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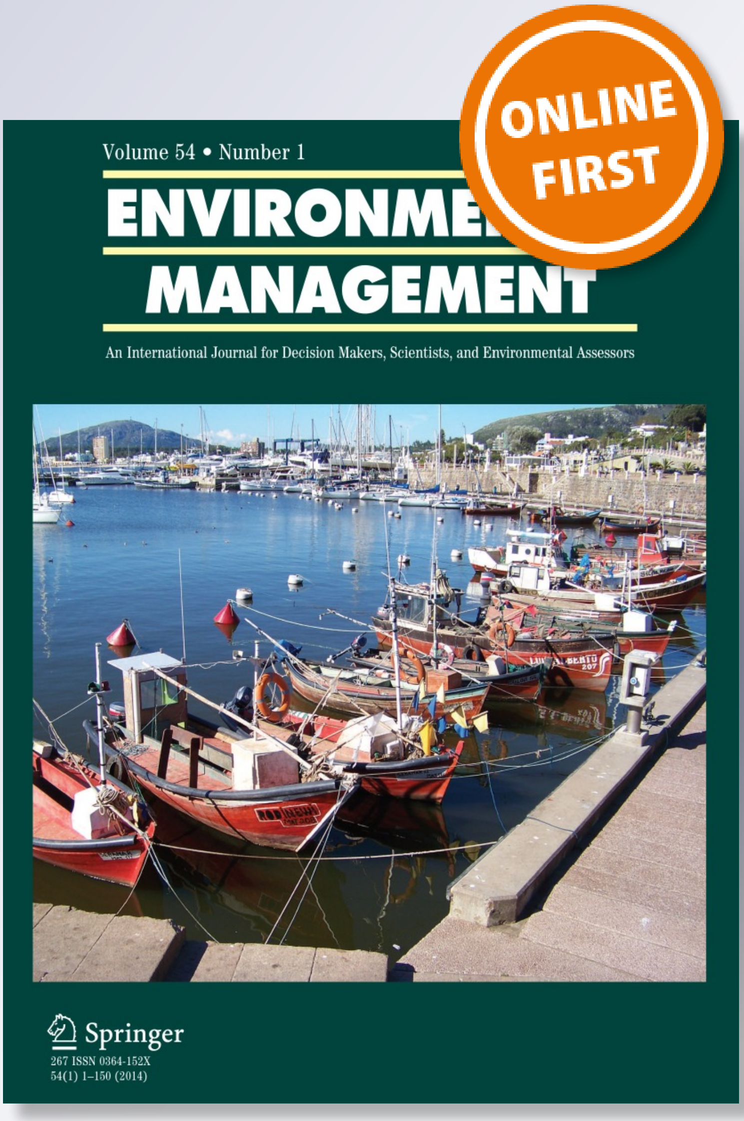
Environmental Management

ISSN 0364-152X

Environmental Management
DOI 10.1007/s00267-014-0302-2



Springer

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Modeling the Potential Impacts of Climate Change on Pacific Salmon Culture Programs: An Example at Winthrop National Fish Hatchery

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Received: 10 May 2013 / Accepted: 26 May 2014

Abstract Hatcheries have long been used in an attempt to mitigate for declines in wild stocks of Pacific salmon (*Oncorhynchus* spp.), though the conservation benefit of hatcheries is a topic of ongoing debate. Irrespective of conservation benefits, a fundamental question is whether hatcheries will be able to function as they have in the past given anticipated future climate conditions. To begin to answer this question, we developed a deterministic modeling framework to evaluate how climate change may affect hatcheries that rear Pacific salmon. The framework considers the physiological tolerances for each species, incorporates a temperature-driven growth model, and uses two metrics commonly monitored by hatchery managers to determine the impacts of changes in water temperature and availability on hatchery rearing conditions. As a case study, we applied the model to the US Fish and Wildlife Service's Winthrop National Fish Hatchery. We projected that hatchery environmental conditions remained within the general physiological tolerances for Chinook salmon in the 2040s (assuming A1B greenhouse gas emissions scenario), but that warmer water temperatures in summer accelerated juvenile salmon growth. Increased growth during summer coincided with periods when water availability should also be lower, thus increasing the likelihood of physiological stress in juvenile salmon. The identification of these climate sensitivities led to a consideration of potential mitigation strategies such as chilling water, altering rations, or modifying rearing cycles. The framework can be refined with new information, but in its present form, it provides a consistent, repeatable method to assess the vulnerability of hatcheries to predicted climate change.

Keywords Vulnerability assessment · Salmon · Hatchery · Thermal stress · Hydrology

Introduction

Pacific salmon (*Oncorhynchus* spp.) are iconic to many peoples around the Pacific Rim. Salmon are spiritually and culturally significant for many indigenous cultures, and salmon fishing has been a fundamental way of life for millennia (National Research Council [NRC] 1996). During the past century, salmon harvest has formed the backbone of large commercial and recreational fisheries that generate millions of dollars of economic activity in the Pacific Northwest of North America (WDFW and ODFW 2002). Unfortunately, many salmon populations declined in the twentieth century due to overfishing and habitat alteration (Nehlsen et al. 1991; National Research Council [NRC] 1996). To compensate for these losses, fisheries managers and agencies have often relied on hatcheries as a technological solution. Part of the appeal is feasibility: hatcheries can quickly produce a large number of fish of desired size and condition through the direct manipulation of rearing conditions such as water temperature, rearing

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Electronic supplementary material The online version of this article (doi:10.1007/s00267-014-0302-2) contains supplementary material, which is available to authorized users.

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densities, rations, and rearing schedules (Piper et al. 1982). Another part of the appeal may be expediency: other approaches, such as large-scale habitat restoration or fishing closures, may be more costly or less politically tenable (Moring 1986; Lichatowich and McIntyre 1987). The conservation benefit of hatcheries and their ecological impacts on wild salmon are a subject of considerable debate (e.g., Waples 1999), but the fact remains that hatcheries have become institutionalized, and their use has led to the development of a system which includes hundreds of state, Tribal, and federal hatcheries in the Pacific Northwest and Alaska which annually release hundreds of millions of juvenile salmon (Moring 1986; Lichatowich and McIntyre 1987). Conservation implications aside, there is a fundamental question that has been largely overlooked until recently (Hanson and Ostrand 2011): will these hatcheries be able to function in the future as they have in the past?

The climate is changing, and trends in water temperature and hydrology are already apparent in western North America (Kaushal et al. 2010; Mantua et al. 2010; Isaak et al. 2011; Leppi et al. 2011). Projected changes should not only affect wild Pacific salmon and their natural freshwater (e.g., Battin et al. 2007; Ruesch et al. 2012) and marine habitats (e.g., Scheuerell and Williams 2005; Fabry et al. 2008), but also the hatcheries which produce salmon in the Pacific Northwest (Hanson and Ostrand 2011). For example, increased stress and mortality of salmon may occur if the thermal tolerances of salmon residing within hatchery facilities are exceeded (Barton and Iwama 1991; Barton 2002). Hydrological changes due to snowpack loss may affect the ability of facilities to acquire sufficient water for rearing or damage infrastructure through increased frequency of flood events (Mantua et al. 2010). Water availability for fish production may also come into increasing competition with other water users as an increasing human population seeks more water for irrigation, hydropower generation, and human consumption (Wood et al. 1997; Payne et al. 2004; Hamlet et al. 2010). Thus, an over-reliance on hatcheries as a mitigation tool may become an even more tenuous proposition under climate change.

Extensive efforts are underway that investigate potential changes to wild salmon populations in response to climate change (e.g., Crozier et al. 2008a, b) and to understand how best to implement habitat restoration in a changing climate (Beechie et al. 2013). In contrast, the impact of climate change on salmon production facilities has been largely unstudied (Hanson and Ostrand 2011), and their future utility as a salmon conservation or mitigation tool in a changed climate is unknown. Given this, our intent was to investigate the in-hatchery portion of the life cycle of propagated salmon to understand how changes in water temperature and availability anticipated under climate change may affect salmon production. This emphasis is based on two premises. First, the freshwater rearing phase of the salmon's life cycle could become a population bottleneck if climatic conditions exceed a species' physiological tolerances, regardless of whether rearing 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, within which managers have the ability to directly design and implement climate mitigation strategies. Public recognition of the effects of climate change on aquatic systems may intensify political and social pressure to conserve salmon, in turn accelerating the implementation of traditional conservation and mitigation techniques such as salmon production hatcheries.

