U.S. Fish and Wildlife Service

Columbia-Pacific Northwest Region

Entiat National Fish Hatchery

Climate Change Vulnerability Assessment

Final Report: December 2021

U.S. Fish and Wildlife Service

Columbia-Pacific Northwest Region

Climate Change Vulnerability Assessment Team

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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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I. SUMMARY

Purpose and need

The U.S. Fish and Wildlife Service (USFWS) is assessing the vulnerability of its National Fish Hatcheries (NFHs) in Washington, Oregon and Idaho in response to projected future climates. The Assessment Team has completed climate change vulnerability assessments (CCVAs) for Winthrop NFH (USFWS 2013a), Quilcene NFH (USFWS 2016), Makah NFH (USFWS 2019), and Warm Springs NFH (USFWS 2021).[1] These assessments are focused on NFH vulnerabilities at the hatchery and local watershed levels and are motivated by long-term trends in climate and the increased likelihood of extreme weather events that could significantly affect USFWS programs and hatcheries in the Columbia-Pacific Northwest Region. Other agencies are evaluating climate change vulnerabilities of anadromous salmonid fishes in the marine environment and freshwater migration corridors.[2] The report presented here represents the Assessment Team's CCVA for Entiat NFH in central Washington State.

Definitions

A vulnerability assessment consists of four key components: sensitivity, exposure, impact, and adaptive capacity.

Sensitivity is the degree to which a system or species is likely to be affected by an environmental disturbance. ***Exposure*** is the magnitude or degree to which a system or species is expected to be subjected to an environmental disturbance. ***Impact*** is the combination of sensitivity and exposure of a system or species to an environmental disturbance. ***Adaptive capacity*** is the ability or *capacity* of a system or species to adjust or *adapt* to the impact of an environmental disturbance. ***Vulnerability*** of a species or system is an *impact* that cannot be adequately addressed by existing *adaptive capacity*.

Background and methods

Entiat NFH is located near Entiat, Washington at river mile (RM) 6.3 of the Entiat River, a tributary to the Columbia River at RM 485. The hatchery was originally authorized by the Grand Coulee Dam Project, 49 Statue 1028, as part of the Rivers and Harbors Act in 1935, and began operations in 1942.

Entiat NFH currently propagates an introduced hatchery population of Summer Chinook Salmon (*Oncorhynchus tshawytscha*) derived originally from adult fish trapped at Wells Dam on the

[1] Completed reports are available for download at: https://www.fws.gov/pacific/fisheries/CC%20Vulnerability%20Analyses/CCVulnerabilityIndex.cfm .

[2] https://www.fisheries.noaa.gov/feature-story/west-coast-salmon-vulnerable-climate-change-some-show-resilience-shifting-environment

Columbia River. Entiat NFH has reared and released Chinook Salmon annually since 1942, except for brood years 1967 and 1968. Spring Chinook Salmon, derived originally from the population propagated at Carson NFH in the Columbia River Gorge, were raised at the hatchery until 2007 when that population was replaced by the current population of Summer Chinook Salmon. Adult salmon returning to Entiat NFH must migrate approximately 490 miles upstream from the Pacific Ocean and must pass over eight Columbia River hydropower dams. The site elevation of the hatchery is 1,030 feet above sea level.

Both surface water and groundwater are used to maintain Chinook Salmon at Entiat NFH. Surface water from the Entiat River is used for the adult homing pond during broodstock collection July – October, but 100% groundwater is used in a second pond to hold adults until they are spawned in October. Groundwater is used exclusively during the first year of culture, from egg incubation to the yearling life history stage (October to mid-November one year later). A blend of 80 – 85% surface water from the Entiat River and 15 – 20% well water is used for maintaining Chinook Salmon during their final six months in the hatchery, November to April prior to release as yearling (age 1+) smolts.

The vulnerability assessment described here was based on climate projections for the 2040s and information provided by the NFH staff and the USFWS's Hatchery Evaluation Team (HET).[3] We used historical data for Entiat NFH to assess the *Sensitivity* of the hatchery and Chinook Salmon to potential future changes in air temperature, precipitation, surface and ground water temperatures and availabilities. Climate projections for the 2040s were derived from downscaled temperature, precipitation, and hydrologic projections in the Entiat River basin based on an ensemble of 10 *General Circulation Models* (GCMs)[4], the *A1B emission scenario* (IPCC 2007; UW-CIG[5]), and the *Variable Infiltration Capacity* (VIC) hydrologic model of Liang et al. (1994; as described by Mantua et al. 2010). The outputs of those models for the 2040s represent the *Exposure* of Entiat NFH to projected future climate.

We used the climate and hydrology projections, empirical data on recent fish culture conditions at Entiat NFH, and the fish growth model of Iwama and Tautz (1981) to predict future mean body size and total biomass of Chinook Salmon at the hatchery each month during the freshwater life history phase. We then derived water *flow index* (FI) and fish *density index* (DI) values for the cultured fish based on in-hatchery environmental conditions projected for the 2040s. We used those indexes to assess the *Impacts* of the future climate to Chinook Salmon propagated at Entiat NFH in response to climate-mediated changes in water temperature and availability. We

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[3] The Hatchery Evaluation Team consists of the hatchery manager and other technical staff of the USFWS who coordinate activities at a hatchery including, but not limited to, (a) scheduling of major activities, (b) biosampling of fish and tissues for fish health and other assessments, and (c) marking and tagging of juvenile fish prior to release.

[4] GCMs are large, three-dimensional mathematical models that incorporate the latest understanding of the physics, fluid motion, chemistry and other physical processes of the atmosphere to simulate weather and climate globally.

[5] Climate Impacts Group, University of Washington, Seattle, Washington: http://warm.atmos.washington.edu/2860/.

then used expert opinions from the HET, NFH staff, and partners/comanagers to assess the *Adaptive Capacity* and *Vulnerability* of Entiat NFH to the future climate projected for the 2040s.

Sensitivity of Entiat NFH: main points

- Entiat NFH is considered to have low sensitivity to low surface flows of the Entiat River when surface water is withdrawn for fish culture (November – June) and when water is withdrawn for the adult collection pond and ladder during broodstock collection (July – September).
- Entiat NFH has moderate sensitivity to high surface flows and flood risks of the Entiat River. The biggest hazard during high surface flows may be debris and silt entering the water intake system and not necessarily floods per se.
- Entiat NFH has moderate sensitivity to low air and surface water temperatures, due primarily to the formation of frazzle/slush ice in the Entiat River that can clog the screen chamber if not removed manually. As such, the hatchery is considered very sensitive to future conditions that would increase the frequency of freeze-thaw cycles and the formation of frazzle/slush ice, as has occurred in recent years.
- Chinook Salmon broodstock held on station during the summer, and juveniles during winter, are considered to have low sensitivity to high surface water temperatures under current culture protocols. However, Chinook Salmon adults migrating upstream in the Entiat River are considered sensitive to increases in surface water temperatures when adults are trapped for broodstock (July – October).
- Chinook Salmon at Entiat NFH are considered to have low sensitivity to future changes in groundwater temperature.
- Chinook Salmon at Entiat NFH have moderate to high sensitivity to potential decreases in groundwater availability, particularly during the summer and early fall when surface water flows of the Entiat River are lowest, and subyearlings and adult broodstock are maintained on 100% well water.
- Juvenile and adult Chinook Salmon at Entiat NFH have low to moderate sensitivities, respectively, to disease risks under current fish culture and broodstock collection protocols.
- The Entiat River basin and Entiat NFH have high sensitivity to wildfire risks based on recent wildfire events and summer conditions, and those risks appear to be increasing with more frequent and larger wildfires in the region since the 1980s.

Exposure of Entiat NFH to projected climate change: main points

- Mean air temperatures over the entire Entiat River watershed are projected to increase every month (mean increase = 2.0 °C) with the largest absolute increases (2.6 – 3.0 °C) occurring July – September.

- Mean monthly water temperatures of the Entiat River adjacent to the hatchery are projected to increase by an average of 1.2 °C (range = 0.7 – 1.9 °C) by the 2040s with future mean temperatures in July and August of 16.7 °C and 16.5 °C, respectively. Mean groundwater temperatures of the wells at Entiat NFH are projected to increase by 0.07 to 0.2 °C in all months when compared to the historic baseline.
- Total annual precipitation, averaged over the Entiat River watershed, is expected to increase by approximately 6% in the 2040s compared to the historic average, with most of that increase occurring in November through January. However, substantially more of the total annual precipitation is projected to fall as rain and less as snow with the mean peak snow pack in April projected to be 26% less in the 2040s than historically.
- Although mean annual flows of the Entiat River in the 2040s are projected to increase by only 12%, the shape of the hydrograph in the 2040s is expected to differ considerably from historic patterns, with mean monthly flows of the Entiat River from June through August projected to decrease by approximately 38% but increase by approximately 65% from November through April. Those changes reflect transition of the Entiat River basin from primarily a snow-melt driven watershed historically to a mixed rain-and-snow-melt driven watershed in the 2040s.
- The lowest consecutive seven-day flows over a ten-year period are projected to decrease slightly from 68 cfs historically to 65 cfs in the 2040s, whereas 100-year peak flows are projected to increase substantially from about 8,000 cfs historically to nearly 14,000 cfs in the 2040s.

Impacts of climate change to Entiat NFH: main points

- Groundwater temperatures projected for the 2040s (9.0 – 10.5 °C) are not expected to affect the ability of Entiat NFH to continue rearing Summer Chinook Salmon.
- Surface water temperatures projected for the Entiat River during November – April in the 2040s (2.5 – 7.6 °C), when a blend of 80 – 85% surface and 15 – 20% well water is used for culture, are not expected to affect the ability of Entiat NFH to continue rearing Summer Chinook Salmon at the hatchery. However, higher temperatures of the Entiat River in summer (14.5 to 16.7 °C) could increase the incidence of disease among upstream-migrating adults and/or affect the ability of the hatchery to trap broodstock if high water temperatures in summer impede upstream migration of adults.
- Chinook Salmon smolts at Entiat NFH in the 2040s are predicted to be approximately 15% heavier and 5% longer at release than historically.
- Flow index values (FI) in the 2040s are expected to follow historic averages assuming the quantities of surface and groundwater available to the hatchery remain unchanged (Scenario A). However, if groundwater availability during the summer decreases in response to lower base flows of the Entiat River, then FI values are projected to increase substantially during July, August and September (FI > 1.0) when subyearlings are maintained on 100% well water.

- Density index values projected for the 2040s followed a pattern similar to flow index values under Scenario A with only slight increases in DI values relative to historic values but never exceeded the upper threshold guideline value of DI = 0.2.
- We did not directly model flood or fire risks to Entiat NFH. However, we expect flood risks to increase in the 2040s because of substantial increases in peak flows of the Entiat River in winter. Similarly, we expect fire risks to increase in the 2040s because of projected increases in mean summer air temperatures (+ 2.1 – 3.0 °C, June through September) coupled with substantial decreases in spring/summer snow pack.

Adaptive Capacity of Entiat NFH: main points

- Entiat NFH may have limited capacity currently to reduce water temperatures in the adult capture pond and ladder if higher water temperatures of the Entiat River in the future become a physiological stress and/or disease issue for Summer Chinook Salmon. Groundwater supplies are already 100% allocated (or nearly so) during the summer and early fall, and the ability to chill surface water at Entiat NFH does not exist currently.
- Maintaining existing groundwater supplies is critical to the successful operation of Entiat NFH. The capacity to continue relying on groundwater to meet fish culture needs in face of climate change depends on regularly-scheduled maintenance of the groundwater infrastructure (wells, infiltration gallery). However, dedicated funds earmarked explicitly for that maintenance are not provided currently.
- High flows of the Entiat River result in high debris and sediment loads that are expected to increasingly impact Entiat NFH in the future. Those impacts could be mitigated if existing groundwater capacity could be increased that would allow closure of the surface water intake during very high flows of the Entiat River.
- Additional groundwater capacity may be available on a recently purchased 10-acre parcel adjacent to the hatchery. However, exploratory wells and evaluations would need to be conducted before additional groundwater capacity could be added to the hatchery.

