Across the rearing cycle, the 2040's predicted water temperatures will not exceed any physiological thresholds during the two year rearing period of this program. During the initial February through June when steelhead are developing as eggs or fry, water temperatures are predicted to be within or below the optimal temperature egg and fry development range for this species (Table A.1). The predicted temperatures that steelhead will experience across the remainder of the rearing period are also within or below the optimal temperature range for this species (Table A.1). At the time of release, the predicted water temperature within the facility in April (8.4°C) is well below the upper limit for proper smoltification at 14°C (Table A.1). As the thermal environment within the hatchery in 2040 is predicted to be similar to the current conditions, water temperatures are not predicted to rise to within the optimal growth temperature for common salmon pathogens (Table A.2). However, the risk for disease outbreaks in May and June may increase compared to historical trends as water temperatures are predicted to increase by almost 1°C. Since fish in this program are held through multiple years, the potential for infection and mortality in months with elevated temperatures is greatly increased.

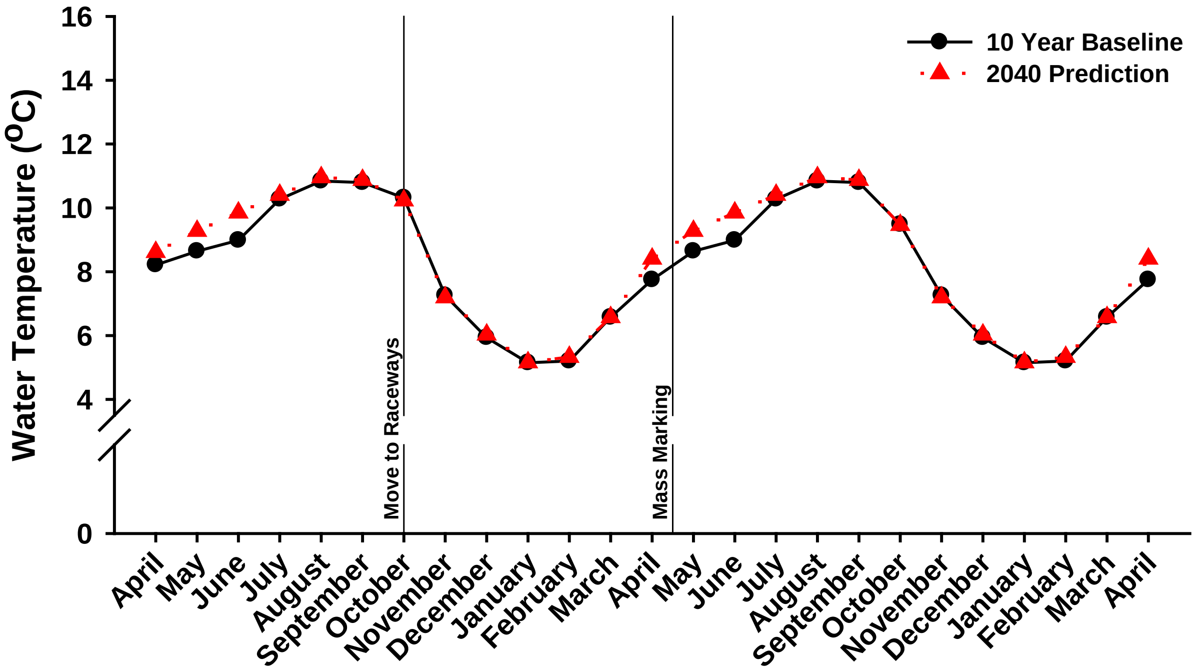


Figure 17: *Comparison of the mean water temperatures experienced by juvenile steelhead trout reared for two years at Winthrop NFH based on the 10 year historical baseline (2000 – 2009) and projected values for the 2040's. The approximate dates of important hatchery events are denoted by labeled vertical lines.*

Alterations to growth rates based upon predicted temperatures will be magnified within steelhead in the two year program due to the duration of time that fish are held at Winthrop NFH. Average juvenile steelhead weight and length in the 2040s is predicted to be greater relative to historical trends in each month across the rearing period (Table 10, Figure 18). Relative differences in weight and length will be the greatest during the first June and July with another spike in size during the second June and July of the rearing cycle (Table 10, Figure 18). Though 2040's rearing temperatures are predicted to be lower than historical temperatures from November to January in both years of rearing, decreases in growth rates will not be sufficient to compensate for accelerated growth over the summer months (Table 10, Figure 18). As such, steelhead smolts released from the facility are predicted to be 6.1% heavier and 2.0% longer than the historical size of fish at release (Table 10, Figure 18).

Table 10: Monthly size differences of juvenile steelhead trout reared for two years at Winthrop NFH exposed to projected water temperatures for the 2040's relative to fish reared at water temperatures from the 10 year historical baseline (2000 – 2009).

Month	Life-History Stage	Weight (g) difference	Length (mm) difference
June (1)	egg/fry	9.1%	2.9%
July (1)	egg/fry	7.6%	2.5%
August (1)	egg/fry	6.6%	2.1%
September (1)	egg/fry	5.8%	1.9%
October (1)	egg/fry	4.5%	1.5%
November (1)	egg/fry	3.8%	1.2%
December (1)	juvenile	3.8%	1.2%
January (1)	juvenile	3.6%	1.2%
February (1)	juvenile	3.7%	1.2%
March (1)	juvenile	3.4%	1.1%
April (1)	juvenile	5.1%	1.7%
May (2)	juvenile	6.4%	2.1%
June (2)	juvenile	8.1%	2.6%
July (2)	juvenile	7.7%	2.5%
August (2)	juvenile	7.3%	2.3%
September (2)	juvenile	6.8%	2.2%
October (2)	juvenile	6.3%	2.0%
November (2)	juvenile	5.8%	1.9%
December (2)	juvenile	5.7%	1.9%
January (2)	juvenile	5.5%	1.8%
February (2)	juvenile	5.5%	1.8%
March (2)	juvenile	5.2%	1.7%
April (2)	smolt	6.1%	2.0%

The model-based climate scenarios suggest the flow index for the two-year steelhead program may experience a relative increase of 25-98% during each of the two summer and early fall cycles (June-September; Table 11, Figure 19A). Applying these relative increases to the observed mean flow index values during 2003-09 implies that the flow indices will increase from 0.37 to 0.51, 0.53 to 1.06, 0.63 to 0.98, and 0.47 to 0.59 for the first June-September, cycle; and 0.73 to 0.99, 0.88 to 1.75, 1.12 to 1.75, and 1.31 to 1.66, for the second June-September cycle assuming no change in rearing practices. Smaller relative increases were in other months (Figure 19A), but the flow index value observed in the hatchery has consistently exceeded the target of 1.0 during August-April in the second year of the rearing cycle (Table 11). The density index is also predicted to increase and peak in summer, but relative increases were relatively minor (≤6.0%; Table 11, Figure 19B). Though the density index observed in the hatchery increases toward the end of the production cycle, the small relative increase predicted under climate change suggest the values, on average, will remain below the 0.2 threshold value.

Sensitivity analysis of flow index values during summer indicates a strong effect of reduced water availability (Figures 20 & 21, note shift from right to between historical and 2040s periods). Temperature also appeared to have an effect in June of both years (Figures 20 & 21, note vertical shift of data point between time periods).