Our goal was to develop a framework to evaluate whether hatchery programs can operate in a "business as usual" paradigm under future climatic conditions. As a case study, we focused on the U.S. Fish and Wildlife Service's (USFWS) Winthrop National Fish Hatchery (WNFH), which is a part of the 15 National Fish Hatcheries operated by the USFWS in the Pacific Northwest, USA. Our specific objectives were to (a) determine if future environmental conditions are likely to preclude rearing of certain stocks, and (b) identify the magnitude and timing of sub-lethal effects that may affect production. To do this, we synthesized physiological tolerance data for various Pacific salmon species, adapted a temperature-driven growth model to predict fish growth, and developed a modeling framework using flow index and density index measures, which integrate the effects of changing temperature and water availability on salmon production (Piper et al. 1982; Wedemeyer 2001). Using empirical data for recent rearing conditions within WNFH, we predicted the future production of each of three salmon stocks by implementing the growth model and modeling flow and density indices based on in-hatchery environmental conditions for the 2040s under one greenhouse gas scenario (A1B) and based on various combinations of temperature and water availability.

Methods

Conceptual Model

Hatcheries can be considered a special type of habitat where the carrying capacity for the fish population is largely influenced by the natural resources—primarily water—legally available to the facility and the infrastructure used to deliver those resources. We sought to model the hatchery environment in terms of whether this environment was limiting for the hatchery population. This approach is analogous to determining if and how spawning, rearing, or marine habitats might limit production of a wild stock.

Our fundamental question was “How will climate change affect onsite hatchery populations of Pacific salmon?”. To structure our thinking, we developed a conceptual model to show how changing climatic conditions would affect the hatchery environment, the resulting effect on the fish, and to identify important variables or metrics with threshold values or endpoints that would represent the biological effects of climate change. At the same time, we wanted to consider the scope for hatchery managers to manipulate this system through modifications to hatchery infrastructure and rearing practices. After consultation with a group of hatchery managers, biologists, and fish health experts who work in federal and tribal hatcheries in the Pacific Northwest, we developed the following conceptual diagram to represent the system we wanted to model (hereafter, conceptual framework; Fig. 1).

In the conceptual framework, climate change will affect the water temperature and hydrology in the local watershed that supplies the hatchery’s water, and changes in the natural environment will be translated to changes in the water quality and quantity available to the hatchery. An initial question was whether climate-forced temperature changes would make the hatchery thermal environment fundamentally unsuitable for Pacific salmon by exceeding salmon physiological tolerances or leading to disease outbreaks. Thus, it was important to identify species-specific temperature preferences for Pacific salmon and their pathogens.

Smaller temperature changes may not result in mortality or disease, but could affect fish growth and size at release. To model this effect, we included a temperature-driven growth model for Pacific salmon in hatcheries following the methods of Iwama and Tautz (1981). To integrate changes in water availability and fish growth, we used two metrics familiar to hatchery managers: flow index and density index. In a general sense, these indices represent carrying capacity during the production cycle (Piper et al. 1982; Wedemeyer 2001). Flow index is a surrogate for carrying capacity based largely on the amount of dissolved oxygen in water and the ability to remove metabolic waste (Wedemeyer 2001), and is calculated from total fish mass, average fish size, and the rate that water enters the rearing habitat (Piper et al. 1982). 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. Fish culturists monitor these two index values throughout the rearing cycle, and each

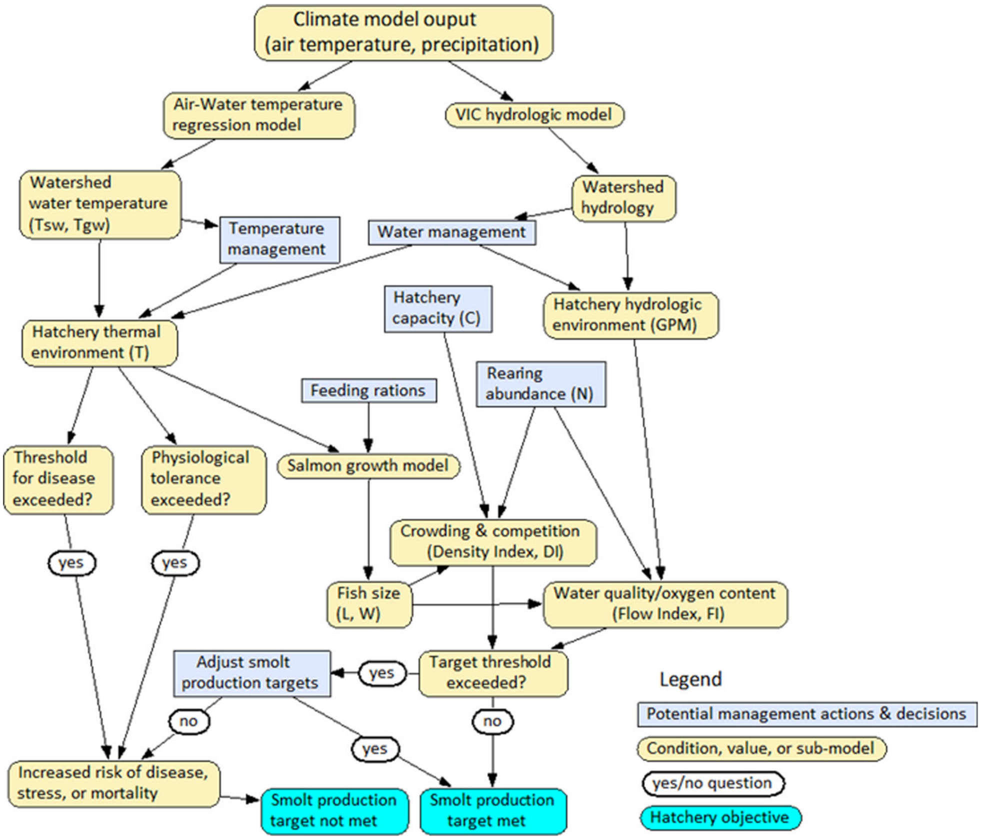

Fig. 1 Conceptual diagram for how changes in water temperature and hydrology caused by climate change might lead to increased risk of disease, stress, or mortality in salmon reared and changes in smolt production in Pacific Northwest hatcheries. The diagram consists of potential management decisions, yes/no questions, ecological relationships, sub-models, values, and indicator variables. Variables that were explicitly modeled have abbreviations in parentheses (e.g., T_{sw}, N, C); see text and Online Resource 2 for variable details

stock is managed to remain below a threshold value above which there is increased risk of disease, stress, or mortality in salmon.

Hatchery managers can change environmental conditions and fish growth within the hatchery by a few mechanisms. They can manage the flow of water (e.g., flow rate, recirculation), alter the water temperature (e.g., heaters/chillers), change the size of rearing containers or rearing densities, and also control rations or diet composition. Other actions are possible, but for simplicity, we only represented these few in our initial model.

Case Study—Winthrop National Fish Hatchery

The WNFH is located on the Methow River at 48.47367°N latitude, 120.18913°W longitude, near the town of Winthrop, WA. The hatchery was initially authorized by the Grand Coulee Fish Maintenance Project in 1937 to produce Pacific salmon for release into the Columbia River Basin, and re-authorized by the Mitchell Act in 1938 (USFWS 2005). Current rearing programs are dedicated to releasing 600,000 spring Chinook salmon smolts (*O. tshawytscha*) and 100,000 summer steelhead trout (*O. mykiss*) smolts annually (USFWS 2005). Additionally, the facility annually produces 250,000 coho salmon smolts (*O. kisutch*) as part of a reintroduction program initiated by the Yakama Nation (USFWS 2005). The WNFH has a water right to 50 cubic feet per second (cfs) from the Methow River, and approximately 25 cfs of groundwater from shallow infiltration galleries adjacent to the Methow River (Mayer and Strachan 2012).