Vulnerability of Entiat NFH: main points

Vulnerabilities were assessed according to the ability and uncertainty to successfully implement the adaptive capacity measures identified by the Workgroup.

- Summer Chinook Salmon at Entiat NFH appear to have a comparatively low vulnerability to the future impacts of climate change because of the high dependence on groundwater for fish culture. However, that low vulnerability depends on the capacity to conduct regularly-scheduled maintenance of the groundwater infrastructure.
- The infrastructure of Entiat NFH is considered moderately vulnerable to the future impacts of climate change, largely because of uncertainties regarding future impacts to groundwater supplies and the high dependency of the hatchery on groundwater. The

hatchery may also be moderately vulnerable to higher peak flows of the Entiat River and flood risks to the existing well field.

- Potential impacts to adult Summer Chinook Salmon from higher water temperatures of the mainstem Columbia River is a major uncertainty that was not addressed in the vulnerability assessment presented here. However, based on other published studies, Summer Chinook Salmon at Entiat NFH could be vulnerable to higher water temperatures projected for the Columbia River (see below).

Biological and environmental uncertainties

The vulnerability assessment presented here does not address two major uncertainties: (1) the effect of climate change on the marine environment and ecosystems, including temperature and flow impacts to the *migration corridor* of the Columbia River, from the Pacific Ocean to the Entiat River, and (2) the future epidemiology of fish pathogens and disease under the climates projected for the 2040s. Both factors could greatly affect the ability of all hatcheries in the Columbia River basin and other regions of the Pacific Northwest to propagate Pacific salmon and Steelhead through the 21st Century.

Conclusions

1. Overall, Entiat NFH and the Summer Chinook Salmon program appear to have a comparatively low vulnerability to the future impacts of climate change. This low vulnerability is due primarily to the ability of the hatchery to rely on 100% groundwater for the culture of Summer Chinook Salmon during the first year of the rearing cycle (October to October). The incidence of disease and other physiological issues (i.e., stress) have been minimal in the past and are expected to be minimal in the future if groundwater can continue to be used for fish culture according to current protocols. We conclude that the future climate projected for the 2040s will most likely not preclude the ability of Entiat NFH to continue propagating Summer Chinook Salmon.
2. The potential impact to groundwater supplies of reduced flows of the Entiat River during the summer are unknown. Our modeled scenario of reduced groundwater availability during the summer in response to reduced surface flows suggested flow index values for Summer Chinook Salmon that may exceed fish health guidelines, especially considering that each of one-third of the total number of fish are reared on 2nd-pass and 3rd-pass reuse water, respectively. However, we consider our modeled direct relationship between groundwater availability and flows of the Entiat River to be a worse-case scenario and speculate that potential reductions in groundwater availability will most likely be less severe, if measurable, than the direct-proportional relationship to surface flows that we modeled.
3. The greatest vulnerability of Entiat NFH to the projected impacts of climate change, other than the groundwater itself, is the infrastructure for delivering that water to the hatchery

(six wells and the infiltration gallery). Indeed, one might consider the infrastructure for delivering groundwater as the Achilles heel of the hatchery under current culture protocols.

4. Entiat NFH is also vulnerable to debris loads, siltation, and floating ice during high flows of the Entiat River with 100-year peak-flows projected to increase from about 8,000 cfs historically to nearly 14,000 cfs by the 2040s. Potential impacts from high debris and siltation loads of the Entiat River could be mitigated if groundwater supplies were sufficient to close off the surface water intake to the hatchery and rely exclusively on groundwater during peak flows of the Entiat River.
5. Direct flood risks to the infrastructure of Entiat NFH in the 2040s appear to be low, although the area of the hatchery grounds where the wells are located may be vulnerable to 100-year peak flows.
6. Summer Chinook Salmon at Entiat NFH may be vulnerable to projected increases in water temperatures of the Columbia River during the traditional upstream-migration period. However, modeling those impacts was beyond the scope of the assessment presented here (see Appendix D).

Recommendations

1. Ensure that the current well field and groundwater supplies to the hatchery are secure. Hydrologists should assess the flood-risk vulnerability of the existing wells at projected peak flows of the Entiat River of 14,000 cfs. If flood risks to the well field are considered significant, then consider construction of a diversion structure to prevent damage and/or contamination of the wells and infiltration gallery during possible floods.
2. Rehabilitate the existing groundwater infiltration gallery, including the addition of a third water collection line, to maximize the delivery of existing groundwater to the hatchery.
3. Secure dedicated funding for regularly-scheduled maintenance (e.g., every 3 to 5 years) of the groundwater infrastructure for the hatchery.
4. Explore opportunities for additional wells on a recently-purchased 10-acre parcel adjacent to the hatchery grounds.
5. Provide additional groundwater and/or mechanically-chilled surface water to the adult capture pond and ladder to reduce water temperatures and disease risks if higher water temperatures of the Entiat River during the summer become a physiological stress and/or disease issue in the future.
6. Monitor and evaluate potential changes in the timing and physiological condition (e.g., pathogen load) of upstream-migrating Summer Chinook Salmon in the mainstem Columbia River and Entiat River in response to projected increases in water temperatures.

II. INTRODUCTION

The U.S. Fish and Wildlife Service (USFWS) in the Columbia-Pacific Northwest Region operates 13 National Fish Hatcheries (NFHs) that annually release more than 60 million juvenile Pacific salmon and Steelhead (*Oncorhynchus* spp.) in the Columbia River basin and Olympic Peninsula (USFWS 2009). Collectively, more than 150 State, Tribal, Federal, and Provincial fish hatcheries in Oregon, Washington, and British Columbia annually release more than 100 million juvenile salmon and Steelhead (ODFW 2011). Fisheries supported by these hatcheries generate billions of dollars in economic activity annually (Lichatowich and McIntyre 1987; Caudill 2002).

Despite the biological, economic, and cultural significance of hatchery-origin fish, little attention has been spent, until recently, assessing how future trends in climate will affect hatchery operations in the Pacific Northwest (Hanson and Ostrand 2011). Higher stream temperatures, earlier timing of snowmelt runoff, and reduced snowpack have been observed in recent years in the western U.S. (Kaushal et al. 2010; Luce and Holden 2009; Mote et al. 2008). Continuing thermal and hydrologic changes are projected to accelerate in coming decades (IPCC 2007) thereby affecting water quality and quantity within river basins in the Pacific Northwest (ISAB 2007; Mote and Salathé 2010; Mantua et al. 2010; Elsner et al. 2010). As a result, a clear need exists to understand how future environmental conditions may constrain the ability of NFHs to meet their fish propagation objectives, treaty obligations, and conservation goals. Robust and transparent evaluations are needed for (a) identifying facility and program-specific impacts and vulnerabilities from climate change and (b) developing adaptation and mitigation strategies to cope with those projected impacts and vulnerabilities.

In response, the USFWS is assessing the effects of climate change on the future viability of fish and wildlife resources under its federal jurisdiction. These efforts include identification of specific mitigation, engagement, and adaptation priorities (USFWS 2010a,b,c). One of the USFWS's priorities is the development of *climate change vulnerability assessments* (CCVAs) for species and habitats under federal jurisdiction, including National Wildlife Refuges and National Fish Hatcheries.

In 2011, all NFHs in the United States underwent *qualitative* CCVAs based on a standardized, spreadsheet template (Appendix A). The USFWS subsequently identified the need for *quantitative* CCVAs derived from scientific assessments of future modeled climates (USFWS 2010a, b). The Fish and Aquatic Conservation Program of the Columbia-Pacific Northwest Region of the USFWS has responded to this priority by developing a strategy and plan for using downscaled, future climate projections at the local watershed level to assess, quantitatively, the vulnerability of 13 NFHs and their respective culture programs. Winthrop NFH in the upper Columbia River basin was chosen as the pilot assessment (USFWS 2013a) followed by

assessments at Quilcene NFH (USFWS 2016), Makah NFH (USFWS 2019), and Warm Springs NFH (USFWS 2021).[6]

The report presented here describes the results of the USFWS's *quantitative* CCVA for Entiat NFH and the one species propagated there: Summer Chinook Salmon (*Oncorhynchus tshawytscha*).[7] Entiat NFH is located at river mile (RM) 6.3 on the Entiat River, a tributary to the Columbia River near Entiat, Washington on the east side of the Cascade Mountains (Figure B1, Appendix B.

III. METHODOLOGIES

A. Assessing future climate

Episodic environmental events (droughts, floods, wildfires, summer heatwaves, etc.) have occurred historically throughout the Pacific Northwest. Since the 1970s, our scientific understanding of the relationships of these events to global oceanic and atmospheric conditions has increased substantially. For example, winters in the Pacific Northwest tend to be warmer and dryer than average during *El Niño* events when sea surface temperatures (SSTs) in the equatorial eastern Pacific Ocean are significantly warmer than average. Conversely, winters in the Pacific Northwest tend to be cooler and wetter than average during *La Niña* events when SSTs in the equatorial eastern Pacific Ocean are significantly cooler than average. In the Pacific Northwest, summer drought conditions are more likely during an *El Niño*, while winter/spring floods are more likely during a *La Niña*.

More recently, functional relationships among atmospheric chemistry, heat retention by the atmosphere, mean air temperatures and precipitation have been established (IPCC 2007; 2014). Physics-based, thermodynamic *General Circulation Models* (GCMs) of global atmospheric temperatures and precipitation have been developed that quantify those relationships mathematically.[8] As a result, dynamic changes or trends in atmospheric parameters (e.g., mean concentration of carbon dioxide in the atmosphere, solar radiation intensity, etc.) can be modelled forward in time to project expected mean values for air temperature and precipitation at

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[6] Completed reports are available at: https://www.fws.gov/pacific/fisheries/CC%20Vulnerability%20Analyses/CCVulnerabilityIndex.cfm.

[7] Chinook Salmon are usually characterized by the time of year when adults enter freshwater to spawn. The Columbia River historically supported three seasonal "runs" of Chinook Salmon: fall-run, spring-run, and summer-run representing the time of the year when adults were available for harvest in the lower river downstream from the The Dalles, Oregon. Juvenile Spring Chinook Salmon in the Columbia River basin rear in freshwater for approximately 18 months prior to smolting and outmigrating to the Pacific Ocean. In contrast, juvenile Fall Chinook Salmon rear in freshwater for only about six months prior to smolting and outmigrating. Summer Chinook Salmon exhibit both life histories.

[8] GCMs, also known as global climate models, are large, three-dimensional mathematical models that incorporate the latest understanding of the physics, fluid motion, chemistry and other physical processes of the atmosphere to simulate weather and climate globally.

both global and regional scales. Such projections can then be used by government agencies, the private sector, other organizations, and individuals to assess the vulnerability of natural resources and physical infrastructures to future climate conditions and extreme environmental events.

B. Vulnerability assessments: An introduction to concepts

The vulnerability of a species or system to an environmental change can be thought of as a function of four key factors: sensitivity, exposure, impact and adaptive capacity (Figure 1).