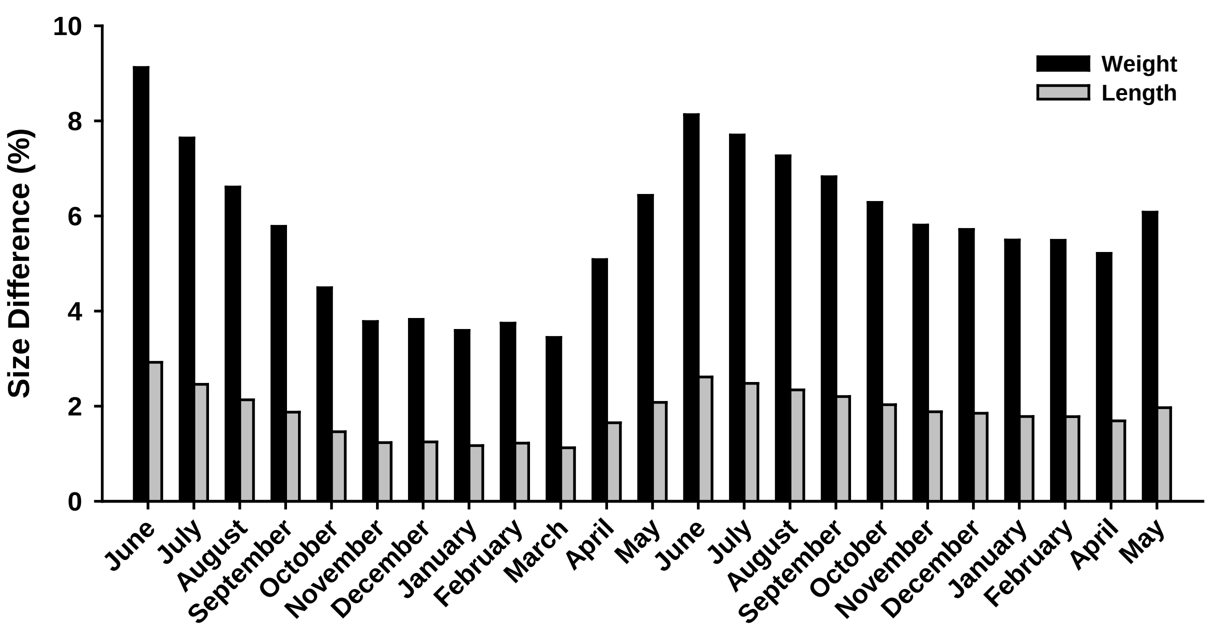


Figure 18: *Monthly size differences of juvenile steelhead trout reared for two years at Winthrop NFH. Values are the simulated mean differences in weight and length of fish exposed to water temperatures predicted for the 2040s versus fish exposed the 10 year historical baseline (2000 – 2009).*

Table 11. Mean input conditions, simulated flow indices (FI) and density indices (DI), and recently observed (empirical) flow and density index values for the two-year steelhead at Winthrop NFH.

	Mean values used to initiate simulations						Empirical		Simulated FI [7]		Simulated DI [7]	
Month	Abundance (1000s) [1]	Capacity (1000s ft^3) [2]	Mass per fish (g) [3]	Days	Flow (cfs) [4]	2040s flow (cfs) [5]	Mean FI [6]	Mean DI [6]	Mean	2040s	Mean	2040s
May (1)	55.000	0.220	0.220	30	0.13	0.13	-	-	0.44	0.44	0.11	0.11
June (1)	54.780	0.220	0.673	31	0.13	0.10	0.37	0.18	0.93	1.27	0.24	0.25
July (1)	54.561	0.356	1.710	30	0.18	0.09	0.53	0.12	1.23	2.43	0.28	0.29
August (1)	54.343	0.653	3.580	31	0.33	0.22	0.63	0.14	1.09	1.69	0.25	0.26
September (1)	54.125	1.510	6.302	31	0.52	0.43	0.47	0.09	1.00	1.25	0.15	0.16
October (1)	53.909	2.683	10.015	30	0.74	0.74	0.50	0.06	0.95	0.98	0.12	0.12
November (1)	53.693	2.650	13.089	31	0.78	0.78	0.50	0.07	1.08	1.10	0.14	0.15
December (1)	53.478	2.650	16.011	30	0.78	0.78	0.51	0.07	1.23	1.26	0.16	0.17
January (1)	53.264	2.650	18.751	31	0.78	0.78	0.54	0.07	1.36	1.39	0.18	0.18
February (1)	53.051	2.650	21.405	31	0.78	0.78	0.60	0.08	1.48	1.52	0.20	0.20
March (1)	52.839	2.650	25.726	28	0.78	0.78	0.65	0.09	1.67	1.71	0.22	0.23
April (1)	52.628	2.650	31.338	31	0.78	0.78	0.81	0.11	1.90	1.96	0.25	0.26
May (2)	52.417	3.533	38.771	30	1.04	1.04	0.73	0.1	1.63	1.70	0.22	0.23
June (2)	52.208	4.417	47.168	31	1.30	1.01	0.73	0.1	1.48	2.02	0.20	0.21
July (2)	51.999	4.417	58.657	30	1.30	0.69	0.88	0.12	1.71	3.39	0.23	0.24
August (2)	51.791	4.417	72.466	31	1.30	0.88	1.12	0.15	1.96	3.05	0.26	0.27
September (2)	51.584	4.417	87.164	31	1.30	1.08	1.31	0.17	2.21	2.79	0.29	0.31
October (2)	51.377	5.300	101.333	30	1.56	1.56	1.06	0.14	2.03	2.12	0.27	0.28
November (2)	51.172	5.300	111.183	31	1.56	1.56	1.04	0.14	2.15	2.24	0.28	0.30
December (2)	50.967	5.300	118.913	30	1.56	1.56	1.05	0.14	2.24	2.33	0.30	0.31
January (2)	50.763	5.300	124.942	31	1.56	1.56	1.02	0.13	2.31	2.39	0.31	0.32
February (2)	50.560	5.300	129.947	31	1.56	1.56	1.11	0.15	2.36	2.45	0.31	0.32
March (2)	50.358	5.300	139.582	28	1.56	1.56	1.25	0.17	2.47	2.55	0.33	0.34
April (2)	50.157	5.300	151.854	31	1.56	1.56	1.40	0.18	2.60	2.71	0.34	0.36

[1] Abundance based on production target of at least 50,000 smolts and assuming a monthly mortality rate of 0.4% estimated from hatchery data from 2003-2009.

[2] Mean capacity during 2003-2009.

[3] Initial or “seed” fish mass based on calculated by dividing total fish mass by number of fish in the facility annually from 2000 – 2009; subsequent monthly values are based on growth model and rearing conditions.

[4] Inflow to rearing containers based on monthly means during 2003-2009.

[5] Inflows to rearing containers in 2040s based on incremental adjustments of historical values determined by projected changes in streamflow at the Methow River gage (CIG site 6042; USGS Id: 12448500) Flows based on incremental adjustments under the A1B emissions scenario and an ensemble of GCMs. The calculations assume: (a) a direct correspondence between the gaged river flow and water availability at the hatchery for months where a reduction in flow is projected; and (b) the facility cannot utilize additional water (above the mean historical value) for months where an increase in mean flow is projected.

[6] Mean flow index (FI) and density index (DI) values recorded at the Winthrop NFH during 2003-09.

[7] Simulated mean (historical) and future (2040s) index values based on fish size and mass estimated under the temperature-driven growth model.