Thermal Tolerances of Pacific Salmon and of Their Common Pathogens

We conducted a literature review to document the likely thermal tolerances of the three species of Pacific salmon reared at WNFH (Online Resource 1). From empirical studies and review papers of fish thermal tolerance, we attempted to extract data on five metrics (after Elliott 1981): optimal temperature, optimal growth temperatures, optimal spawning temperatures, upper smoltification temperature limit, and critical thermal maximum (CTM) or upper incipient lethal temperature (UILT) (see Table 1). For each datum, we recorded the target species, life-history stage, fish length (mean ± SD or range in mm), and fish weight (mean ± SD or range in g). The acclimation temperature, maximum temperature, and test endpoint criterion for CTM or UILT tests were also recorded when available. Thermal tolerance data were organized into life-history stages relevant to hatchery populations of Pacific salmon: (1) egg/fry—eggs, sac fry, and fry (<70 mm length); (2) juvenile—sexually immature fish (>70 mm length); (3) smolt—juvenile salmon migrating to the ocean; and (4) broodstock—sexually mature adult fish that have returned to the facility at the end of their spawning migration. Data were averaged by life-history stage to determine representative thermal tolerances for each species at each stage (Table 2).

We also conducted a literature review to establish the range of temperatures over which common pathogens are known to infect and cause disease in hatchery populations of Pacific salmon. We used a protocol similar to that used to determine fish thermal tolerances (Online Resource 1), and located four citations that gave detailed information on the optimal temperatures for transmission and disease outbreak (Table 3).

Table 1 Definition of thermal metrics influencing reproduction, growth, survival, life-history transition, and pathogen susceptibility in Pacific salmon

Taxa	Temperature metric	Definition
Pacific salmon	Optimal	Temperature range that allows for normal physiological response and behavior without thermal stress symptoms
	Optimal growth	Temperature range that results in the highest growth rates assuming a full ration
	Optimal spawning	Temperature range that results in lowest pre-spawn mortality and the highest fertilization rates and egg survival
	Upper smoltification limit	Minimum temperature at which smoltification is inhibited
	CTM or UILT	Maximum temperature that induces 50 % mortality in the fish previously acclimated to a constant temperature
Pathogens of Pacific salmon	Optimal	Pathogen-specific temperature range for optimal transmission between fish and moderate mortality in Pacific salmon
	Optimal outbreak	Pathogen-specific temperature range corresponding to optimal pathogen growth and virulence coinciding with major mortality in infected Pacific salmon

Thermal Rearing Conditions Within WNFH

Thermal conditions within WNFH during 2000–2009 were estimated from temperature data recorded at the facility's surface and groundwater sources to establish a historical

Table 2 Thermal tolerances (°C) of Pacific salmon species reared at Winthrop National Fish Hatchery based upon previously published information

Species	Life-history stage	Optimal range	Optimal growth range	Spawn range	Upper smoltification limit
Chinook salmon (*O. tshawytscha*)	Adult	6–14		9–12.3	
	Egg/fry	8.4–12.4			
	Juvenile	8.6–15.9	14–18.4		14
Steelhead trout (*O. mykiss*)	Adult			6.4–15.3	
	Egg/fry	7.4–14			
	Juvenile	13.1–17.2	11.2–18		12.6
Coho salmon (*O. kisutch*)	Adult			5.7–11.7	
	Egg/fry	1.7–9.9			
	Juvenile	7.4–15.6	17		14.3

Table 3 Thermal range (°C) at which common salmon pathogens cause disease in Pacific salmon based upon previously published information

Taxa	Name	Optimal growth	Outbreak
Bacteria	Furunculosis—*Aeromonas salmonicida*	20–22	12
	Motile aeromonad disease—*A. hydrophila*, *A. punctata*	20–22	12–14
	Vibriosis—*Vibrio anguillarum*	18–20	14
	Pseudomonad septicemia—*Pseudomonas fluorescens*	20–25	–
	Enteric redmouth disease—*Yersinia ruckeri*	22	11–18
	Columnaris disease—*Flavobacterium columnare*	28–30	15
	Coldwater disease (fin rot)—*F. psychrophilum*	4–10	4–10
	Mycobacteriosis—*Mycobacterium marinum*, *M. fortuitum*	25–35	–
	Nocardiosis—*Nocardia asteroides*	–	37
	Streptococcus septicemia—*Streptococcus* spp.	–	37
	Bacterial kidney disease—*Renibacterium salmoninarum*	–	15
Fungi	Saprolegniasis—*Saprolegnia parasitica*, *Achyla hoferi*, *Dictyuchus* spp.	15–30	–
	Parasitic ichtyobodiasis (costiasis)—*Ichthyobodo necatrix*, *I.pyriformis*	10–25	
	Ichthyophthirius (ich)—*Ichthyophthirius multifiliis*	24–26	12–15
Parasites	Proliferative kidney disease—*Tetracapsuloides bryosalmonae*	16	–
Viruses	Infectious pancreatic necrosis virus (IPNV)—unknown virus	20–23	–
	Infectious hematopoietic necrosis (IHN)	13–18	15

baseline. For WNFH's surface water source, we calculated mean monthly temperatures based on daily mean values recorded at the surface water intake chamber during 2000–2009, and we assumed that these temperature data are representative of conditions in the Methow River adjacent to WNFH. For the groundwater source, we calculated mean monthly temperatures from weekly temperature recordings taken within the facility's infiltration galleries, perforated pipes buried adjacent to the river that collect shallow groundwater (3–5 m depth). Since the thermal environment experienced by hatchery fish during the rearing cycle depends on the blend of surface and groundwater sources that supply each rearing container in each month, thermal rearing conditions experienced by fish were estimated based on average monthly temperatures weighted by the proportion of surface versus groundwater sources used at that time.

Estimated Thermal Conditions in WNFH During the 2040s

To estimate future surface water temperatures in the Methow River near WNFH, we established a regression relationship between recent air and water temperature. We then used air temperatures predicted for the 2040s under a "middle-of-the-road" greenhouse gas emissions scenario to generate water temperature predictions for the 2040s based on the above-mentioned regression model. Weekly air temperature readings from sites within the 1/16th degree latitude × longitude grid cell (48.46875°N latitude, 120.15625°W longitude) containing WNFH were fit to water temperatures recorded at the hatchery's surface water intake during 2001–2010 using the regression model of Mohseni et al. (1998) and following the approach of Mantua et al. (2010). Model fit was estimated by the Nash–Sutcliffe coefficient (NSC) (Nash and Sutcliffe 1970), and we assumed 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 predictions from an ensemble of 10 global circulation models (GCM's)—ccsm3, cgcm3.1_t47, cnrm_cm3, echam5, echo_g, hadcm, hadgem1, ipsl_cm4, miroc_3.2, and pcm1—forced by the A1B emissions scenario (Hamlet et al. 2010). The A1B scenario is often referred to as middle-of-the-road in terms of emissions levels and projected warming, and has been utilized as a reference in a number of studies (e.g., Mantua et al. 2010; Wenger et al. 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 (Intergovernmental Panel on Climate Change [IPCC] 2007), though whether recent emission levels are exceeding those used in the fourth assessment report is a subject of some debate (e.g., Le Quéré et al. 2009; Ganguly et al. 2009; Manning et al. 2010).