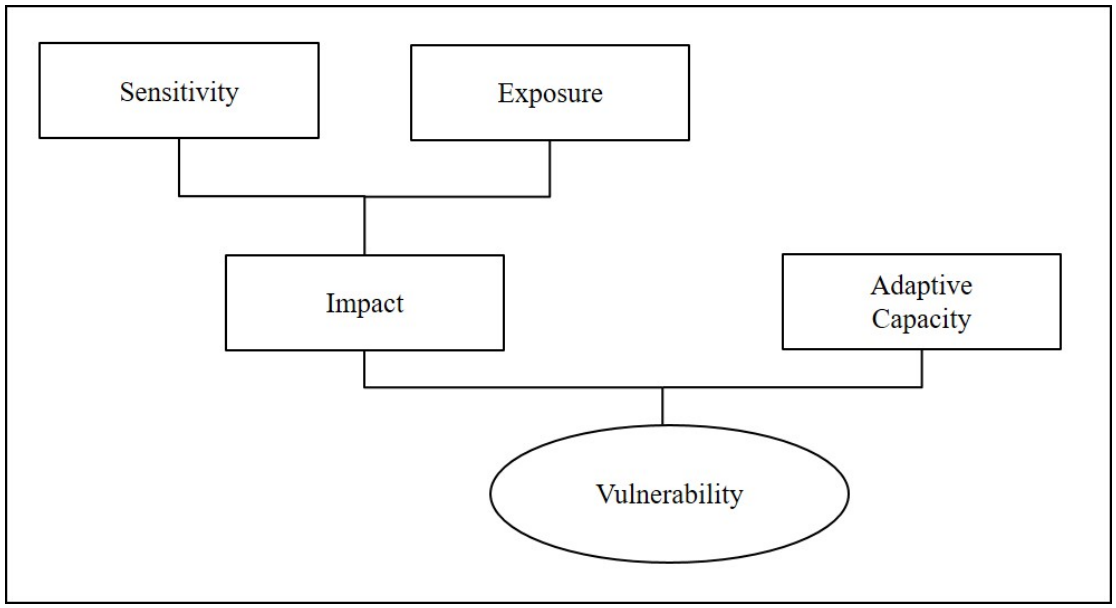

Figure 1. Key components of a vulnerability assessment.

Sensitivity is the degree to which a system or species is likely to be affected by an environmental disturbance like climate change. For example, a hatchery currently lacking adequate water during the summer months would be highly sensitive to prolonged periods of low surface-flow conditions during summer. We assess sensitivity here in terms of (a) future stressors to the water supply and infrastructure at Entiat NFH and (b) the current biomass capacity and productivity limitations of rearing Summer Chinook Salmon to the smolt stage of development at Entiat NFH.

Exposure is the magnitude or degree to which a system or species is expected to be subjected to an environmental disturbance like climate change. We describe the climate change exposure anticipated in the Entiat River basin and the Entiat NFH based on downscaled climate projections for the 2040s.

Impact is the combination of sensitivity and exposure of a system or species to an environmental disturbance like climate change. To achieve a quantitative understanding of potential climate change impacts to the Summer Chinook Salmon program at Entiat NFH, we developed biological models that describe how fish growth and associated culture indices (density index and flow index) may change due to future projected changes in climate.

Adaptive capacity is the current ability or capacity of a system or species to adjust or adapt to the impact of an environmental disturbance like climate change. As part of our assessments, we considered adaptive strategies that could potentially mitigate for the future effects of climate change; however, we did not directly assess the practicality or economic cost of employing those potential strategies.

Vulnerability of a system or species represents future impacts of an environmental disturbance like climate change that cannot be adequately addressed by adaptive capacity. We describe climate change vulnerabilities as the impacts to the Summer Chinook Salmon program at Entiat NFH and hatchery infrastructure that, most likely, cannot be adequately addressed by existing adaptive capacity.

At a local (individual hatchery) level, a clear understanding of the future vulnerabilities of a NFH program to changes in climate can provide managers and biologists with the information necessary to plan for future demands and stressors as well as an ability to better determine the most appropriate management direction. At the regional level (across NFHs and programs), this understanding allows resources to be more effectively allocated in a proactive manner rather than reactive in nature. A robust vulnerability assessment provides resource managers and stakeholders with the information needed to understand which NFHs and programs are most vulnerable to climate change. That understanding is expected to lead to discussions among parties as how best to address identified vulnerabilities.

NFH Vulnerability Assessments help determine:

- Which regional programs and species will be most affected by climate change.
- What aspects of a NFH's facilities and programs will be most affected by climate change.
- Why specific hatchery programs/species are most vulnerable to climate change.

This information will allow us to determine the most appropriate management response to climate change now and in the future.

NFH Vulnerability Assessments help us to:

- Establish practical/informed management and planning priorities (e.g., *What should we be doing differently?*).
- Inform adaptation planning (e.g., *What do we need to accomplish so we can continue to meet our goals?*).
- Allocate resources efficiently (e.g., *What resources do we need to obtain and how are they best distributed?*).

C. Assessment process

A NFH Climate Change Vulnerability Assessment Team (Assessment Team) was created to develop a process for assessing the possible future impacts of climate change to NFH facilities and programs in the Columbia-Pacific Northwest Region. This process (a) allows assessments of individual facilities and culture programs and (b) complements existing planning and management efforts. This climate change assessment process has three steps.

1. Outputs from an ensemble of ten GCMs are first downscaled to the river basin of interest to project mean monthly air temperatures and precipitation quantities over the entire watershed for the period of interest (2040s). A hydraulic model is then coupled to the temperature and precipitation projections to obtain mean monthly surface water temperatures and flow volumes (cubic feet per second, or cfs) at the vicinity of the hatchery (Appendix B).
2. Fish growth at the hatchery is modeled mathematically based on the projected temperatures of the culture water derived from climate change projections and watershed-specific hydrologic data. Species-specific biological parameters for fish growth and temperature *sensitivities* are combined with operational information at the local hatchery level to assess *exposure* and future *impacts* of climate change to specific facilities and fish culture programs (Appendix B).
3. A team of experts – including NFH staff and the USFWS's Hatchery Evaluation Team (HET) for the hatchery – work collaboratively with relevant co-managers and partners to assess projected impacts that may impede the ability of a hatchery and its programs to meet their goals and then identifies possible adaptive measures. Ultimately, impacts with little or no adaptive capacity are vulnerabilities for the NFH (Appendix C).

IV. BACKGROUND

A. Entiat River watershed

Entiat NFH is located at RM 6.3 on the Entiat River, a tributary to the Columbia River at RM 485 on the east slope of the Cascade Mountains (Figure 2). The Entiat River watershed encompasses approximately 420 square miles with elevations ranging from 700 feet at the confluence of the Entiat and Columbia rivers to 9,249 feet at the peak of Mt. Furnow. The Mad River is a major tributary to the Entiat River. Adult salmon returning to Entiat NFH must migrate upstream approximately 490 miles and past eight Columbia River hydropower dams. The Entiat River provides spawning and rearing habitat for several native species of salmonid fishes including Spring Chinook Salmon, Summer Chinook Salmon, Summer Steelhead (*O. mykiss*), Westslope Cutthroat Trout (*O. clarki lewisi*), and Bull Trout (*Salvelinus confluentus*). Naturally-spawning populations of Spring Chinook Salmon (endangered), Steelhead (threatened), and Bull Trout (threatened) in the Entiat River are currently listed under the U.S. Endangered Species Act (ESA).

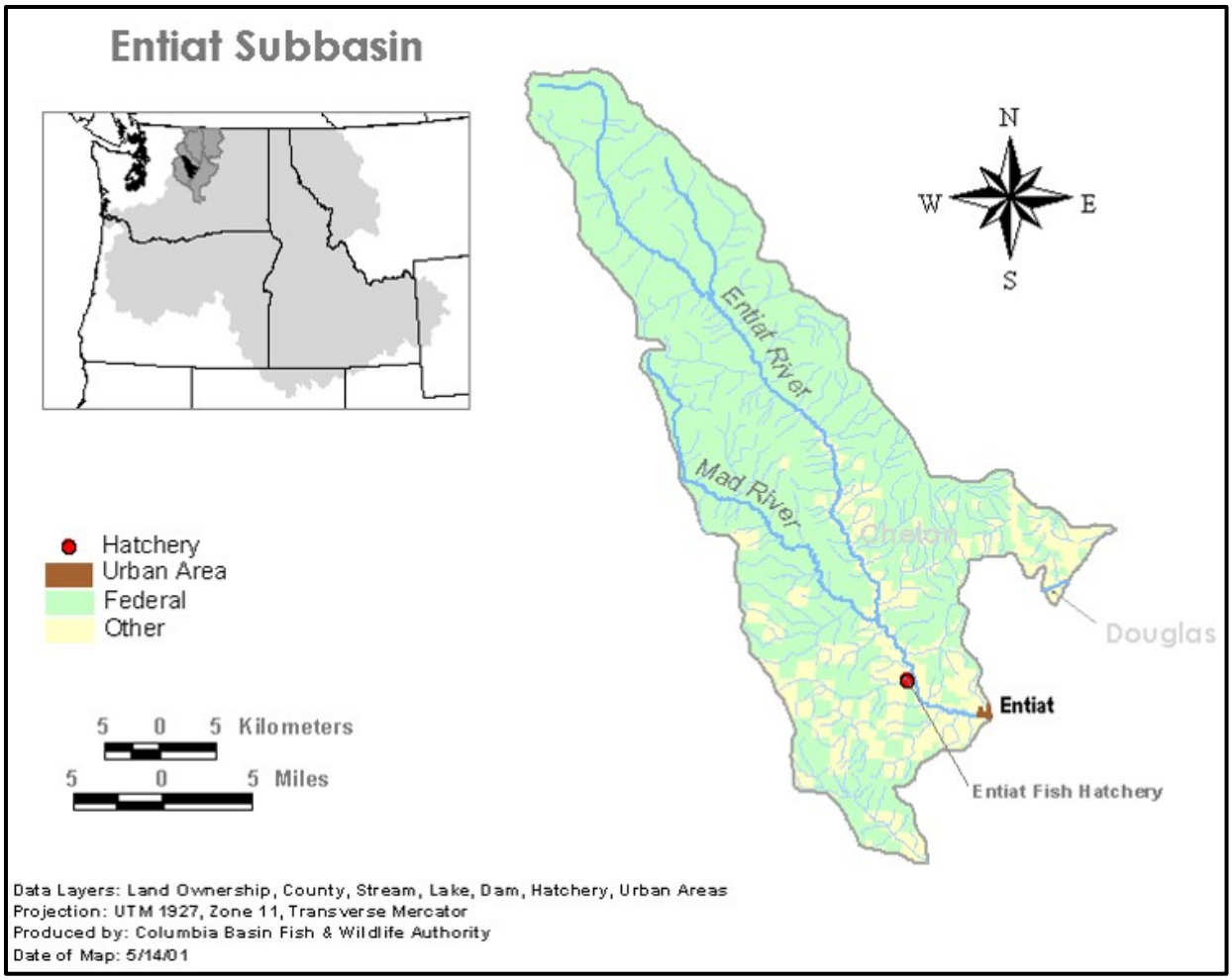

Figure 2. Location of the Entiat River watershed within the Columbia River basin. Entiat National Fish Hatchery is located at RM 6.3 of the Entiat River, a tributary to the Columbia River at RM 485.

B. Entiat NFH infrastructure

Entiat NFH was originally authorized on April 3, 1937 by the Grand Coulee Fish Maintenance Project as part of the Rivers and Harbors Act (49 Statue 1028) and reauthorized on May 11, 1938 by the Mitchell Act (52 Statue 345) dated May 11, 1938. The U.S. Bureau of Reclamation (BOR) purchased approximately 34 acres for the hatchery from P.B. Packwood on April 30, 1940 (cost = $7,495). A natural spring located on the property, Limekiln Spring (aka Packwood Spring) was a significant factor in selecting the hatchery site. The hatchery was constructed in 1940 and began limited operations in August, 1941. The hatchery was upgraded and remodeled in 1979.

Entiat NFH is comprised of the following buildings and facilities (see Figure B2, Appendix B):

- Main Hatchery Building, which includes the office, visitor area, maintenance shop, chemical storage room, two-stall garage, and a nursery room/building with (a) 225 egg incubation trays in 18 stacks (15 trays/stack), (b) four 15 x 1.25 ft. incubation troughs, and (c) sixteen 16 x 4 ft. starter tanks

- Thirty 80 x 8 ft. Juvenile Rearing Raceways
- Two 120 x 16 ft. adult holding ponds
- Adult Fish Ladder from the Entiat River into the Adult Holding Ponds
- Water intake dam (155 feet long) spanning the Entiat River with two water control valves and a pole building
- 36-inch diameter water intake concrete pipe used to deliver surface water from the Entiat River to a screen chamber building
- Well Field consisting of six wells
- Infiltration gallery and aeration chamber
- Surface water influent Sand Settling Basin, 95 x 14 ft.
- Fishing Pond 170 x 45 ft.
- Effluent Pollution Abatement Pond, 270 x 78 ft.
- Generator Building housing a 2018 Generac diesel 300 kW generator
- Three residence houses for staff
- 15,000-gallon concrete water storage tank used for the domestic water supply to the hatchery and residences.