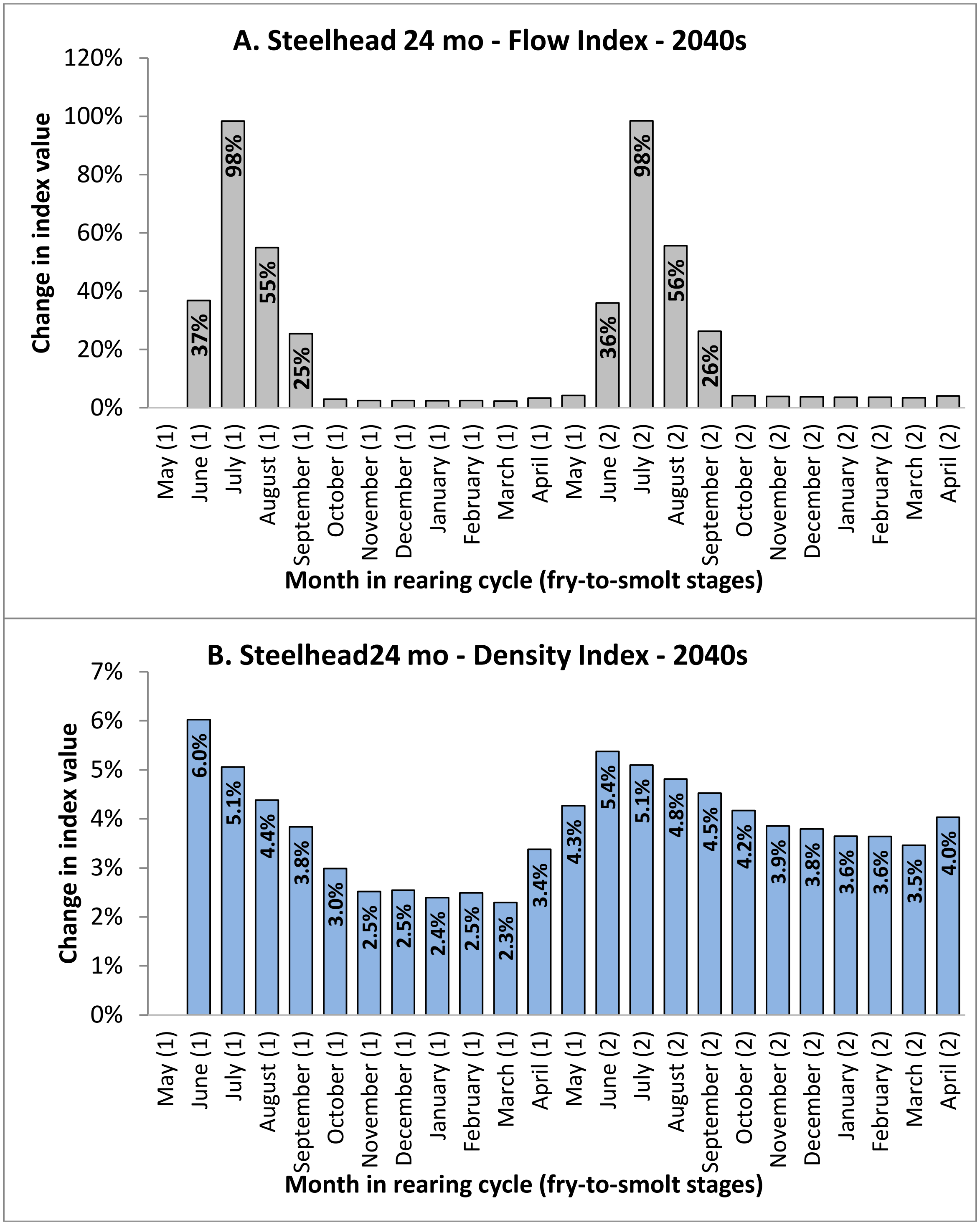


***Figure 19**. Predicted changes in flow (A) density indices (B) two-year steelhead salmon at Winthrop NFH in the 2040s based on statistically downscaled projections for water temperature and stream flow (A1B emissions scenario, environmental variables are ensemble means). Changes are relative to the modeled historical average (see Table 11).*

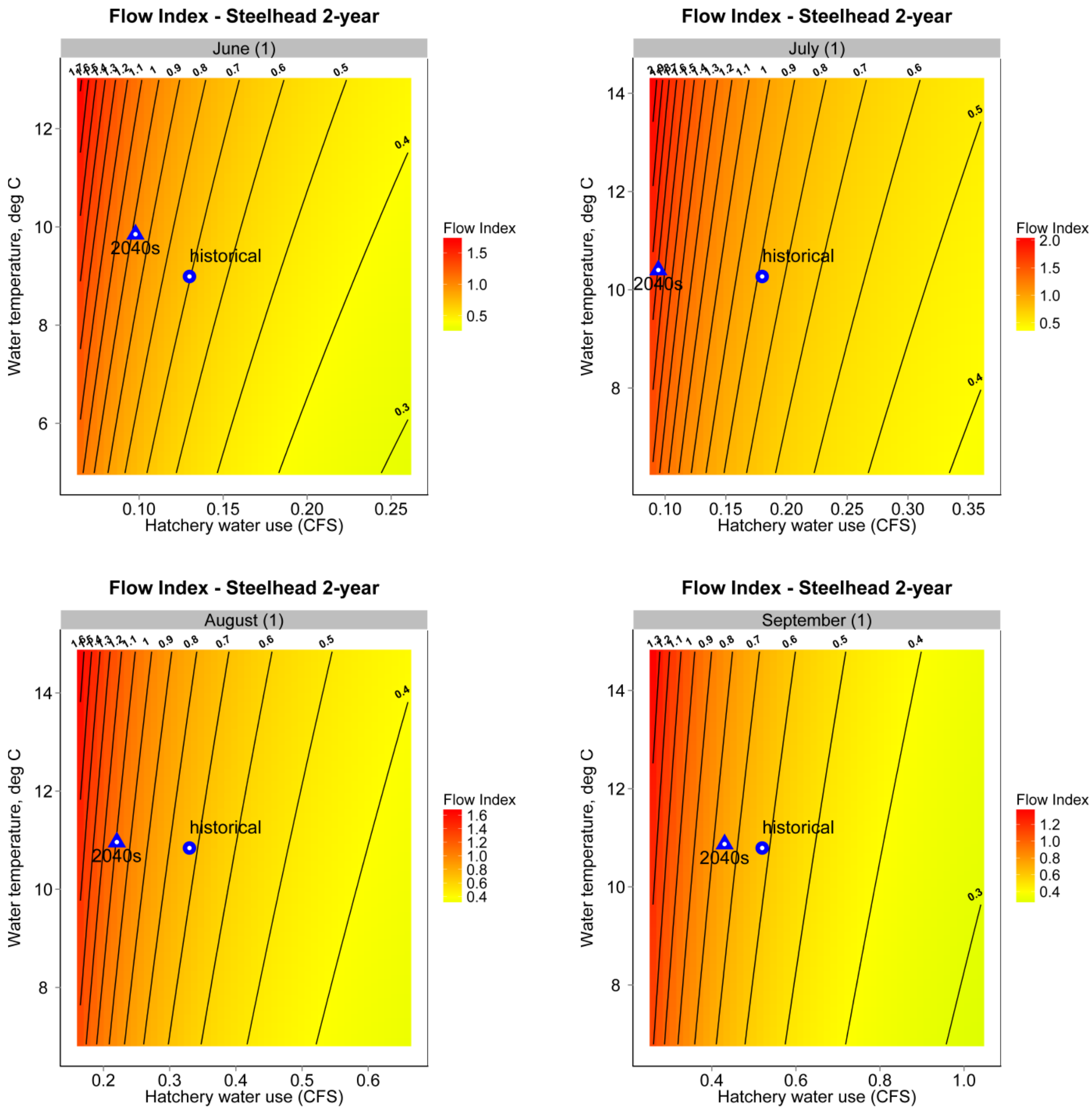


Figure 20. *Predicted flow index in June-September during year 1 of the two-year steelhead salmon rearing cycle based on incremental changes in water availability and temperature. Contour lines are 0.1 isopleths. Points represent historical average conditions (circle) and conditions projected for the 2040s (triangle).*