To estimate future temperatures for WNFH's groundwater source, we established a regression relationship between surface and groundwater, and applied the expected increase in surface water temperature (as estimated above) to estimate future groundwater temperatures. We regressed mean monthly groundwater temperatures against mean monthly surface water temperatures during 2000–2009 assuming a 1-month lag in groundwater temperature to account for the delay as surface water infiltrated into the shallow local aquifer (Mayer and Strachan 2012). Surface water temperatures and a one-month lag explained 83 % of the variation in groundwater temperatures at WNFH ($P < 0.001$), with temperatures estimated as

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

where T_{GW} is the groundwater temperature (°C) and T_{SW} represents the surface water temperature (°C). Groundwater temperature predictions for the 2040s were generated by applying the above equation to the corresponding surface water temperature predictions for the 2040s, assuming that the linear relationship that exists in the historical baseline would remain under future conditions. Thermal rearing conditions within WNFH during the 2040s were predicted from monthly surface and groundwater temperatures weighted by the relative contribution of each water source during each month of the salmon rearing cycle.

Projected Water Availability at WNFH During the 2040s

To generate estimates for water availability at WNFH under the A1B emissions scenario, we used simulated streamflow data from the variable infiltration capacity (VIC) hydrologic model (Liang et al. 1994). In this instance, we used VIC data forced by output from the same 10 GCM ensemble used to derive water temperatures (e.g., Mantua et al. 2010). Flow data were summarized as mean monthly surface water discharge in the Methow River routed to the location of WNFH (Hamlet, Climate Impacts Group, University of Washington, unpublished data). We assumed that the water available to the hatchery from all sources would change in direct proportion to the change in mean monthly flow estimated by the VIC model for the 2040s because an empirical relationship between actual water availability at WNFH and surface water discharge in the Methow River was not available. The flow of water into the hatchery during the 2040s was estimated by applying the modeled change in mean monthly flow to the average monthly water use during 2003–2009. For example, if the Chinook salmon program uses 15 cfs on average during a hypothetical month, and the hydrologic model predicted that the mean monthly discharge would decline by 40 % in the 2040s, then the estimated water available to the hatchery from all sources would be 9 cfs (15 cfs × 0.60). Additionally, we assumed the facility cannot utilize additional water (above the mean historical value) for months where an increase in mean flow is projected.

Temperature-Based Growth Model for Hatchery-Reared Pacific Salmon

We used the fish growth model of Iwama and Tautz (1981) to estimate how the growth of hatchery-reared Pacific salmon might change in response to climate warming. This model has been widely applied to evaluate growth of captive salmonids (Dumas et al. 2007; Good et al. 2009; Jobling 2010), and we used it here to estimate fish size as a function of water temperature assuming unlimited ration. We solved the equation to estimate mean fish weight at time step i (W_i) as

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

where W_0 is the initial weight (g), and T_i and d_i are the average temperature and number of days in time step

i. Iwama and Tautz (1981) analyzed growth data for three species of salmonid and proposed that $b = 0.33$ provided a reasonable approximation that balanced model accuracy and simplicity, and we applied that exponent in our analyses.

To estimate mean fish length (L_i) by time step, we rearranged an equation for Fulton-type fish condition factor (Anderson and Gutreuter 1983) to solve for fish fork length (L_i in mm) as

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

where K is the condition factor which was held constant at 1 to represent fish in a healthy condition.

We applied the growth model to estimate monthly fish sizes of Pacific salmon after ponding. The initial weight at ponding (when fish are transferred to outdoor raceways for rearing) was the input for the first month in the growth simulation, and subsequent months were initialized using the predicted final weight of the fish from the preceding month. The growth model was implemented with hatchery thermal environments consistent with recent historical conditions and those projected for the 2040s, and we compared cumulative differences in size between those thermal regimes (Online Resource 2).

Integrating the Effect of Water Temperature, Water Availability, and Rearing Capacity on Hatchery Operations

Hatcheries typically operate to achieve a production target, while remaining below flow and density index values identified as thresholds based on empirical observations of fish disease, mortality, or poor growth. These indices essentially function as general rules of thumb based on oxygen saturation for different water temperatures and elevations (e.g., Piper et al. 1982), and act as a surrogate for carrying capacity within the facility. Conceptually, these indices are the total fish mass divided by the product of the mean fish length by water use (flow index) or by rearing capacity (density index)

$$FI_i = \frac{N_i \cdot W_i}{L_i \cdot GPM_i} \text{ and } DI_i = \frac{N_i \cdot W_i}{L_i \cdot C_i},$$

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

We utilized these indices to integrate the effect of changing water temperatures, water availability, and rearing capacity, and more generally as surrogates for carrying capacity under historical and future conditions using two approaches to represent variation in climate and rearing conditions. First, we used both recent historical conditions and climate model output for the 2040s to drive the salmon growth model and to simulate flow and density indices for each stock in each monthly time step after initial ponding. This produced two monthly values for each index at each time step (modeled historical and modeled future values). The modeled historical and empirical FI_i and DI_i values recorded in the hatchery could differ because of real-time changes implemented by hatchery managers, such as reducing feed rations or increasing hatchery water use in response to environmental conditions. We could not explicitly represent these factors in the analyses, so we adjusted the future simulated values based on the ratio between the empirical and modeled historical values (rFI_i and rDI_i) as

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

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

Thus, the future bias-corrected index values were

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

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

A complete description of the model formulation and underlying equations used for the case study analysis are presented in Online Resource 2.

Second, we conducted a sensitivity analysis to examine how the flow and density indices changed based on incremental changes in temperature and water availability. For the flow index, we plotted monthly index values based on combinations of water temperature (100 increments covering historical mean temperature ±4 °C) and water use (50 increments ranging from 40 to 150 % of historical mean water utilization in cfs) to generate a monthly response surface of 5,000 points. We did the same for the density index but used incremental changes in capacity (50 increments ranging from 50 to 200 % the historical mean). The generating equations for the sensitivity analyses are those for FI_i and DI_i presented above, with the appropriate substitutions for temperature and fish size (Online Resource 2). To focus on times when environmental conditions are most likely to stress Pacific salmon and thus be of significant interest to hatchery managers, we generally limited the presentation of results for each species to months where large (>20 %) relative changes in index values were predicted.

Results

Projected Future Climate at Winthrop NFH

Under the A1B emissions scenario, the Methow River basin is projected to experience warmer air temperatures, reduced snowpack, earlier snowmelt runoff, and lower summer baseflows by the 2040s (Figs. 2, 3; Online Resource 3). Mean monthly air temperature is expected to increase in every month, with the largest absolute increases predicted for June–September. Overall, the mean increase across months is 2.07 °C (SD = 0.54). Total annual precipitation is expected to be similar to current conditions, but the fraction that falls as snow and forms winter snowpack is expected to decline (Online Resource 3), and snow levels should rise in elevation as air temperatures increase resulting in a shift from a snowmelt to the so-called transitional or rain-driven basin (Mantua et al. 2010). Changes in runoff, average flow, winter floods, and summer drought severity are also anticipated for the Methow River basin upstream from the WNFH (Online Resource 3). Based on the VIC modeling, spring snowmelt runoff will occur earlier in the year at WNFH (Fig. 2), and there will be changes in the magnitude of flows in particular seasons. Flows in the Methow River at WNFH are predicted to increase during October through May, with the largest increases (68–105 %) predicted to occur from December through March (Fig. 2). Conversely, summer flows are predicted to decline 19–51 % (Fig. 2).

Surface water temperatures in the Methow River near WNFH are projected to increase by less than 1 °C across all months compared to a recent 10-year empirical average, but with substantial variation between months (Fig. 3a). Changes in groundwater temperatures track those of surface water, but the changes are smaller in magnitude. For example, May and June groundwater temperatures will increase by 0.7 and 0.9 °C (Fig. 3b). The hatchery thermal environment, which is a blend of surface and groundwater sources, is thus expected to change in response to warming in the Methow River basin.