C. Water resources at Entiat NFH

Entiat NFH uses a combination of surface and groundwater to rear Chinook Salmon. Groundwater is used exclusively for egg incubation and early rearing, from October through mid-November one year later during the first year of culture (Table B7, Appendix B). Approximately 80 – 85% surface water mixed with 15 – 20% well water is used for subsequent rearing of juveniles from mid-November through the following April when fish are released as yearling (age 1+) smolts. Surface water is used for the adult holding pond (Holding Pond #2) during broodstock collection July – October, but 100% groundwater is used to maintain adults (Holding Pond #1) until they are spawned in October. Outflow water from both ponds is combined and diverted into the fish ladder.

Entiat River

Surface water is diverted from the Entiat River to the hatchery via a 36-inch diameter concrete intake pipe approximately 0.47 miles (0.75 km) upstream from the effluent outflow of the hatchery. The intake structure was built during the station's original construction in 1940. No screening exists at the point of diversion, but approximately 1,000 feet downstream, intake water passes through inclined screens that meet NOAA Fisheries screening requirements. The screened debris is returned to the river.

Groundwater

Groundwater is drawn from six wells for fish culture and domestic use. The hatchery also has access to Packwood Spring (aka Limekiln Spring) which is located on the hatchery property.

Reuse water

Water is re-used via gravity flow among three banks of 8 x 80 ft. raceways (10 raceways per bank). The middle and lower banks receive second pass and third pass water, respectively, from the upper bank when fish are reared on 100% groundwater. In addition, adult broodstock are maintained on 4th pass groundwater (100%) after passing serially through three banks of raceways. For yearlings, all 30 raceways receive first-pass surface water from mid-November through release in April when flows of the Entiat River are sufficient.

Water rights

Hatchery water rights total 35 cfs, although only around 26 cfs are available for fish culture (Table 1).

From November 1 through April 30, the hatchery water right allows it to divert up to 10% of the U.S. Geological Survey (USGS) stream gage flow of the Entiat River whenever the instream flow minus the amount diverted is less than 100 cfs. The hatchery can withdraw its full water right (up to 35 cfs) when the surface flows exceed 122 cfs, but is restricted to 10% when surface flows are 111 cfs or less.

From May 1 to October 31, the hatchery water right allows it to divert up to 5% of the USGS gage flow of the Entiat River whenever the instream flow minus the amount diverted is less than 200 cfs. The hatchery can withdraw its full water right when the surface flows exceed 222 cfs, but is restricted to a maximum of 5% when surface flows are 210 cfs or less.

Table 1. Water rights appurtenant to the Entiat NFH and temperature range of sources. Entiat NFH has a combined water right of 35 cfs from the Entiat River and six groundwater wells for fish culture. Water amounts in parentheses for the groundwater wells are the approximate average annual amounts actually used.

Source	Certificate Number[a]	Purpose or Use	Priority Date	Amount	Temperature Range
Entiat River	3058	Fish culture and adult collection pond	1943	22 cfs	0.1 – 24 °C
Groundwater, Well No. 1	4584-A	Fish culture	1960	800 gpm (350 gpm)	9 – 11 °C
Groundwater, Well No. 2	G4-25874C	Fish culture	1978	(200 gpm)[b]	9 – 11 °C
Groundwater, Well No. 3	G4-25874C	Fish culture	1978	(375 gpm)[b]	9 – 11 °C
Groundwater, Well No. 4	G4-25874C	Fish culture	1978	(275 gpm)[b]	9 – 11 °C
Groundwater, Well No. 5	3058B	Fish culture	1996	(125 gpm)	9 – 11 °C
Groundwater, Well No. 6	3058B	Fish culture	1996	(100 gpm)	9 – 11 °C

Source	Certificate Number[a]	Purpose or Use	Priority Date	Amount	Temperature Range
Packwood Spring	3059	Fish culture and domestic use	1943	7.0 cfs	7 – 12 °C

[a]Certificate number 3058 for the Entiat River was amended on February 21, 1996 to include two new wells (5 and 6) with a combined water right allocation of 22.5 cfs.

[b]Wells 2, 3 and 4 have a combined water right allocation of 1,300 gpm, as approved by Certificate G4-25874C in 1978.

D. Chinook Salmon programs

Summary

Spring Chinook Salmon was the primary species propagated at Entiat NFH from 1976 to 2007. The Spring Chinook population was an introduced stock derived from Leavenworth NFH which, in turn, had been derived from Spring Chinook Salmon propagated at Carson NFH.[9] The Spring Chinook program at Entiat NFH was terminated in 2007 because of (a) biological risks posed to the ESA-listed natural population of Spring Chinook Salmon in the Entiat River and (b) the inability to fish for hatchery-origin Spring Chinook Salmon because of "incidental take" on ESA-listed fish. Hatchery-origin adult Spring Chinook Salmon returning to Entiat NFH in 2008 – 2010 were provided to Columbia River Tribes.

Entiat NFH began raising Summer Chinook Salmon as a *segregated-harvest* program in the fall of 2009 as continued mitigation for Grand Coulee Dam. The goal of the program is to provide harvest of 1,600 adult Chinook Salmon in recreational and Tribal fisheries in the Entiat and mainstem Columbia rivers (Fraser et al. 2019). The program was initiated with eyed eggs from the Summer Chinook population propagated at the Wells Fish Hatchery at Wells Dam.[10] Since 2014, the broodstock has been composed of 100% adults returning back to Entiat NFH. The current release objective is 400,000 yearling smolts. Initial releases in 2011 and 2012 were less than 200,000 yearling smolts, and approximately 400,000 to 450,000 yearling smolts have been released each year since (2013 – 2020). This relatively new hatchery program is considered highly successful with Entiat NFH contributing approximately 14 % of all Summer Chinook Salmon crossing Bonneville Dam with a daily harvest limit of six adult fish on the Entiat River.[11] Overall, approximately 1,000 – 4,200 adult Chinook Salmon from Entiat NFH have

[9] The Carson NFH population of Spring Chinook Salmon was derived from upstream-migrating adults trapped at Bonneville Dam in the 1950s. Those fish most likely represented a mixture of adults that originated from populations in the upper Columbia and Snake Rivers.

[10] The Wells Fish Hatchery is located at Wells Dam on the mainstem Columbia River and is owned and operated by the Douglas County Public Utility District. Prior to 2017, the hatchery was operated by the Washington Department of Fish and Wildlife.

[11] https://www.wenatcheeworld.com/news/northwest/fish-tales-salmon-fishery-started-small/article_d4fdef06-a96b-11e9-800b-

been harvested annually since 2013 (commercial, recreational, and tribal fisheries) with an additional 952 to 2,884 adults trapped at the hatchery.[12]

Adult Chinook Salmon returning to Entiat NFH are captured for broodstock from early July to the first week of October and retained in holding ponds until they are spawned in mid-October.[13] The broodstock spawning goal is 150 pairs (300 fish total) to meet the 400,000 smolt release objective (~600,000 green eggs at ~4,000 eggs/female). Fertilized eggs are incubated on 100% well water and chilled from the first week of October to the first week of May. Following yolk absorption, the fry are transferred directly from the incubation trays to 8 x 80-ft. outdoor raceways in May after release of the previous brood year as yearling smolts. Fish are 100% marked (adipose fin clip) and coded wire tagged (~50%) typically around the first week of August. All fish are reared on 100% well water from egg incubation through mid-November of the following year (~1 year) and then subsequently reared on a mixture of river and well water (80 – 85% river water, 15 – 20% well water) from mid-November until force-released as smolts the following April (~18 months of on-station rearing; Table B7, Appendix B).

Fish health measures

To minimize pre-spawn mortalities of adults, formalin is administered at 167 ppm into the holding ponds for one hour, five times per week, to inhibit fungus and parasites (Fraser et al. 2019). Prior to 2020, all spawned females and a minimum of 60 males were ELISA-tested for *Renibacterium salmoninarum*, the causative agent of bacterial kidney disease (BKD). However, beginning in 2020, only a minimum of 60 females are ELISA-tested for *R. salmoninarum* because the low prevalence of the pathogen warrants a less stringent testing strategy (Table 2). In addition, broodstock kidney/spleen and ovarian fluid samples from spawned females are collected and tested for *R. salmoninarum* at a 5% *assumed pathogen presence level* (APPL). Fertilized eggs are water hardened in iodophor and transferred to Heath-type incubation trays. Eggs typically hatch in January, and the resulting alevins are monitored closely until they have completely absorbed their yolk sacs. The fry are then transferred directly to outside raceways in the spring.

33c2851bc726.html#:~:text=In%20the%20case%20of%20Entiat,releases%20just%20400%2C000%20fish%20annually.

[12] Greg Fraser, USFWS, Mid-Columbia Fish and Wildlife Office, Leavenworth, Washington, personal communication.

[13] A pulse of adult fish typically ascend the ladder during the first week of October and are included in the broodstock population.

Table 2. Percent of female broodstock at Entiat NFH with ELISA test values for *Renibacterium salmoninarum* in each of six categories of prevalence. Source: Fraser et al. (2019).

Year	None	Very Low	Low	Moderate	High	Very High	No Data	N
2018	0	85.7	14.3	0	0	0	0	154
2017	0	81.3	17.3	0	0.7	0.7	0	150
2016	0	97.3	2.0	0	0	0.7	0	150
2015	0	72.7	26.7	0	0	0.7	0	150
2014	0	78.2	19.2	0.6	0.6	1.3	0	156
2013	0	62.7	35.3	0.7	0.0	0.7	0.7	153
2012	0.7	11.1	83.7	0	0	0	4.4	135
2011	3.5	85.2	11.3	0	0	0	0	115
2010	0	80.0	18.0	0	0	2.0	0	50
2009	2.3	95.5	2.3	0	0	0	0	44

USFWS fish health guidelines for culture of Summer Chinook Salmon at Entiat NFH specify density index (DI) values of DI < 0.2 (lbs./in.*ft^3), flow index (FI) values of FI < 0.6 (lbs./in.* gpm), and water exchange rates in raceways no greater than 30 minutes to minimize stress and disease risks. Monthly health examinations are conducted throughout the rearing cycle on a minimum of 60 fish per raceway.

E. Disease history at Entiat NFH

The primary disease of concern to Summer Chinook Salmon at Entiat NFH is Bacterial Coldwater Disease, but only incidental mortalities have occurred in the past. Summer Chinook Salmon also show very low prevalence of *R. salmoninarum*, the causative agent of BKD (Table 2). In short, Summer Chinook Salmon at Entiat NFH have had very low incidence of disease since inception of the program in 2009.

V. SENSITIVITY

Sensitivity is the degree to which a system or species is likely to be affected by an environmental disturbance like climate change.

We assessed the known sensitivities of Entiat NFH and the propagated population of Summer Chinook Salmon under current culture protocols.

A. Low surface water flows

Entiat NFH relies on surface water from the Entiat River for rearing Summer Chinook Salmon only during the last six months of culture, mid-November through mid-April of the second culture year (Table B7). Mean monthly flows of the Entiat River for November through April, 1996 – 2019, ranged from approximately 190 cfs (December and January) to approximately 250 cfs in March and 580 cfs in April (Figure B8). Currently, Entiat NFH must implement a

negotiated flow conservation plan from November 1 through April 30 where the quantity of water diverted from the Entiat River cannot exceed 10% of the mean daily flow measured at the USGS stream gage (Appendix A) whenever the flow minus the quantity diverted into the hatchery is less than 100 cfs.[14] During the winter of 2018 – 2019, the hatchery diverted approximately 8 cfs (December) to 17 cfs (March) from the Entiat River. The greatest proportion of surface flow is diverted in March with an average of about 7% of measured flow or 70% of the allowed allocation.