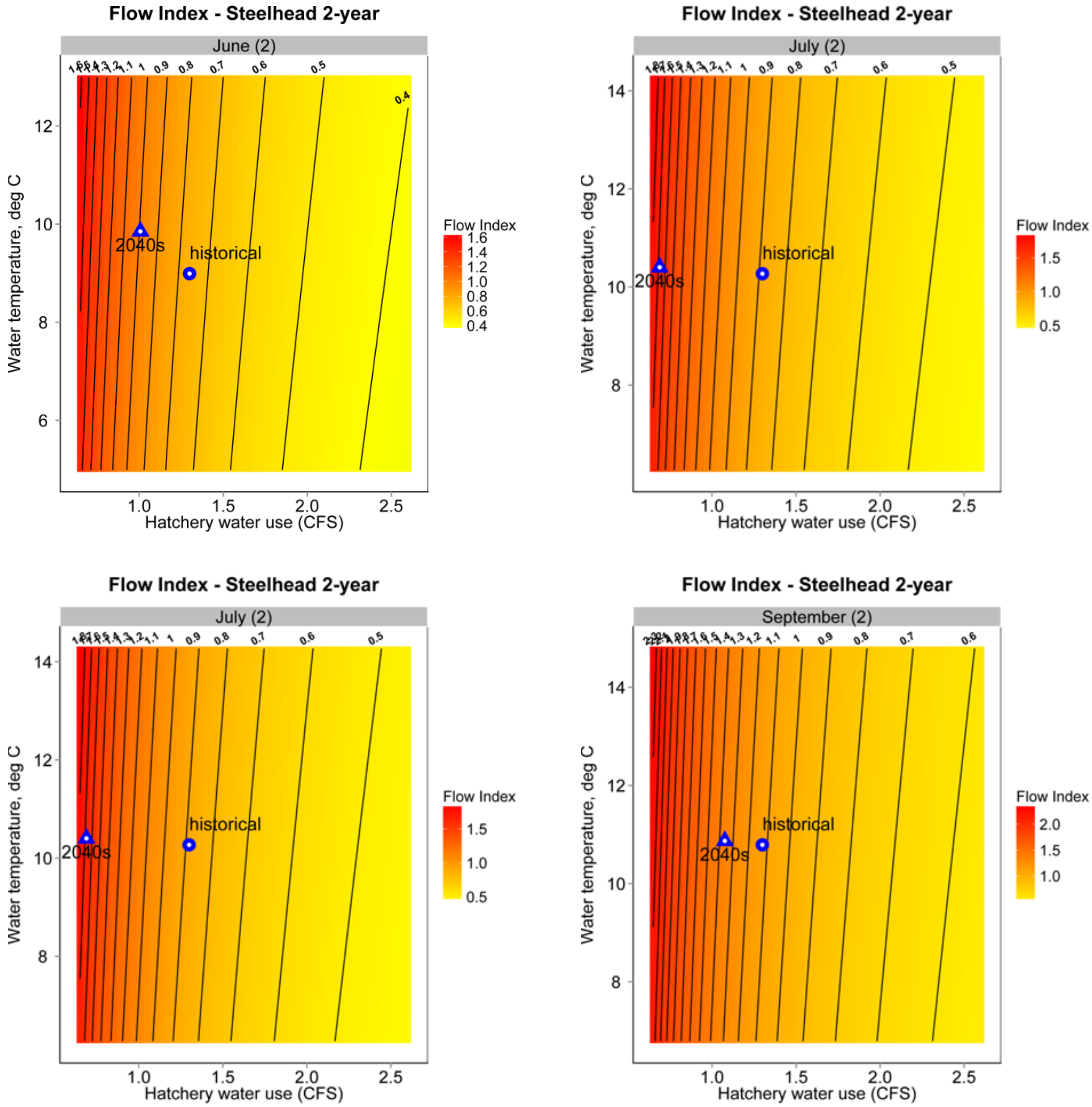


Figure 21. *Predicted flow index in June-September during year 2 of the two-year steelhead salmon rearing cycle based on incremental changes in water availability and temperature. Contour lines are 0.1 isopleths. Points represent historical average conditions (circle) and conditions projected for the 2040s (triangle).*

Coho Salmon Program

During a standard production cycle, adult coho salmon are captured in October and November and retained in holding ponds supplied with groundwater until artificial spawning. During this time period, groundwater temperatures in the 2040's are predicted to increase by less than 0.25°C (Table 12, Figure 22). The maximum predicted groundwater temperature during the broodstock holding time period is 10.2°C which is within the range of optimal spawning temperatures (5.7 – 11.7°C) for coho as documented in the literature (Table A.1). As such, the predicted climate in the 2040s should have a minimal impact on broodstock holding conditions.

Table 12: Mean monthly water temperatures and water sources experienced by juvenile coho salmon reared at Winthrop NFH based on the 10 year historical baseline (2000 – 2009) and projected values for the 2040's. Water sources are separated into either groundwater (GW) or surface water (SW).

			Rearing Temperature (^{o}C)	
Month	Life-History Stage	Water Source	10 year historical baseline	2040s predicted
October	broodstock	100% GW	10.3	10.2
November	broodstock	100% GW	9.4	9.3
October	egg/fry	100% GW	10.3	10.2
November	egg/fry	100% GW	9.4	9.3
December	egg/fry	100% GW	8.6	8.4
January	egg/fry	100% GW	8.2	8.0
February (1)	egg/fry	100% GW	7.9	7.9
March (1)	juvenile	100% GW	8.0	8.2
April (1)	juvenile	100% GW	8.2	8.6
May (2)	juvenile	100% GW	8.6	9.3
June (2)	juvenile	100% GW	9.0	9.9
July (2)	juvenile	100% GW	10.3	10.4
August (2)	juvenile	100% GW	10.8	11.0
September (2)	juvenile	100% GW	10.8	10.9
October (2)	juvenile	50% GW, 50% SW	9.3	9.3
November (2)	juvenile	50% GW, 50% SW	7.3	7.2
December (2)	juvenile	50% GW, 50% SW	5.9	6.0
January (2)	juvenile	40% GW, 60% SW	5.1	5.2
February (2)	juvenile	30% GW, 70% SW	5.2	5.3
March (2)	juvenile	30% GW, 70% SW	6.6	6.6
April (2)	smolt	30% GW, 70% SW	7.8	8.4