Spring Chinook Salmon Program

Adult Chinook salmon are captured between May and September and retained in holding ponds supplied with groundwater until spawning. By the 2040s, average predicted groundwater temperatures should remain well within the optimal temperature range for spawning (Table 2; Fig. 4). In general, the average hatchery thermal environment in the 2040s is not predicted to exceed thermal

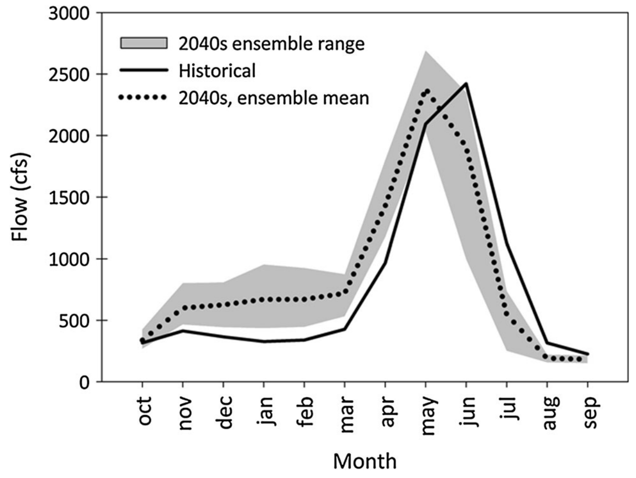

Fig. 2 Mean monthly surface flow in the Methow River adjacent to the Winthrop National Fish Hatchery based on raw VIC simulations. Projected (2040s) surface flows are based on the VIC model forced by output from an ensemble of 10 general circulation models (GCMs) under the A1B greenhouse gas emissions scenario

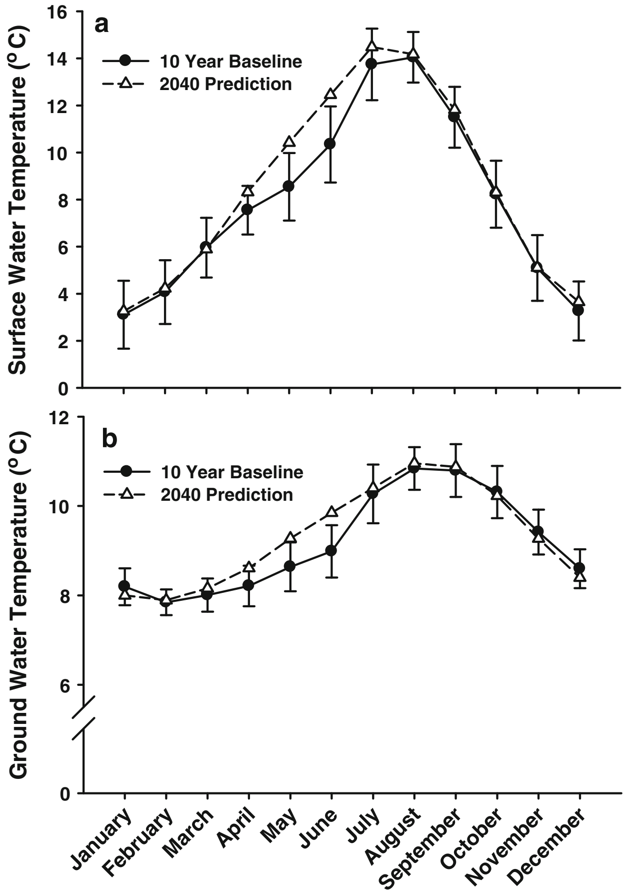

Fig. 3 Comparison of the mean (±2 SD) water temperatures of water sources that supply Winthrop National Fish Hatchery from the 10-year historical baseline (2000–2009) and projected values for the 2040s

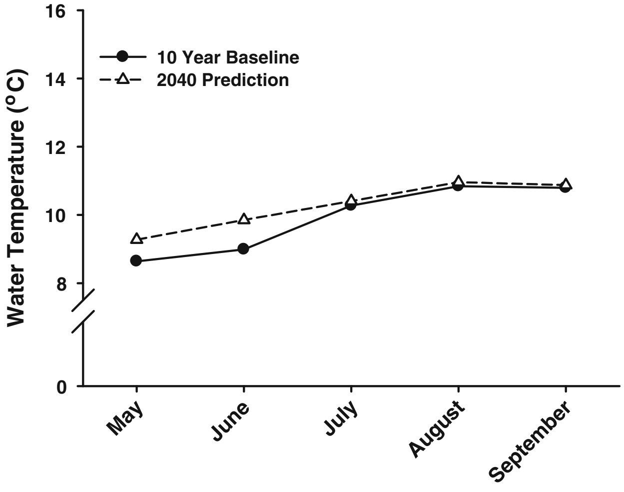

Fig. 4 Comparison of the mean water temperatures experienced by spring Chinook salmon broodstock held at Winthrop National Fish Hatchery based on the 10-year historical baseline (2000–2009) and projected values for the 2040s

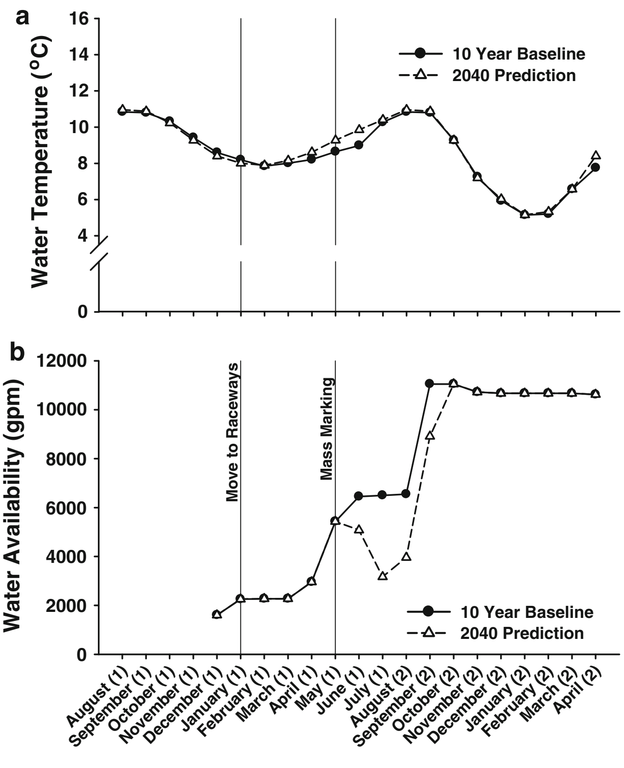

Fig. 5 Comparison of mean **a** water temperatures (°C) and **b** water availability (gpm) during rearing of juvenile spring Chinook salmon at Winthrop National Fish Hatchery based on the 10-year historical baseline (2000–2009) and projected values for the 2040s. Water availability is presented for months after which fish are moved from early rearing (egg and fry) containers, and it was assumed that the facility cannot utilize additional water (above the mean historical value) for months where an increase in mean Methow River flow is projected. The approximate dates of important hatchery events are denoted by labeled vertical lines

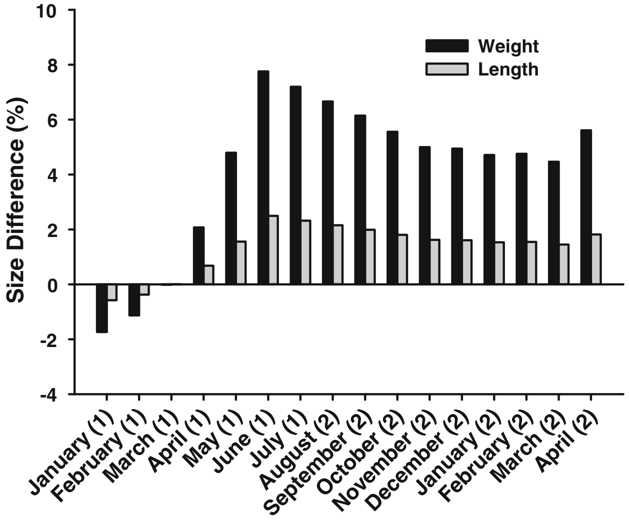

Fig. 6 Cumulative predicted monthly size differences of juvenile spring Chinook salmon reared at Winthrop National Fish Hatchery. Values are the simulated mean differences in weight and length of fish exposed to water temperatures predicted for the 2040s versus fish exposed the 10-year historical baseline (2000–2009)

tolerances for eggs and fry, juveniles, or smolts (Table 2; Fig. 5a). Temperatures are not predicted to rise to within the optimal growth range for common salmon pathogens (Table 3). However, increases in water temperatures approaching 1 °C in May and June may increase the risk for disease outbreaks in these months. Growth of juvenile Chinook salmon in the hatchery will change due to increased water temperatures expected by the 2040s. Compared to recent observations, fish growth rates might be lower in January and March because of slightly colder temperatures, but will be higher in most other months, especially in June (Fig. 6). At the end of the rearing cycle, Chinook salmon smolts are predicted to be about 5.6 % heavier and 1.8 % longer than the historical size at release (Fig. 6).