Surface water is also used during broodstock collection, July – September, when an average of approximately 8.7, 3.8 and 3.3 cfs, respectively, have been diverted from the Entiat River into the broodstock collection pond and fish ladder to attract adult salmon. Mean monthly flows of the Entiat River during those months, 1996 – 2019, were approximately 650 cfs in July, 250 cfs in August, and 140 cfs in September (Figure B8). Currently, Entiat NFH must implement a negotiated flow conservation plan from May 1 to October 31where the quantity of water diverted from the Entiat River cannot exceed 5% of mean daily flow at the USGS stream gage whenever the flow minus the quantity diverted into the hatchery is less than 200 cfs.[15] During the low flow month of September, the hatchery has diverted an average of approximately 2.4% of the surface flow of the Entiat River, about 48% of the allowable allocation under the conservation plan.

Overall, Entiat NFH is considered to have low sensitivity to low surface flows of the Entiat River when surface water is withdrawn for fish culture (November – June) and when water is withdrawn for broodstock collection (July – September). The hatchery could still meet its surface water demand during the low flow month of September even if surface flows decreased by 30%.

B. High surface water flows and flood risks

The Entiat River is largely a snow-driven watershed with mean flows of approximately 1,500 – 1,600 cfs during the snowmelt months of May and June but less than ~650 cfs during the other 10 months (Figure B8). Entiat NFH is thus considered sensitive to increased precipitation and/or warmer temperatures in the spring that would increase peak flows of the Entiat River relative to historic values.

In addition to peak flows during the spring, ice dams are a frequent occurrence on the Entiat River upstream from the hatchery during severe cold weather.[16] These dams often "blow out," thus posing a potential flood risk to facilities downstream. An increase in winter precipitation coupled with an increase in the number of days of severe cold weather conditions that create ice dams could thus increase flood risks.

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[14] Craig Chisam, Manager, Entiat NFH, personal communication, February 25, 2020.

[15] Ibid.

[16] Ibid.

One of the biggest hazards to the hatchery from high surface flows are debris and siltation that can enter the intake structure and sand-settling basin. When those events occur, hatchery staff must expend considerable effort removing debris and sediment from the sand-settling basin to prevent clogging of the screen chamber.

Overall, Entiat NFH is considered to have moderate sensitivity to flood risks and high surface flows of the Entiat River.

C. Low air and surface water temperatures[17]

Water temperatures of the Entiat River tend to be consistently near freezing during the coldest months of the year, anytime from mid-November to mid-February (Table B3). Those temperatures are modulated with 15 – 20% groundwater to yield fish-culture temperatures of approximately 2 – 4 °C (Table B7). Those temperatures inhibit ice formation in raceways and simulate natural growth cycles of juvenile Chinook Salmon (optimum growth temperatures = 8.6 – 15.9 °C; Table B1).

Low water temperatures of the Entiat River, coupled with freeze-thaw cycles, generate large quantities of surface-frazil ice during winter. Direct icing of the intake rack is not a significant issue because the old metal rack was replaced with a high-density polyethylene (HDPE) rack a few years ago. However, large quantities of slush ice do enter the water intake system and are transported approximately 1,000 feet to the screen chamber where the ice is separated and transported back to the river through a 700-foot bypass pipe. Hatchery staff must closely manage this water intake system in winter to ensure a constantly-moving "conveyor belt" of slush-ice through the 1,700 foot-long system to prevent the screen chamber from clogging. Any interruption of this flow results in the screen chamber quickly filling with ice, instantly blocking the water supply to the fish and hatchery.

Ice problems occur primarily under two conditions: (1) when the river is not frozen but water temperatures reach 0 °C, resulting in large quantities of surface ice and slush in the river, and (2) during snowstorms when the river is not frozen over but near freezing, and snowflakes do not melt on the surface. Any increase in the frequency of freeze-thaw cycles in the Entiat River Valley would increase the frequency of slush-ice problems in the water intake system at Entiat NFH. In the past, the surface of the Entiat River tended to stay frozen during winter, but in recent years, that trend has transitioned to more frequent freeze-thaw cycles, thus increasing the risk of slush-ice problems in the water intake system. When ice accumulates in the screen chamber and associated water delivery pipelines, hatchery staff must work several hours to unclog the system. Hatchery staff have been able to lessen those impacts by injecting well water into the intake vault, thus increasing the water temperature by a few tenths of a degree to help mitigate ice accumulation.

[17] Information in this section was provided by Craig Chisam (IBID).

Under current and historic conditions, Entiat NFH is considered to have moderate sensitivity to sustained low air and surface water temperatures during winter. However, the hatchery appears to be very sensitive to future conditions that would increase the frequency of freeze-thaw cycles in the Entiat River Valley, as has occurred in recent years.

D. High surface water temperatures

Mean monthly water temperatures of the Entiat River in July (15.4 °C), August (17.3 °C) and September (13.8 °C;) – when adults are trapped for broodstock – currently exceed or approach the upper optimal temperature threshold for adult Chinook Salmon (14.0 °C) (Tables B1 and B3). However, most broodstock are collected in July before the river reaches its maximum annual temperature and are transferred to an adult holding pond supplied with 100% well water (3rd pass reuse water from raceways) at ~10 °C (Table B6). A second pulse of adult fish typically swim up the ladder and into the collection pond during the first week of October after surface water temperatures have dropped below 14 °C. As such, Chinook Salmon broodstock held on station during the summer are considered to have low sensitivity to high surface water temperatures. However, any increase in the magnitude or duration of high water temperatures from late spring through early fall could impede the upstream migration of Chinook Salmon adults, and thus, the ability of the hatchery to collect broodstock. Consequently, Chinook Salmon adults migrating upstream in the Entiat River are considered sensitive to increases in surface water temperatures when adults are trapped for broodstock (July – October). Disease risks to adults entering the hatchery could also increase because of warmer water temperatures, but the prevalence of disease has largely been a non-issue at Entiat NFH because of the extensive use of groundwater.

Juvenile Chinook Salmon at Entiat NFH have very low sensitivity to increases in surface water temperatures because those fish are reared on surface water only during the late fall through early spring of their second year when water temperatures are well below critical levels.

E. Groundwater temperatures

Summer Chinook Salmon at Entiat NFH depend significantly on well water throughout all life history stages (Table B7). Mean monthly groundwater temperatures have ranged historically from 9.0 °C (March, April) to 10.4 °C (October), well within the optimum temperature ranges for Chinook Salmon (6.0 – 15.9 °C; Table B1). As such, Summer Chinook Salmon at Entiat NFH have low sensitivity to potential changes in groundwater temperatures.

F. Groundwater availability

Flow index (FI) values for juvenile Chinook Salmon at Entiat NFH, when subyearlings are maintained on 100% well water, have historically been less than the upper guideline value of FI = 0.6 except in September and October when mean monthly values have peaked at FI = 0.81 (Table B9, Part A.). August, September and October are particularly critical months when

surface flows of the Entiat River are lowest (Figure B8), and 100% well water is used for maintaining sub-yearlings and adult broodstock. FI values drop significantly in November (FI < 0.4) when culture water is switched from 100% well water to 80 – 85% surface water.

Because of the high dependence of Entiat NFH on groundwater for rearing juvenile Chinook Salmon, regular maintenance of the wells and infiltration gallery is critical. Groundwater supplies during the summer must be sufficient to meet fish culture demands when the quantity of surface water is inadequate and/or the temperature too high for maintaining salmon on station. Currently, dedicated funding for regular maintenance of the groundwater infrastructure is not provided. Almost all funds used for operating Entiat NFH are through an Interagency Agreement with the U.S. Bureau of Reclamation (BOR), and that funding must first support recurring operational expenses (e.g., salaries, power, fish feed, supplies, etc.) with any remaining funds available for deferred maintenance. Those latter funds are limited, and some maintenance is deferred for many years. This lack of dedicated funding for maintaining the groundwater infrastructure was revealed as a significant deficiency and potential vulnerability of Entiat NFH during the adaptive capacity meeting between the CCVA Team and the HET (Appendix C). Indeed, the inability of Entiat NFH to perform regularly scheduled maintenance of the groundwater infrastructure (e.g., every 3 to 5 years) due to the lack of dedicated funding may be the greatest sensitivity of the hatchery.

Based on water-use patterns, we consider Summer Chinook Salmon at Entiat NFH to have moderate sensitivity to potential decreases in groundwater availability, particularly in the early fall when surface flows of the Entiat River are lowest.

G. Disease risks

In general, disease risks for Chinook Salmon are greatest at water temperatures above 14 °C (Tables B1 and B2). Summer Chinook Salmon at Entiat NFH during the juvenile rearing phase are considered to have low risk for disease because they are reared on 100% groundwater at ~9.0 – 10.5 °C during their first year (12 months) and subsequently on 80 – 85% surface water (~ 0 – 9.0 °C) during the coldest six months of the year (November – April). Indeed, mortalities due to disease have generally been very low for juvenile Chinook Salmon at Entiat NFH with incidental mortalities caused primarily by bacterial coldwater disease.[18] Although flow indexes exceed the generalized FI < 0.6 fish health guideline in the early fall prior to transition to 80 – 85% surface water in November, fish health staff consider water exchange rates per raceway to be sufficient to minimize disease risks. On the other hand, a portion of those fish are also on 2nd pass or 3rd pass reuse water which increases the effective flow index values above calculated values. High flow index values in the early fall are mitigated by the use of pathogen-free groundwater. Those risks would likely increase in the future if water temperatures increase or the availability of

[18] Craig Chisam, Manager, Entiat NFH, personal communication.

groundwater decreases. Overall, we consider juvenile Summer Chinook Salmon at Entiat NFH to have low sensitivity to disease risks under current culture protocols.

In contrast to the relatively low water temperatures experienced by juveniles, adult Summer Chinook Salmon return to the hatchery during the three warmest months of the year (July – September) when mean monthly water temperatures of the Entiat River approach or exceed the 14 °C risk threshold for disease (Tables B2 and B7). However, the majority of those fish are collected in early July and transferred within one to seven days to an adult holding pond supplied with 100% groundwater. Few adults return to the hatchery in August and September, but a second pulse of adults are trapped and retained for broodstock after water temperatures cool during the first week of October.[19] The ability to hold adult broodstock in 100% groundwater during the summer significantly reduces disease risks and pre-spawning mortality. Any increase in temperature of the Entiat River during the summer and fall months would be expected to also increase disease risks to upstream-migrating adults trapped for broodstock. Hence, we consider adult Summer Chinook Salmon at Entiat NFH to have moderate sensitivity to disease risks under current broodstock collection protocols.

H. Fire risks

Significant fires have been recorded within the Entiat River basin since the 1880's. The Tyee Creek fire, one of the largest in Washington State history, was initiated by a lightning strike on July 24, 1994 and burned over 140,000 acres in the Mad River and upper Entiat River valleys. More recently, the Cougar Creek fire burned over 43,000 acres in August, 2018. The incidence and severity of wildfires in Washington State have increased significantly since the 1980s. Wildfires in the summer and early fall are often followed by mudslides the following winter and spring. High siltation of the Entiat River upstream of the hatchery following major wildfire and precipitation events reduces water quality in the hatchery when yearling Summer Chinook Salmon are reared on surface water. We thus consider the Entiat River basin and the hatchery to have high sensitivity to wildfire risks, although those risks may be due primarily to floating debris and siltation during heavy rains following a fire event and not necessarily due to direct fire effects. [20]

I. Sensitivity main points

- Entiat NFH is considered to have low sensitivity to low surface flows of the Entiat River when surface water is withdrawn for fish culture (November – June) and when water is withdrawn for the adult collection pond and ladder during broodstock collection (July – September).

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[19] Craig Chisam, Manager, Entiat NFH, personal communication.