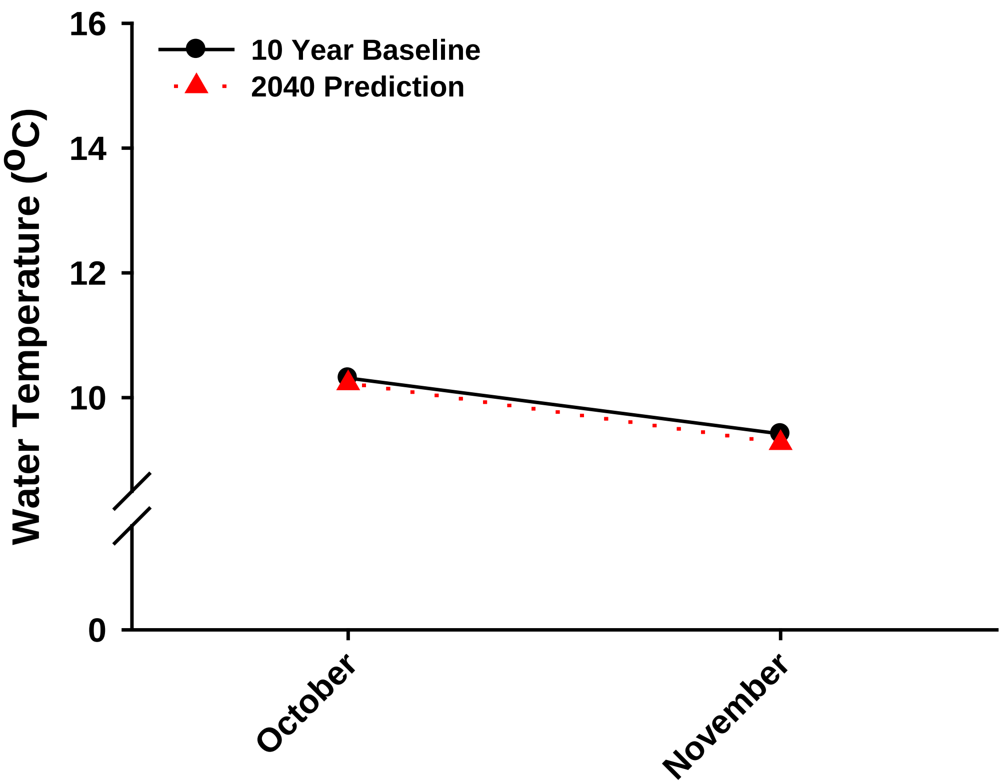


Figure 22: *Comparison of the mean water temperatures experienced by adult coho salmon broodstock held at Winthrop NFH based on the 10 year historical baseline (2000 – 2009) and projected values for the 2040's.*

Juvenile steelhead will be exposed to altered rearing conditions during the production cycle as a result of the predicted changes in both surface and groundwater in 2040. In general, the thermal environment inhabited by juvenile coho in the 2040s is predicted to be quite similar to current conditions at Winthrop NFH with minor increases or decreases of less than 0.25°C in most months (Table 12, Figure 23). The greatest deviations from historical baseline are predicted to occur April (+0.4°C), May (+0.7°C), June (+0.9°C), and at release in the subsequent April (+0.6°C) (Table 12). Across the rearing cycle, water temperatures are not predicted to exceed any physiological thresholds in the 2040's at Winthrop NFH. During the months when coho are developing as eggs or fry (October – February), water temperatures are predicted to be within or below the optimal temperature egg and fry development range for this species (Table A.1). The predicted temperatures that coho will experience as juveniles between March and the April of release are also within or below the optimal temperature range for this species (Table A.1). At the time of release, the predicted water temperature within the facility in April (8.4°C) is well below the upper limit for proper smoltification at 14.3°C (Table A.1). As the thermal environment within the hatchery in 2040 is predicted to be similar to the current conditions, water temperatures are not predicted to rise to within the optimal growth temperature for common salmon pathogens (Table A.2). However, increases in water temperatures approaching 1°C in May and June may increase the risk for disease outbreaks in these months compared to historical trends.

Table 13: Monthly size differences of juvenile coho salmon reared at Winthrop NFH exposed to projected water temperatures for the 2040s relative to fish reared at water temperatures from the 10 year historical baseline (2000 – 2009).

Month	Life-History Stage	Weight (g) difference	Length (mm) difference
March (1)	egg/fry	1.3%	0.4%
April (1)	egg/fry	3.8%	1.2%
May (2)	juvenile	6.9%	2.2%
June (2)	juvenile	10.2%	3.3%
July (2)	juvenile	9.2%	2.9%
August (2)	juvenile	8.3%	2.7%
September (2)	juvenile	7.5%	2.4%
October (2)	juvenile	6.7%	2.2%
November (2)	juvenile	6.0%	1.9%
December (2)	juvenile	5.9%	1.9%
January (2)	juvenile	5.6%	1.8%
February (2)	juvenile	5.6%	1.8%
March (2)	juvenile	5.2%	1.7%
April (2)	smolt	6.4%	2.1%

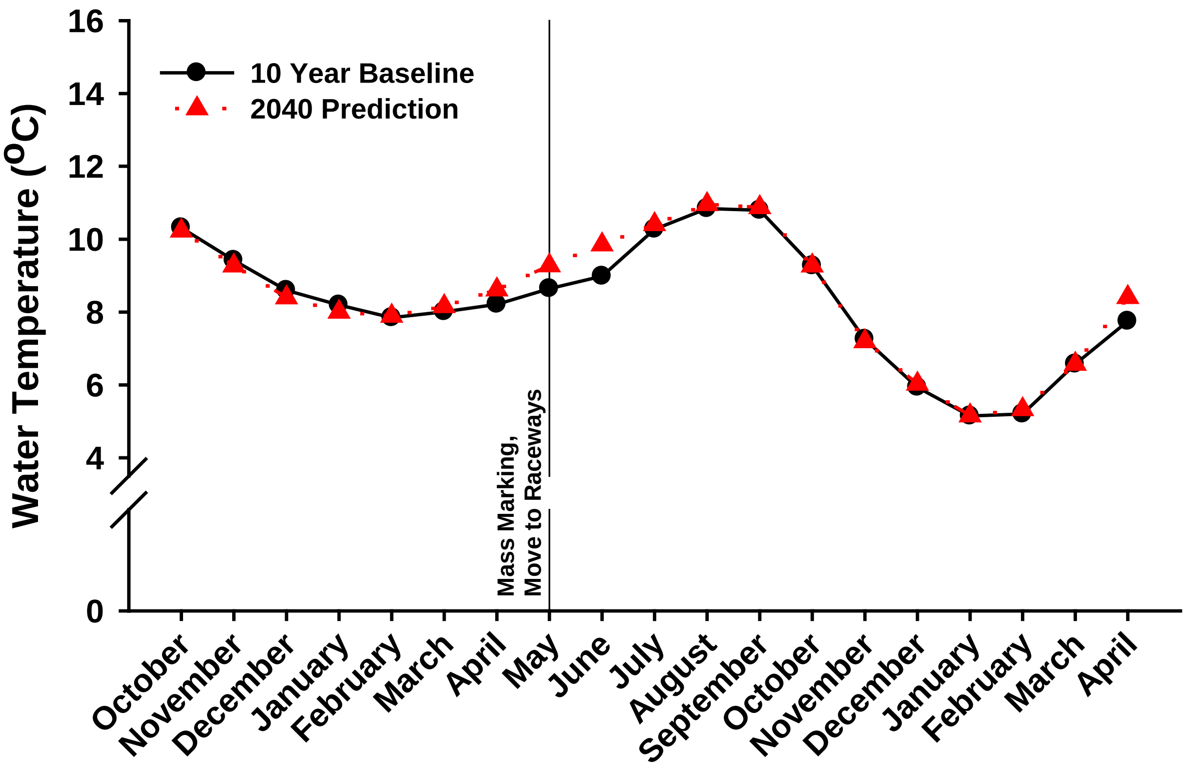


Figure 23: *Comparison of the mean water temperatures experienced by juvenile coho salmon reared at Winthrop NFH based on the 10 year historical baseline (2000 – 2009) and projected values for the 2040's. The approximate dates of important hatchery events are denoted by labeled vertical lines.*

While the predicted temperature changes in the 2040s may not exceed physiological tolerances of coho salmon, fish will grow at a different rate compared to the present. Juveniles are predicted to experience higher rearing temperatures during the summer months resulting in drastically increased fish sizes when compared to historical averages (Table 13, Figure 24). Relative differences in weight and length will be the greatest June and July (Table 13, Figure 24). Though 2040's rearing temperatures are predicted to be lower than historical temperatures from November to January, decreases in growth rates will not be sufficient to compensate for accelerated growth over the summer months (Table 13, Figure 24). Accordingly, due to the altered thermal environment, coho smolts released from the facility are predicted to be 6.4% heavier and 2.1% longer than the historical size of fish at release (Table 13, Figure 24).