Under the future climate conditions, anticipated faster fish growth and reduced water availability (Fig. 5b) caused the flow index to increase by 29–115 % during June–September (Fig. 7a), and the bias-corrected estimate for late summer nearly met (August) or exceeded (July) the threshold value (1.0) under which this stock is managed. The projected density index values showed a pattern similar during the summer and early fall, but the changes were minor, and future values did not approach or exceed the threshold value (Fig. 7b).

Sensitivity analyses suggest 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. Contour plots of historical and future flow index values during June, July, August, and September indicate that the future values exhibit a greater relative shift along the plot's horizontal

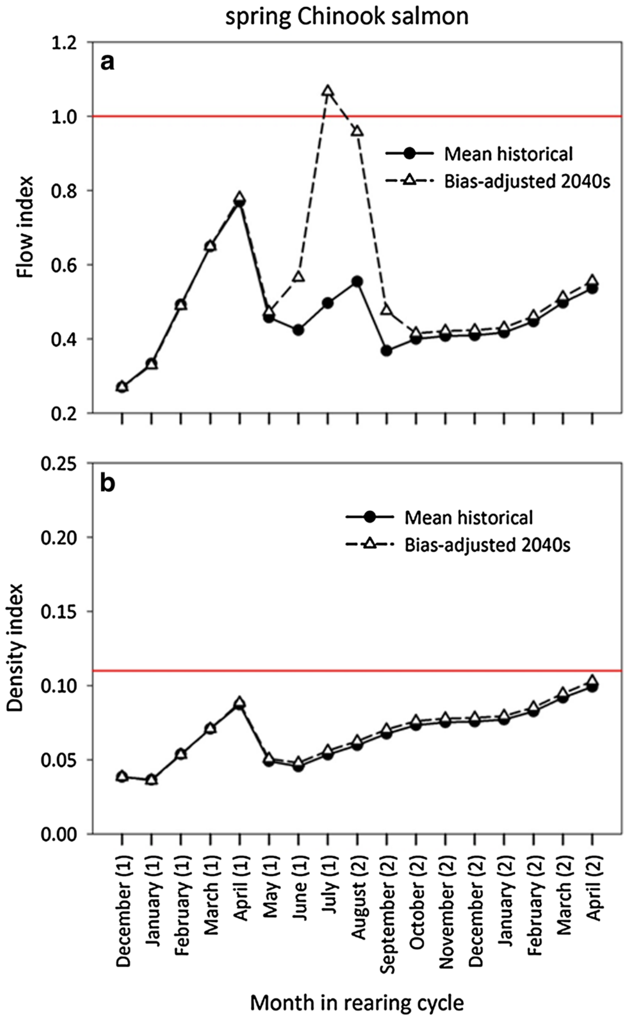

Fig. 7 Mean historical and bias-corrected future **a** flow index and **b** density index values for spring Chinook salmon at Winthrop National Fish Hatchery. Values for the 2040s have been bias corrected by multiplying the uncorrected future values by the ratio: $\frac{\text{mean historical value 2003–2009}}{\text{simulated historical value}}$. See Table 4 for bias correction values. The *horizontal lines* in each plot denote the target "do not exceed" value for each index

axis (water availability) than along the vertical axis (water temperature) (Fig. 8). While we do not present the corresponding contour plots for density index, the changes in density index values followed a similar temporal pattern to the changes to flow index, though the magnitude of perturbation was lower and did not approach or exceed established thresholds (Table 4), indicating that WNFH has physical rearing capacity adequate to accommodate larger fish without exceeding its density index threshold value, assuming no changes to the number of fish reared.

Steelhead and Coho Salmon Programs

The results for the 1-year steelhead, 2-year steelhead, and coho salmon programs were qualitatively similar to those for Chinook salmon: future conditions did not exceed the species' basic thermal tolerances, smolts were larger at release, and periods of potential physiological stress tended to occur in summer due to warmer temperatures and less water for the hatchery rearing environment. Because results were similar to those for Chinook salmon, the detailed results for these programs are presented in Online Resources 4, 5, and 6.

Discussion

Predicted Effects of Climate Change on WNFH Pacific Salmon Production Programs

Based on the climate models we considered, the Methow River basin will experience many of the changes anticipated for snowmelt dominated basins in the interior Columbia River basin, such as warmer summer air temperatures, reduced winter snowpack, earlier snowmelt runoff, and lower summer flows by the 2040s (Mantua et al. 2010; Wenger et al. 2011a). Functionally, this results in warmer stream temperatures in most seasons and a hydrologic shift toward higher winter and lower summer flows. Our hatchery model predicts that anticipated changes in water temperature and availability at WNFH will cause mostly sub-lethal effects for the Chinook and coho salmon and steelhead programs. Modeled water temperatures increased by less than 2 °C and remained well within the physiological tolerances for all species, so the facility should not become thermally unsuitable for Pacific salmon. However, fish mortality caused by acute thermal stress may still occur, especially as extreme weather events like heat waves may become more frequent under future climatic conditions (Meehl and Tebaldi 2004; Mitchell et al. 2006). While temperatures may not exceed lethal thermal thresholds, chronic exposure to suboptimal water temperatures can cause increased stress and associated decreased immune function in individual fish (Barton and Iwama 1991; Barton 2002). Combined with the acute stressors that are a part of hatchery operations (e.g., mass marking, moving fish between containers, and disturbance during maintenance), chronic stress from thermal conditions could increase the probability for epizootic outbreaks (Barton and Iwama 1991; Barton 2002; Marcos-López et al. 2010; Okamura et al. 2011).

Higher average water temperatures, especially during summer months, would also lead to increased growth for all stocks, resulting in measurably larger fish. Increased growth rates may result in ecological, behavioral, or phenotypic changes (Benjamin et al. 2013; Berejikian et al. 2012; Larsen et al. 2004, 2006). For example, increased growth rate can lead to earlier maturity in salmonids (i.e.,