[20] An *Entiat Valley Community Wildfire Protection Plan* was developed between 2005 and 2010. The plan (106 pages) addresses the high wildfire risks of the Entiat River Valley. Available at: https://www.dnr.wa.gov/publications/rp_burn_cwpp_entiatvalley.pdf .

- Entiat NFH has moderate sensitivity to high surface flows and flood risks of the Entiat River. The biggest hazard during high surface flows may be debris and silt entering the water intake system and not necessarily floods per se.
- Entiat NFH has moderate sensitivity to low air and surface water temperatures, due primarily to the formation of frazzle/slush ice in the Entiat River that can clog the screen chamber if not removed manually. As such, the hatchery is considered very sensitive to future conditions that would increase the frequency of freeze-thaw cycles and the formation of frazzle/slush ice, as has occurred in recent years.
- Chinook Salmon broodstock held on station during the summer, and juveniles during winter, are considered to have low sensitivity to high surface water temperatures under current culture protocols. However, Chinook Salmon adults migrating upstream in the Entiat River are considered sensitive to increases in surface water temperatures when adults are trapped for broodstock (July – October).
- Chinook Salmon at Entiat NFH are considered to have low sensitivity to future changes in groundwater temperature.
- Chinook Salmon at Entiat NFH have moderate to high sensitivity to potential decreases in groundwater availability, particularly during the summer and early fall when surface water flows of the Entiat River are lowest, and subyearlings and adult broodstock are maintained on 100% well water.
- Juvenile and adult Chinook Salmon at Entiat NFH have low to moderate sensitivities, respectively, to disease risks under current fish culture and broodstock collection protocols.
- The Entiat River basin and Entiat NFH have high sensitivity to wildfire risks based on recent wildfire events and summer conditions, and those risks appear to be increasing with more frequent and larger wildfires in the region since the 1980s.

VI. EXPOSURE

Exposure is the magnitude or degree to which a system or species is expected to be subjected to an environmental disturbance such as climate change.

The methods we used to quantitatively assess the future exposure of Entiat NFH to climate change in the 2040s are described in Appendix B. Those methods are summarized below.

A. Methods

Surface water temperatures in the 2040s

Outputs from 10 statistically downscaled GCM simulations for the A1B emissions scenario were used to project future air temperatures of the Entiat River watershed upstream of the hatchery. The methods of Mohseni et al. (1998) and Mantua et al. (2010) were used to first parameterize the non-linear relationship between (a) modelled historic mean weekly air temperatures of the

watershed upstream of the hatchery[21] and (b) historic water temperatures of the Entiat River adjacent to the hatchery (Figures B3, B4; Table B3). That relationship between air and water temperature was then used to project future water temperatures of the Entiat River in the 2040s based on projected air temperatures from the 10 GCM models.

Groundwater temperatures in the 2040s

Exploratory regression analyses revealed a positive statistical correlation between groundwater temperatures from the wells and surface water temperatures of the Entiat River adjacent to the hatchery but with a three-month lag of groundwater temperature (Appendix B).[22] A parameterized regression relationship between groundwater and surface water temperatures was used to project future groundwater temperatures in the 2040s from the projected temperatures of the Entiat River.

Water availability at Entiat NFH during the 2040s

The variable infiltration capacity (VIC) hydrologic model of Liang et al. (1994) was used to project future, mean-monthly stream flows of the Entiat River in the 2040s under the A1B emissions scenario as forced by output from the same ensemble of 10 GCMs used to project future water temperatures (Appendix B). Groundwater availability in the 2040s was assessed according to four separate scenarios (see following Impacts section) because available data were insufficient to allow derivation of a predictive mathematical relationship between surface flows and well-recharge rates, although the two water sources appear to be hydraulically connected.

B. Results and Discussion

Climate and hydrologic modeling under the A1B emissions scenario indicate that the Entiat River basin will most likely experience (a) warmer air and stream temperatures, (b) reduced snowpack and earlier snowmelt runoff, (c) lower base flows and more extreme low-flow events in summer, and (d) higher flows in winter and larger magnitude peak flows (Tables B3 – B6; Figures B4 – B15).

Temperature projections

Mean air temperatures over the entire Entiat River watershed are projected to increase every month (mean increase = 2.0 °C) with the largest absolute increases (2.6 – 3.0 °C) occurring during summer, July – September (Table B4; Figure B4).

Mean monthly water temperatures of the Entiat River adjacent to the hatchery are projected to increase every month in the 2040s, compared to the historic baseline values, by an average of 1.2 °C (range = 0.7 – 1.9 °C), with projected peak temperatures of 16.7 °C and 16.5 °C in July and

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[21] Data available from Climate Impacts Group, University of Washington: http://warm.atmos.washington.edu/2860 .

[22] $T_{GW} = 8.693 + (0.110 \times T_{SW})$, where T_{GW} is the mean monthly water temperature (°C) measured in the groundwater wells, and T_{SW} is the mean monthly surface water temperature in the Entiat River adjacent to the hatchery three months earlier.

August, respectively (Table B6; Figure B15). The largest increases in mean monthly water temperatures of the Entiat River are projected for May (+1.6 °C), August (+1.5 °C), September (+1.9 °C) and October (+1.5 °C).

Mean monthly groundwater temperatures in the 2040's are projected to increase by 0.07 to 0.2 °C when compared to the historical baseline (Table B6).

Precipitation projections

Total annual precipitation and mean monthly precipitation, averaged over the entire Entiat River watershed, were projected to be largely unchanged in the 2040s compared to historic values with a mean annual increase of approximately 6% (historical = 83 mm; 2040s =88 mm; Table B4, Figure B5). Most of that increase is projected to occur November through January (Figure B5).

Despite little change in mean annual and monthly precipitations in the 2040s, substantially more of that precipitation is projected to fall as rain and less as snow in the 2040s relative to historic patterns (Figure B6). For example, the peak snow water equivalent (SWE, aka snow pack) in April in the 2040s is projected to decrease from a mean of 433 mm to 322 mm (26% decrease) based on the mean output values from the 10 GCMs.

Hydrographic projections

Mean annual flows of the Entiat River for the 2040s are projected to increase from a modeled historical value of 653 cfs to a GCM ensemble mean of 729 cfs, a ~12% increase (Table B5). More importantly, the shape of the hydrograph for the 2040s is expected to differ considerably from historic averages (Figures B8, B9). Mean monthly flows of the Entiat River at the hatchery from June through August are projected to decrease by 38.5% (GCM range = 20.0% – 56.5%) compared to the modeled historic average, whereas mean flows from late fall through early spring (November – April) are projected to increase by 65% (GCM range = 53.7 – 113.8%). Half of the annual discharge of the Entiat River was projected to occur at least 18 days earlier in the 2040s compared to the historic average for most of the watershed upstream from the hatchery (Figure B10). These hydrograph changes reflect more precipitation falling as rain and less as snow in the 2040s compared to historic values.

Warmer air temperatures with more precipitation falling as rain and less as snow is expected to affect minimum and maximum flows of the Entiat River. Minimum 7-day low flows over a 10-year period (7Q10 statistics) were projected to decrease slightly from a historical mean of 68 cfs to a GCM average of approximately 65.4 cfs by the 2040s (Figure B12). On the other hand, the magnitudes of peak flows with recurrence probabilities of 20, 50, and 100 years (aka as 20, 50, and 100 year floods) are expected to increase substantially in the 2040s with the highest flows (100 year recurrence interval) projected to increase from about 8,000 cfs historically to a GCM average of approximately 13,700 cfs, a 70% increase (Figure B14).

C. Exposure main points

- Mean air temperatures over the entire Entiat River watershed are projected to increase every month (mean increase = 2.0 °C) with the largest absolute increases (2.6 – 3.0 °C) occurring July – September.
- Mean monthly water temperatures of the Entiat River adjacent to the hatchery are projected to increase by an average of 1.2 °C (range = 0.7 – 1.9 °C) by the 2040s with future mean temperatures in July and August of 16.7 °C and 16.5 °C, respectively. Mean groundwater temperatures of the wells at Entiat NFH are projected to increase by 0.07 to 0.2 °C in all months when compared to the historic baseline.
- Total annual precipitation, averaged over the Entiat River watershed, is expected to increase by approximately 6% in the 2040s compared to the historic average, with most of that increase occurring in November through January. However, substantially more of the total annual precipitation is projected to fall as rain and less as snow with the mean peak snow pack in April projected to be 26% less in the 2040s than historically.
- Although mean annual flows of the Entiat River in the 2040s are projected to increase by only 12%, the shape of the hydrograph in the 2040s is expected to differ considerably from historic patterns, with mean monthly flows of the Entiat River from June through August projected to decrease by approximately 38% but increase by approximately 65% from November through April. Those changes reflect transition of the Entiat River basin from primarily a snow-melt driven watershed historically to a mixed rain-and-snow-melt driven watershed in the 2040s.
- The lowest consecutive seven-day flows over a ten-year period are projected to decrease slightly from 68 cfs historically to 65 cfs in the 2040s, whereas 100-year peak flows are projected to increase substantially from about 8,000 cfs historically to nearly 14,000 cfs in the 2040s.

VII. IMPACT

Impact is the combination of sensitivity and exposure of a system or species to an environmental disturbance such as climate change.

To assess the impacts of the projected future climate to Entiat NFH, we first addressed the following question: Could the current Summer Chinook Salmon program continue to operate successfully, according to existing schedules and protocols, under the climatic conditions projected for the Entiat River watershed in the 2040s? To address this question, we focused primarily on projected changes in water temperature and water availability at the hatchery, as summarized in the preceding Exposure section. Our specific objectives were to: (a) determine if future climate conditions are likely to preclude culture of Summer Chinook Salmon at Entiat NFH, and (b) identify the magnitude and timing of sub-lethal effects (e.g., altered growth rates, disease risks, etc.) that may affect survival and growth of Summer Chinook Salmon at the

hatchery. Details of our analyses are presented in Appendix B. Our methods are summarized below.

A. Methods

To assess potential impacts of projected future climate, we first collated physiological tolerance data for Chinook Salmon and thermal growth data for common salmon pathogens (Tables B1and B2). We used the temperature-driven fish growth model of Iwama and Tautz (1981) and empirical data on recent rearing conditions at the hatchery to predict future mean size and total biomass of Chinook Salmon each month during the freshwater hatchery phase as a function of projected water temperatures in the 2040s, assuming an unlimited food ration. We then derived flow index (FI) and density index (DI) parameters (Piper et al. 1982, Wedemeyer 2001) for each month of culture in the 2040s as part of the modeling framework to assess future impacts of changing water temperature and availability to Summer Chinook Salmon at the hatchery (Appendix B). Flow and density index values were then bias-corrected based on the ratio of mean historical empirical values to the modeled historical values (see Appendix B for details).

Many uncertainties exist regarding the actual quantities of groundwater and surface water available to the hatchery as a function of future flows of the Entiat River. Consequently, we modeled groundwater and surface water availability in the 2040s according to four separate scenarios.

- Scenario A. The *status quo*: The quantities of surface or groundwater available to the hatchery in the 2040s was equal to the quantities used for brood years 2013 – 2017.
- Scenario B. Surface water available to the hatchery would change (increase or decrease) in proportion to mean flows of the Entiat River[23], but the quantity of well water available to the hatchery would remain unchanged from the quantity used for brood years 2013 – 2017.
- Scenario C. The hatchery could utilize more surface water in months when flow of the Entiat River was projected to increase, but groundwater from the wells was assumed to buffer or compensate for any potential reduction in surface water availability in months when flows of the Entiat River were projected to decrease.
- Scenario D. This was the most pessimistic scenario: Future reductions in surface water flows would result in the same proportional decrease in groundwater availability from the wells, but the hatchery could not use additional surface or well water in months when flows of the Entiat River are projected to increase.