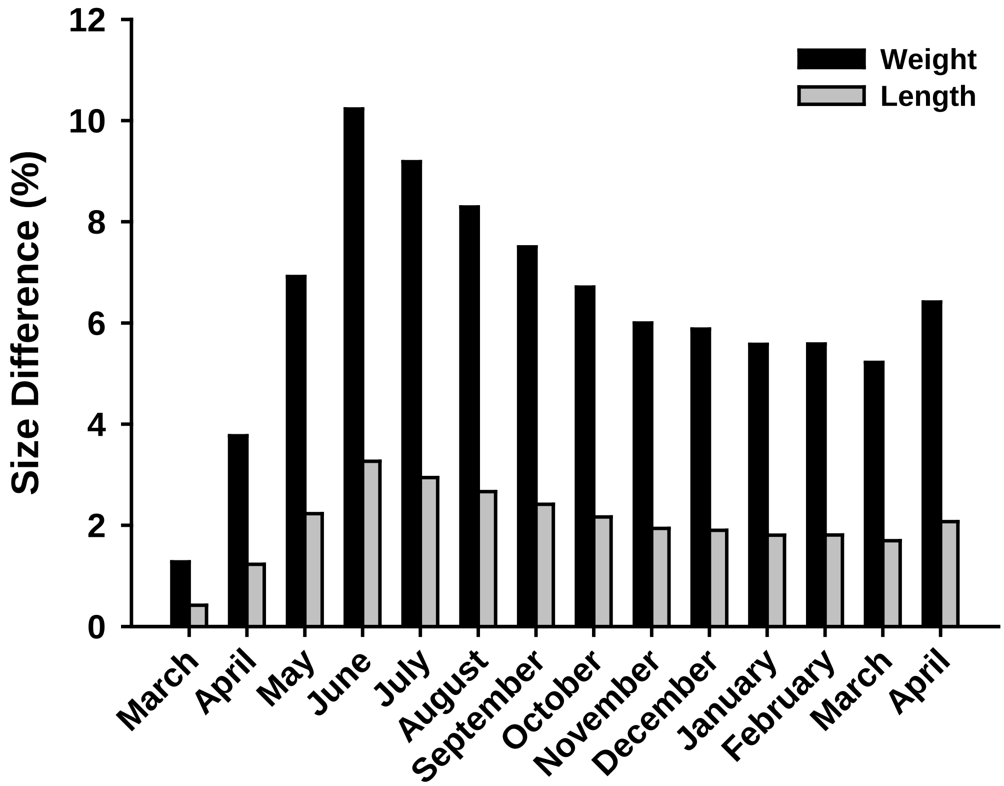


Figure 24: *Monthly size differences of juvenile coho salmon reared at Winthrop NFH. Values are the simulated mean differences in weight and length of fish exposed to water temperatures predicted for the 2040s versus fish exposed to the 10 year historical baseline (2000 – 2009).*

The model-based climate scenarios suggest the flow index for the coho salmon program may experience a relative increase of 27-100% during each of the two summer and early fall cycles (June-September; Table 14, Figure 25A). Applying these relative increases to the observed mean flow index values during 2003-09 implies that the flow indices will increase from 0.70 to 0.97, 0.783 to 1.57, 0.78 to 1.21, and 0.95 to 1.21 during June-September, assuming no change in rearing practices. Smaller relative increases were in other months (Figure 25A), but the flow index value observed in the hatchery have consistently exceeded the target of 1.0 during October-April (Table 14). The density index is also predicted to increase and peak in summer, but overall the relative increases were relatively minor (≤6.7% relative increase) (Table 14, Figure 25B). Though the density index observed in the hatchery increases toward the end of the production cycle (Table 14), the small relative increase predicted under climate change suggest the values, on average, will remain below the 0.2 threshold value.

Sensitivity analysis of flow index values during summer indicates a strong effect of reduced water availability, especially in July and August (Figure 26). Temperature also appeared to have an effect in June (Figure 26).

Table 14. Mean input conditions, simulated flow indices (FI) and density indices (DI), and recently observed (empirical) flow and density index values coho salmon at Winthrop NFH.

	Mean values used to initiate simulations						Empirical		Simulated FI [7]		Simulated DI [7]	
Month	Abundance (1000s) [1]	Capacity (1000s ft^3) [2]	Mass per fish (g) [3]	Days	Flow (cfs) [4]	2040s flow (cfs) [5]	Mean FI [6]	Mean DI [6]	Mean	2040s	Mean	2040s
February (1)	269.000	1.564	0.590	28	0.78	0.78	0.47	0.11	0.67	0.67	0.15	0.15
March (1)	267.599	2.250	1.289	31	1.13	1.13	0.73	0.16	0.79	0.79	0.18	0.18
April (1)	266.206	3.163	2.373	30	1.19	1.19	1.01	0.18	1.11	1.14	0.19	0.19
May (2)	264.819	8.398	4.079	31	2.42	2.42	0.84	0.11	0.78	0.82	0.10	0.11
June (2)	263.440	11.357	6.434	30	3.34	2.59	0.70	0.09	0.77	1.06	0.10	0.11
July (2)	262.068	12.114	10.174	31	3.57	1.89	0.78	0.10	0.97	1.95	0.13	0.14
August (2)	260.703	14.386	15.368	31	4.23	2.85	0.78	0.10	1.07	1.68	0.14	0.15
September (2)	259.346	14.386	21.659	30	4.23	3.50	0.95	0.13	1.34	1.70	0.18	0.19
October (2)	257.995	14.386	28.272	31	4.23	4.23	1.03	0.14	1.60	1.67	0.21	0.22
November (2)	256.652	14.386	33.707	30	4.23	4.23	1.09	0.14	1.79	1.86	0.24	0.25
December (2)	255.315	14.386	38.495	31	4.23	4.23	1.11	0.15	1.94	2.02	0.26	0.27
January (2)	253.985	14.386	42.696	31	4.23	4.23	1.12	0.15	2.07	2.15	0.27	0.28
February (2)	252.663	14.386	46.553	28	4.23	4.23	1.22	0.16	2.19	2.27	0.29	0.30
March (2)	251.347	14.007	52.959	31	4.12	4.12	1.39	0.18	2.43	2.52	0.32	0.33
April (2)	250.038	14.007	61.089	30	4.12	4.12	1.55	0.20	2.66	2.78	0.35	0.37

[1] Abundance based on production target of at least 250,000 smolts and assuming a monthly mortality rate of 0.5% estimated from hatchery data from 2003-2009.

[2] Mean capacity during 2003-2009.

[3] Initial or "seed" fish mass based on calculated by dividing total fish mass by number of fish in the facility annually from 2000 – 2009; subsequent monthly values are based on growth model and rearing conditions.

[4] Inflow to rearing containers based on monthly means during 2003-2009.

[5] Inflows to rearing containers in 2040s based on incremental adjustments of historical values determined by projected changes in streamflow at the Methow River gage (CIG site 6042; USGS Id: 12448500) Flows based on incremental adjustments under the A1B emissions scenario and an ensemble of GCMs. The calculations assume: (a) a direct correspondence between the gaged river flow and water availability at the hatchery for months where a reduction in flow is projected; and (b) the facility cannot utilize additional water (above the mean historical value) for months where an increase in mean flow is projected.

[6] Mean flow index (FI) and density index (DI) values recorded at the Winthrop NFH during 2003-09.

[7] Simulated mean (historical) and future (2040s) index values based on fish size and mass estimated under the temperature-driven growth model.