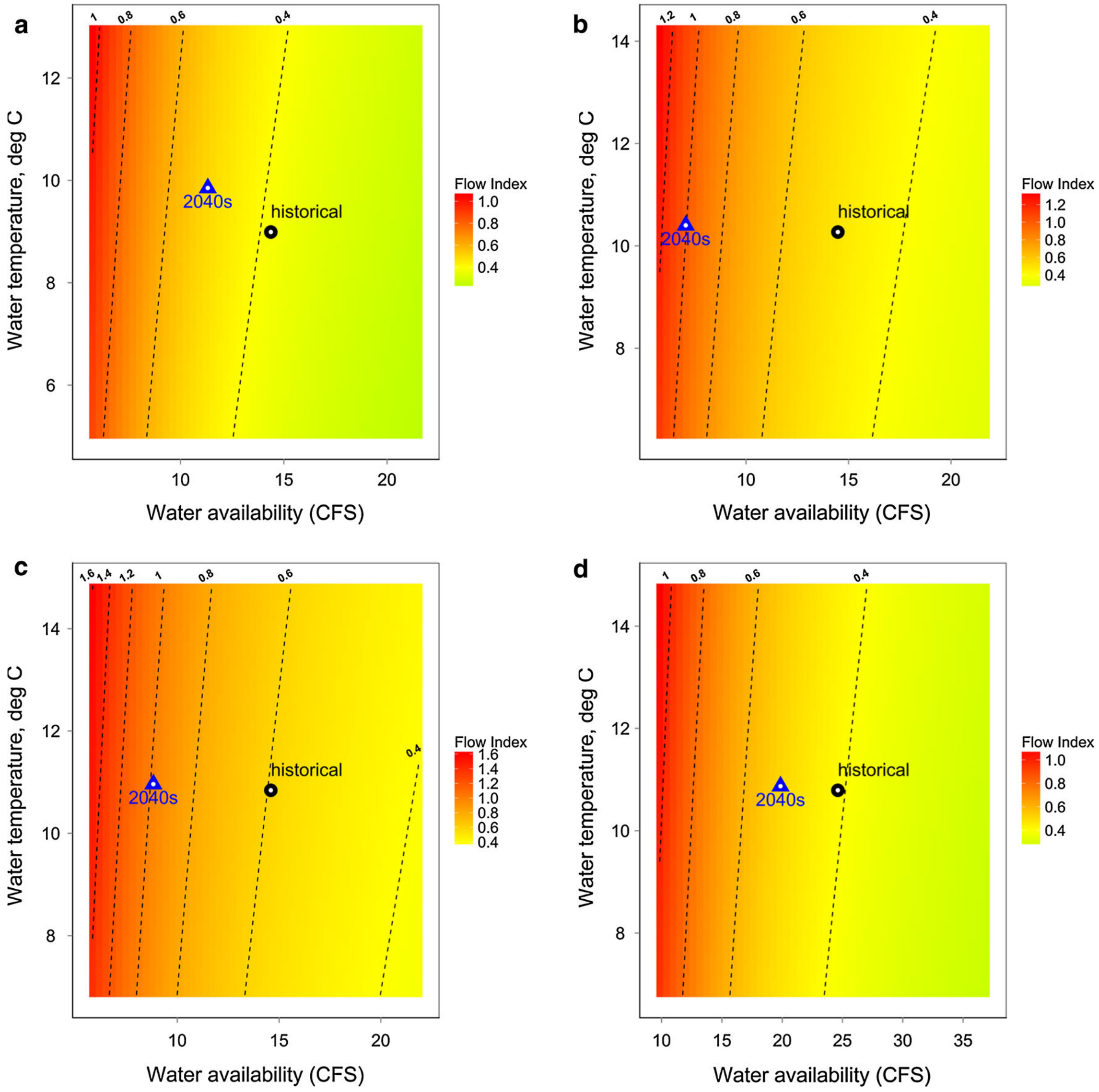

Fig. 8 Predicted flow index for spring Chinook salmon during the consecutive months of June (**a**)–September (**d**) at Winthrop National Fish Hatchery based on incremental changes in water availability and temperature. *Dotted lines* are 0.2 isopleths for flow index. *Points* represent historical average conditions (*black circle*) and conditions projected for the 2040s (*blue triangle*) (Color figure online)

jacking—males who return to spawn after only 1 year at sea) and increase the frequency of residualism, where salmon smolts forgo emigration to the ocean and precocially mature in freshwater (Larsen et al. 2004). If the hatchery program is designed to mitigate for the decline of a culturally or economically important Tribal, recreational or commercial fishery that targets large-bodied adults in the ocean, estuary, or freshwater migratory corridor, both early maturation and residualism would be an impediment to attaining production goals (e.g., Larsen et al. 2004, 2006). Variation in smolt size could also affect overall production, because smolt size influences survival in the migratory corridor (Connor et al. 2004) and can also influence adult returns (Passolt 2012). Some hatcheries are required by legal agreement to produce a certain number of smolts of a specific body size or condition for release at a specific time (United States vs. Oregon 2008), and higher growth rates may make it difficult or impossible for a facility to meet these obligations in their current form.

Increased growth of hatchery-reared juvenile salmon during the summer and early fall coincides with a period of declining surface water flows in the annual hydrograph. The interplay between these two factors will drastically change WNFH's rearing conditions during these time periods as there will be less water available when the fish need it most. This was demonstrated in our modeling scheme by large

Table 4 Mean input conditions used to simulate flow and density indices in monthly time steps (i), and bias correction factor used to adjust those index values for spring Chinook salmon at Winthrop National Fish Hatchery

i	Month	Mean values used to initiate simulations				Bias correction factors	
		N_i^{a}	C_i (ft^3)^{b}	W_i (g)^{c}	d_i^{d}	rFI_i^{e}	rDI_i^{e}
1	December	752,000	8,526	0.47	31	0.76	0.58
2	January	741,472	8,526	1.10	31	0.75	0.31
3	February	731,091	22,000	1.97	28	0.77	0.82
4	March	720,856	22,000	3.36	31	0.72	0.76
5	April	710,764	22,000	5.26	30	0.84	0.71
6	May	700,813	22,000	7.96	31	0.70	0.31
7	June	691,002	64,890	11.43	30	0.62	0.67
8	July	681,328	64,890	16.64	31	0.57	0.62
9	August	671,789	64,890	23.52	31	0.52	0.56
10	September	662,384	64,890	31.52	30	0.49	0.52
11	October	653,111	64,890	39.66	31	0.46	0.49
12	November	643,967	64,890	46.12	30	0.42	0.46
13	December	634,952	64,890	51.67	31	0.39	0.44
14	January	626,063	64,890	56.42	31	0.38	0.43
15	February	617,298	64,890	60.69	28	0.39	0.44
16	March	608,656	64,890	67.92	31	0.41	0.46
17	April	600,134	64,890	77.07	30	0.41	0.47

[a] Abundance (N_i) 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 to 2009

[b] Mean hatchery capacity (C_i) during 2003–2009

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

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

[e] Bias correction factors are the ratio between mean empirical index values and simulated historical values as $rFI_i = \frac{FI_i \text{ mean empirical historical}}{FI_i \text{ modeled historical}}$, and $rDI_i = \frac{DI_i \text{ mean empirical historical}}{DI_i \text{ modeled historical}}$. For additional details, see Online Resource 2. Historical and bias-corrected future index values are presented in Fig. 7

increases in flow index values during June, July, and August. These increases may have consequences for production targets depending on the risk strategy used by the hatchery manager and whether climate mitigation is possible. For example, the spring Chinook program at WNFH has a production target of 600,000 smolts. To keep flow index values from increasing by no more than 50 or 25 % relative to the historical values in any month, then production would need to decrease to 420,000 and 350,000 smolts under the mortality rates and bias correction factor we used in the case study analyses. If the objective was to simply keep the flow index value below the threshold value for the stock, then production would only need to be reduced to 559,000.

Flow index is a surrogate measure of carrying capacity that integrates fish biomass and water use (flow rate). Biologically, flow index is meant to account for the amount of dissolved oxygen in the source water and the removal of metabolic waste (Wedemeyer 2001). When the flow index threshold is exceeded, captive fish may experience acute or chronic physiological stress, disease outbreaks, and mortality (C. Pasley, WNFH, personal communication). For WNFH, the modeling exercise indicates that increases in flow index values are caused primarily by decreases in summer water availability, though this effect is exacerbated by the increase in fish size due to increased water temperatures. Regardless of the proximate cause, flow indices for all four salmon programs are expected to be elevated at the same time. This may present logistical challenges for hatchery staff that must not only account for the fishes' basic biological needs, but also need to coordinate other required activities, like moving fish between raceways or implementing marking and tagging programs that can cause additional stress to the fish.