[23] For example, if the hatchery utilized 100% surface water in a given month and historically used 10 cfs but surface flows in that month were projected to decline by 40%, then the water available to salmon rearing in the future would be 10 cfs × 0.6 = 6 cfs)

B. Results and Discussion

Summer Chinook Salmon program

Groundwater temperatures projected for the 2040s (9.0 – 10.5 °C) are within the optimal temperatures for eggs and fry (8.4 – 12.4 °C) and juveniles (8.6 – 15.9 °C) when 100% well water is used for fish culture. Projected groundwater temperatures from July through October (9.5 – 10.5 °C) are within the optimal spawning temperatures of Chinook Salmon (9.0 – 12.3 °C) when adults are maintained for broodstock on 100% well water. Groundwater temperatures in the 2040s are not expected to affect the ability of Entiat NFH to continue rearing Chinook Salmon.

Surface water temperatures projected for the Entiat River during November – April in the 2040s (2.5 – 7.6 °C), when a blend of 80 – 85% surface water and 15 – 20% groundwater is used for fish culture, will result in culture temperatures (2.2 – 7.8 °C) that are well below the upper optimal temperature limits for juvenile Chinook Salmon (15.9 °C) and smolts (14.0 °C; Table B1). Those temperatures are also below the outbreak temperatures for common salmon diseases except bacterial coldwater disease (outbreak temperature = 4.0 – 10.0 °C, Table B2). During the summer months (July – September) when adults are collected for broodstock, projected water temperatures of the Entiat River (14.5 to 16.7 °C; Table B6) exceed the upper temperature optima for adults (14 °C), potentially increasing physiological stress on adults returning to the hatchery in the 2040s. Overall, higher temperatures projected for the Entiat River in the 2040s are not expected to affect the ability of Entiat NFH to continue rearing Summer Chinook Salmon at the hatchery, but those higher temperatures could impede the ability of the hatchery to trap broodstock during the summer. They could also increase disease risks for adults.

In response to warmer water temperatures in the 2040s, growth rates of juvenile Chinook Salmon are projected to increase throughout the rearing period (Table B8). Most of the increase in mean size of juveniles is predicted to occur in December through April of the second year when yearlings are reared on 80 – 85% surface water. Overall, Chinook Salmon smolts at the time of release from the hatchery in April are predicted to be, on average, 15.6% heavier and 4.9% longer compared to historical sizes (Table B8).

Mean monthly flow index (FI) patterns under the four water availability scenarios modeled for the 2040s are similar to the historic pattern with one notable exception (Figure B18a). Scenario D yielded rather significant increases in FI values in July, August and September (FI = 0.87 – 1.68) compared to historic values because that scenario assumed that groundwater availability during the summer would decrease in proportion to projected decreases in surface flows of the Entiat River. For example, mean surface flows of the Entiat River for July in the 2040s are projected to be approximately 35% lower than the stream gage average for 1996 – 2019 and over 50% lower than the modeled historic mean (Figure B8). Conversely, under Scenario B, flow index values for the 2040s during the final six months of rearing (November – April) are projected to decrease from a historic average of FI = 0.41 to an average of FI = 0.26, despite

greater total biomass of fish, because that scenario assumed more surface water could be used in proportion to higher surface flows in winter. Scenario C yielded identical results to Scenario B over the entire rearing cycle because Chinook Salmon are reared on 100% well water when surface flows are projected to decrease (June – September), and thus, a reduction in surface water availability – which distinguished those two scenarios – did not affect groundwater availability for the hatchery.

Flow index values for Chinook Salmon at Entiat NFH have historically exceeded the threshold guideline value of 0.6 during July, September and October (FI = 0.69 – 0.81) when subyearling juveniles are reared on 100% well water. The use of 100% groundwater allows flow index values greater than FI = 0.6 without increasing disease risks appreciably compared to hatcheries that use surface water during the summer when water temperatures may approach the upper physiological tolerance levels of Chinook Salmon. That pattern of FI > 0.6 during the summer at Entiat NFH is projected to continue in the 2040s; hence, any decrease in groundwater availability during the summer would be expected to further increase FI values, as illustrated by Scenario D. On the other hand, Scenario D may represent a worse-case scenario because it assumes a strict proportional relationship between surface flows and groundwater availability (i.e., a regression coefficient = 1.0). Much less uncertainty exists regarding the relationship between surface water and groundwater temperatures, and the regression coefficient for that relationship was estimated as only 0.11 (Appendix B).

Density index values projected for the 2040s followed a pattern similar to flow index values under Scenario A with only slight increases in DI values in November – April compared to historic values (Figure B18b). Those slightly higher DI values resulted from a proportionate increase in total biomass prior to release because of slightly warmer stream temperatures in winter, but density indexes never exceeded the guideline value of DI = 0.2. Density and flow index projections for 2040s assume no future changes in the number of fish reared or total rearing capacity of the hatchery.

Hatchery infrastructure

The hydrologic modeling projects dramatic increases in the magnitude of winter flows (Figures B8, B9) and peak flows over 20, 50 and 100 year time frames (Figure B14). However, we did not model the effects of potential future floods on hatchery infrastructure because such analyses were beyond the scope of our objectives. As such, we defer to hatchery staff and hydraulic engineers to assess potential flooding and infrastructure damage at projected peak flows of 8,000 – 14,000 cfs in the Entiat River.

In a similar context, we did not attempt to model future fire risks in the Entiat River watershed and their potential direct effects (e.g., fire damage) or indirect effects (e.g., mudslides, siltation) to the operations and infrastructure of Entiat NFH. However, mean air temperatures over the entire Entiat River watershed are projected to increase by 1.5 to 3.0 °C relative to historic values with the greatest increases occurring June through October (Table B4). Those higher temperatures coupled with substantial reductions in spring snow pack projected for the 2040s are

expected to increase fire risks. We note those fire risks here, and the likelihood of them increasing in the future, to provide a framework for assessing the adaptive capacity of the hatchery to respond to those higher risks.

C. Impact main points

- Groundwater temperatures projected for the 2040s (9.0 – 10.5 °C) are not expected to affect the ability of Entiat NFH to continue rearing Summer Chinook Salmon.
- Surface water temperatures projected for the Entiat River during November – April in the 2040s (2.5 – 7.6 °C), when a blend of 80 – 85% surface and 15 – 20% well water is used for culture, are not expected to affect the ability of Entiat NFH to continue rearing Summer Chinook Salmon at the hatchery. However, higher temperatures of the Entiat River in summer (14.5 to 16.7 °C) could increase the incidence of disease among upstream-migrating adults and/or affect the ability of the hatchery to trap broodstock if high water temperatures in summer impede upstream migration of adults.
- Chinook Salmon smolts at Entiat NFH in the 2040s are predicted to be approximately 15% heavier and 5% longer at release than historically.
- Flow index values (FI) in the 2040s are expected to follow historic averages assuming the quantities of surface and groundwater available to the hatchery remain unchanged (Scenario A). However, if groundwater availability during the summer decreases in response to lower base flows of the Entiat River, then FI values are projected to increase substantially during July, August and September (FI > 1.0) when subyearlings are maintained on 100% well water.
- Density index values projected for the 2040s followed a pattern similar to flow index values under Scenario A with only slight increases in DI values relative to historic values but never exceeded the upper threshold guideline value of DI = 0.2.
- We did not directly model flood or fire risks to Entiat NFH. However, we expect flood risks to increase in the 2040s because of substantial increases in peak flows of the Entiat River in winter. Similarly, we expect fire risks to increase in the 2040s because of projected increases in mean summer air temperatures (+ 2.1 – 3.0 °C, June through September) coupled with substantial decreases in spring/summer snow pack.

VIII. ADAPTIVE CAPACITY

Adaptive capacity is the ability or capacity of a system or species to adjust or adapt to the impact of an environmental disturbance such as climate change.

The Assessment Team identified two types of adaptation strategies in response to each of the climate change impacts described in the preceding section: (1) infrastructure adaptations to the physical plant of the hatchery, and (2) protocol and management adaptations of the culture programs.

A. Methods

The Assessment Team led a meeting on August 25, 2021 to discuss the existing adaptive capacity of Entiat NFH and possible adaptation strategies in response to projected climate impacts in the 2040s (Appendix C). The purposes of the meeting were: (a) assess the ability of Entiat NFH to maintain its current Spring Chinook Salmon program in view of future climate impacts, and (b) propose possible adaptation strategies to reduce those impacts consistent with the mission and goals of the hatchery and its programs. Meeting participants consisted of the Assessment Team, the HET for Entiat NFH, and a representative of the U.S. Bureau of Reclamation. Members of the HET provided technical expertise and experience to assess the capability of Entiat NFH and its programs to adapt to the projected impacts of climate change.

Overall, Entiat NFH may be one of the least climate-impacted National Fish Hatcheries in the Pacific Northwest because of its ability to use groundwater for a significant portion of its fish culture needs. Nevertheless, issues related to warmer surface water temperatures in summer and substantially higher peak flows of the Entiat River in late fall and winter suggest the need for adaptive planning. As such, the Workgroup identified a limited number of adaptive capacity options to address impacts that could affect future operations.

B. Results and Discussion

Summer Chinook Salmon program

1. ***Impact:*** Higher temperatures of the Entiat River in summer (14.5 to 16.7 °C) exceed the upper optimal temperature for adults (14 °C) and could impede the ability of the hatchery to trap broodstock. Higher surface water temperatures in the 2040s may also increase disease risks among adults trapped for broodstock.

   (a) Infrastructure adaptations:

   - Additional groundwater and/or mechanically-chilled surface water could be provided to the adult capture pond and ladder to reduce water temperatures and disease risks if higher water temperatures of the Entiat River become a physiological stress and/or disease issue in the future. However, available groundwater appears to already be 100% allocated, and the capacity to chill surface water does not currently exist.
   - Overall, potentially fewer adults back to the hatchery in the 2040s is not currently anticipated to be a problem, even with warmer water temperatures of the Entiat River during the summer. The hatchery currently traps 2,000 – 4,000 adults for potential broodstock each year, but only 150 females and 150 males are typically needed to meet the 400,000 smolt release objective of the program.

   (b) Protocol and management adaptations*:*

- Fish Health staff recommends case-specific treatments, as needed, if the pathogen load of adults entering the hatchery becomes an issue due to warmer temperatures of the Entiat and Columbia rivers. For bacterial pathogens/diseases, antibiotics may be necessary, but their use should be minimized and targeted to specific pathogens isolated by Fish Health staff. In general, disease issues at Entiat NFH have been minimal in the past because adults trapped for broodstock are transferred to holding ponds supplied with 100% groundwater until they are spawned.
- Higher water temperatures of the Entiat River during the summer could result in fewer adults trapped in July and August, but more adults trapped in late September and October after river temperatures start to cool. Large numbers of fish in excess of broodstock needs arriving in late September and October would likely require additional personnel temporarily to assist with sorting and surplusing of fish prior to spawning.[24]
- The potential shift in return timing from summer to early fall of adult Chinook Salmon could impact the quality of surplus fish provided to the Tribes for subsistence and ceremonial purposes. Any modification of broodstock collection protocols in response to climate-mediated impacts would need to consider those Tribal resource needs.

2. ***Impact:*** Chinook Salmon smolts at Entiat NFH in the 2040s are predicted to be approximately 15% heavier and 5% longer at release than yearling smolts historically.

   (a) Infrastructure adaptations: None identified.

   (b) Protocol and management adaptations:

   - The HET did not consider slightly faster growth rates due to warmer water temperatures to be a concern. Warmer temperatures in winter could be an advantage by reducing icing conditions.
   - If faster growth rates become a problem in the future (e.g., precocious maturation of males), the hatchery can extend the period of chilling, adjust feeding rates and schedules, and/or release smolts earlier in the spring.[25]

3. ***Impact:*** If groundwater availability during the summer decreases in proportion to lower base flows of the Entiat River (modelled Scenario D), then flow index (FI) values are

[24] The ladder is currently open July 1 through October 31, but those dates could be adjusted in response to any shifts in the return timing of adult Chinook Salmon.