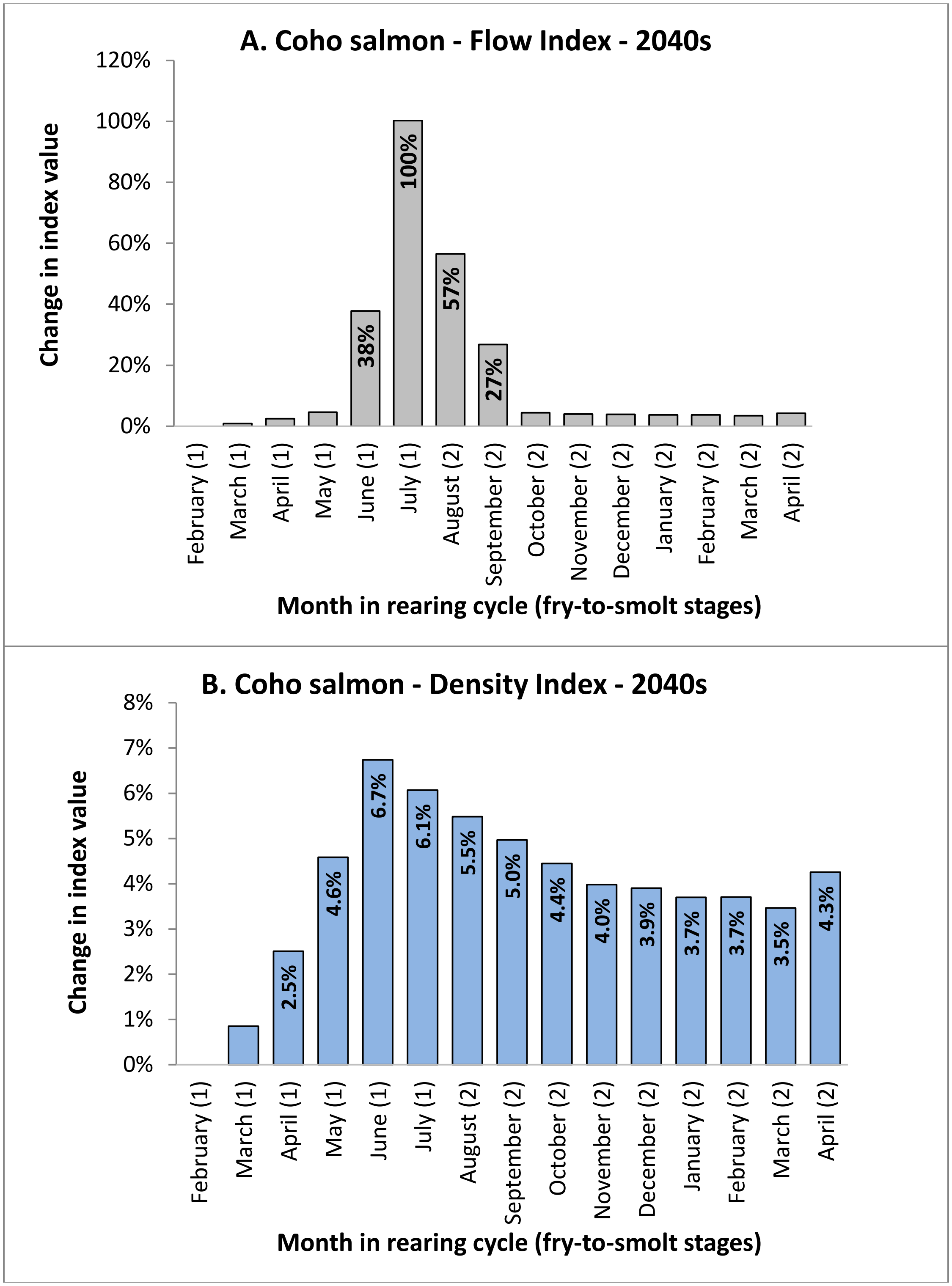


Figure 25. *Predicted changes in flow (A) density (B) indices for coho salmon at Winthrop NFH in the 2040s based on statistically downscaled projections for water temperature and stream flow (A1B emissions scenario, environmental variables are ensemble means). Changes are relative to the modeled historical average (see Table 14).*

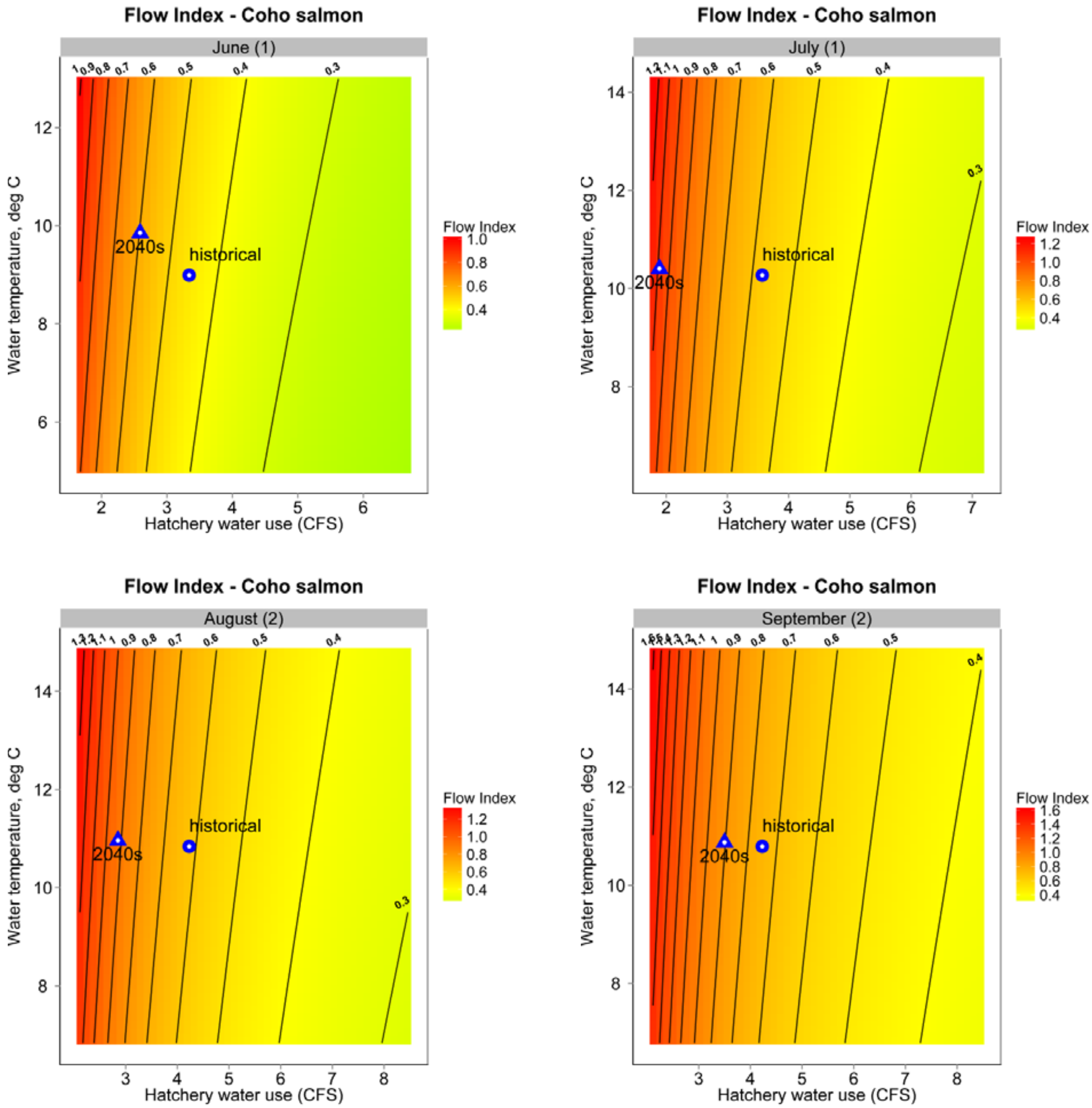


Figure 26. *Predicted flow index during June-September for coho salmon at Winthrop NFH based on incremental changes in water availability and temperature. Contour lines are 0.1 isopleths. Points represent historical average conditions (circle) and conditions projected for the 2040s (triangle).*