Potential Climate Mitigation Strategies Based on Case Study Analysis of WNFH

Our analyses indicated that future salmon production at WNFH should be sensitive to warmer water temperatures and reduced water availability in summer, with the latter having a stronger influence on carrying capacity within the hatchery. These projections lead logically to a consideration of potential mitigation strategies that are within the scope of the hatchery manager. Chillers could be used to moderate temperature increases during summer months or reduce fish growth in other months to compensate for the increases during summer. Greater utilization of (colder) groundwater during summer could compensate for the anticipated increases in (warmer) surface water temperatures. Reduced surface water availability during summer could be mitigated through increased efficiency. For example, installing recirculation equipment could be used to maximize efficiency of water use, though this could require major capital investments in infrastructure to pump, chill, sterilize, and oxygenate water. The hatchery could seek additional water sources through acquisition of existing water rights or by filing new claims. However, many river basins in the US are already over appropriated (i.e., existing water rights exceed average water yield), and the prior appropriation doctrine (first in time, first in right) that applies in Washington state and elsewhere in the western US (Miles et al. 2000) means that additional rights may not even be available, or, if they are, that they might be less of an asset because the junior users are the first curtailed when water rights are enforced. In the case of WNFH, these considerations led to a targeted, in-depth assessment of water resources for the facility (Mayer and Strachan 2012). The biological effects of the increased growth or physiological stress could be partially mitigated by altering hatchery rearing practices. For example, rations could be reduced or the composition of the diet altered to moderate growth rates and compensate for the effect of increased temperature (Piper et al. 1982). Multi-year rearing cycles may also be less sustainable. In this case, continuation of the two-year steelhead program at WNFH may prove unfeasible since the fish could be subjected to two summers of elevated temperature and reduced water availability. Whether they involve investment in new infrastructure or operational changes, potential mitigation actions, would require appropriate cost-benefit analyses to ensure that they were meeting the hatchery's biological objectives given its financial resources.

Uncertainty and Links to Other Climate-Related Effects and Habitats

The framework we developed to assess vulnerability of WNFH is best considered a first-generation model. The approach has a number of caveats and limitations, but it did provide a coherent and repeatable process to evaluate how climatic changes expected in the next few decades will affect such facilities, suggested some adaptation and mitigation strategies that managers could implement to increase the resilience of their programs, and indicated where additional data or integrated modeling could improve decision-making and planning. We assumed that the climate change projections used in this study are not precisely correct, but are still representative, reasonable, and internally consistent. Our modeling objective was to develop a system to consider how future changes in water temperature and availability could affect captive Pacific salmon, not to determine which climate scenario or climate model was correct. As such, we did not explore the consequences of uncertainty in GCM predictions, different methods to downscale output from GCMs, or different emissions scenarios. In addition to forcing the hatchery model with the internally consistent GCM data with a single-emission scenario, we also forced it by imposing incremental changes in water temperature and availability to determine each stock's relative sensitivity to these two factors, as measured by flow and density indices.

Clearly, additional refinements to the modeling approach and a deeper understanding of other factors that could potentially limit hatchery and wild populations of Pacific salmon would extend its utility. We assumed that conditions in the Methow River are and will be representative of conditions within the facility. While this is reasonable considering WNFH takes water from the river and shallow wells adjacent to the river, there are additional details that we did not explicitly consider because of data uncertainty. For example, surface flows in winter are projected to be greater under climate change, but we assumed that the hatchery would not be able to use this additional water at those times because infrastructure was limiting and existing water rights might preclude its use. If this water could be used during the winter months, then our winter flow index estimates would be biased high.

We modeled incremental changes in water availability at the hatchery and average conditions, but dramatic fluctuations in water availability are possible based on the interplay between human water use elsewhere in the Methow River basin and the prevailing environmental conditions. Human-caused decreases in discharge would be most likely during periods of low water availability when demand for irrigation is high (i.e., summer). Our modeling suggests that this would be the same time period when the hatchery rearing conditions would be affected by the climate-forced reduction in water availability. Larger or more abrupt decreases in stream flow would obviously exacerbate any existing problems within the hatchery. A water resource assessment for the contributing watershed (e.g., Mayer and Strachan 2012) may reduce some of this uncertainty, and assess the potential human dimensions of hydrologic changes including competition for water among agricultural, municipal, hydroelectric, and recreational user groups (Barnett et al. 2004; Miles et al. 2000). Local hydrologic conditions at the WNFH are more complex than we were able to represent in the model. We represented the interaction between surface water and shallow groundwater via a simple lag effect because we did not have site-specific data on the local groundwater dynamics. Clearly, a focused study on the relationship between surface and groundwater near WNFH could help improve water management, or at least increase the likelihood that managers could identify thresholds for surface flows below which the infiltration galleries would not be fully operational.

We limited our modeling to the hatchery environment and the interacting effect of decreased water availability and increased temperature. It is obvious that climate-mediated conditions we did not evaluate could impose additional bottlenecks that impact the conservation or mitigation goals of a hatchery program and could make a consideration of hatchery rearing a moot point. Short-duration but unpredictable climate-related events like flooding can damage water utility infrastructure (US EPA 2012), and hatcheries may be somewhat analogous. Severe droughts and heat waves are expected to occur with greater frequency under climate change (Meehl and Tebaldi 2004; Mitchell et al. 2006) and could have a major influence on water availability and quality even if such events lasted only a few days. Increased frequency of forest fires (Westerling et al. 2006) could potentially damage hatchery infrastructure and interrupt operations where fires posed a risk to human safety . Such events should occur in specific seasons (e.g., dewatering in summer), but their precise timing is unpredictable. Thus, we chose to focus initially on modeling average future conditions that we expect to be correlated with the frequency and intensity of those more stochastic events, like floods, dewatering, or fires. Climate change is also expected to further disrupt the connectivity between freshwater and marine habitats (e.g., thermal blocks—Mantua et al. 2010; Strange 2010; Martins et al. 2011) and alter the productivity of marine habitats upon which salmon depend (Fabry et al. 2008; Healey 2011). Although we focused here on an inland hatchery, coastal hatcheries could also be affected by sea-level rise and salt water intrusion (Hanson and Ostrand 2011). The interplay of factors external to the hatchery may drastically impact the function and utility of individual facilities, and will need to be evaluated on a case-by-case basis.

Future Directions

The hatchery model we have developed can be refined to incorporate new information or refined sub-models, such as a growth model that includes rations as well as temperature, or supplemented with additional sub-models to account for local effects like sea-level rise. Additional refinements to our modeling approach and a deeper understanding of other factors that could potentially limit hatchery and wild populations of Pacific salmon would extend the model's utility. Slight modifications to this model can be used to determine the sensitivity of multiple salmon hatcheries in a quantifiable manner. The hatchery model could also be utilized as a module for a larger population model, like the Shiraz model, that includes every life stage and habitat for a cultured population of Pacific salmon (e.g., Scheuerell et al. 2006). Ultimately, this model represents an initial step to demonstrate its use in climate vulnerability assessment and adaptation planning. At the facility scale, this was an effort to determine potential challenges to rearing salmon, identify logical mitigation actions and data needs, and facilitate planning and assist with day-to-day hatchery operations. At the regional scale, this was an effort to develop a standardized assessment method that can be used to facilitate strategic conservation planning. The larger objective here would be to understand how the hatcheries contribute, collectively, to agency conservation/mitigation objectives or legal obligations.

For hatcheries to serve a continuing role in salmon conservation/mitigation given a changing climate, several obvious questions need to be addressed. Managers need to determine if hatcheries will be physically able to operate as in the past and meet their current objectives. If not, the extent and cost of production adjustments or infrastructure investments would need to be calculated and evaluated. If a facility would no longer be able to function as before, then alternative roles may deserve consideration. An honest and timely discussion of how climate will affect salmon hatcheries and influence institutional priorities will be needed to ensure efficient and meaningful allocation of conservation resources intended to benefit Pacific salmon, and delay means the hard decisions will only get more difficult.

Acknowledgments We thank Chris Pasley and the staff at WNFH for providing data and comments during the modeling process. The USFWS Pacific Region Climate Change Planning Team of Chris Pasley, Bill Gale, Patty Crandell and Don Campton provided general guidance on the scope and content of this project, and also contributed useful comments on this report. Ingrid Tohver and Nate Mantua (University of Washington, Climate Impacts Group) provided water temperature predictions for the Methow River basin. Tim Mayer (USFWS) provided valuable advice on how to consider surface–groundwater interactions in our analyses. Bill Brignon (USFWS), Joy Evered (USFWS), Doug Olsen (USFWS), David Patte (USFWS), Bruce Marcot (US Forest Service), Keeley Murdoch (Yakama Nation Fisheries Program), Tim Roth (USFWS), Brad Thompson (USFWS), and Nate Wiese (USFWS) raised important issues and participated in helpful discussions to inform the modeling approach. The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the U. S. Fish and Wildlife Service.

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