[25] Outmigration of salmon smolts is timed naturally to river conditions. With warmer water temperatures and earlier snow melt, outmigration of natural-origin smolts may occur earlier in the spring. Hatchery management could likewise adapt by releasing smolts earlier in response to faster growth rates and future river conditions.

projected to increase substantially during July, August and September (peak FI > 1.6) when subyearlings are maintained on 100% well water.

(a) Infrastructure adaptations:

- Rehabilitate the infiltration gallery and ensure funding is available for regular maintenance of the wells and gallery.
- Add a third water collection line to the infiltration gallery to potentially increase flows and yield.
- Explore opportunities for additional wells on 10 acres that were recently purchased adjacent to the hatchery.
- As a last resort, develop a partial-reuse aquaculture system (PRAS) if the groundwater availability during the summer decreases appreciably and other adaptive measures are insufficient for maintaining the Summer Chinook Salmon program.

(b) Protocol and management adaptations:

- Establish a budgeted maintenance and rejuvenation schedule for the wells and infiltration gallery (e.g., every 5 years) to maximize groundwater flows into the wells and infiltration gallery (e.g., AquaFreed process).
- Release a portion of the juveniles as subyearlings to maintain flow index values within fish health guidelines if the incidence of disease among juvenile Chinook Salmon increases because of an increase in water temperature and/or a decrease in water availability when fish are reared on 100% groundwater.

Hatchery infrastructure

1. ***Impact:*** Transition of the Entiat River from primarily a snowmelt-driven watershed to a mixed-snow-and-rain-driven watershed is expected to increase mean monthly flows of the Entiat River by approximately 65% from November through April in the 2040s. In addition, 100-year peak flows of the Entiat River are projected to increase from about 8,000 cfs historically to nearly 14,000 cfs by the 2040s. As a result, flood risks and issues related to floating debris and high sediment loads of the Entiat River are expected to increase in the future. Flood risks also increase during freeze-thaw cycles when ice dams form in the Entiat River. Higher mean air temperatures of the Entiat River watershed in winter (1.6 – 1.8 °C) are expected to increase the frequency of freeze-thaw cycles, thus increasing the likelihood of ice-dam blow-out and slush-ice in the water intake system.

   (a) Infrastructure adaptations:

   - None identified.
   - The hatchery buildings and raceways are above the flood plain of the Entiat River, 100-year flood risks are primarily in the area around the wells.

(b) Protocol and management adaptations:

- The biggest concern from high flows of the Entiat River is floating debris and silt in the water intake system of the hatchery.
- Ensure the wells and infiltration gallery are well maintained so that 100% groundwater can be used for fish culture if the surface water intake needs to be closed during high flows of the Entiat River to prevent silt and debris from entering the water intake system for the hatchery and during freeze-thaw cycles that produce large amounts of frazzle ice .

2. ***Impact:*** Higher mean air temperatures during the spring and summer, coupled with slight decreases in mean monthly precipitation, are expected to increase fire risks to the Entiat River watershed and hatchery through the 2040s.

(a) Infrastructure adaptations:

- None identified.
- Fire at the hatchery is not as big of a concern as mud, ash and debris washed into the Entiat River from upper watershed after major fires have occurred. Several inches of mud and debris have been deposited in the raceways following fires in the upper watershed. Such debris flows can pose a fish health risk by introducing pathogens and/or increasing fish stress due to poor water quality.

(b) Protocol and management adaptations:

- Ensure the wells and infiltration gallery are well maintained so that 100% groundwater can be used for fish culture if the surface water intake needs to be closed during high sediment loads of the Entiat River.

C. Adaptive Capacity main points (options)

- Entiat NFH may have limited capacity currently to reduce water temperatures in the adult capture pond and ladder if higher water temperatures of the Entiat River in the future become a physiological stress and/or disease issue for Summer Chinook Salmon. Groundwater supplies are already 100% allocated (or nearly so) during the summer and early fall, and the ability to chill surface water at Entiat NFH does not exist currently.
- Maintaining existing groundwater supplies is critical to the successful operation of Entiat NFH. The capacity to continue relying on groundwater to meet fish culture needs in face of climate change depends on regularly-scheduled maintenance of the groundwater infrastructure (wells, infiltration gallery). However, dedicated funds earmarked explicitly for that maintenance are not provided currently.
- High flows of the Entiat River result in high debris and sediment loads that are expected to increasingly impact Entiat NFH in the future. Those impacts could be mitigated if

existing groundwater capacity could be increased that would allow closure of the surface water intake during very high flows of the Entiat River.

- Additional groundwater capacity may be available on a recently purchased 10-acre parcel adjacent to the hatchery. However, exploratory wells and evaluations would need to be conducted before additional groundwater capacity could be added to the hatchery.

IX. VULNERABILITY

Vulnerability is the effect of impacts from an environmental disturbance, such as climate change, that cannot be adequately addressed by existing adaptive capacity.

A. Summer Chinook Salmon program

The Summer Chinook Salmon program at Entiat NFH has proven to be very successful since its inception in 2009. Extensive use of groundwater for fish culture is credited with a very low incidence of disease reported by Fish Health staff. The ability of the hatchery to rear Chinook Salmon for their first year on 100% groundwater is unique among National Fish Hatcheries in the Pacific Northwest. Surface water is used primarily (a) during the fall, winter and early spring of the second year of juvenile rearing when water from the Entiat River is generally abundant and (b) during the summer to supplement groundwater in the adult capture pond and ladder when adults are trapped for broodstock. As such, the Summer Chinook program at Entiat NFH is considered to have low vulnerability to the projected impacts of climate change through the 2040s assuming that the groundwater supply is secure and the infrastructure can be adequately maintained. However, our assessment did not model potential impacts from anticipated increases in water temperatures of the mainstem Columbia River and the future ability of Chinook Salmon to migrate upstream during the summer when water temperatures are expected to be highest. These latter impacts are a major uncertainty (Appendix D).

B. Hatchery infrastructure

Debris flows, siltation, and floating ice are considered the greatest risks to the hatchery infrastructure during high flows of the Entiat River. The incidence of these events is expected to increase in the future as the Entiat River basin continues to transition from primarily a snow-melt-driven watershed to a mixed-rain-and-snow-melt watershed. Direct flood and fire risks to the hatchery are considered low, but hatchery staff did note possible flood risks to the area of the hatchery grounds where the wells are located, particularly during projected 100-year peak flows that could exceed 14,000 cfs. Overall, the infrastructure of Entiat NFH is considered to have moderate vulnerability to the future impacts of climate change, due largely to the vulnerability of the groundwater supply and infrastructures necessary for delivering that water year-round to the hatchery for fish culture.

C. Vulnerability main points

- Summer Chinook Salmon at Entiat NFH appear to have a comparatively low vulnerability to the future impacts of climate change because of the high dependence on groundwater for fish culture. However, that low vulnerability depends on the capacity to conduct regularly-scheduled maintenance of the groundwater infrastructure.
- The infrastructure of Entiat NFH is considered moderately vulnerable to the future impacts of climate change, largely because of uncertainties regarding future impacts to groundwater supplies and the high dependence of the hatchery on groundwater. The hatchery may also be moderately vulnerable to higher peak flows of the Entiat River and flood risks to the existing well field.
- Potential impacts to adult Summer Chinook Salmon from higher water temperatures of the mainstem Columbia River is a major uncertainty that was not addressed in the vulnerability assessment presented here. However, based on other published studies, Summer Chinook Salmon at Entiat NFH could be vulnerable to higher water temperatures projected for the Columbia River (see below).

X. BIOLOGICAL AND ENVIRONMENTAL UNCERTAINTIES

The vulnerability assessment presented here does not address two major uncertainties: (1) the effect of climate change on the marine environment and ecosystems, including the *migration corridor* from the Pacific Ocean to the Entiat River via the mainstem Columbia River, and (2) the future epidemiology of fish pathogens and disease under the climates projected for the 2040s. Both factors could greatly affect the ability of hatcheries in the Columbia River basin of the Pacific Northwest to propagate Pacific salmon and Steelhead through the 21st Century. Details regarding these uncertainties are described in Appendix D.

XI. CONCLUSIONS

1. Overall, Entiat NFH and the Summer Chinook Salmon program appear to have a comparatively low vulnerability to the future impacts of climate change. This low vulnerability is due primarily to the ability of the hatchery to rely on 100% groundwater for the culture of Summer Chinook Salmon during the first year of the rearing cycle (October to October). The incidence of disease and other physiological issues (i.e., stress) have been minimal in the past and are expected to be minimal in the future if groundwater can continue to be used for fish culture according to current protocols. We conclude that the future climate projected for the 2040s will most likely not preclude the ability of Entiat NFH to continue propagating Summer Chinook Salmon.
2. The potential impact to groundwater supplies of reduced flows of the Entiat River during the summer are unknown. Our modeled scenario of reduced groundwater availability

during the summer in response to reduced surface flows suggested flow index values for Summer Chinook Salmon that may exceed fish health guidelines, especially considering that each of one-third of the total number of fish are reared on 2nd-pass and 3rd-pass reuse water, respectively. However, we consider our modeled direct relationship between groundwater availability and flows of the Entiat River to be a worse-case scenario and speculate that potential reductions in groundwater availability will most likely be less severe, if measurable, than the direct-proportional relationship to surface flows that we modeled.

3. The greatest vulnerability of Entiat NFH to the projected impacts of climate change, other than the groundwater itself, is the infrastructure for delivering that water to the hatchery (six wells and the infiltration gallery). Indeed, one might consider the infrastructure for delivering groundwater as the Achilles heel of the hatchery under current culture protocols.
4. Entiat NFH is also vulnerable to debris loads, siltation, and floating ice during high flows of the Entiat River with 100-year peak-flows projected to increase from about 8,000 cfs historically to nearly 14,000 cfs by the 2040s. Potential impacts from high debris and siltation loads of the Entiat River could be mitigated if groundwater supplies were sufficient to close off the surface water intake to the hatchery and rely exclusively on groundwater during peak flows of the Entiat River.
5. Direct flood risks to the infrastructure of Entiat NFH in the 2040s appear to be low, although the area of the hatchery grounds where the wells are located may be vulnerable to 100-year peak flows.
6. Summer Chinook Salmon at Entiat NFH may be vulnerable to projected increases in water temperatures of the Columbia River during the traditional upstream-migration period. However, modeling those impacts was beyond the scope of the assessment presented here (see Appendix D).

XII. RECOMMENDATIONS

1. Ensure that the current well field and groundwater supplies to the hatchery are secure. Hydrologists should assess the flood-risk vulnerability of the existing wells at projected peak flows of the Entiat River of 14,000 cfs. If flood risks to the well field are significant, then consider construction of a diversion structure to prevent damage and/or contamination of the wells and infiltration gallery during possible floods.
2. Rehabilitate the existing groundwater infiltration gallery, including the addition of a third water collection line, to maximize the delivery of existing groundwater to the hatchery.
3. Secure dedicated funding for regularly-scheduled maintenance (e.g., every 3 to 5 years) of the groundwater infrastructure for the hatchery.

4. Explore opportunities for additional wells on a recently-purchased 10-acre parcel adjacent to the hatchery grounds.
5. Provide additional groundwater and/or mechanically-chilled surface water to the adult capture pond and ladder to reduce water temperatures and disease risks if higher water temperatures of the Entiat River during the summer become a physiological stress and/or disease issue in the future.
6. Monitor and evaluate potential changes in the timing and physiological condition (e.g., pathogen load) of upstream-migrating Summer Chinook Salmon in the mainstem Columbia River and Entiat River in response to projected increases in water temperatures.

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IX. APPENDICES

A. Appendix A. Qualitative Assessments of Climate Change Vulnerability of National Fish Hatcheries in the Pacific Region, Entiat National Fish Hatchery.

B. Appendix B. Modeling the Potential Effects of Changed Water Availability and Temperature on Pacific Salmon Culture Programs at Entiat National Fish Hatchery.

C. Appendix C. Work Group Adaptation Meeting Notes, August 25, 2021.

D. Appendix D. Biological and Environmental Uncertainties.