Discussion

The overall trends of impacts of predicted climate change upon each program within Winthrop NFH show some consistent patterns for the entire facility. Regardless of fish species, no physiological thresholds are violated, indicating that temperatures that cause physiological dysfunction and lethal temperatures are not likely to occur or impact the ability to use this facility to rear Pacific salmon. However, sub lethal effects in reared fish may occur in the late summer and early fall months of July – September as water temperatures will be highest during this time of year. High water temperatures are inherently stressful to all Pacific salmon, and increased exposure to high temperatures will induce chronic stress, decrease immune function in individual fish, and cause an increased potential for disease outbreaks in the population. Standard hatchery practices that are stressful to fish (e.g., handling, tagging, moving fish between rearing containers) would need to be avoided during periods of high water temperatures as these would function as yet another acute stress on the population. Additionally, increased water temperatures will result in increased growth rates in fish in all programs, thereby leading to altered flow and density indices within the facility.

Higher water temperatures should lead to increased growth in all programs, but the modeling exercises with flow index suggest that decreased water availability during summer months will present a more significant challenge to hatchery managers For the summer months when flow index values are predicted to increase or exceed target values for a program, the change is largely the result of reduced water availability (Figures 11, 16, 20, 21, and 26). Flow index integrates growth and water use, and can be interpreted as a surrogate for carrying capacity that considers dissolved oxygen levels and removal of metabolic waste (Wedenmeyer 2001). The biological result of elevated flow index values could include reduced fish growth and condition; and effects similar to those expected for exposure to high temperatures, such as chronic stress, decreased immune function and higher risk of disease.

For the A1B emissions scenario, projected decreases in summer flow were concordant across models (Figure 1). The general inference that there will be less water in the Methow River during the summer months which could lead to potential problems in the Winthrop NFH seems plausible. We caution however that there are a number of assumptions and uncertainties with the modeling approach and available data that limit our ability to make more precise predictions. First, reductions in water availability at the Winthrop NFH were based on hydrologic conditions projected for a gage on the Methow River downstream from the facility, but for which data were readily available (Figure 1, http://www.hydro.washington.edu/2860/products/sites/?site=6042). In fact, this gage measures discharge for a contributing area of the watershed that is much larger than that which directly influences hydrologic conditions at the hatchery. Given the available data, we must assume that conditions at this gage are and will be representative of conditions at the hatchery. We will be able to reduce this uncertainty by using hydrologic projections routed to stream segments next to the hatchery. Second, the effect of increased mean discharge projected for some winter months has not been explicitly considered in our modeling. We evaluated how less water would affect hatchery programs, and assumed the hatchery would not be able to use so-called additional water in months where the projected flows were greater than historical values. For simplicity, we assumed that the hatchery infrastructure, rearing schedules, or water rights would preclude use of this water. If it could be utilized, then the flow index values for certain (winter) months could be significantly less than we have estimated. However, additional water would be most likely to benefit the hatchery during the summer months, not during the winter. Also, any effects on hatchery operations associated with increased mean discharge (or flooding) have not been considered. For example, reduced water quality in the Methow River during periods of high sediment transport could potentially cause siltation of infiltration galleries or affect other water delivery infrastructure, increasing maintenance costs and influencing fish growth and health. Third, we have modeled incremental changes in water availability at the hatchery. More dramatic fluctuations in water availability are possible, based on consumptive use elsewhere in the Methow River basin and the hierarchy of water rights. Human-caused decreases in discharge would be most likely during periods of low water availability, and when demand for irrigation is high. Our modeling suggests this would be the same time period when the hatchery would also be affected by more modest, incremental declines in water availability. Larger or more abrupt decreases in stream flow would obviously exacerbate any existing problems within the hatchery. Lastly, local hydrologic conditions at the Winthrop NFH are more complex that we were able to represent in the modeling exercise. We did consider (via a lag effect) how surface flow conditions would affect shallow ground water sources used by the hatchery. Our reasoning is logical, but simplistic; better data are needed.

The modeling predictions and inferences notwithstanding, the modeling exercise helped to identify uncertainties that could be investigated to allow a more robust, detailed assessment of climate impacts and facilitate adaptation planning. Three suggestions are: (a) an analysis of water rights in the Methow River basin upstream from the Winthrop hatchery to permit a risk assessment of the human dimensions of potential hydrologic changes; (b) focused study on the shallow groundwater dynamics near the hatchery to better understand surface-ground water interactions and identify surface flow levels that lead to cavitation at the infiltration galleries.

Overall, the impact of future climate change at Winthrop NFH is predicted to be rather benign under the climate scenario and time slice we modeled. We did not explore the consequences of uncertainty in GCM predictions, downscaling methods, or different emissions scenarios. Because of this, the results are best considered as representative of what could happen under one set of future climate conditions, rather than being accurate in an absolute sense. Uncertainties notwithstanding, the approach is clearly useful suggest months when the 'business as usual' paradigm may prove difficult and bottlenecks in the rearing cycle may occur, and identifying information needed to help design robust climate adaptation strategies. Based on the climate scenario we modeled, the maximum change in monthly average temperature of both surface and ground water sources is relatively modest (< 2 °C), indicating that the facility should not become thermally unsuitable for Pacific salmon. However, alterations to the local watershed hydrology may be quite problematic for rearing Pacific salmon. Decreases to summer flows coupled with increased air temperatures in the area may increase the demand for irrigation water removal from the Methow River. Currently, the seniority of the water rights of Winthrop NFH in comparison to upstream users are unknown, so there is the possibility that more senior water users may remove a sufficient quantity of water from the river to impact salmon rearing activities. A more thorough understanding of Winthrop NFH's water rights as well as the volumes of water diverted by more senior water users in the Methow River basin is required to accurately determine the impact of declining summer flows (e.g, Mayer and Strachan 2012).

Multiple mitigation strategies can be potentially used to compensate the anticipated effects of increased water temperatures on fish growth within the facility. Chillers can be used to cool water during the hottest months. Additionally, chillers could be potentially used to slow down the early development of fish to mitigate for accelerated growth during the warmer temperatures of late summer and early fall, thereby compensating for the predicted alterations to flow and density indices within the facility. Feeding regimes can also be altered to constrain fish sizes and growth rates throughout the rearing period. If the above methods were to fail, the number of fish reared in a raceway could be altered to meet target flow and density index constraints, though this may influence whether the facility can meet its production objectives for each program. Longer rearing schedules, especially those of steelhead reared within the facility for two years, may need to be reevaluated. Finally, additional water rights or sources of ground water may need to be secured to ensure sufficient water access for fish rearing activities during the drier months.

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APPENDICES

Table A.1: Thermal tolerances (°C) of species reared at Winthrop NFH

Species	Latin Binomial	Life-History Stage	Optimal Range	Optimal Growth Range	Spawn Range	Smoltification Threshold
Chinook salmon	*O. tshawytscha*	adult	6 – 14°C		9 – 12.3°C	
		egg/fry	8.4 – 12.4°C			
		juvenile	8.6 – 15.9°C	14 – 18.4°C		14°C
Steelhead trout	*O. mykiss*	adult			6.4 – 15.3°C	
		egg/fry	7.4 – 14°C			
		juvenile	13.1 – 17.2°C	11.2 – 18°C		12.6°C
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 A.2: 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